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Modelling and Simulating Social Systems with MATLAB

Project Report

Placing Police Officers in Circle Pits Effectively

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Zurich
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1 Abstract

Concerts are dangerous, in particular the "moshpits". The aim of this paper is to reduce the hazard introducing "police officers" among the crowd, arranged as efficiently as possible. We developed a model based on Silverberg et al.'s studies. We used it to simulate the effects of police officers on circle pits. Interesting results emerged: namely, the simulations showed a central positioning of officer barely slowed down people, whereas an arrangment blocking off an entire section of the arena quickly stopped them.

2 Individual Contributions

The authors contributed equally to this work.

3 Introduction and Motivations

If you have ever been to a rock concert, you probably know the term "mosh pit". That means people dance and run together in a form of crowd with the loud music. People often forget how dangerous it could be – even fatal – for individuals in the crowd.

Our group wanted to reduce the danger in the crowd movement. We set up different configurations corresponding to different security arrangement. We developed a simulation based on Java and ran fifteen thousand rounds of simulations for each configuration. Although we did not collect real-world data, with the help of modeling the crowd using existing physical models – based on a study from Silverberg et al –, we drew interesting conclusions based on our simulation results.

We extracted three major factors from the data, namely average danger level in time evolution, participating rate and danger levels of individuals. Then we use python scripts to generate three sorts of graphs correspondent to configurations we have chosen.

3.1 Research Question

Our research question is therefore: what is the most efficient placement of police officers among the crowd at a heavy metal concert so that the formation of circle pits is stopped swiftly (in the least amount of time) and safely (subjecting both the participants and non-participants of the circle pit to the least possible amount of danger)?

4 Description of the Model

The model is based on a paper by Silverberg et al. [1]. We will briefly explain the chief ideas of their model before explaining which adaptations and additions we had to make. In the following sections, we will refer to this model as the *Silverberg model*.

4.1 Explanation of the Silverberg Model

The Silverberg model is essentially a social force model: each individual is subject to a certain number of forces, which are composed of *individual interests* and *environmental influences* [2]. The motion of the crowd is calculated analogously to a many-particle system: Together with the initial conditions, the time evolution of a system of N particles is determined by Newton's law, which allows us to compute the acceleration of one particle a_j out of the sum of the forces F_i acting on it:

$$\sum_i F_i = ma_j \tag{1}$$

whereby masses are assumed to be the same for all individuals and therefore not considered in the model.

One of the forces used in the Silverberg model is the repulsive force that acts between two individuals as soon as they collide with each other. It acts by increasing the distance between the colliding people (equation 2). The social force model also considers a force that accelerates or decelerates the individuals towards a specific *preferred speed*: a propulsive force is added which is proportional to the difference of the preferred speed and the actual current speed (equation 3). To simulate the flocking behavior of the members of a circle pit, a flocking force that simply averages the velocities of the individuals within a certain radius r_{flock} is added (equation 4). The authors of [1] also added a random noise vector to the individuals to simulate the randomness of human movements (equation 5).

Putting all this together, Silverberg et al. obtained the following set of equations governing the movements of individual i:

$$\vec{F}_i^{\text{repulsion}} = \begin{cases} \epsilon\left(1 - \frac{r_{ij}}{2r_0}\right)^{\frac{5}{2}} \hat{r}_{ij} & \text{for } r_{ij} < 2r_0 \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

$$\vec{F}_i^{\text{propulsion}} = \mu(v_0 - v_i)\hat{v}_i \tag{3}$$

$$\vec{F}_i^{\text{flocking}} = \alpha \sum_{j=0}^{N_i} \vec{v}_j \Bigg/ \left\| \sum_{j=0}^{N_i} \vec{v}_j \right\| \tag{4}$$

$$\vec{F}_i^{\text{noise}} = \vec{\eta}_i \quad (\vec{\eta}_i \text{ is random}) \tag{5}$$

where r_0 is the radius of an individual, r_{ij} is the center-to-center distance between two individuals i and j, v_0 is the preferred speed of an individual, and v_i is the instantaneous speed of individual i. N_i is the number of neighbors of i within the radius r_{flock}. A circumflex ($\hat{}$) above a variable denotes a unit vector. ϵ, μ, and α are real numbers representing the relative magnitudes of these forces.

4.2 Adaptations and Additions to the Silverberg Model

The Silverberg model focuses on simulating moshpits. To adapt it to circle pits and to simulate the effects of the policemen on the crowd, we had to make a couple changes to it

4.2.1 Centripetal force

A commonly stated goal while participating in a circle pit is to move towards the center of the circle. According to the social force model, this *individual interest* can be considered as a further acting force on the individual. We therefore chose to consider a centripetal force that pulls each participating individual towards one specific point in the center $\vec{c}$ (which is the same for each participating individual). The centripetal force on individual i can be described by equation 6:

$$\vec{F}_i^{\text{centripetal}} = \gamma \frac{\vec{c} - \vec{x}_i}{\|\vec{c} - \vec{x}_i\|} \tag{6}$$

where $\vec{x}_i$ is the position vector of individual i and γ is a real number representing the relative magnitude of the centripetal force.

4.2.2 Removal of noise

The Silverberg model is designed to simulate general coordinated crowd phenomena, which also includes the mosh pits. In a mosh pit, people move in random directions with the aim of colliding with their neighbors as often as possible. The random noise that is added to the force

therefore fulfills a considerable function. Since we are limiting our analysis to circle pits and since people generally do not aim to collide with other people while participating in a circle pit, we decided not to implement the random noise.

4.2.3 Repulsive force

The repulsive force that is used in the Silverberg model acts between two individuals as soon as they touch each other. This choice of force is sensible when analyzing general mosh pits in which the participating people do not try to avoid collisions (and even aim for them). Since collisions are considered undesirable in circle pits, our choice of the repulsive force leads to a repulsion even if two individuals approach within a certain radius of each other, even though they are not yet touching. This can be led back to an additional *individual interest*. We consider two separate cases: either two individuals i and j are already "overlapping" (i.e. they are occupying the same physical space) or they are merely in proximity to each other. This leads to the following set of equations for the repulsive force:

$$\vec{F}_i^{\text{repulsion}} = \begin{cases} 500\epsilon\hat{r}_{ij} & \text{if } r_{ij} < 2r_0 \\ \frac{\epsilon\vec{r}_{ij}}{r_{ij}(2r_0 - r_{ij})} & \text{if } r_{ij} < 2r_1 \\ 0 & \text{otherwise} \end{cases} \tag{7}$$

The reason for splitting the calculation of the repulsive force into these categories is to discourage the overlapping of individuals much more strongly than their being close to each other. In equation 7, r_0 remains the radius of one individual, but r_1 is another constant that represents the radius within which being in proximity to another individual incurs a repulsive force.

4.2.4 Effect of policemen

The effect of a policeman that is placed within the crowd is to prevent people in its direct environment to participate in the circle pit. That means that as soon as an individual is closer to a policeman than a given radius, its participating state will automatically change to "is not participating", with all the consequences discussed in the subsection 4.2.5.

4.2.5 Participation condition

Contrary to the Silverberg model, the number of participants in the circle pit is not fixed. An individual's will to participate is influenced by its neighborhood: conditions — such the number of people participating around him — will increase, or respectively, decrease it. This *will* is represented by the boolean variable `isParticipating`, which follows two conditions:

1. If the individual is not participating and has at least `minParticipantNeighbors` other participating individuals around him, he will start participating
2. If the individual is participating and has less than `minCirclePitSize` other participating people around him, he will stop participating.

If a person is participating, he is subject to all the forces described by our model. Otherwise, he is not subject to the flocking force and the centripetal force and his *preferred speed* is considerably reduced.

In total, the force $\vec{F}_i$ acting on individual i is calculated as follows:

$$\vec{F}_i = \begin{cases} \vec{\tilde{F}}_i^{\text{repulsion}} + \vec{F}_i^{\text{propulsion}} + \vec{F}_i^{\text{flocking}} + \vec{F}_i^{\text{centripetal}} & \text{if } i \text{ is participating in the circle pit} \\ \vec{\tilde{F}}_i^{\text{repulsion}} + \vec{F}_i^{\text{propulsion}} & \text{otherwise} \end{cases} \tag{8}$$

4.2.6 Calculating the danger an individual is in

Since one of our goals is to analyze how much danger individuals are subject to in a circle pit and minimize it through the clever placement of police officers and the arena, we need a way to assess how much danger an individual is in.

An individual i can be said to be in danger if the norm of the force $\vec{F}_i$ acting upon it is large. Due to equation 1, a high force implies an increase of velocity and a high acceleration, both of which are dangerous. Furthermore, the danger is increased if i is at a very dense spot in the arena (i.e. has many neighbors). We therefore define the function density(i) as the amount of neighbors of i within the radius r_{flock}. Putting this together, we obtain the following danger function:

$$\text{danger}(i) = \frac{||\vec{F}_i||}{\zeta} + \frac{\text{density}(i)}{\eta} \tag{9}$$

where ζ and η are real numbers that must be chosen so that $||\vec{F}_i||$ and density(i) contribute approximately equally to danger(i) (they depend on the values chosen for α, ϵ, μ, and γ).

5 Implementation

We decided to implement our model in Java because MATLAB was too slow to be able to animate the simulation in real time.

5.1 Implementation of an Individual

An individual is represented by the `Individual` class. This class simply stores the position, velocity, and preferred speed of the individual. Furthermore, it stores whether the individual is participating in the circle pit, the parameters necessary to calculate the danger the individual is in (norm of force and density) and the current danger level.

There are also convenience methods to facilitate certain tasks like finding the distance between two individuals or between the individual and a point.

5.2 Development of the Main Data Structure

5.2.1 Requirements for the main data structure

In order to implement our model, we needed a data structure for the individuals that could do the following things efficiently:

1. Get the neighbors of a given individual (we should not have to traverse the entire data structure to find them)
2. Move an individual in the arena
3. Place an individual at an arbitrarily precise position in the arena

5.2.2 Design of the data structure

To do this, we initially considered using position matrix like the one used in the cellular automaton model (where each individual x is located at a particular cell (i, j) of the matrix). This would allow us to efficiently find the neighbors of x, as we simply need to look at the cells around position (i, j). However, implementing such a matrix would not be possible to due the large number of individuals involved (by our estimates, even a simulation with 500 individuals would have resulted in a matrix taking up approximately 2 GB of RAM). Furthermore, one of the drawbacks to this method would be that the number of positions an individual can be at at any given time is limited to the number of cells of the matrix.

We therefore decided to split the matrix up into sectors. Each sector can contain several individuals at the position indicated by their position property (the positions are relative to the entire matrix, not the sector). This also does not affect the ability to efficiently find the neighbors of an individual x, since if the partition into sectors is fine-grained enough, we can simply look at the sectors in the vicinity of the sector containing x, which would not incur too large of a performance loss. Each sector contains a specific coordinate space, so the position of an individual must be in the coordinate space of its sector. For example, in our implementation, each sector contains 10 coordinate positions, so any individuals with a position $(i, j) \in [0, 10) \times [0, 10)$ are in the sector at position $(0, 0)$ in the matrix (i.e., the sector in the upper left corner). This approach also allows individuals to be located at arbitrarily precise locations (subject only to the machine precision ε).

5.2.3 Implementation in Java

In our implementation, such a sector is actually a `java.util.ArrayList` to which we can add as many individuals as we want. The precise location of each individual within its sector is defined by its position property.

The final result is a data structure based on a matrix of `ArrayList`s, whereby each `ArrayList` is a list containing all the `Individual` objects in the sector represented by that `ArrayList`. We also defined certain convenience methods and properties to simplify the usage of the data structure, including:

- A `Sector` inner class to represent a sector (defined by a row and a column index within the matrix)
- An `ArrayList` of all the individuals currently in the matrix to allow easy iteration over all the individuals in the matrix
- Getter methods for getting the `ArrayList` at a particular position (i, j) or at the location specified by a `Sector` object
- An "add" method to add an individual to the matrix at the proper sector
- Methods to transform (x, y) coordinates to a sector
- A method to get the neighbors of a specified individual

This functionality is implemented in the `PositionMatrix` class. The precise functionality of each method is described in the Javadoc comments.

5.3 Implementation of the Model

Using the `PositionMatrix` and `Individual` classes, implementing the model was relatively straightforward. The entire simulation is implemented in the `Simulation` class, which has methods to initialize the simulation, to run one timestep of the simulation and to run the simulation as a live animation.

5.3.1 Initializing the simulation

All the necessary parameters of the simulation are read via the constructor of the `Simulation` class. After that, we simply need to initialize the position matrix. To do this, we simply generate individuals with a random position and velocity and then add them to the position matrix. Each individual participates in the circle pit with a certain probability.

5.3.2 Running one timestep

In this method, we run the simulation for all individuals in one time step. In order to achieve this, we iterate over all the individuals and calculate the joint force $\vec{F_i}$ acting upon them, which according to equation 1 gives the second derivative of the position. To integrate this differential equation numerically, we make use of the *Leapfrog Method*. This method is based on the idea of updating the positions and velocities at interleaved time points. It is known to be less affected by error accumulation due to rounding errors (i.e. more numerically stable). The formulas and parameters we use for calculating $\vec{F_i}$ are based on equation 8 derived from the Silverberg model [1] and our own additions and adaptations of it.

We also update the individuals' levels of danger based on an appropriate scale of joint force and density in two ways: we calculate a *discrete danger level* (DDL) (DDL $\in \{0, \ldots, 6\}$ is a discrete measure of the danger level useful for visualizing the danger level) and a *continuous danger level* (CDL) corresponding to danger(i) from equation 9. We use different levels of colors to represent the DDLs. The two factors contributing to the DDL, density and joint force, can be activated or deactivated respectively by two check boxes in the GUI. This helps the users to see different impacts from these two factors.

5.3.3 Animating the simulation

Animating the simulation was very simple: every 50 milliseconds, we run one timestep of the simulation and update the graphics. If necessary, we also collect data (see Section 5.6).

5.4 Graphical Code

This subsection describes the code necessary to create the GUI and animate the simulation on the screen.

We used the Swing framework to create the graphics. The main window is simply a `JFrame` containing two `JPanels`: one for the simulation and one for the controls pertaining to the model.

Drawing the simulation is very simple: we simply need to iterate over all the individuals of the matrix and draw them based on their position property, with some additional scaling to fit the window size. The animation is achieved simply by periodically running one timestep and then refreshing the window.

The controls were also very simple to implement: each one of them simply changes the corresponding field of the current `Simulation` instance.

The main window is implemented in the `SimulationGUI` class, the animation is done is `SimulationPanel`, and the panel with the controls is in `ControlPanel`.

5.5 Configuring the Simulation

To be able to efficiently vary the parameters and police officer configurations, we needed a way to efficiently specify how a simulation should be run so that it could be run automatically. To this end, we defined how a configuration should be run using configuration files. The format of these configuration files is explained in Appendix B.

5.6 Collecting Data

In order to perform our analysis, we needed a way to automatically collect data. We defined two classes for this: `DataCollector` and `AutomaticSimulator`. `DataCollector` simply runs the simulation by repeatedly running one timestep and gathers the positions and velocities acting on the individuals as well as the forces acting on them and their densities according to the density function. Furthermore, we output the CDLs as well as the average CDL, maximum CDL and median CDL. `AutomaticSimulator` runs several simulations with various random seeds using the configuration files specified in a file called `configs.sim` and uses `DataCollector` to run one instance of the simulation and collect data on that simulation.

6 Experiment & Methods

6.1 Determining the Parameters α, γ, μ, ϵ, ζ, and η

We had to find a suitable configuration of these parameters in order to make the simulation closer to reality. This set of parameters is applied to every configuration of policemen, since varying would exceed the bounds of this study (lead to too much data). By experimenting with different values, we established that the values $\alpha = 700$, $\gamma = 600$, $\mu = 10$, and $\epsilon = 2$ generate a reasonably accurate-looking circle pit simulation. Having fixed these values, we could determine ζ and η by looking at the average force and density and selecting them so that $||\vec{F}_i||$ and density(i) contribute approximately equally to danger(i). We selected $\zeta = 10000$ and $\eta = 50$.

6.2 Configurations of Police Officers Used

We decided to test eleven police officer configurations. The configuration files for these configurations are given in Appendix C.

Each configuration has exactly ten police officers so that the effectiveness of the configurations can be easily compared.

6.3 Method for Data Collection

We collected data once every second of the simulation, i.e. every 20 timesteps. We also chose 50 different random seeds for the initial velocities and positions of the individuals.

6.4 Methods Used for Analysis of Data

To analyze the data we collected, we plotted two graphs for each arrangement of police oficers, that show the time evolution of quantities describing how the circle pit situations evolve. Those graphs showed the median of the *danger level* along the time, averaged over the various simulations with different random seeds. That did not only allow a good and immediate comprehension about the efficiency of a certain configuration, but also gives us a good method to compare the methods to each other. The y-axis of the graph showing the median of the danger level with respect to the time as for example seen in 1, is chosen so that median danger = 1 corresponds to the maximum value, which in our cases is achieved shortly after the police officers are inserted to the crowd.

We also generated a graph showing the participation rate over time of all the configurations. The participation rate equals one if all individuals in the crowd are joining the circle pit and it is zero as soon as nobody is participating anymore.

Furthermore, we created phase diagrams showing the danger "hot spots" at a specific time, averaged over all the random seeds. We generated separate phase diagrams to show the influence of force and the danger of density of the total danger level of the individual.

7 Simulation Results and Discussion

7.1 Effectiveness of Exemplary Police Officer Configurations

In the graphs below, if we compare the graphs with the danger level to the graphs with the participating rate, it seems that when the participation rate is zero, the danger level hovers at around 0.47 (just below 0.5).

7.1.1 Configuration: Arrow

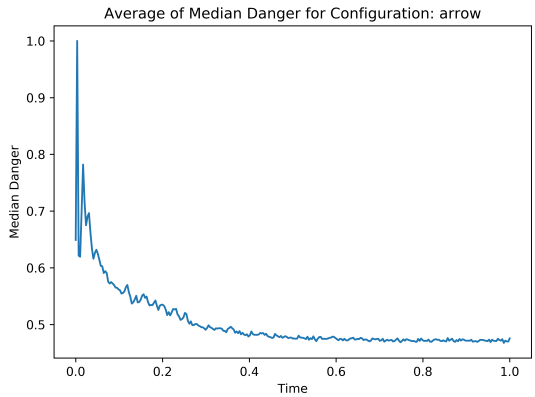


Figure 1

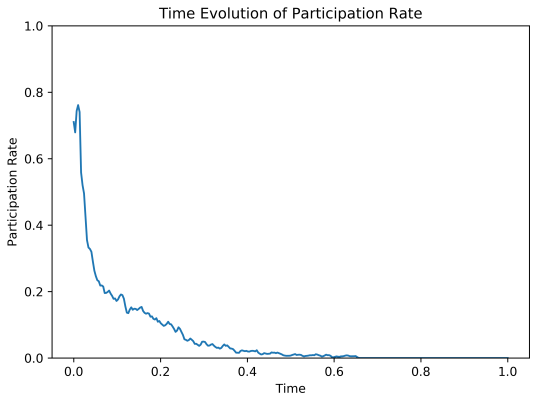


Figure 2

The configuration “arrow” is similar to the configuration ”double half line”. And it is also very good at decreasing the participation rate, since the two lines of policemen stop quite a lot of people. From the median danger aspect this configuration is also very useful since the level converges to 0.5 within a short period of time.

7.1.2 Configuration: Big Circle

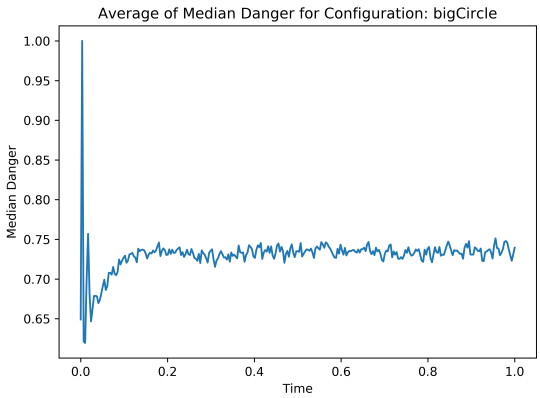


Figure 3

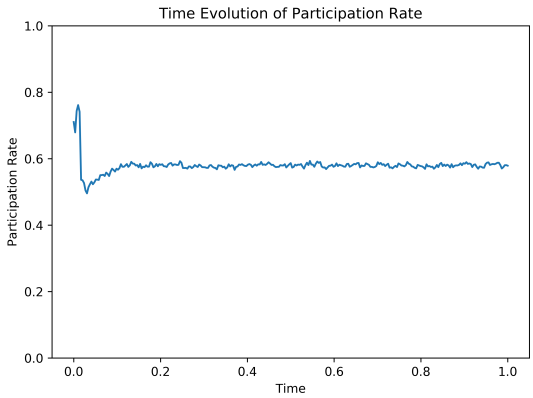


Figure 4

The configuration “big circle” is not very effective. First of all, the policemen are all placed near the middle of the arena, so the circle pit can still move around the policemen. Also, since the line of policemen outlining the big circle is not complete, the participants of the circle pit can still slip in between the gaps where there are policemen, thus contaminating the people inside the circle and rendering the circle of policemen quite useless.

7.1.3 Configuration: Center

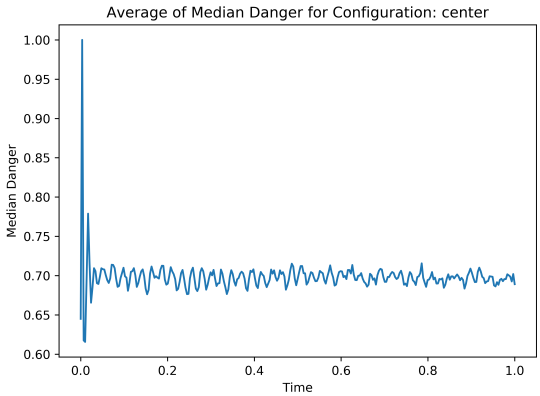


Figure 5

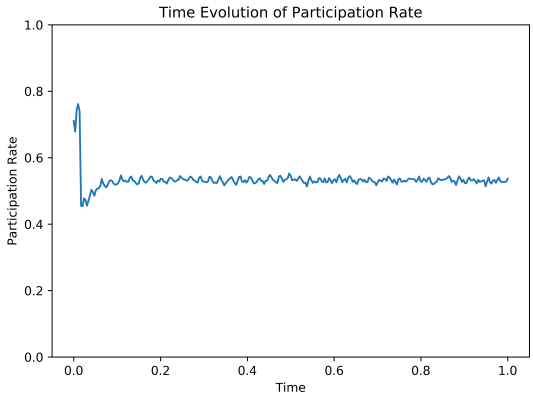


Figure 6

The configuration "center" is also does not work very well. Since all the policemen are in the middle, they do not affect the crowd circling around them. Thus, both median danger level and participation rate stay at a high level (0.7 and 0.45 respectively).

7.1.4 Configuration: Circle

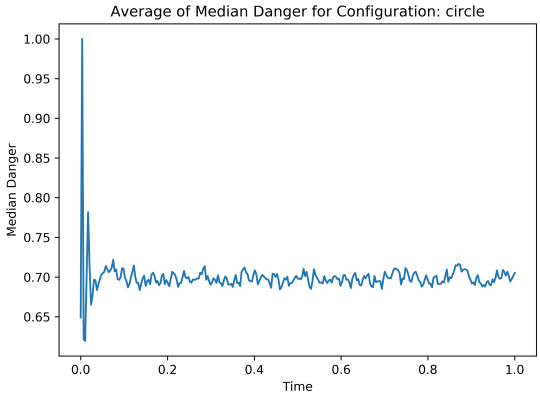


Figure 7

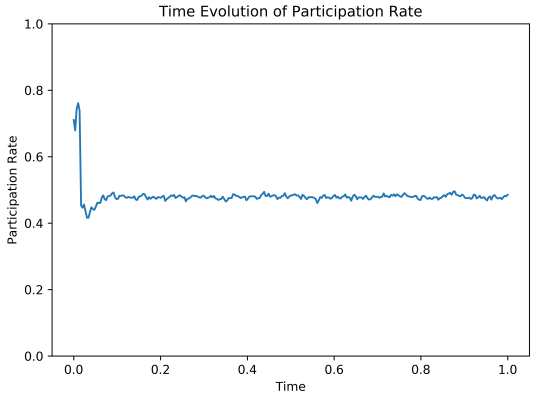


Figure 8

The "circle" configuration is not very effective at stopping the circle pit because the policemen are only placed at the center of the arena (similarly to the "center" configuration). The circle pit can still rotate around the cluster of policemen. Moreover, the non-participants inside the circle of policemen often are squeezed very tightly since they experience repulsive forces from all sides of the circle due to the influx of participating members that suddenly stop participating, making the density in the circle very high (and therefore making it very dangerous).

7.1.5 Configuration: Control

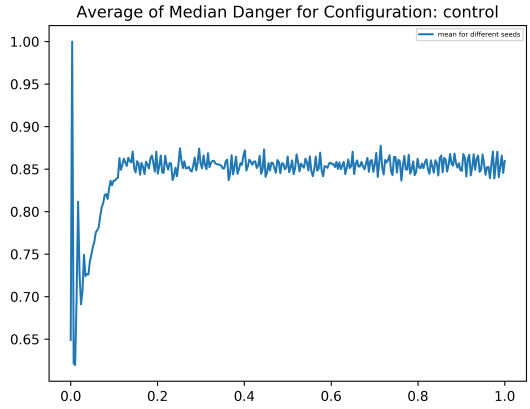


Figure 9

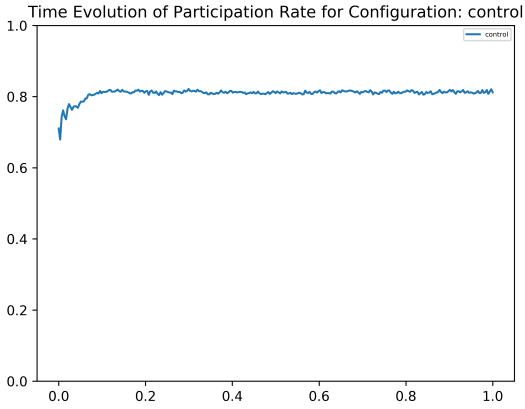


Figure 10

The configuration "control" works as a control group to show that the policemen really make a difference in controlling the crowd movement. The danger level without police officers controlling the crowd is much higher than the danger level with police officers, even if the police officer configuration did not succeed in stopping the crowd. The participating rate is also much higher than the other configurations.

7.1.6 Configuration: Corner

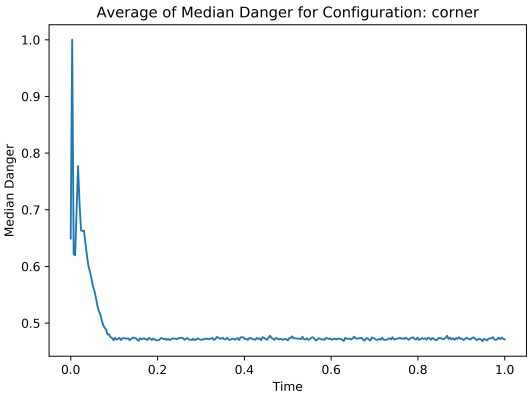


Figure 11

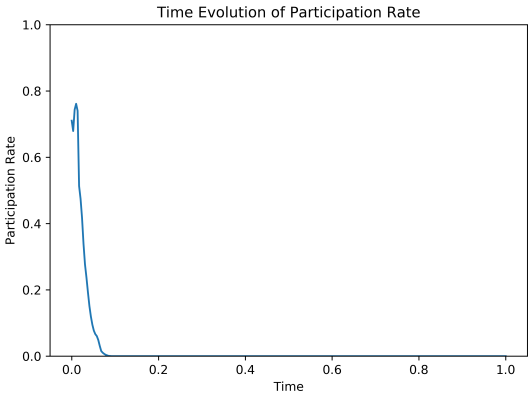


Figure 12

The "corner" configuration proved to be very effective at stopping the circle pit without causing a large amount of danger. Since one entire corner is blocked off by the police and since the individuals move freely, at some point, all the participating individuals will have moved out of that corner. This means that now anyone entering the corner will enter a "region" of the arena where no one is participating. After a while, every participating individual has passed through the corner and the circle pit is stopped. Since the circle pit tends to accumulate in one big mass (i.e. not distributed evenly across the arena), an individual exiting from the corner does not join the circle pit again (the "mass" of participating individuals is at the "entrance" to the corner).

7.1.7 Configuration: Cross

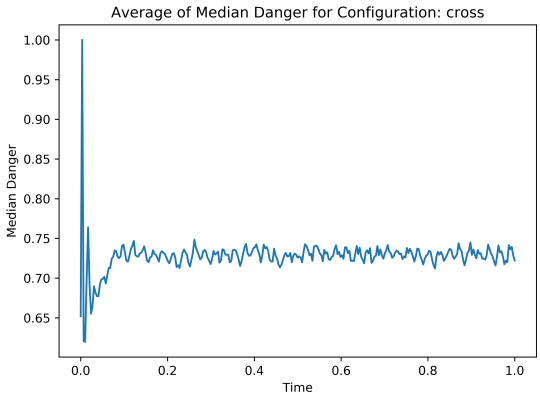


Figure 13

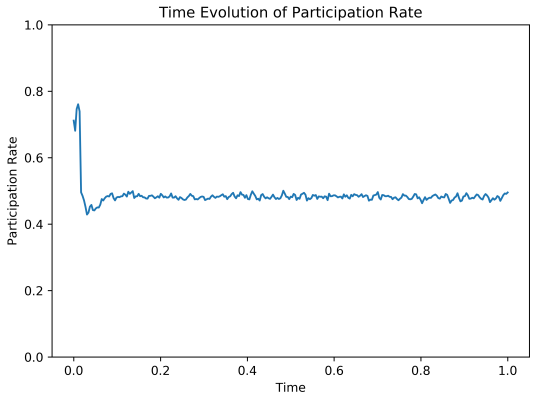


Figure 14

The "cross" configuration did not prove to be very effective. The circle pit was never stopped (the participation rate never reached 0) and individuals remained at a very high level of danger (around 0.73). This can be explained by the fact that the police officers are only present in the center of the arena. The individuals are still free to circle around the cross formed by the policemen. Furthermore, after passing one "arm" of the cross, individuals can still be "contaminated" by individuals circling around the cross.

7.1.8 Configuration: C-shape

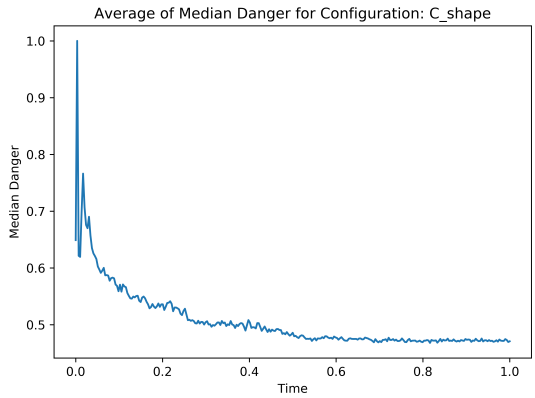


Figure 15

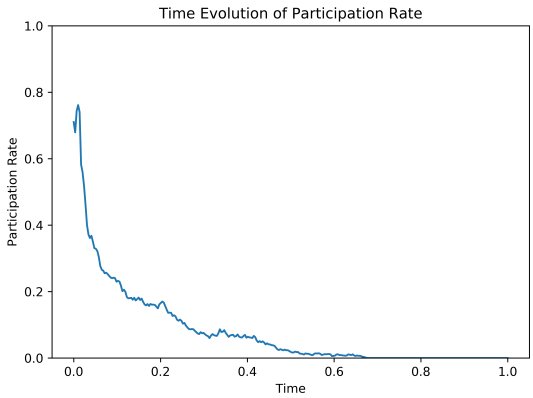


Figure 16

The "C-shape" configuration seems to be quite useful. The circle pit stopped rather quickly, namely the rate of participation goes to zero rapidly. Also the average of median danger declined in short time as well. The two curves are similar to the the configuration "Double Half-Line". But we observed the crowd is slightly split into two discontinuous parts.

7.1.9 Configuration: Diagonal

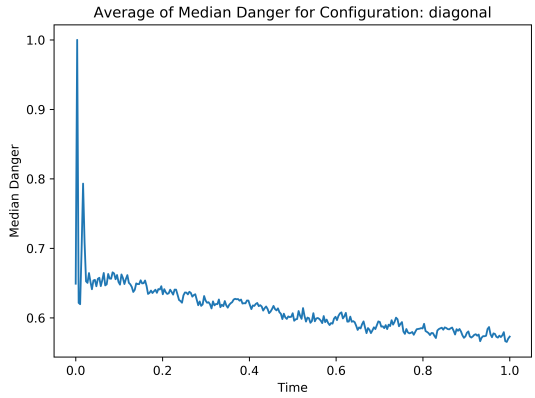


Figure 17

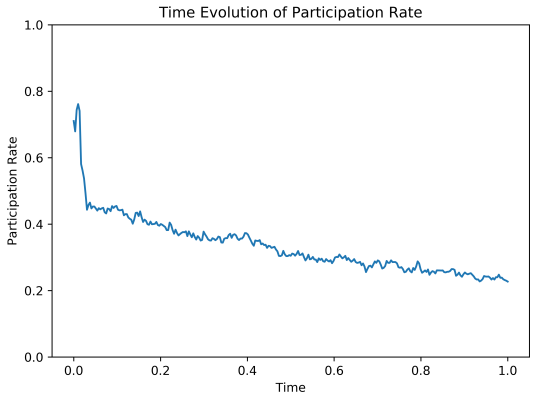


Figure 18

The "diagonal" configuration works not very well with decreasing the median danger (to around 0.6). The circle pit was also never stopped. This can be explained by the fact that the police officers are standing on the diagonal of the arena. The individuals can still rotate and move like without policemen, but decrease their speed every time passing the diagonal. The area of influence of the policemen is a square and these squares are arranged in a diagonal line. This means that two squares always touch corners (i.e. the lower right corner of one square touches the upper left corner of the next square etc.). This means that at the points where two squares are touching, the policemen have almost no effect. The circle pit can therefore still be propagated across these interstices, and the diagonal configuration is almost always unable to stop the circle pit.

7.1.10 Configuration: Double Half-Line

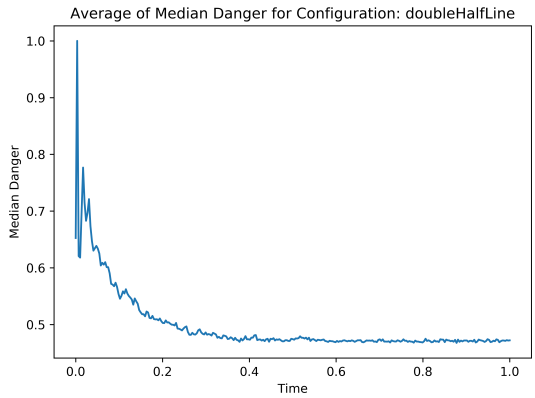


Figure 19

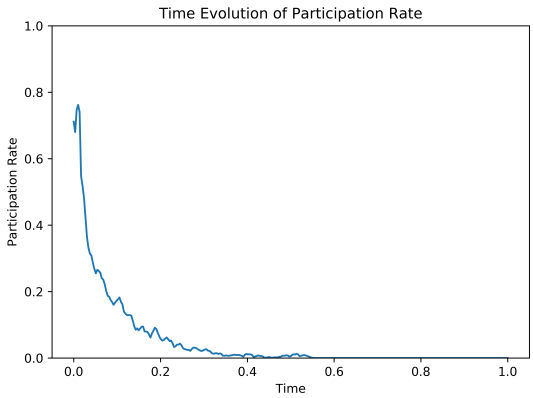


Figure 20

The configuration "double half-line" is very effective. It decreases both the median danger level and the participating rate to a very low level within a short time. One reason for this is that the area created by the policemen effectively stores many people and forces them stop participating. However, we noticed while running the simulation that the circle pit has a tendency to split up into two separate direction after crossing the double half-line and collides at the double half-line. This possibly contributes to the fact that danger remains fairly high and only tapers off gradually compared to other configurations.

7.1.11 Configuration: U-shape

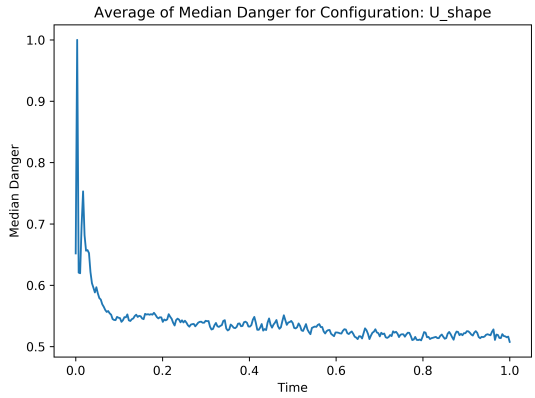


Figure 21

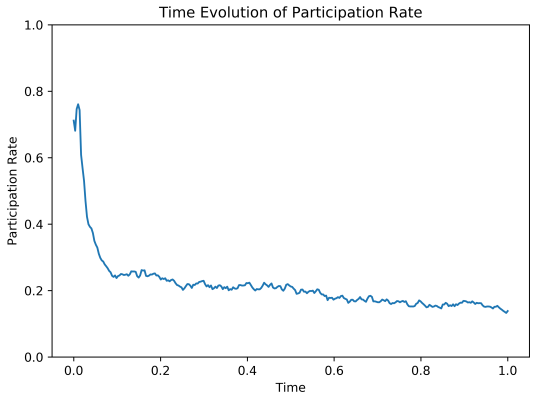


Figure 22

The configuration "U-shape" is very effective in decreasing of the median danger level, since it quickly stops almost half of the people within the U shape. But the entire group never stops (participating rate never goes to zero) because there will be a small group of people keeps on moving outside the area of U shape. It is likely that increasing the size of the U would be much more effective because more people would get "trapped" in the U.

7.1.12 Configuration: Vertical Line

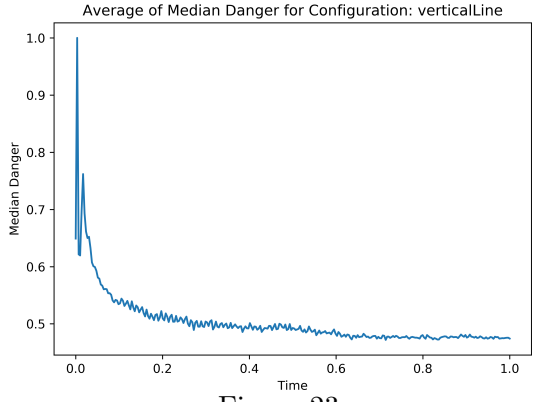


Figure 23

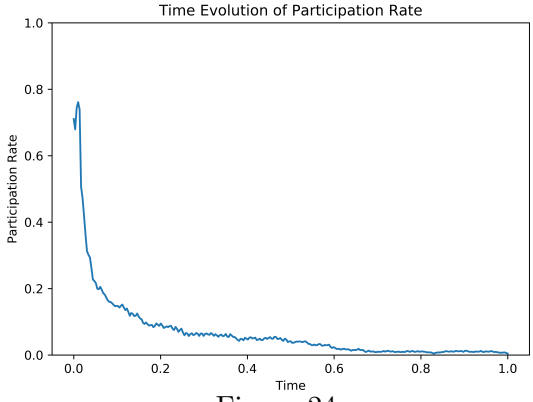


Figure 24

The configuration "vertical line" is very powerful in stopping the crowd. Initially, there are participants on both sides of the line. However, after both sides cross the line several times, the amount of participants dwindles significantly until there are so few participants on either side of the line that they do not influence "newcomers" having just crossed over the line from the other side. Because of this, the participation rate very quickly converges to a level below 0.5.

7.2 Comparison of Police Configurations

Since the aim of this simulation was to determine the most efficient placement of policemen, we will now compare the different configurations we tested.

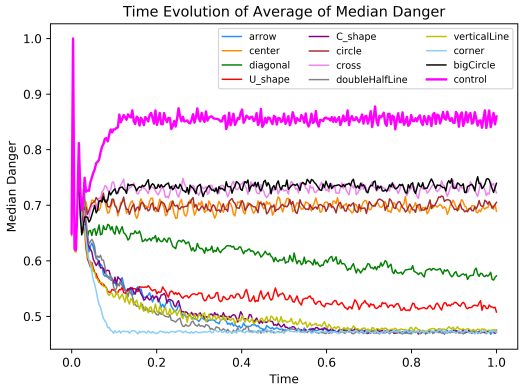


Figure 25

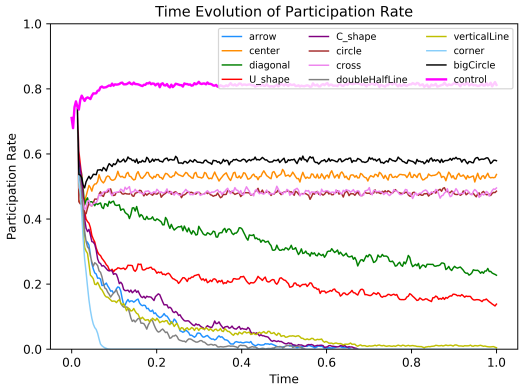


Figure 26

Figure 25 shows a graph containing the danger levels of all the configurations we tested. As mentioned before, all the configurations induce a lower danger level than the control configuration, even if the circle pit was not stopped.

Based on Figure 25, we classified the configurations into three categories:

1. Circle pit eliminated (danger level below 0.5)
2. Circle pit not eliminated, but danger level at end below 0.6
3. Circle pit not eliminated and final danger level between 0.6 and 0.8

Looking at Figures 25 and 26, we can easily see that the configurations "arrow", "C-shape", "corner", "diagonal", and "double half-line" belong to the first category. "Corner" stands out from the other in that it decreases the participation rate to zero considerably faster than the other configurations. These configurations all block off a section of the arena through an impenetrable wall of police offices large enough to substantially reduce the amount of participating individuals passing through it. Furthermore, the wall is placed in such a way that individuals emerging from the wall are far away from the mass of participating individuals and do not feel any motivation to join the circle pit again.

The configurations "U-shape" and "diagonal" fall within the second category. Although they do not manage to bring the participation rate to zero, they keep the amount of danger at a fairly safe level. As mentioned in sections 7.1.9 and **??**, they both reduce the amount of participating individuals, but do not provide enough coverage over the entire arena (in the case of "U-shape") or have interstices that allow the circle pit to seep through the line of policemen (in the case of "diagonal").

The third category contains the configurations "big circle", "center", "circle", and "cross". These configurations all have the property that the policemen are clustered at the center of the arena so that the crowd can still form a circle pit around them. Therefore, the participation rate and danger level do not decrease as with the other configurations, but remain at a fairly stable level.

In conclusion, we can see that all of the configurations from the first category fulfill the needs of our research question. However, "corner" seems to be particularly well suited. Also, the mere presence of police officers is enough to substantially reduce the danger level and participation rate at the rock concert (compared to the "control" configuration with no police officers).

7.3 Issues with our Analysis

For our analysis, we had to collect data once every second instead of every timestep since collecting data every timestep would have lead to around 250 GB of data to analyze as well as slowing down the simulation considerably. Ideally, we would have to rerun the simulation on a supercomputer while collecting data every timestep to obtain more precise results.

7.4 Limits to our Model

In our model, we are only simulating the appearance of one single circle pit with respect to a pre-defined center. In reality, often more than one circle pit occur simultaneously and, since they mostly happen spontaneously, the center emerges naturally and may even change with time. Moreover, our experiment omits phenomena that would have to be considered in a real-life situation. First of all, the danger the police is in while regulating the circle pit is not considered. It could very well be that the "corner" configuration (which was very effective at stopping the circle pit) puts the police officers in so much danger that it would be practically infeasible to implement such security measures at a real concert. Related to this, even if one of our configurations could be implemented in real life, the police officers would probably not be able to remain in formation due to the flow of the circle pit. Also, in real life, not every individual would react to the police officers the same way. In our model, an individual under the influence of a police officer immediately stops participating. In real life, certain individuals might be more daring and might continue participating even when faced with a police officer. Finally, using our model, we could only test a finite amount of police officer configurations. In our implementation, the police officers cam only be at 100 different positions. They also have the exact same area of influence, whereas in real life, certain police officers might have a more pronounced effect on the crowd than others.

7.5 Judgment of the Danger Function

Looking at Figures 25 and 26, we can see that the danger function described by equation 9 was well-chosen. The curves for the danger level and the participation rate correspond quite closely, which makes sense due to the fact that a circle pit is obviously associated with more danger.

7.6 Comments on the Results

All in all, our results were somewhat unexpected (in fact, we only included the "corner" configuration because we thought it might be interesting, not because we suspected it might be an effective configuration). Also, configurations that we thought would do well actually turned out not to work at all (for example with diagonal). However, in each case, the results can be easily explained. In section 7.1.6 we explained why we think "corner" turned out to be so effective and also explained the major flaw with "diagonal" in section 7.1.9.

Furthermore, we discovered that the circle pit is actually quite sensitive to small changes in the configurations. For example, the "U-shape" and "C-shape" configurations are very similar (one is the rotation of the other; the motivation behind both of them was to provide a "hollow" that the members of the circle pit would run into, thereby stopping the circle pit). However, "U-shape" did not stop the circle pit whereas "C-shape" did.

Also, asymmetric configurations such as "C-shape" and "arrow" were able to stop the circle pit, even though they were both designed with the same "hollow" idea as mentioned previously. This means that even though the circle pit did not always move counter-clockwise, these configurations were still effective.

Finally, we would like to note that configuration with a double line of police officers seemed to be a little more effective than configurations with only a single line. For example, most of the time the danger level for "double half-line" was lower than that of "vertical line" (see Figure 25), whereby we can consider "double half-line" as a doubled version of half of the "vertical line" configuration.

8 Summary and Outlook

To summarize, as seen in Figures 25 and 26, we were able to compare the quality of different police configurations by observing the time evolution of the danger level and the participation rate.

We found out that the configuration "corner" (a configuration in which the police officers completely block off one of the corners of the arena) was by far the most effective.

On the other hand, we found that placing police officers near the center of the arena was the least effective because the individuals could simply circle around the police officers and continue participating.

The following ideas would have exceeded the bounds of our project but would be very interesting to consider: first of all, it would have been exciting to test our simulation with varying numbers of police officers so as to determine the relative effectiveness of single police officers. Also, as an alternative measure of crowd control, we also would have liked to implement barriers that the members of the audience could not traverse (and no social forces between people on opposite sides of the wall are present).

However, all in all, we are fairly satisfied with our results since we were able to answer our research question to a reasonable extent. For us, it was a challenge at first to get the code to run (for example, we had trouble defining a functioning version of the repulsive force since the individuals always overlapped). At first, we did not quite know where our project was headed, but after our simulation ran properly, we were able to think about the analysis of our results and find a path to a satisfactory answer to our research question.

9 References

[1] J. L. Silverberg, M. Bierbaum, J. P. Sethna, and I. Cohen, "Collective Motion of Moshers at Heavy Metal Concerts," *Physical Review Letters*, vol. 110, no. 228701, 2013.

[2] D. Helbing and P. Molnár, "Social Force Model for Pedestrian Dynamics," *Physical Review E*, vol. 51, no. 4282, 1995.

Appendix A: Launching the Simulation

Before launching the program, you must decide whether to run an automated simulation or a manual simulation. To do so, comment out the corresponding section in `Main.java`. In the example below, we are running an automated simulation.

```
    // Run a manual simulation
    // Simulation simulation = new Simulation(2, 10, 700, 600, 500,
    //                                        8, 0.01, 0.5, 6, 1, 3);
    // simulation.runManualSimulation();

    // Run an automatic simulation
    AutomaticSimulator simulator = new AutomaticSimulator();
    simulator.run();
```

If you are running an automated simulation, you must also specify which configuration files from the `configs` folder to test by listing their names (without the trailing `.config`) in the `configs.sim` file. The program can then be launched in one of the following ways:

1. Importing the Eclipse/IntelliJ IDEA project located in the `java_source` folder into Eclipse or IntelliJ IDEA and running the target `Main`
2. Executing the following commands from the `java_code` folder in a terminal (assuming the Java compiler `javac` and the Java Runtime Environment (JRE) are installed)

```
    $ javac -classpath . -sourcepath src -d . src/Main.java
    $ java Main
```

Appendix B: Explanation of Configuration File Format

The format for the `.config` files is given in the example below. Note that in an actual `.config` file, the comments (starting with `#`) must be removed.

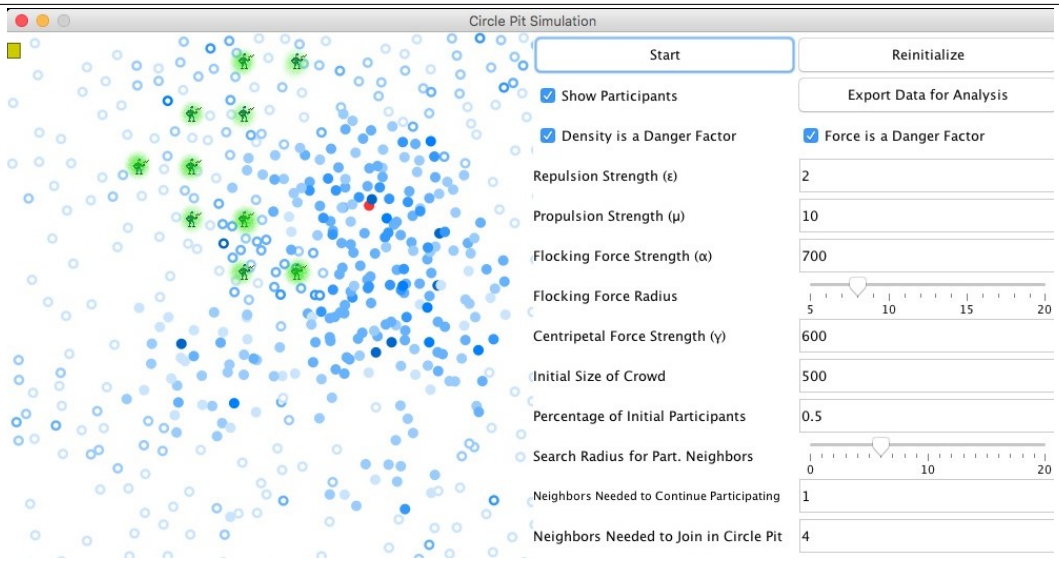
```
# This is a guide to show how to write a config file. In a real config file,
# all lines starting with '#' MUST be removed.
# Have a look at Appendix C to see a real config file.
# Each config file must start with a one-line comment:
This comment briefly explains the configuration.
# These next lines are fairly self-explanatory, they are the same as in the
# Simulation class.
epsilon:                2     # Strength of repulsive force
mu:                     10    # Strength of propulsive force
alpha:                  700   # Strength of flocking force
gamma:                  600   # Strength of centripetal force
numberOfPeople:         500   # Initial number of people in the arena
flockRadius:            8     # r_flock (radius in which to search for
                              # neighbors for the flocking force
dt:                     0.01  # Timestep
percentParticipating:   0.5   # Proportion of people initially participating
                              # in the circle pit
rParticipating:         6     # Radius in which to search for participating
                              # neighbors
```

```
minCirclePitSize:          1     # Min. number of neighbors needed to continue
                                 # participating in the circle pit
minParticipatingNeighbors: 3     # Min. number of neighbors needed to join in
                                 # circle pit
dataCollectionInterval:    2000  # After how many milliseconds to collect data
insertPoliceAfter:         0     # After how many timesteps (not milliseconds!)
                                 # police should be inserted.
collectDataThisManyTimes:  3     # How many times to collect data
useThisManySeeds:          2     # How many seeds to test
# The next section is a "graphical" representation of where the policemen are
# located. Each policeman is denoted by an 'x'. The representation below must
# include the  borders of the matrix and should be 10 spaces wide and 10 lines
# long.
policeConfig:
 ----------
|    x     |
|    x     |
|    x     |
|    x     |
|    x     |
|    x     |
|    x     |
|    x     |
|    x     |
|    x     |
 ----------
```

Appendix C: Configuration Files Used

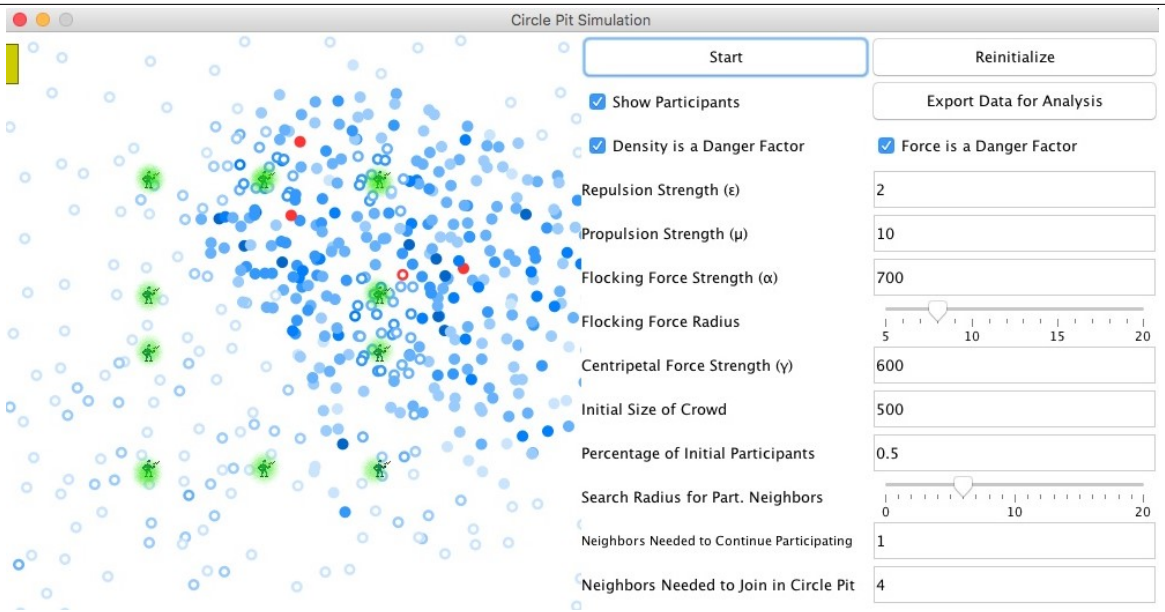
C.1: Arrow

```
A policeman configuration in the shape of a left-pointing arrow. Policemen are added after 5 se
epsilon:                    2
mu:                         10
alpha:                      700
gamma:                      600
numberOfPeople:             500
flockRadius:                8
dt:                         0.01
percentParticipating:       0.5
rParticipating:             6
minCirclePitSize:           1
minParticipatingNeighbors:  4
dataCollectionInterval:     1000
insertPoliceAfter:          100
collectDataThisManyTimes:   300
useThisManySeeds:           50
policeConfig:
 ----------
|    xx    |
|   xx     |
|  xx      |
|   xx     |
|    xx    |
|          |
|          |
|          |
|          |
|          |
 ----------
```



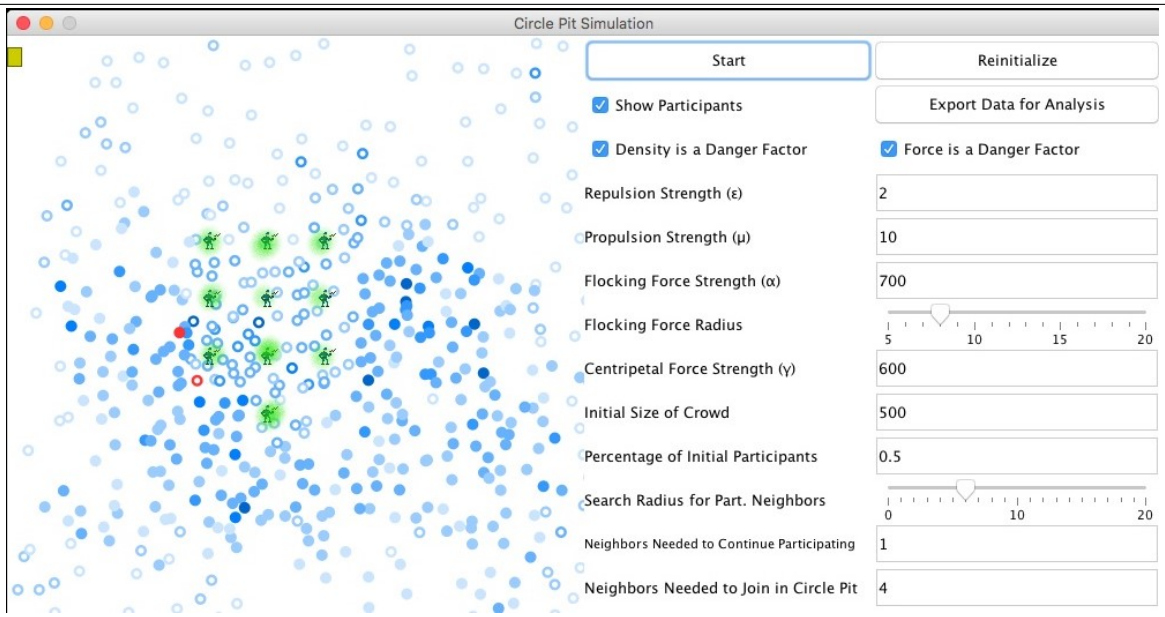
C.2: Big Circle

```
A "circle" of policemen larger than the 'circle' config file. Policemen are added after 5 secon
epsilon:                    2
mu:                         10
alpha:                      700
gamma:                      600
numberOfPeople:             500
flockRadius:                8
dt:                         0.01
percentParticipating:       0.5
rParticipating:             6
minCirclePitSize:           1
minParticipatingNeighbors:  4
dataCollectionInterval:     1000
insertPoliceAfter:          100
collectDataThisManyTimes:   300
useThisManySeeds:           50
policeConfig:
 ----------
|          |
|          |
|  x x x   |
|          |
|  x   x   |
|  x   x   |
|          |
|  x x x   |
|          |
|          |
 ----------
```



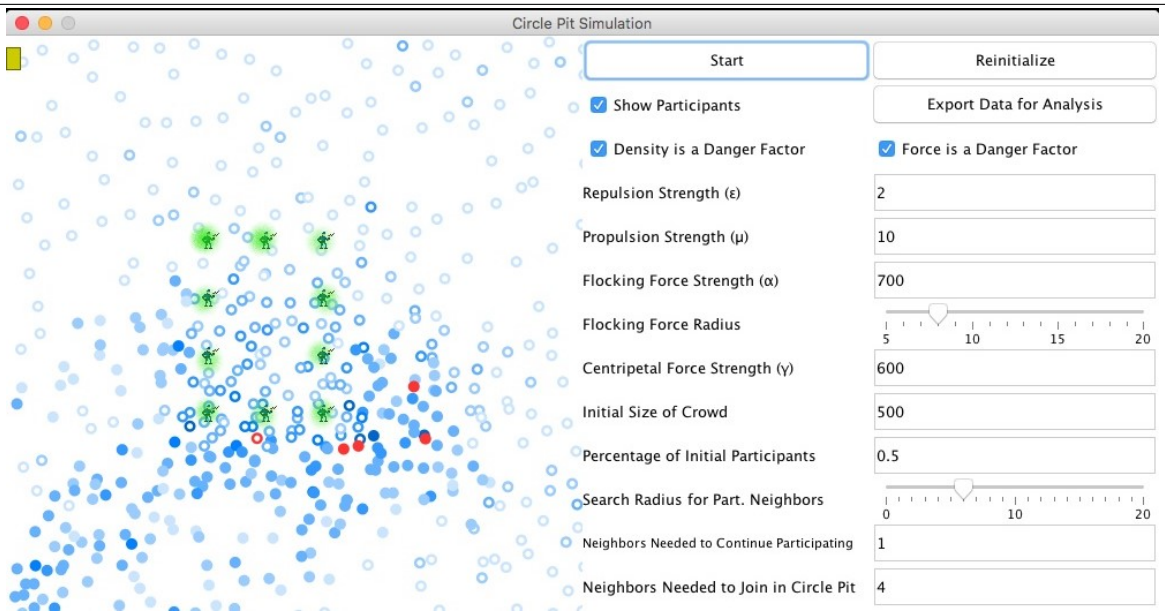
C.3: Center

```
A configuration with all the policemen grouped in the center of the arena. Policemen are added a
epsilon:                    2
mu:                         10
alpha:                      700
gamma:                      600
numberOfPeople:             500
flockRadius:                8
dt:                         0.01
percentParticipating:       0.5
rParticipating:             6
minCirclePitSize:           1
minParticipatingNeighbors:  4
dataCollectionInterval:     1000
insertPoliceAfter:          100
collectDataThisManyTimes:   300
useThisManySeeds:           50
policeConfig:
 ----------
|          |
|          |
|          |
|   xxx    |
|   xxx    |
|   xxx    |
|    x     |
|          |
|          |
|          |
 ----------
```



C.4: Circle

```
A "circle" of policemen in the center of the arena. Policemen are added after 5 seconds.
epsilon:                    2
mu:                         10
alpha:                      700
gamma:                      600
numberOfPeople:             500
flockRadius:                8
dt:                         0.01
percentParticipating:       0.5
rParticipating:             6
minCirclePitSize:           1
minParticipatingNeighbors:  4
dataCollectionInterval:     1000
insertPoliceAfter:          100
collectDataThisManyTimes:   300
useThisManySeeds:           50
policeConfig:
 ----------
|          |
|          |
|          |
|   xxx    |
|   x x    |
|   x x    |
|   xxx    |
|          |
|          |
|          |
 ----------
```



C.5: Control

```
A configuration with no policemen.
epsilon:                    2
mu:                         10
alpha:                      700
gamma:                      600
numberOfPeople:             500
flockRadius:                8
dt:                         0.01
percentParticipating:       0.5
rParticipating:             6
minCirclePitSize:           1
minParticipatingNeighbors: 4
dataCollectionInterval:     1000
insertPoliceAfter:          100
collectDataThisManyTimes:   300
useThisManySeeds:           50
policeConfig:
 ----------
|          |
|          |
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|          |
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|          |
|          |
 ----------
```
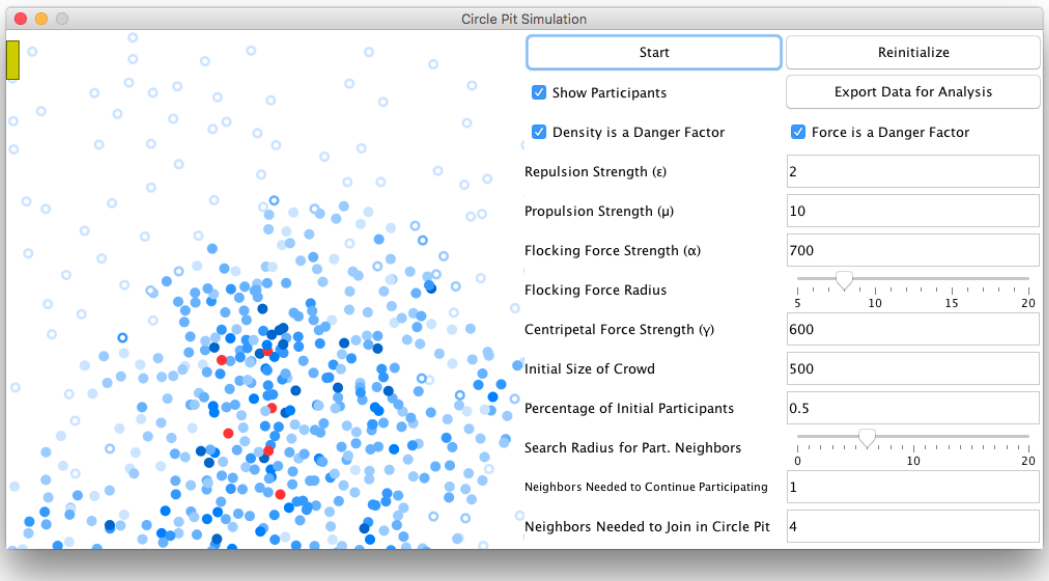
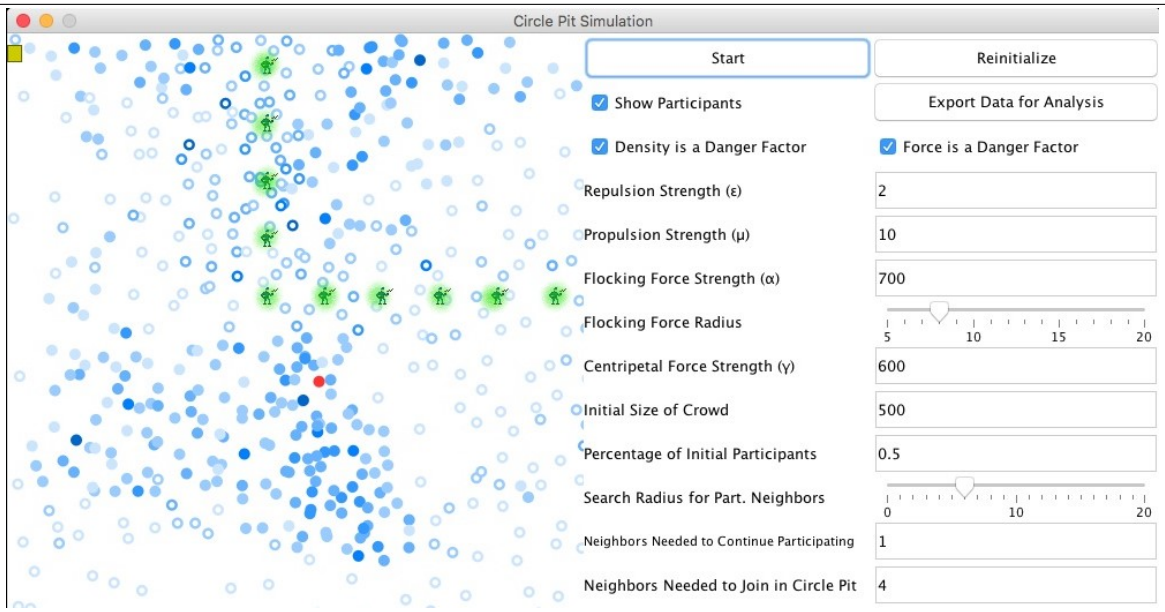



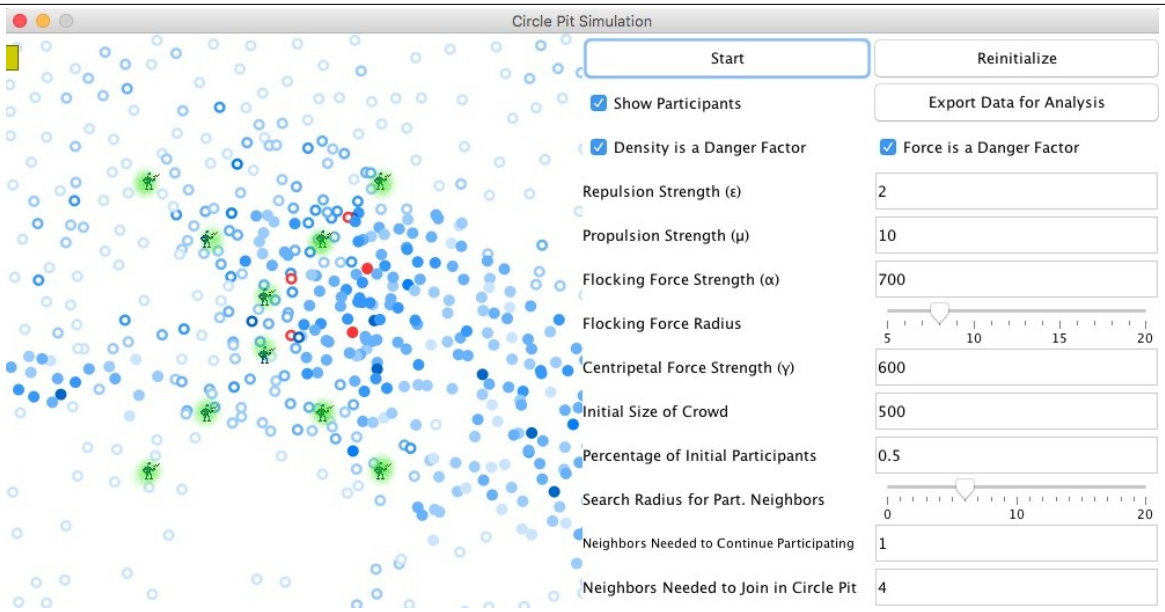
C.6: Corner

```
A line of policemen completely blocking off one corner of the arena. Policemen are added after
epsilon:                    2
mu:                         10
alpha:                      700
gamma:                      600
numberOfPeople:             500
flockRadius:                8
dt:                         0.01
percentParticipating:       0.5
rParticipating:             6
minCirclePitSize:           1
minParticipatingNeighbors:  4
dataCollectionInterval:     1000
insertPoliceAfter:          100
collectDataThisManyTimes:   300
useThisManySeeds:           50
policeConfig:
 ----------
|    x     |
|    x     |
|    x     |
|    x     |
|    xxxxxx|
|          |
|          |
|          |
|          |
|          |
 ----------
```



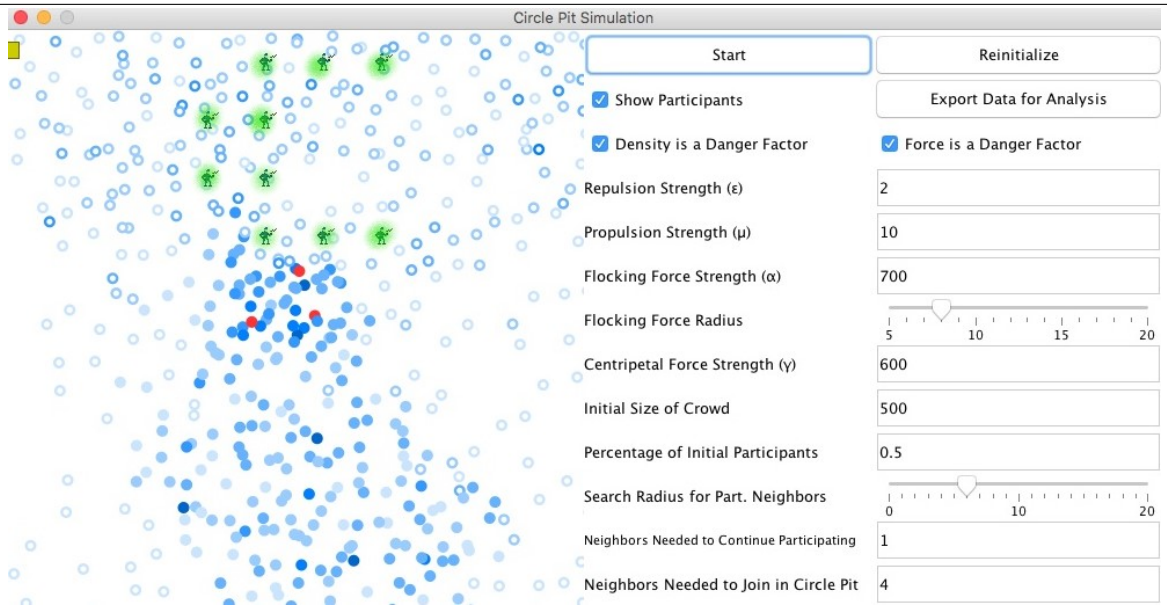
C.7: Cross

```
Policemen resembling a cross in the center of the arena. Policemen are added after 5 seconds.
epsilon:                    2
mu:                         10
alpha:                      700
gamma:                      600
numberOfPeople:             500
flockRadius:                8
dt:                         0.01
percentParticipating:       0.5
rParticipating:             6
minCirclePitSize:           1
minParticipatingNeighbors:  4
dataCollectionInterval:     1000
insertPoliceAfter:          100
collectDataThisManyTimes:   300
useThisManySeeds:           50
policeConfig:
 ----------
|          |
|          |
|  x   x   |
|   x x    |
|    x     |
|    x     |
|   x x    |
|  x   x   |
|          |
|          |
 ----------
```



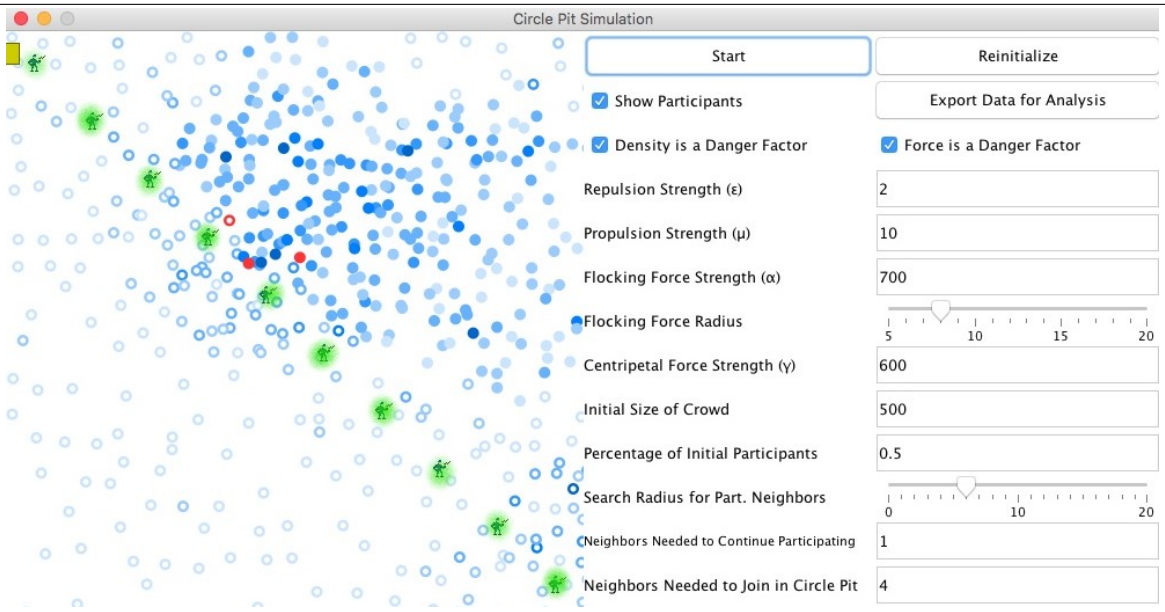
C.8: C-shape

```
A policeman configuration resembling a 'C'. Policemen are added after 5 seconds.
epsilon:                    2
mu:                         10
alpha:                      700
gamma:                      600
numberOfPeople:             500
flockRadius:                8
dt:                         0.01
percentParticipating:       0.5
rParticipating:             6
minCirclePitSize:           1
minParticipatingNeighbors:  4
dataCollectionInterval:     1000
insertPoliceAfter:          100
collectDataThisManyTimes:   300
useThisManySeeds:           50
policeConfig:
 ----------
|    xxx   |
|   xx     |
|   xx     |
|    xxx   |
|          |
|          |
|          |
|          |
|          |
|          |
 ----------
```



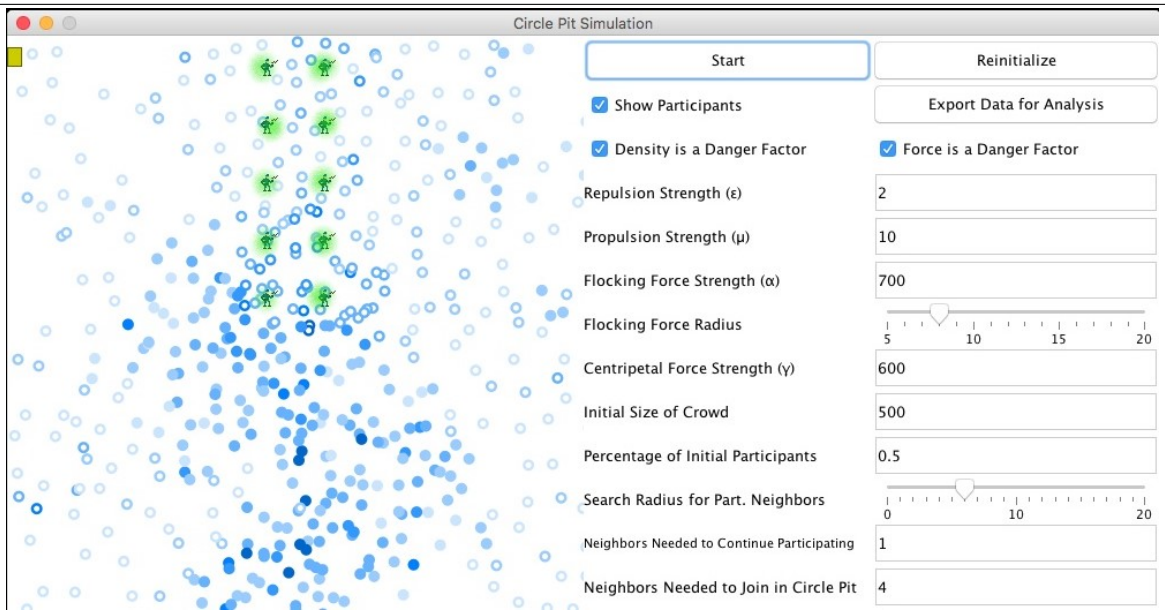
C.9: Diagonal

```
A diagonal line of policemen from upper left to lower right. Policemen are added after 5 second
epsilon:                    2
mu:                         10
alpha:                      700
gamma:                      600
numberOfPeople:             500
flockRadius:                8
dt:                         0.01
percentParticipating:       0.5
rParticipating:             6
minCirclePitSize:           1
minParticipatingNeighbors: 4
dataCollectionInterval:     1000
insertPoliceAfter:          100
collectDataThisManyTimes:  300
useThisManySeeds:           50
policeConfig:
 ----------
|x         |
| x        |
|  x       |
|   x      |
|    x     |
|     x    |
|      x   |
|       x  |
|        x |
|         x|
 ----------
```



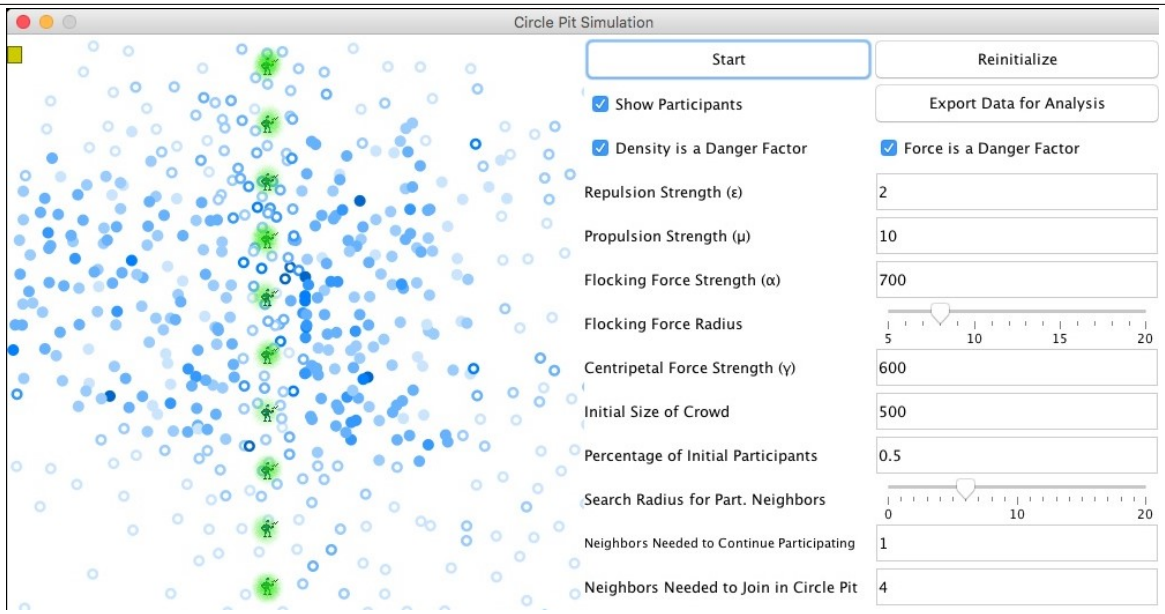
C.10: Double Half-Line

```
A double half-line of policemen at the top center of the arena. Policemen are added after 5 sec
epsilon:                    2
mu:                         10
alpha:                      700
gamma:                      600
numberOfPeople:             500
flockRadius:                8
dt:                         0.01
percentParticipating:       0.5
rParticipating:             6
minCirclePitSize:           1
minParticipatingNeighbors:  4
dataCollectionInterval:     1000
insertPoliceAfter:          100
collectDataThisManyTimes:   300
useThisManySeeds:           50
policeConfig:
 ----------
|    xx    |
|    xx    |
|    xx    |
|    xx    |
|    xx    |
|          |
|          |
|          |
|          |
|          |
 ----------
```



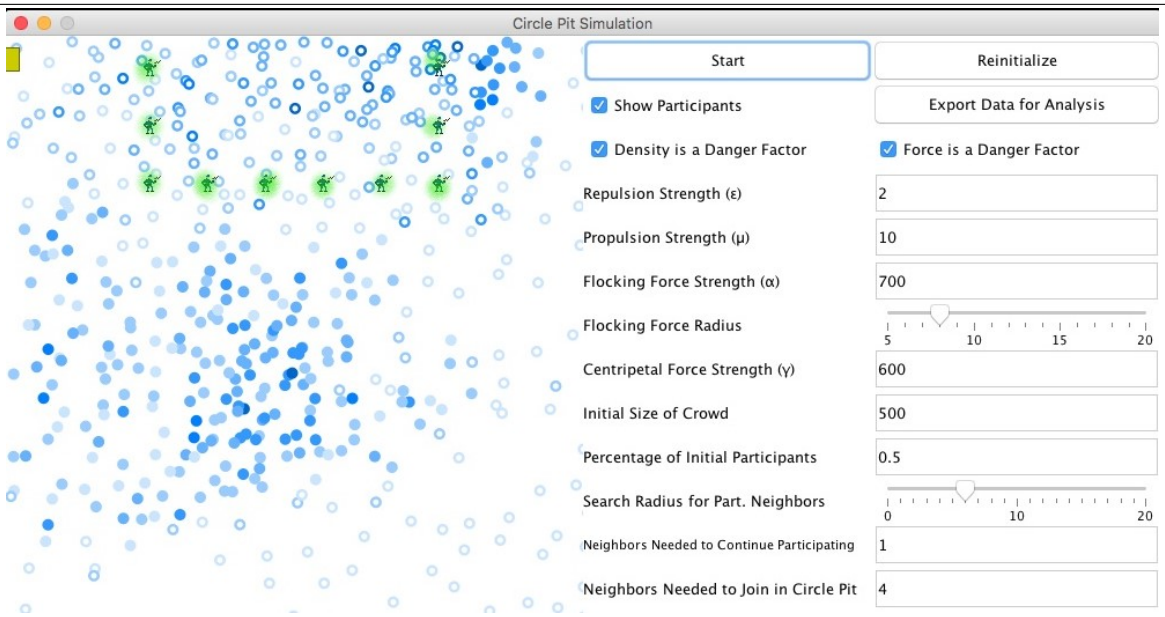
C.11: Vertical Line

```
A vertical line of policemen in the center of the arena. Policemen are added after 5 seconds.
epsilon:                    2
mu:                         10
alpha:                      700
gamma:                      600
numberOfPeople:             500
flockRadius:                8
dt:                         0.01
percentParticipating:       0.5
rParticipating:             6
minCirclePitSize:           1
minParticipatingNeighbors: 4
dataCollectionInterval:     1000
insertPoliceAfter:          100
collectDataThisManyTimes:  300
useThisManySeeds:           50
policeConfig:
 ----------
|    x     |
|    x     |
|    x     |
|    x     |
|    x     |
|    x     |
|    x     |
|    x     |
|    x     |
|    x     |
 ----------
```



C.12: U-Shape

```
A configuration of police officers resembling a 'U' at the top center of the arena. Policemen a
epsilon:                    2
mu:                         10
alpha:                      700
gamma:                      600
numberOfPeople:             500
flockRadius:                8
dt:                         0.01
percentParticipating:       0.5
rParticipating:             6
minCirclePitSize:           1
minParticipatingNeighbors:  4
dataCollectionInterval:     1000
insertPoliceAfter:          100
collectDataThisManyTimes:   300
useThisManySeeds:           50
policeConfig:
 ----------
|  x    x  |
|  x    x  |
|  xxxxxx  |
|          |
|          |
|          |
|          |
|          |
|          |
|          |
 ----------
```



Appendix D: Phase Diagrams

The following appendix shows phase diagrams of where the danger is located at two time points, one time point right after the point when the police were inserted and one time point after the circle pit had been mostly stopped.

D.1: Arrow

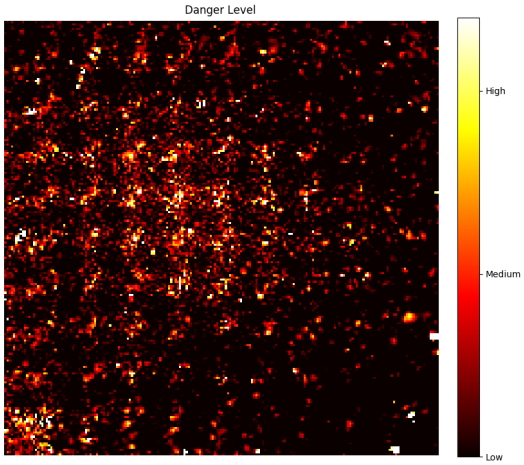


Figure 27: *Arrow's configuration* phase diagram after fifteen time steps, global danger level has already decreased significantly, with a peak in the first quadrant – where the inner wings of the guards stays.

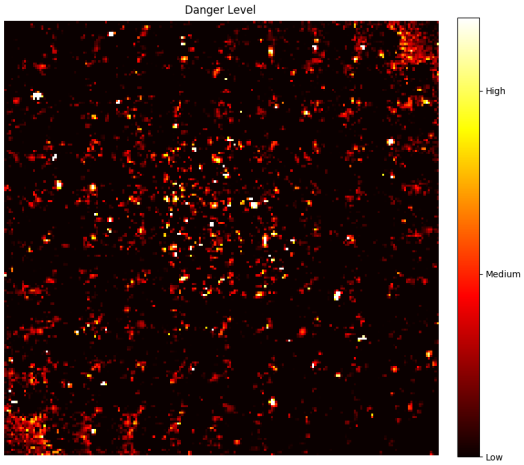


Figure 28: Phase diagram shot after 110 steps, almost a third compared to the second shot of other configurations as *arrow's arrangement* already killed the circle pit by the time.

D.2: Big Circle

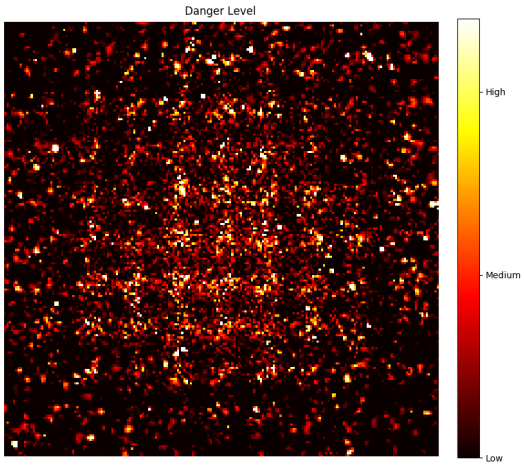


Figure 29: *Big Circle's configuration* phase diagram after ten time steps. It is possible to distinguish a slight darker circumference: the perimeter created by the *guards*.

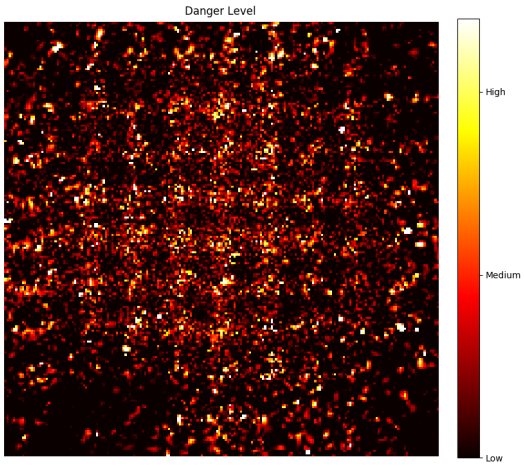


Figure 30: Phase diagram taken at the 290th time step, danger level is still high all above the plane.

D.3: Center

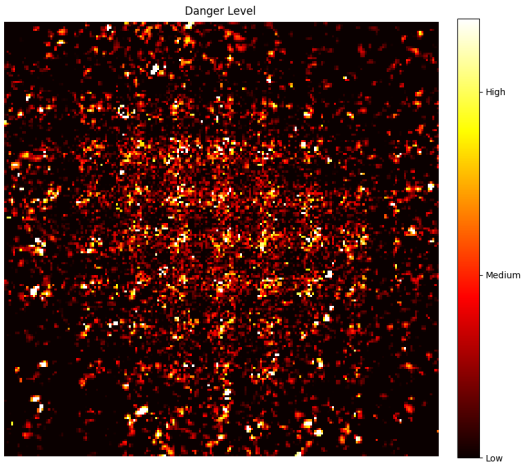


Figure 31: Phase diagram shot after ten steps w.r.t. the *center's arrangement* of guards. Danger is concentrated in the middle of the diagram; people – attracted there by the centripetal force – stop as they reach the police officers, producing a *high-density zone*.

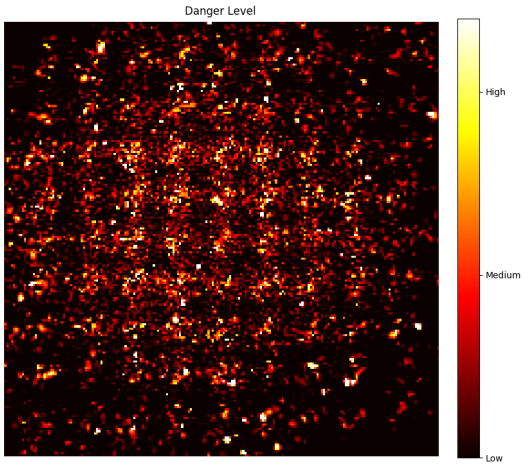


Figure 32: Image of the phase diagram took after 200 time steps: the pit is still spinning.

D.4: Circle

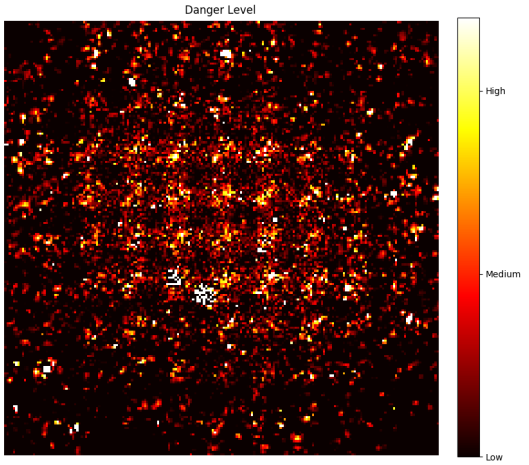


Figure 33: *Circle's disposition* of the guards phase diagram, after ten steps. As this configuration is similar to the previous two, the diagram resemble theirs: higher danger levels concentrated in the center.

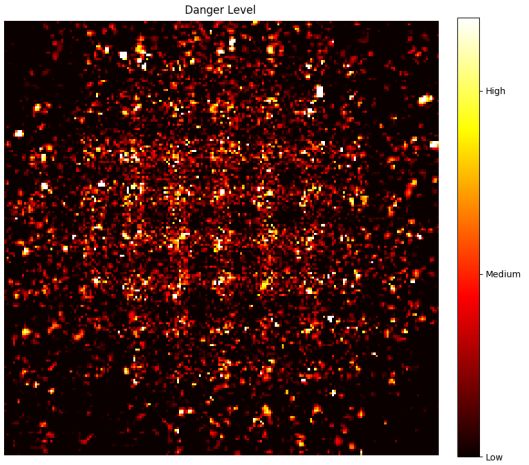


Figure 34: Phase diagram at the two hundred ninetieth step: as for the preceding diagrams yellow is still painting the plan, meaning people didn't stop spinning.

D.5: Corner

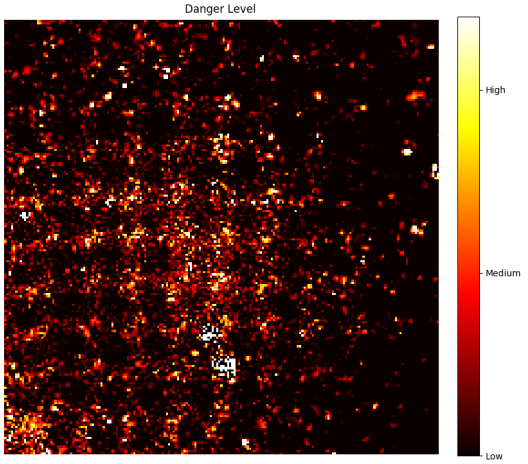


Figure 35: Phase diagram of the *corner's configuration* at the tenth time step. Danger has already strongly decreased, but for a curious spot in the middle of the lower part of the plane.

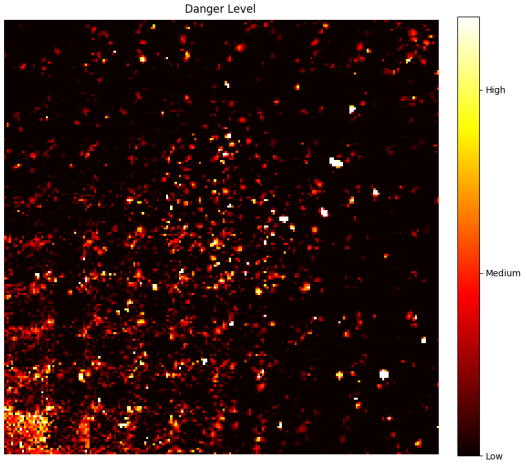


Figure 36: Phase diagram after thirty time steps, circle pit is almost dead by now. *Corner's arrangement* of police officers seems to be the most effective among the eleven we tried.

D.6: Control

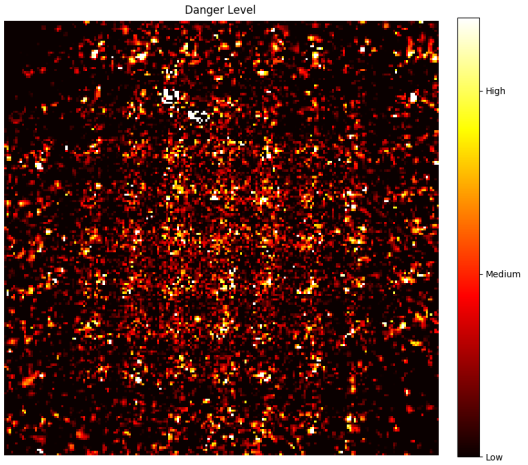


Figure 37: Phase diagram of a simulation run without *guards* at the most common time step w.r.t. the other phase diagrams, namely ten. Danger is overall high.

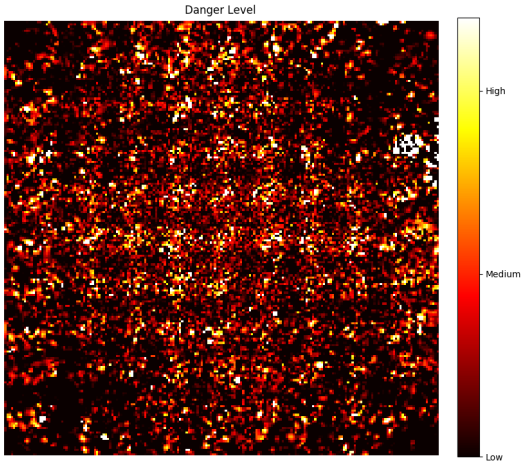


Figure 38: Phase diagram after two hundred ninety steps. Without guards, people keep running.

D.7: Cross

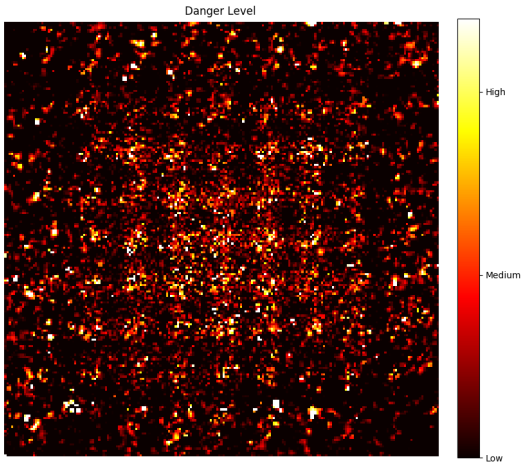


Figure 39: emphCross' profile depicted in a phase diagram at the twelfth time step. Global danger level is under the media and it is well distributed overall the space.

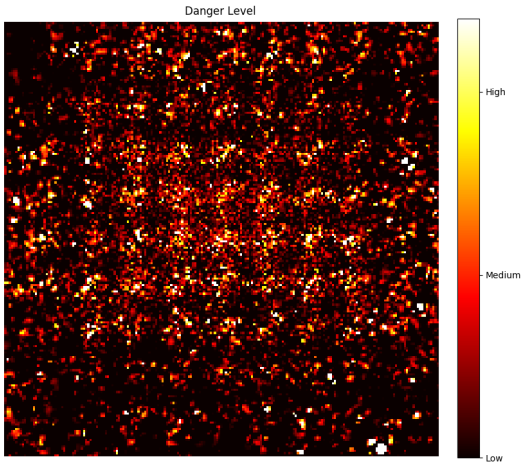


Figure 40: *Cross' profile* depicted in a phase diagram at the twelfth time step. Global danger level is under the media and it is well distributed overall the space

D.8: C-Shape

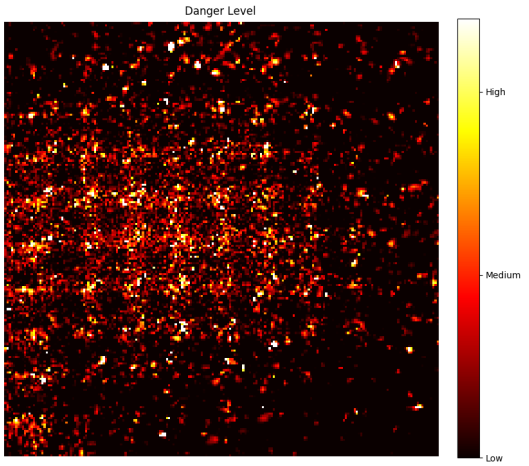


Figure 41: *C-shape configuration* phase diagram after nine time steps. Comparing it to the *arrow configuration* – which a similar shape has – danger is more homogeneously allocated. Moreover it has no danger concentration over the police officers.

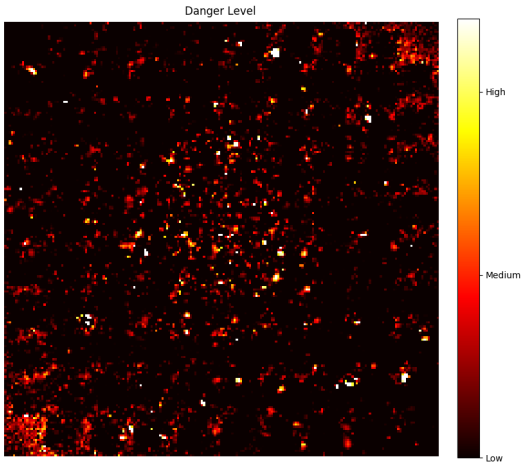


Figure 42: Phase diagram at hundred fiftieth time steps. *C-shape* arrangement has a good effectiveness, it has indeed by the time stopped the circle pit.

D.9: Diagonal

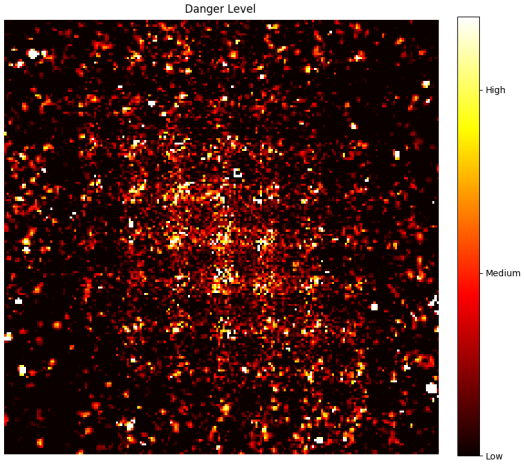


Figure 43: Phase diagram of *diagonal configuration* after six time step. Here is visible the yellow-red shape exactly over the position of the *guards*

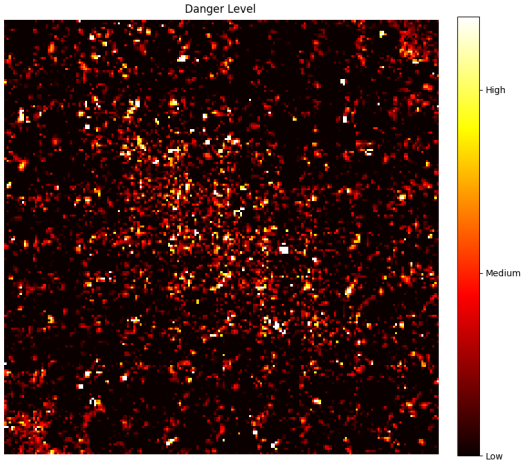


Figure 44: Shot of phase diagram at time step two hundred and ninety. The "shadow" above the police officers is still visible. People are spinning less, but the pit keeps living.

D.10: Double Half-Line

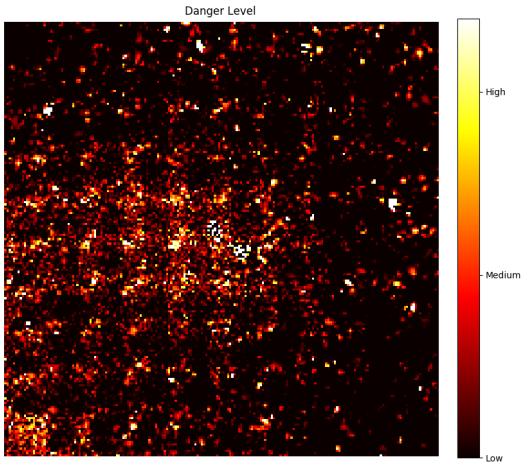


Figure 45: Phase diagram after fifteen time steps, danger level decreases rapidly. emphDouble Half-Line is a relatively efficient configuration. Its effect is similar to the *C-shape* configuration.

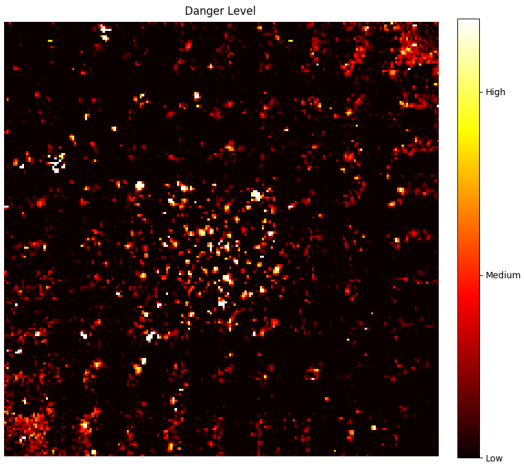


Figure 46: Phase diagram after one hundred thirty time steps, circle pit is almost dead by now. *Double Half-Line* is a relatively efficient configuration. Its effect is similar to the *C-shape* configuration.

D.11: U-Shape

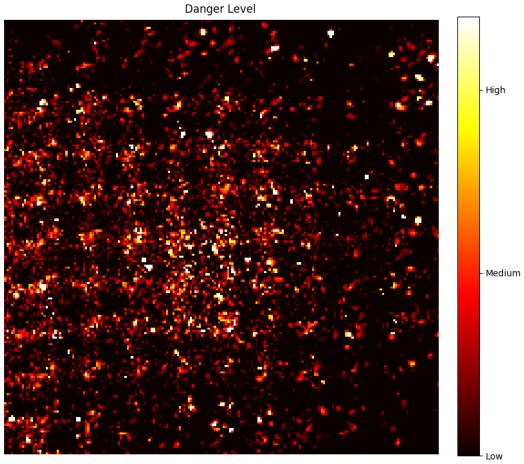


Figure 47: Phase diagram after ten time steps, the degree of danger declines very fast. *U-shape* is a very efficient configuration.

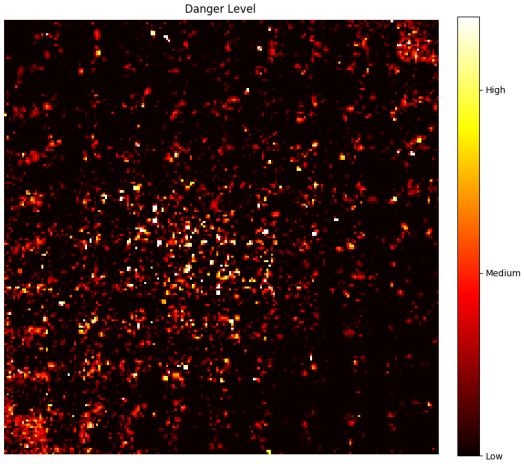


Figure 48: Phase diagram at time step two hundred ninety. People have almost stopped to spin: not the most efficient arrangement of *guards*, but it slowly slowed down everybody in the pit.

D.12: Vertical Line

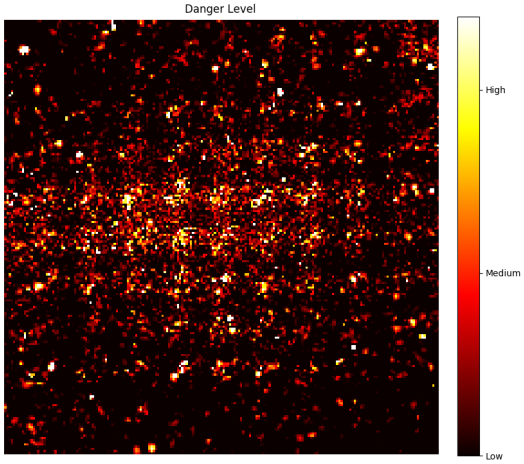


Figure 49: Phase diagram w.r.t. *vertical line configuration* at the tenth time step. Opposite to diagonal line, higher danger level seems to arrange himself on a line perpendicular to the line of police officers.

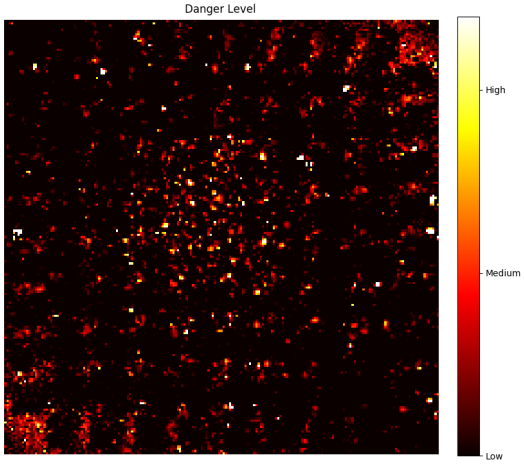


Figure 50: Last phase diagram, shot after two hundred eighty steps. As for the previous arrangement of *guards* circle pit has stopped, but late in time.

Appendix E: Java Code

E.1: Main Code

```
import java.io.FileNotFoundException;

public class Main {
    public static void main(String[] args) throws FileNotFoundException {
        // Run a manual simulation
        // Simulation simulation = new Simulation(2, 10, 700, 600,500, 8,
        //                                        0.01, 0.5, 6, 1, 3);
        // simulation.runManualSimulation();

        // Run an automatic simulation
        AutomaticSimulator test = new AutomaticSimulator();
        test.run();
    }
}
```

E.2: Automatic Simulation

```java
import java.io.File;
import java.io.FileNotFoundException;
import java.util.Arrays;
import java.util.LinkedList;
import java.util.Queue;
import java.util.Scanner;

/**
 * An object that reads the configs given in <code>configs.sim</code> and
 * executes the corresponding simulations while dumping data for analysis.
 */
public class AutomaticSimulator {

    private Queue<String> configNames = new LinkedList<String>();
            // The configs to simulate
    private Simulation simulation;

    public AutomaticSimulator() throws FileNotFoundException {
        readConfigNames();
    }

    /**
     * Runs the automatic simulation.
     *
     * @throws FileNotFoundException either if <code>configs.sim</code> could
     *                               not be found or if a configuration
     *                               specified in <code>configs.sim</code> could
     *                               not be found.
     */
    public void run() throws FileNotFoundException {
        // Keep going while not all configurations have been tested
        while (!configNames.isEmpty()) {
            String config = configNames.poll();
            Config c = readConfigFile(config);
            newSimulation(c);
            // Poll the simulation to see if it is done yet (really ugly but
            // oh well...)
            while (!simulation.isCurrentIterationFinished) {
                try {
                    Thread.sleep(1000);
                } catch (InterruptedException e) {
                    e.printStackTrace();
                }
            }
            simulation.isCurrentIterationFinished = false;
        }
        System.exit(0);
    }

    // Reads the configurations to simulate from configs.sim
```

```
51      private void readConfigNames() throws FileNotFoundException {
52          Scanner scanner = new Scanner(new File("configs.sim"));
53          scanner.nextLine();
54          while (scanner.hasNext()) {
55              configNames.add(scanner.next());
56          }
57          System.out.println("Starting simulation with configs: " + configNames);
58      }
59
60      // Reads a configuration file
61      private Config readConfigFile(String config) throws FileNotFoundException {
62          Scanner scanner =
63                  new Scanner(new File("configs/" + config + ".config"));
64          scanner.nextLine();  // Skip comment on first line
65          double[] data = new double[15];
66          Config c = new Config();
67          c.name = config;
68          for (int i = 0; i < data.length;
69               i++) {  // Read parameters from config file
70              scanner.next();
71              data[i] = scanner.nextDouble();
72          }
73          c.readNumbersFromArray(data);
74          scanner.nextLine();  // Move to line after all the number values
75          scanner.nextLine();  // Move over line with "policeSectors: "
76          scanner.nextLine();  // Move over upper boundary of ASCII-based
77                               // representation of matrix
78          for (int i = 0; i < 10; i++) {
79              String line = scanner.nextLine();
80              for (int j = 0; j < 10; j++) {
81                  if (line.charAt(j + 1) ==
82                          'x') {  // j+1 because of leading |, 'x' means there
83                                  // is a policeman there
84                      c.policeSectors[j][i] = true;
85                  }
86              }
87          }
88          System.out.println("Current config: " + config);
89          System.out.println("    data = " + Arrays.toString(data));
90          System.out.println("    policeSectors = ");
91          for (int i = 0; i < c.policeSectors.length; i++) {
92              System.out.println("       " + Arrays.toString(c.policeSectors[i]));
93          }
94          return c;
95      }
96
97      private void newSimulation(Config c) {
98          if (simulation == null) {
99              // Initialize the simulation with data from the config file
100             simulation = new Simulation(c.epsilon, c.mu, c.alpha, c.gamma,
101                                         c.numberOfPeople, c.flockRadius, c.dt,
```

```
                                        c.percentParticipating,
                                        c.rParticipating, c.minCirclePitSize,
                                        c.minParticipatingNeighbors);
            simulation.createWindow();
            simulation.createNewTimer(new DataCollector(simulation, c.name,
                                                        c.dataCollectionInterval,
                                                        c.insertPoliceAfter,
                                                        c.amountOfSeeds,
                                                        c.collectionTimes,
                                                        c.policeSectors));
            simulation.start();
        } else {
            // Reinitialize all the parameters with data from the config file
            simulation.stop();
            simulation.epsilon = c.epsilon;
            simulation.alpha = c.alpha;
            simulation.mu = c.mu;
            simulation.gamma = c.gamma;
            simulation.numberOfPeople = c.numberOfPeople;
            simulation.flockRadius = c.flockRadius;
            simulation.dt = c.dt;
            simulation.percentParticipating = c.percentParticipating;
            simulation.rParticipating = c.rParticipating;
            simulation.minCirclePitSize = c.minCirclePitSize;
            simulation.minParticipatingNeighbors = c.minParticipatingNeighbors;
            simulation.createNewTimer(new DataCollector(simulation, c.name,
                                                        c.dataCollectionInterval,
                                                        c.insertPoliceAfter,
                                                        c.amountOfSeeds,
                                                        c.collectionTimes,
                                                        c.policeSectors));
            simulation.basicReset();
            simulation.start();
        }
    }

    // A class that stores all the parameters from a config file
    private class Config {
        String name;
        double epsilon, alpha, mu, gamma, dt, percentParticipating;
        int numberOfPeople, flockRadius, rParticipating, minCirclePitSize,
                minParticipatingNeighbors, dataCollectionInterval,
                insertPoliceAfter, collectionTimes, amountOfSeeds;
        boolean[][] policeSectors = new boolean[10][10];

        private void readNumbersFromArray(double[] array) {
            assert array.length == 15;
            epsilon = array[0];
            mu = array[1];
            alpha = array[2];
            gamma = array[3];
```

```
153             numberOfPeople = (int) array[4];
154             flockRadius = (int) array[5];
155             dt = array[6];
156             percentParticipating = array[7];
157             rParticipating = (int) array[8];
158             minCirclePitSize = (int) array[9];
159             minParticipatingNeighbors = (int) array[10];
160             dataCollectionInterval = (int) array[11];
161             insertPoliceAfter = (int) array[12];
162             collectionTimes = (int) array[13];
163             amountOfSeeds = (int) array[14];
164         }
165     }
166 }
```

E.3: Control Panel

```
import javax.swing.*;
import javax.swing.event.ChangeEvent;
import javax.swing.event.ChangeListener;
import java.awt.*;
import java.awt.event.ActionEvent;
import java.awt.event.ActionListener;
import java.beans.PropertyChangeEvent;
import java.beans.PropertyChangeListener;

public class ControlPanel extends JPanel
        implements PropertyChangeListener, ChangeListener {

    private Simulation simulation;
    private SimulationPanel simulationpanel;
    private JButton startPauseButton;
    private JButton restartButton;
    private JButton exportDataButton;
    private JCheckBox enableDensity;
    private JCheckBox enableForce;
    private JCheckBox showParticipants;
    private JLabel epsilonLabel, muLabel, alphaLabel, flockRadiusLabel,
            gammaLabel, initialParticipantsLabel, percLabel, rPartLabel,
            sizeLabel, minNeighborsLabel;
    private JFormattedTextField epsilonField, muField, alphaField, gammaField,
            initialParticipantsField, percField, sizeField, minNeighborsField;
    private JSlider rPartSlider, flockRadiusSlider;

    private boolean paused = true;

    public ControlPanel(Simulation simulation,
                        SimulationPanel simulationpanel) {
        this.simulation = simulation;
        this.simulationpanel = simulationpanel;
        setPreferredSize(new Dimension(500, 230));
        setBackground(Color.WHITE);
        setLayout(new GridLayout(13, 2));

        initComponents();
        addListeners();
        addComponents();
    }

    private void initComponents() {
        startPauseButton = new JButton("Start");
        restartButton = new JButton("Reinitialize");
        showParticipants = new JCheckBox("Show Participants");
        showParticipants.setSelected(true);
        exportDataButton = new JButton("Export Data for Analysis");

        enableDensity = new JCheckBox("Density is a Danger Factor");
```

```
51          enableDensity.setSelected(true);
52          enableForce = new JCheckBox("Force is a Danger Factor");
53          enableForce.setSelected(true);
54
55          epsilonLabel = new JLabel("Repulsion Strength (\u03b5)");
56
57          epsilonField = new JFormattedTextField();
58          epsilonField.setValue(simulation.epsilon);
59          epsilonField.setColumns(10);
60
61          muLabel = new JLabel("Propulsion Strength (\u03bc)");
62
63          muField = new JFormattedTextField();
64          muField.setValue(simulation.mu);
65          muField.setColumns(10);
66
67          alphaLabel = new JLabel("Flocking Force Strength (\u03b1)");
68
69          alphaField = new JFormattedTextField();
70          alphaField.setValue(simulation.alpha);
71          alphaField.setColumns(10);
72
73          flockRadiusLabel = new JLabel("Flocking Force Radius");
74          flockRadiusSlider = new JSlider();
75          flockRadiusSlider.setValue((int) simulation.flockRadius);
76          configureSlider(flockRadiusSlider, 1, 5, 5, 2 * Simulation.SECTOR_SIZE);
77
78          gammaLabel = new JLabel("Centripetal Force Strength (\u03b3)");
79
80          gammaField = new JFormattedTextField();
81          gammaField.setValue(simulation.gamma);
82          gammaField.setColumns(10);
83
84          initialParticipantsLabel = new JLabel("Initial Size of Crowd");
85
86          initialParticipantsField = new JFormattedTextField();
87          initialParticipantsField.setValue(simulation.numberOfPeople);
88          initialParticipantsField.setColumns(10);
89
90          percLabel = new JLabel("Percentage of Initial Participants");
91
92          percField = new JFormattedTextField();
93          percField.setValue(simulation.percentParticipating);
94          percField.setColumns(10);
95
96          rPartLabel = new JLabel("Search Radius for Part. Neighbors");
97
98          rPartSlider = new JSlider();
99          rPartSlider.setValue((int) simulation.rParticipating);
100         configureSlider(rPartSlider, 1, 10, 0, 2 * Simulation.SECTOR_SIZE);
101
```

```
102         sizeLabel = new JLabel("Neighbors Needed to Continue Participating");
103
104         String fontFamily = sizeLabel.getFont().getFamily();
105         sizeLabel.setFont(new Font(fontFamily, Font.PLAIN, 11));
106
107
108         sizeField = new JFormattedTextField();
109         sizeField.setValue(simulation.minCirclePitSize);
110         sizeField.setColumns(10);
111
112         minNeighborsLabel = new JLabel(
113                 "Neighbors Needed to Join in Circle Pit");
114
115         minNeighborsField = new JFormattedTextField();
116         minNeighborsField.setValue(simulation.minParticipatingNeighbors);
117         minNeighborsField.setColumns(10);
118
119     }
120
121     private void configureSlider(JSlider slider, int minorSpacing,
122                                  int majorSpacing, int lowerLimit,
123                                  int upperLimit) {
124         slider.setMajorTickSpacing(majorSpacing);
125         slider.setMinorTickSpacing(minorSpacing);
126         slider.setMinimum(lowerLimit);
127         slider.setMaximum(upperLimit);
128         slider.setPaintLabels(true);
129         slider.setPaintTicks(true);
130     }
131
132     private void addListeners() {
133         startPauseButton.addActionListener(new ActionListener() {
134             /* @Override */
135             public void actionPerformed(ActionEvent e) {
136                 if (paused) {
137                     simulation.getSimulationTimer().start();
138                     startPauseButton.setText("Pause");
139                 } else {
140                     simulation.getSimulationTimer().stop();
141                     startPauseButton.setText("Start");
142                 }
143                 paused = !paused;
144             }
145         });
146
147         restartButton.addActionListener(new ActionListener() {
148             /* @Override */
149             public void actionPerformed(ActionEvent e) {
150                 startPauseButton.setText("Start");
151                 paused = true;
152                 simulation.resetMatrix();
```

```
153             }
154         });
155 
156         showParticipants.addActionListener(new ActionListener() {
157             /* @Override */
158             public void actionPerformed(ActionEvent e) {
159                 simulationpanel.shouldShowParticipants =
160                         !simulationpanel.shouldShowParticipants;
161                 getParent().repaint();
162             }
163         });
164 
165         exportDataButton.addActionListener(new ActionListener() {
166             /* @Override */
167             public void actionPerformed(ActionEvent e) {
168                 simulation.exportData();
169             }
170         });
171 
172         enableDensity.addActionListener(new ActionListener() {
173             /* @Override */
174             public void actionPerformed(ActionEvent e) {
175                 if (!simulation.enableDensity) {
176                     simulation.enableDensity = true;
177                 } else {
178                     simulation.enableDensity = false;
179                     for (Individual individual : simulation.getMatrix()
180                                                            .getIndividuals()) {
181                         individual.dangerLevel = 0;
182                     }
183                 }
184             }
185         });
186 
187         enableForce.addActionListener(new ActionListener() {
188             /* @Override */
189             public void actionPerformed(ActionEvent e) {
190                 if (!simulation.enableForce) {
191                     simulation.enableForce = true;
192                 } else {
193                     simulation.enableForce = false;
194                     for (Individual individual : simulation.getMatrix()
195                                                            .getIndividuals()) {
196                         individual.dangerLevel = 0;
197                     }
198                 }
199             }
200         });
201 
202         epsilonField.addPropertyChangeListener("value", this);
203         alphaField.addPropertyChangeListener("value", this);
```

```
204         flockRadiusSlider.addChangeListener(this);
205         muField.addPropertyChangeListener("value", this);
206         gammaField.addPropertyChangeListener("value", this);
207         initialParticipantsField.addPropertyChangeListener("value", this);
208         percField.addPropertyChangeListener("value", this);
209         rPartSlider.addChangeListener(this);
210         sizeField.addPropertyChangeListener("value", this);
211         minNeighborsField.addPropertyChangeListener("value", this);
212     }
213
214     private void addComponents() {
215         add(startPauseButton);
216         add(restartButton);
217         add(showParticipants);
218         add(exportDataButton);
219         add(enableDensity);
220         add(enableForce);
221         add(epsilonLabel);
222         add(epsilonField);
223         add(muLabel);
224         add(muField);
225         add(alphaLabel);
226         add(alphaField);
227         add(flockRadiusLabel);
228         add(flockRadiusSlider);
229         add(gammaLabel);
230         add(gammaField);
231         add(initialParticipantsLabel);
232         add(initialParticipantsField);
233         add(percLabel);
234         add(percField);
235         add(rPartLabel);
236         add(rPartSlider);
237         add(sizeLabel);
238         add(sizeField);
239         add(minNeighborsLabel);
240         add(minNeighborsField);
241
242         setVisible(true);
243     }
244
245     /**
246      * Called when a field's "value" property changes.
247      */
248     /* @Override */
249     public void propertyChange(PropertyChangeEvent e) {
250         Object source = e.getSource();
251         if (source == epsilonField) {
252             simulation.epsilon =
253                     ((Number) epsilonField.getValue()).doubleValue();
254         } else if (source == muField) {
```

```
255             simulation.mu = ((Number) muField.getValue()).doubleValue();
256         } else if (source == alphaField) {
257             simulation.alpha = ((Number) alphaField.getValue()).doubleValue();
258         } else if (source == gammaField) {
259             simulation.gamma = ((Number) gammaField.getValue()).doubleValue();
260         } else if (source == initialParticipantsField) {
261             simulation.numberOfPeople =
262                     ((Number) initialParticipantsField.getValue()).intValue();
263         } else if (source == percField) {
264             simulation.percentParticipating =
265                     ((Number) percField.getValue()).doubleValue();
266         } else if (source == rPartSlider) {
267             simulation.rParticipating =
268                     ((Number) rPartSlider.getValue()).doubleValue();
269         } else if (source == sizeField) {
270             simulation.minCirclePitSize =
271                     ((Number) sizeField.getValue()).intValue();
272         } else if (source == minNeighborsField) {
273             simulation.minParticipatingNeighbors =
274                     ((Number) minNeighborsField.getValue()).intValue();
275         }
276     }
277
278     /* @Override */
279     public void stateChanged(ChangeEvent e) {
280         JSlider source = (JSlider) e.getSource();
281         if (source == rPartSlider && !source.getValueIsAdjusting()) {
282             simulation.rParticipating = (double) rPartSlider.getValue();
283         } else if (source == flockRadiusSlider &&
284                 !source.getValueIsAdjusting()) {
285             simulation.flockRadius = (double) flockRadiusSlider.getValue();
286         }
287     }
288 }
```

E.4: Data Collection

```
import java.awt.event.ActionEvent;
import java.awt.event.ActionListener;
import java.io.*;
import java.util.ArrayList;
import java.util.List;

/**
 * Class that automatically runs the simulation for one police configuration and
 * harvests data from it.
 */
public class DataCollector implements ActionListener {

    private final int MAX_TIME;  // Max amount of timepoints to dump data for
    private final int MAX_SEEDS;  // Max amount of seeds to test
    private final int dataCollectionInterval;  // How often to collect data
    public boolean hasInsertedPolice = false;  // True if police inserted
    private Simulation simulation;  // Simulation for which to collect data
    private PrintWriter fileCounterWriter; // Writes number of timepoints and
                                           // number of seeds
    private PrintWriter outWriter;  // Writes data
    private int seedCounter = 0; // Counts how many seeds have already been
                                 // tested
    private int timeCounter = 0; // Counts how many timepoints we have
                                 // already dumped data for
    private int realTimeElapsed = 0; // Amount of timesteps of the simulation
                                     // elapsed
    private int insertPoliceAfterCounter = 0; // Counter to test if we should
                                              // insert police
    private boolean stillWaitingToInsertPolice = true; // True if police not
                                                       // inserted yet
    private int insertPoliceAfter; // How many timesteps to wait before
                                   // inserting police
    private boolean[][] policeSectors = new boolean[10][10]; // Sectors with
                                                             // police

    private String configurationName; // Name of the configuration we are
                                      // currently testing

    public DataCollector(Simulation simulation, String configurationName,
                         int dataCollectionInterval, int insertPoliceAfter,
                         int maxSeeds, int maxTime, boolean[][] policeSectors) {
        this.simulation = simulation;
        this.dataCollectionInterval = dataCollectionInterval;
        this.insertPoliceAfter = insertPoliceAfter;
        this.policeSectors = policeSectors;
        MAX_TIME = maxTime;
        MAX_SEEDS = maxSeeds;
        // Files are named as out_[seed#]_[time#].py in a subfolder for this
        // configuration
        File file = new File(configurationName + "/out_0_0.py");
```

```
51          file.getParentFile().mkdirs();
52          try {
53              fileCounterWriter = new PrintWriter(
54                      configurationName + "/counter.py");
55          } catch (FileNotFoundException e) {
56              e.printStackTrace();
57          }
58          try {
59              outWriter = new PrintWriter(configurationName + "/out_0_0.py",
60                                          "UTF-8");
61          } catch (FileNotFoundException e) {
62              e.printStackTrace();
63          } catch (UnsupportedEncodingException e) {
64              e.printStackTrace();
65          }
66          this.configurationName = configurationName;
67          File initFile = new File(configurationName + "/__init__.py");
68          try {
69              initFile.createNewFile();
70          } catch (IOException e) {
71              e.printStackTrace();
72          }
73      }
74
75      /**
76       * Iterates over the given list and, for each element of that list, adds the
77       * value of the field with the given name to a numpy array that is written
78       * to a file using the provided PrintWriter. The resulting array is named
79       * <code>description</code>.
80       *
81       * @param list         The list from which to gather the data
82       * @param propertyName The property that we want to output
83       * @param writer       The writer with which to write the data
84       * @param description  The name of the numpy array
85       */
86      public static void writeNumPyArray(List list, String propertyName,
87                                         PrintWriter writer, String description) {
88          writer.print(description + " = array([");
89          boolean firstTime = true;
90          try {
91              for (Object object : list) {
92                  Object value = object.getClass().getField(propertyName).get(
93                          object);
94                  if (firstTime) writer.print(value);
95                  else writer.print(", " + value);
96                  firstTime = false;
97              }
98              writer.println("])");
99              writer.flush();
100         } catch (NoSuchFieldException e) {
101             e.printStackTrace();
```

```
102         } catch (IllegalAccessException e) {
103             e.printStackTrace();
104         }
105     }
106
107     /*@Override*/
108     public void actionPerformed(ActionEvent e) {
109         PositionMatrix matrix = simulation.getMatrix();
110         realTimeElapsed +=
111                 Simulation.TIMESTEP;  // Check how much time has elapsed to
112                                       // see if we should dump data
113         if (!simulation.isCurrentIterationFinished) {
114             simulation.runOneTimestep();
115             simulation.repaint();
116             if (stillWaitingToInsertPolice) {
117                 insertPoliceAfterCounter++;
118             }
119             if (insertPoliceAfterCounter >=
120                     insertPoliceAfter) {  // Check if the appropriate amount
121                                           // of time before inserting police
122                                           // has elapsed
123                 stillWaitingToInsertPolice = false;
124             }
125             if (!stillWaitingToInsertPolice &&
126                     !hasInsertedPolice) {  // Insert the police
127                 simulation.setMonitoredSectors(policeSectors);
128                 this.hasInsertedPolice = true;
129             }
130         }
131         // Dump data if now is the right time
132         if (realTimeElapsed % dataCollectionInterval == 0 &&
133                 !simulation.isCurrentIterationFinished) {
134             realTimeElapsed = 0;
135
136             outWriter.println("from numpy import *");
137             outWriter.flush();
138
139             List<Individual> individuals = matrix.getIndividuals();
140
141             // Write data on positions of individuals
142             writeNumPyArray(individuals, "x", outWriter, "x");
143             writeNumPyArray(individuals, "y", outWriter, "y");
144
145             // Write data on danger levels of individuals
146             writeNumPyArray(individuals, "dangerLevel", outWriter,
147                             "dangerLevel");
148             writeNumPyArray(individuals, "continuousDangerLevel", outWriter,
149                             "continuousDangerLevel");
150
151             writeIsParticipatingData(
152                     matrix);  // Write data on which individuals are
```

```
153             // participating
154             writeNumPyArray(individuals, "f", outWriter,
155                             "F");  // Write data on force acting on individuals
156             writeNumPyArray(individuals, "density", outWriter,
157                             "density");  // Write data on density surrounding
158             // individuals
159             writeAverageDanger(matrix);
160             writeMaxDanger(matrix);
161             writeMedianDanger(matrix);
162 
163             // If we have dumped data enough times, restart with a new seed
164             if (timeCounter >= MAX_TIME) {
165                 timeCounter = 0;
166                 simulation.setSeed(seedCounter);
167                 seedCounter++;
168                 simulation.restartSimulation();
169                 hasInsertedPolice = false;
170                 stillWaitingToInsertPolice = true;
171                 insertPoliceAfterCounter = 0;
172             }
173             // If we have tested enough seeds, finish the simulation
174             if (seedCounter >= MAX_SEEDS) {
175                 fileCounterWriter.println("n = " + MAX_TIME);
176                 fileCounterWriter.println("m = " + MAX_SEEDS);
177                 fileCounterWriter.flush();
178                 fileCounterWriter.close();
179                 outWriter.flush();
180                 outWriter.close();
181                 simulation.isCurrentIterationFinished = true;
182             } else {
183                 resetWriters(configurationName + "/out_" + seedCounter + "_" +
184                                 timeCounter + ".py");
185                 timeCounter++;
186             }
187         }
188     }
189 
190     // Writes 1 to a numpy array if individual is participating, else 0
191     private void writeIsParticipatingData(PositionMatrix matrix) {
192         outWriter.print("isParticipating = array([");
193         boolean firstTime = true;
194         for (Individual individual : matrix.getIndividuals()) {
195             if (firstTime) outWriter.print(
196                     (individual.isParticipating ? 1 : 0));
197             else outWriter.print(", " + (individual.isParticipating ? 1 : 0));
198             firstTime = false;
199         }
200         outWriter.println("])");
201         outWriter.flush();
202     }
203 
```

```
204     // Writes the average danger of all the individuals
205     private void writeAverageDanger(PositionMatrix matrix) {
206         outWriter.print("averageDanger = ");
207         double averageDanger = 0;
208         for (Individual individual : matrix.getIndividuals()) {
209             averageDanger += individual.f / 10000 + individual.density / 50;
210         }
211         averageDanger /= matrix.getIndividuals().size();
212         outWriter.println(averageDanger);
213         outWriter.flush();
214     }
215 
216     // Writes the max danger of all the individuals
217     private void writeMaxDanger(PositionMatrix matrix) {
218         outWriter.print("maxDanger = ");
219         double maxDanger = Double.MIN_VALUE;
220         for (Individual individual : matrix.getIndividuals()) {
221             maxDanger = Math.max(maxDanger, individual.f / 10000 +
222                     individual.density / 50);
223         }
224         outWriter.println(maxDanger);
225         outWriter.flush();
226     }
227 
228     private void writeMedianDanger(PositionMatrix matrix) {
229         outWriter.print("medianDanger = ");
230         // Check if there is an even amount of individuals
231         ArrayList<Individual> individuals =
232                 (ArrayList<Individual>) matrix.getIndividuals();
233         int nOver2 = individuals.size() / 2;
234 
235         double median = (individuals.size() % 2 == 0) ?
236                 (getNthSmallestContinuousDangerLevel(individuals, nOver2) +
237                         getNthSmallestContinuousDangerLevel(individuals,
238                                                             nOver2 + 1)) / 2 :
239                 getNthSmallestContinuousDangerLevel(individuals, nOver2);
240 
241         outWriter.println(median);
242         outWriter.flush();
243     }
244 
245     // QuickSelect algorithm
246     private static double getNthSmallestContinuousDangerLevel(
247             ArrayList<Individual> individuals, int n) {
248         double result;
249         double pivot;
250 
251         // 3 ArrayLists for elements smaller than pivot, equal to pivot,
252         // larger than pivot
253         ArrayList<Individual> lessThanPivot = new ArrayList<Individual>();
254         ArrayList<Individual> greaterThanPivot = new ArrayList<Individual>();
```

```
255         ArrayList<Individual> equalToPivot = new ArrayList<Individual>();
256
257         // Select a random pivot
258         pivot = individuals.get((int) (Math.random() *
259                 individuals.size())).continuousDangerLevel;
260
261         // Add each element of the given list to the appropriate category
262         for (Individual individual : individuals) {
263             if (individual.continuousDangerLevel < pivot) {
264                 lessThanPivot.add(individual);
265             } else if (individual.continuousDangerLevel > pivot) {
266                 greaterThanPivot.add(individual);
267             } else {
268                 equalToPivot.add(individual);
269             }
270         }
271
272         // Recurse into the appropriate category or return the pivot
273         if (n < lessThanPivot.size()) {
274             result = getNthSmallestContinuousDangerLevel(lessThanPivot, n);
275         } else if (n < lessThanPivot.size() + equalToPivot.size()) {
276             result = pivot;
277         } else {
278             result = getNthSmallestContinuousDangerLevel(greaterThanPivot, n -
279                     lessThanPivot.size() - equalToPivot.size());
280         }
281
282         return result;
283     }
284
285     // Make sure we are writing to the appropriate file
286     private void resetWriters(String newOutFileName) {
287         try {
288             outWriter.close();
289             outWriter = new PrintWriter(newOutFileName, "UTF-8");
290         } catch (FileNotFoundException e3) {
291             e3.printStackTrace();
292         } catch (UnsupportedEncodingException e3) {
293             e3.printStackTrace();
294         }
295     }
296 }
```

E.5: Individual

```java
/**
 * Represents an individual.
 */
public class Individual {
    /**
     * The x position of this individual.
     */
    public double x;
    /**
     * The y position of this individual.
     */
    public double y;
    /**
     * The x velocity of this individual.
     */
    public double vx;
    /**
     * The y velocity of this individual.
     */
    public double vy;
    /**
     * True if the individual is participating in the circle pit.
     */
    public boolean isParticipating;
    /**
     * The size of the individual.
     */
    public double radius = 2;
    /**
     * The preferred speed of the individual.
     */
    public double preferredSpeed = 30;
    /**
     * The danger level that the individual is currently at. Ranges from 0 to 6.
     */
    public int dangerLevel;
    /**
     * The norm of the force currently acting on the individual.
     */
    public double f;
    /**
     * Number of neighbors of the individual.
     */
    public double density;
    /**
     * Continuous (rather than discrete) measure of the danger level of an
     * individual.
     */
    public double continuousDangerLevel;

```

```
51      public Individual(double x, double y, double vx, double vy,
52                        boolean isParticipating, int dangerLevel) {
53          this.x = x;
54          this.y = y;
55          this.vx = vx;
56          this.vy = vy;
57          this.isParticipating = isParticipating;
58          this.dangerLevel = dangerLevel;
59      }
60
61      public Individual(double[] position, double[] velocity,
62                        boolean isParticipating, int dangerLevel) {
63          this(position[0], position[1], velocity[0], velocity[1],
64               isParticipating, dangerLevel);
65      }
66
67      public double[] getPosition() {
68          return new double[]{x, y};
69      }
70
71      public double[] getVelocity() {
72          return new double[]{vx, vy};
73      }
74
75      public double distanceTo(Individual other) {
76          double dx = Math.abs(x - other.x);
77          double dy = Math.abs(y - other.y);
78
79          return Math.sqrt(dx * dx + dy * dy);
80      }
81
82      public double distanceTo(double[] point) {
83          double dx = Math.abs(x - point[0]);
84          double dy = Math.abs(y - point[1]);
85
86          return Math.sqrt(dx * dx + dy * dy);
87      }
88
89      @Override
90      public String toString() {
91          return "Individual: position = (" + x + ", " + y + "), velocity = (" +
92                  vx + ", " + vy + "), isParticipating = " + isParticipating;
93      }
94  }
```

E.6: Position Matrix

```java
import java.util.ArrayList;
import java.util.LinkedList;
import java.util.List;

/**
 * Data structure representing the position matrix in the simulation.
 */
public class PositionMatrix {

    /**
     * The width of the matrix
     */
    public final int width;
    /**
     * The height of the matrix
     */
    public final int height;
    /**
     * The size of one sector
     */
    public final int sectorSize;
    /**
     * A boolean matrix to indicate whether sector (i, j) is under police
     * surveillance
     */
    public boolean[][] isPoliceAtSector;
    // The actual matrix
    private LinkedList<Individual>[][] matrix;
    // A List containing all the individuals, makes iterating over them easier
    private ArrayList<Individual> individuals;

    /**
     * Creates a new PositionMatrix
     *
     * @param width      The desired width of the matrix
     * @param height     The desired height of the matrix
     * @param sectorSize The desired sector size
     */
    public PositionMatrix(int width, int height, int sectorSize) {
        this.height = height;
        this.width = width;
        this.sectorSize = sectorSize;

        // Initialize the matrix
        matrix = (LinkedList<Individual>[][]) new LinkedList[width][height];
        for (int i = 0; i < width; i++) {
            for (int j = 0; j < height; j++) {
                matrix[i][j] = new LinkedList<Individual>();
            }
        }
```

```
51
52          individuals = new ArrayList<Individual>();
53          isPoliceAtSector = new boolean[width][height];
54      }
55
56      /**
57       * Gets an individual at position (i, j) in the matrix.
58       *
59       * @param i The row of the individual
60       * @param j The column of the individual
61       * @return The individual at (i, j)
62       */
63      public List<Individual> get(int i, int j) {
64          return matrix[i][j];
65      }
66
67      /**
68       * Gets an individual at the specified sector in the matrix.
69       *
70       * @param sector The sector that the individual is in.
71       * @return The individual at the given sector.
72       */
73      public List<Individual> get(Sector sector) {
74          return matrix[sector.row][sector.col];
75      }
76
77      /**
78       * Gets a list of all the individuals.
79       *
80       * @return The list of the individuals.
81       */
82      public List<Individual> getIndividuals() {
83          return individuals;
84      }
85
86      /**
87       * Adds a new individual to the matrix at the proper position.
88       *
89       * @param individual The individual to be added
90       */
91      public void add(Individual individual) {
92          Sector sector = getSectorForCoords(individual);
93          matrix[sector.row][sector.col].add(individual);
94          individuals.add(individual);
95      }
96
97      public void removeAndAdd(Individual individual, Sector oldSector,
98                               Sector newSector) {
99          matrix[oldSector.row][oldSector.col].remove(individual);
100         matrix[newSector.row][newSector.col].add(individual);
101     }
```

```
102
103     /**
104      * Gets the neighbors of an individual.
105      *
106      * @param individual The individual for whom to search for neighbors
107      * @param radius     The radius in which to search
108      * @return A <code>java.util.List</code> of the neighbors.
109      */
110     public List<Individual> getNeighborsFor(Individual individual,
111                                             double radius) {
112         ArrayList<Individual> neighbors = new ArrayList<Individual>(10);
113         ArrayList<Sector> sectorsToSearch = new ArrayList<Sector>(9);
114         Sector sector = getSectorForCoords(individual);
115         sectorsToSearch.add(sector);
116
117         // Look around the current sector
118         for (int i = -1; i <= 1; i++) {
119             for (int j = -1; j <= 1; j++) {
120                 Sector newSector = getSectorForCoords(individual.x + i * radius,
121                                                       individual.y +
122                                                               i * radius);
123                 if (!sector.equals(newSector)) {
124                     sectorsToSearch.add(newSector);
125                 }
126             }
127         }
128
129         // Look for neighbors at the appropriate distance in the sectors to
130         // search
131         for (Sector sectorToSearch : sectorsToSearch) {
132             List<Individual> possibleNeighbors = get(sectorToSearch);
133             for (Individual neighbor : possibleNeighbors) {
134                 if (individual.distanceTo(neighbor) < radius) {
135                     neighbors.add(neighbor);
136                 }
137             }
138         }
139
140         return neighbors;
141     }
142
143     /**
144      * Gets the sector for the given coordinates.
145      *
146      * @param x The x coordinate
147      * @param y The y coordinate
148      * @return A <code>Sector</code> object corresponding the the given
149      * coordinates.
150      */
151     public Sector getSectorForCoords(double x, double y) {
152         int sectorX = (int) x / sectorSize;
```

```
153         int sectorY = (int) y / sectorSize;
154
155         // Make sure the sector is not out of bounds
156         if (sectorX < 0) sectorX = 0;
157         else if (sectorX >= width) sectorX = width - 1;
158
159         if (sectorY < 0) sectorY = 0;
160         else if (sectorY >= height) sectorY = height - 1;
161
162         return new Sector(sectorX, sectorY);
163     }
164
165     /**
166      * Gets the sector that the given individual is in.
167      *
168      * @param individual The individual for whom to get the sector
169      * @return The sector that the individual is in.
170      * @see PositionMatrix#getSectorForCoords(double, double)
171      */
172     public Sector getSectorForCoords(Individual individual) {
173         return getSectorForCoords(individual.x, individual.y);
174     }
175
176     /**
177      * Gets the sector that the given individual is in given an array of {x, y}
178      * coordinates.
179      *
180      * @param position The array of coordinates
181      * @return The sector corresponding to <code>position</code>
182      * @see PositionMatrix#getSectorForCoords(double, double)
183      */
184     public Sector getSectorForCoords(double[] position) {
185         return getSectorForCoords(position[0], position[1]);
186     }
187
188     /**
189      * Checks if the given sector is monitored by the police.
190      */
191     public boolean isSectorMonitored(Sector sector) {
192         return isPoliceAtSector[sector.row][sector.col];
193     }
194
195     /**
196      * Adds the given list of sectors to be monitored by the police.
197      *
198      * @param policeSectors A comma separated list of sectors, e.g. 0, 0, 1, 1,
199      *                      2, 2
200      */
201     public void setMonitoredSectors(int... policeSectors) {
202         for (int i = 0; i < policeSectors.length; i += 2) {
203             isPoliceAtSector[policeSectors[i]][policeSectors[i + 1]] = true;
```

```
204         }
205     }
206
207     /**
208      * An inner class that represents one sector at a particular location in the
209      * matrix.
210      */
211     public class Sector {
212         int row;  // Row of the matrix
213         int col;  // Column of the matrix
214
215         public Sector(int row, int col) {
216             this.row = row;
217             this.col = col;
218         }
219
220         public boolean equals(Sector other) {
221             return row == other.row && col == other.col;
222         }
223     }
224 }
```

E.7: Simulation

```java
import javax.swing.*;
import java.awt.event.ActionEvent;
import java.awt.event.ActionListener;
import java.io.FileNotFoundException;
import java.io.PrintWriter;
import java.io.UnsupportedEncodingException;
import java.util.List;
import java.util.Random;

/**
 * Class representing one or multiple simulations of a circle pit.
 */
public class Simulation {

    /**
     * Size of one sector of the matrix
     */
    public static final int SECTOR_SIZE = 10;
    /**
     * The duration of one timestep (in milliseconds)
     */
    public final static int TIMESTEP = 50;
    /**
     * Strength of repulsive force
     */
    public double epsilon;
    /**
     * Strength of propulsion
     */
    public double mu;
    /**
     * Strength of flocking force
     */
    public double alpha;
    /**
     * Strength of the centripetal force
     */
    public double gamma;
    /**
     * Number of people in the simulation
     */
    public double numberOfPeople;
    /**
     * Radius within which velocity of neighbors has an effect on the flocking
     * force
     */
    public double flockRadius;
    /**
     * Timestep of the simulation
     */
```

```
51      public double dt;
52      /**
53       * Percentage of people initially participating in the circle pit
54       */
55      public double percentParticipating;
56      /**
57       * Radius within which the 'isParticipating' of neighbors affects the
58       * individual
59       */
60      public double rParticipating;
61      /**
62       * Minimum amount of people necessary to constitute a circle pit
63       */
64      public int minCirclePitSize;
65      /**
66       * Necessary number of neighbors participating to start participating
67       */
68      public int minParticipatingNeighbors;
69      /**
70       * Center of the matrix
71       */
72      public double[] center;
73      /**
74       * Window with the simulation
75       */
76      public SimulationGUI window;
77      /**
78       * Safe density level
79       */
80      public int safeDensity = 10;
81      /**
82       * Density danger level 1
83       */
84      public int density1 = 20;
85      /**
86       * Density danger level 2
87       */
88      public int density2 = 40;
89      /**
90       * safe Force danger level
91       */
92      public int safeForce = 1000;
93      /**
94       * Force danger level 1
95       */
96      public int force1 = 3000;
97      /**
98       * Density danger level 2
99       */
100     public int force2 = 4000;
101     /**
```

```
102         * True if force is considered to be a danger factor
103         */
104        public boolean enableForce = true;
105        /**
106         * True if density is considered to be a danger factor
107         */
108        public boolean enableDensity = true;
109        /**
110         * False while the current iteration of the simulation is running (used for
111         * automation)
112         */
113        public boolean isCurrentIterationFinished = false;
114
115        private PrintWriter writer;  // Writes analysis data to a file
116
117        private double maxX;  // Right-hand border of the terrain
118        private double maxY;  // Bottom border of the terrain
119        private Timer timer;  // Timer to run the simulation
120
121        private Random random = new Random(42);  // To generate random numbers
122        private int fileCounter = 0;  // Counts how many files were written
123        private PrintWriter fileCounterWriter;
124                // Writes information about how many files were written to a file
125
126        private PositionMatrix matrix;
127
128        /**
129         * Creates a new Simulation with the specified parameters.
130         *
131         * @param epsilon                   Strength of the repulsive force
132         * @param mu                        Strength of the propulsive force
133         * @param alpha                     Strength of the flocking force
134         * @param gamma                     Strength of the centripetal force
135         * @param numberOfPeople            Number of people at the concert
136         * @param flockRadius               Radius in which to look for neighbors
137         *                                  for the flocking force
138         * @param dt                        Duration of one timestep
139         * @param percentParticipating      Proportion of people initially
140         *                                  participating in the circle pit
141         * @param rParticipating            Radius in which to search for
142         *                                  participating neighbors
143         * @param minCirclePitSize          Minimum number of participating
144         *                                  neighbors needed to continue
145         *                                  participating in the circle pit
146         * @param minParticipatingNeighbors Minimum number of participating
147         *                                  neighbors needed to join in the circle
148         *                                  pit
149         */
150        public Simulation(double epsilon, double mu, double alpha, double gamma,
151                          double numberOfPeople, double flockRadius, double dt,
152                          double percentParticipating, double rParticipating,
```

```
                    int minCirclePitSize, int minParticipatingNeighbors) {
        this.epsilon = epsilon;
        this.mu = mu;
        this.alpha = alpha;
        this.gamma = gamma;
        this.numberOfPeople = numberOfPeople;
        this.flockRadius = flockRadius;
        this.dt = dt;
        this.percentParticipating = percentParticipating;
        this.rParticipating = rParticipating;
        this.minCirclePitSize = minCirclePitSize;
        this.minParticipatingNeighbors = minParticipatingNeighbors;
        try {
            fileCounterWriter = new PrintWriter("special_counter.py");
        } catch (FileNotFoundException e) {
            e.printStackTrace();
        }
        initializeMatrix();
    }

    // Initializes the matrix with individuals with random velocity and
    // position.
    private void initializeMatrix() {
        int matrixSize = 10;

        // The maximum x and y values that an individual can have
        maxX = matrixSize * SECTOR_SIZE;
        maxY = matrixSize * SECTOR_SIZE;

        center = new double[]{maxX / 2, maxY / 2};

        matrix = new PositionMatrix(matrixSize, matrixSize,
                                    SECTOR_SIZE);

        for (int i = 0; i < numberOfPeople; i++) {
            // Generate random coordinates
            double[] coords = new double[2];
            coords[0] = random.nextDouble() * SECTOR_SIZE * matrixSize;
            coords[1] = random.nextDouble() * SECTOR_SIZE * matrixSize;

            // Generate random velocity
            double[] velocity = new double[]{random.nextDouble() - 0.5,
                                             random.nextDouble() - 0.5};

            // Decide whether individual is initially participating
            boolean isParticipating =
                    random.nextDouble() < percentParticipating;

            //levels of danger, 0 is safe, by default it's safe
            int dangerLevel = 0;

```

```
204             Individual individual = new Individual(coords, velocity,
205                                                    isParticipating,
206                                                    dangerLevel);
207
208             // Add individual to appropriate sector
209             matrix.add(individual);
210         }
211     }
212
213     /**
214      * Resets the matrix of the simulation.
215      */
216     public void resetMatrix() {
217         stop();
218         basicReset();
219     }
220
221     /**
222      * Restarts the simulation.
223      */
224     public void restartSimulation() {
225         stop();
226         basicReset();
227         start();
228     }
229
230     /**
231      * Performs a basic reset of the simulation back to its initial state.
232      */
233     public void basicReset() {
234         initializeMatrix();
235         window.resetSimulationPanel();
236         window.repaint();
237     }
238
239     /**
240      * Stops the simulation.
241      */
242     public void stop() {
243         timer.stop();
244     }
245
246     /**
247      * Starts the simulation.
248      */
249     public void start() {
250         timer.start();
251     }
252
253     /**
254      * Creates a new <code>Timer</code> to run the simulation
```

```
255         *
256         * @param listener The <code>ActionListener</code> the new
257         *                 <code>Timer</code> should be based on
258         */
259        public void createNewTimer(ActionListener listener) {
260            timer = new Timer(TIMESTEP, listener);
261        }
262
263        /**
264         * Redraws the simulation.
265         */
266        public void repaint() {
267            window.repaint();
268        }
269
270        /**
271         * Sets the seed of the <code>Random</code> object used during the
272         * simulation.
273         *
274         * @param seed The seed to set the <code>Random</code> object to
275         */
276        public void setSeed(int seed) {
277            random = new Random(seed);
278        }
279
280        // Checks if the given neighbor at the given distance is participating
281        private boolean isNeighborParticipating(Individual neighbor,
282                                                double distance) {
283            return neighbor.isParticipating && distance < rParticipating;
284        }
285
286        /**
287         * Runs the simulation manually (so that the user can interact with it).
288         */
289        public void runManualSimulation() {
290            window = new SimulationGUI(this);
291
292            // Run a new frame every 50 milliseconds
293            timer = new Timer(50, new ActionListener() {
294                /*@Override*/
295                public void actionPerformed(ActionEvent e) {
296                    runOneTimestep();
297                    window.repaint();
298                }
299            });
300
301            window.setVisible(true);
302        }
303
304        /**
305         * Creates a new window that displays and animates the simulation.
```

```
306         */
307        public void createWindow() {
308            window = new SimulationGUI(this);
309            window.setVisible(true);
310        }
311
312        /**
313         * Runs the simulation automatically (for use for automatic data
314         * collection).
315         *
316         * @param name                  The name of the folder in which to put
317         *                              generated data.
318         * @param dataCollectionInterval How often to collect data (in
319         *                              milliseconds)
320         * @param insertPoliceAfter     The amount of time after which police
321         *                              should be inserted, if any
322         * @param amountOfSeeds         How many random seeds to test
323         * @param collectionTimes       How many times to collect data per seed
324         */
325        public void runAutomaticSimulation(String name, int dataCollectionInterval,
326                                           int insertPoliceAfter, int amountOfSeeds,
327                                           int collectionTimes) {
328            window = new SimulationGUI(this);
329
330            DataCollector collector = new DataCollector(this, name,
331                                                        dataCollectionInterval,
332                                                        insertPoliceAfter,
333                                                        amountOfSeeds,
334                                                        collectionTimes,
335                                                        new boolean[10][10]);
336            timer = new Timer(TIMESTEP, collector);
337            timer.start();
338            window.setVisible(true);
339        }
340
341        /**
342         * Runs one timestep of the simulation.
343         */
344        public void runOneTimestep() {
345
346            // List of all the individuals in the matrix
347            List<Individual> individuals = matrix.getIndividuals();
348
349            // Iterate over each individual
350            for (Individual individual : individuals) {
351                // Sector where the individual is before updating position
352                PositionMatrix.Sector initialSector = matrix.getSectorForCoords(
353                        individual);
354                // Amount of neighbors participating with the radius rParticipating
355                int sumParticipating = 0;
356                // Forces acting upon individual
```

```
357             double[] F = {0.0, 0.0};
358             // Sum of the neighbor velocities
359             double[] sumOverVelocities = {0.0, 0.0};
360             // List of neighbors
361             List<Individual> neighbors = matrix.getNeighborsFor(individual,
362                                                                 flockRadius);
363             // Position and velocity of individual
364             double[] position = individual.getPosition();
365             double[] velocity = individual.getVelocity();
366             double r0 = 2 * individual.radius;
367
368             individual.dangerLevel = 0;
369             // Calculate the danger level
370             int numNeighbors = neighbors.size();
371
372             // We use the number of people in the neighbor list to represent
373             // density
374             if (enableDensity) {
375                 if (numNeighbors > density2)
376                     individual.dangerLevel = 3;
377                 else if (numNeighbors > density1)
378                     individual.dangerLevel = 2;
379                 else if (numNeighbors > safeDensity)
380                     individual.dangerLevel = 1;
381                 else if (numNeighbors < safeDensity)
382                     individual.dangerLevel = 0;
383             }
384
385             // ================= CALCULATION OF THE FORCES ====================
386             for (Individual neighbor : neighbors) {
387                 // Make sure we are not using the individual him/herself
388                 if (neighbor == individual) {
389                     continue;
390                 }
391                 double[] positionNeighbor = neighbor.getPosition();
392                 double[] velocityNeighbor = neighbor.getVelocity();
393
394                 double distance = individual.distanceTo(neighbor);
395
396                 sumParticipating += isNeighborParticipating(neighbor,
397                                                             distance) ? 1 : 0;
398
399                 // Repulsive force
400                 // We only use neighbors within a radius of 2 * r0
401
402                 if (distance < 2 * individual.radius) {
403                     F[0] += epsilon * 500 * (individual.x - neighbor.x) /
404                             distance;
405                     F[1] += epsilon * 500 * (individual.y - neighbor.y) /
406                             distance;
407                 } else if (distance < 2 * r0) {
```

```
                F[0] += -epsilon * ((1 / (distance - 2 * r0)) *
                        (position[0] - positionNeighbor[0])) / distance;
                F[1] += -epsilon * ((1 / (distance - 2 * r0)) *
                        (position[1] - positionNeighbor[1])) / distance;
            }

            sumOverVelocities[0] += velocityNeighbor[0];
            sumOverVelocities[1] += velocityNeighbor[1];
        }

        // Calculate the norm of the force
        double jointForce = norm(F);

        if (enableForce) {
            if (jointForce > force2)
                individual.dangerLevel += 3;
            else if (jointForce > force1)
                individual.dangerLevel += 2;
            else if (jointForce > safeForce)
                individual.dangerLevel += 1;
            else if (jointForce < safeForce)
                individual.dangerLevel += 0;
        }

        // Adjust the danger level if only one of the two options is enabled
        if (enableForce ^ enableDensity) {
            individual.dangerLevel *= 2;
        }

        // Decide if the individual is participating or not
        if (sumParticipating >= minParticipatingNeighbors) {
            individual.isParticipating = true;
        }

        if (sumParticipating < minCirclePitSize) {
            individual.isParticipating = false;
        }

        if (matrix.isSectorMonitored(
                matrix.getSectorForCoords(individual))) {
            individual.isParticipating = false;
        }

        // Set preferred speed accordingly
        individual.preferredSpeed =
                individual.isParticipating ? 30 : 5 * random.nextDouble();

        // Propulsion
        // Makes the individual want to travel at their preferred speed
        double vi = individual.preferredSpeed;
        F[0] += -mu * (norm(velocity) - vi) * velocity[0] / norm(velocity);
```

```
459             F[1] += -mu * (norm(velocity) - vi) * velocity[1] / norm(velocity);
460
461             // Flocking
462             if (individual.isParticipating &&
463                     !(sumOverVelocities[0] == 0 && sumOverVelocities[1] == 0)) {
464                 double norm = norm(sumOverVelocities);
465                 F[0] += alpha * sumOverVelocities[0] / norm;
466                 F[1] += alpha * sumOverVelocities[1] / norm;
467             }
468
469             // Centripetal Force
470             if (individual.isParticipating) {
471                 double distanceToCenter = individual.distanceTo(center);
472
473                 // Normalized vector from center to individual
474                 double[] r = new double[]{center[0] - individual.x,
475                                           center[1] - individual.y};
476                 r[0] /= distanceToCenter;
477                 r[1] /= distanceToCenter;
478
479                 F[0] += gamma * r[0];
480                 F[1] += gamma * r[1];
481             }
482
483             // Add noise
484             // TODO: Generate noise
485
486             // Make sure that F does not become too large to fit into a double
487             double normOfF = norm(F);
488
489             if (normOfF > Long.MAX_VALUE) {
490                 F[0] /= normOfF * Long.MAX_VALUE;
491                 F[1] /= normOfF * Long.MAX_VALUE;
492             }
493
494             // ====================== CALCULATE TIMESTEP ======================
495             // Using the leap-frog method to integrate the differential equation
496             // d^2y/dt^2 = rhs(y)
497
498             // Shifted initial velocity for leap-frog
499             double[] v_temp = new double[2];
500             v_temp[0] = velocity[0] + 0.5 * dt * F[0];
501             v_temp[1] = velocity[1] + 0.5 * dt * F[1];
502
503             // New position of the individual
504             double newX = position[0] + dt * v_temp[0];
505             double newY = position[1] + dt * v_temp[1];
506
507             // New velocity of the individual
508             double newVx = v_temp[0] + dt * F[0] / 2;
509             double newVy = v_temp[1] + dt * F[1] / 2;
```

```
510
511             // Make sure individuals rebound off the edges of the space
512             if (newX < 0 || newX > maxX) {
513                 newVx = -newVx;
514                 F[0] = -F[0];
515             }
516             if (newY < 0 || newY > maxY) {
517                 newVy = -newVy;
518                 F[1] = -F[1];
519             }
520
521             // Make sure they don't get stuck in an out-of-bounds area
522             if (newX >= 0 && newX <= maxX)
523                 individual.x = newX;
524             if (newY >= 0 && newY <= maxY)
525                 individual.y = newY;
526
527             individual.vx = newVx;
528             individual.vy = newVy;
529
530             // Add the individual to the correct sector
531             PositionMatrix.Sector newSector = matrix.getSectorForCoords(
532                     individual);
533             if (!newSector.equals(initialSector)) {
534                 matrix.removeAndAdd(individual, initialSector, newSector);
535             }
536
537             // Set the force acting on this individual and the amount of
538             // neighbors so that the danger level can be assessed
539             individual.f = norm(F);
540             individual.density = neighbors.size();
541             individual.continuousDangerLevel =
542                     individual.f / 10000 + individual.density / 50;
543         }
544     }
545
546     /**
547      * Writes a small Python/Numpy script to allow analysis of the current
548      * situation.
549      */
550     public void exportData() {
551         try {
552             writer.close();
553             writer = new PrintWriter("special" + fileCounter + ".py", "UTF-8");
554         } catch (FileNotFoundException e) {
555             e.printStackTrace();
556         } catch (UnsupportedEncodingException e) {
557             e.printStackTrace();
558         } catch (NullPointerException e) {
559             try {
560                 writer = new PrintWriter("special" + fileCounter + ".py",
```

```
                                        "UTF-8");
            } catch (FileNotFoundException e1) {
                e1.printStackTrace();
            } catch (UnsupportedEncodingException e1) {
                e1.printStackTrace();
            }
        }
        try {
            fileCounterWriter.close();
            fileCounterWriter = new PrintWriter("special_counter.py");
        } catch (FileNotFoundException e) {
            e.printStackTrace();
        }
        writer.println("from numpy import *");
        writer.print("x = array([");
        boolean firstTime = true;
        for (Individual individual : matrix.getIndividuals()) {
            if (firstTime) writer.print(individual.x);
            else writer.print(", " + individual.x);
            firstTime = false;
        }
        writer.println("])");
        writer.flush();

        writer.print("y = array([");
        firstTime = true;
        for (Individual individual : matrix.getIndividuals()) {
            if (firstTime) writer.print(individual.y);
            else writer.print(", " + individual.y);
            firstTime = false;
        }
        writer.println("])");
        writer.flush();

        writer.print("dangerLevel = array([");
        firstTime = true;
        for (Individual individual : matrix.getIndividuals()) {
            if (firstTime) writer.print(individual.dangerLevel);
            else writer.print(", " + individual.dangerLevel);
            firstTime = false;
        }
        writer.println("])");
        writer.flush();

        writer.print("isParticipating = array([");
        firstTime = true;
        for (Individual individual : matrix.getIndividuals()) {
            if (firstTime) writer.print((individual.isParticipating ? 1 : 0));
            else writer.print(", " + (individual.isParticipating ? 1 : 0));
            firstTime = false;
        }
```

```
612             writer.println("])");
613             writer.flush();
614 
615             writer.print("F = array([");
616             firstTime = true;
617             for (Individual individual : matrix.getIndividuals()) {
618                 if (firstTime) writer.print(individual.f);
619                 else writer.print(", " + individual.f);
620                 firstTime = false;
621             }
622             writer.println("])");
623             writer.flush();
624 
625             writer.print("density = array([");
626             firstTime = true;
627             for (Individual individual : matrix.getIndividuals()) {
628                 if (firstTime) writer.print(individual.density);
629                 else writer.print(", " + individual.density);
630                 firstTime = false;
631             }
632             writer.println("])");
633             writer.flush();
634             fileCounter++;
635             fileCounterWriter.println("n = " + fileCounter);
636             fileCounterWriter.flush();
637         }
638 
639         // Calculates the norm of the given vector.
640         private double norm(double[] vector) {
641             return Math.sqrt(vector[0] * vector[0] + vector[1] * vector[1]);
642         }
643 
644         /**
645          * Gets the matrix associated with this object.
646          *
647          * @return The <code>PositionMatrix</code> object the individuals are stored
648          * in.
649          */
650         public PositionMatrix getMatrix() {
651             return matrix;
652         }
653 
654         /**
655          * Gets the <code>Timer</code> that is running this simulation.
656          *
657          * @return
658          */
659         public Timer getSimulationTimer() {
660             return timer;
661         }
662 
```

```
663     /**
664      * Sets which sectors are monitored by the police.
665      *
666      * @param sectors A comma-separated list of comma-separated pairs of numbers
667      *                representing sectors monitored by the police
668      */
669     public void setMonitoredSectors(int... sectors) {
670         matrix.setMonitoredSectors(sectors);
671     }
672 
673     /**
674      * Sets which sectors are monitored by the police.
675      *
676      * @param sectors A <code>boolean[][]</code> array containing
677      *                <code>true</code> at position (i, j) if a policeman is in
678      *                that sector
679      */
680     public void setMonitoredSectors(boolean[][] sectors) {
681         matrix.isPoliceAtSector = sectors;
682     }
683 }
```

E.8: Graphical User Interface

```java
import javax.swing.*;
import java.awt.*;

public class SimulationGUI extends JFrame {

    private SimulationPanel simulationPanel;
    private ControlPanel controlPanel;
    private Simulation simulation;

    public SimulationGUI(Simulation simulation) {
        this.simulation = simulation;
        try {
            UIManager.setLookAndFeel(UIManager.getSystemLookAndFeelClassName());
        } catch (ClassNotFoundException e) {
            e.printStackTrace();
        } catch (InstantiationException e) {
            e.printStackTrace();
        } catch (IllegalAccessException e) {
            e.printStackTrace();
        } catch (UnsupportedLookAndFeelException e) {
            e.printStackTrace();
        }
        setTitle("Circle Pit Simulation");
        setDefaultCloseOperation(WindowConstants.EXIT_ON_CLOSE);
        setLayout(new BorderLayout());
        setResizable(false);

        initComponents();
        addComponents();
        pack();
        setLocationRelativeTo(null);
    }

    private void initComponents() {
        PositionMatrix matrix = simulation.getMatrix();
        simulationPanel = new SimulationPanel(500, 500, simulation,
                                              matrix.width * matrix.sectorSize,
                                              matrix.height *
                                                      matrix.sectorSize);

        controlPanel = new ControlPanel(simulation, simulationPanel);
    }

    private void addComponents() {
        add(simulationPanel, BorderLayout.CENTER);
        add(controlPanel, BorderLayout.EAST);
    }

    /**
     * Resets the simulation panel.
```

```
51          */
52      public void resetSimulationPanel() {
53          simulationPanel.setIndividuals(simulation.getMatrix().getIndividuals());
54      }
55  }
```

E.9: Simulation Panel

```java
import javax.imageio.ImageIO;
import javax.swing.*;
import java.awt.*;
import java.awt.event.MouseAdapter;
import java.awt.event.MouseEvent;
import java.awt.geom.Ellipse2D;
import java.awt.geom.Rectangle2D;
import java.awt.image.BufferedImage;
import java.io.File;
import java.io.IOException;

/**
 * Draws the matrix into a JPanel.
 */
public class SimulationPanel extends JPanel {

    public boolean shouldShowParticipants = true;
    private java.util.List<Individual> individuals;
    private double xScalingFactor, yScalingFactor;
    private Simulation simulation;
    private BufferedImage image;

    public SimulationPanel(int width, int height, Simulation simulation,
                           int matrixWidth, int matrixHeight) {
        this.individuals = simulation.getMatrix().getIndividuals();
        xScalingFactor = width / matrixWidth;
        yScalingFactor = height / matrixHeight;
        this.simulation = simulation;
        try {
            image = ImageIO.read(new File("policeman.png"));
        } catch (IOException e) {
            e.printStackTrace();
        }
        this.setSize(new Dimension(width, height));
        this.setPreferredSize(new Dimension(width, height));
        this.setMinimumSize(new Dimension(width, height));
        this.setBackground(Color.WHITE);
        addListeners();
        setFocusable(false);
    }

    private void addListeners() {
        // Add a policeman on mouse click
        this.addMouseListener(new MouseAdapter() {
            @Override
            public void mouseClicked(MouseEvent e) {
                double x = e.getX() / xScalingFactor;
                double y = e.getY() / yScalingFactor;
                PositionMatrix.Sector sector =
                        simulation.getMatrix().getSectorForCoords(x, y);
```

```
                simulation
                        .getMatrix().isPoliceAtSector[sector.row][sector.col] =
                        !(simulation
                                .getMatrix().isPoliceAtSector[sector
                                .row][sector.col]);
                getParent().repaint();
            }
        });
    }

    /**
     * Sets the individuals list to the given parameter.
     */
    public void setIndividuals(java.util.List<Individual> individuals) {
        this.individuals = individuals;
    }

    // Increases the rendering quality of the simulation
    private void increaseRenderingQuality(Graphics2D g2d) {
        g2d.setRenderingHint(RenderingHints.KEY_TEXT_ANTIALIASING,
                             RenderingHints.VALUE_TEXT_ANTIALIAS_ON);
        g2d.setRenderingHint(RenderingHints.KEY_DITHERING,
                             RenderingHints.VALUE_DITHER_ENABLE);
        g2d.setRenderingHint(RenderingHints.KEY_RENDERING,
                             RenderingHints.VALUE_RENDER_QUALITY);
        g2d.setRenderingHint(RenderingHints.KEY_ANTIALIASING,
                             RenderingHints.VALUE_ANTIALIAS_ON);
        g2d.setRenderingHint(RenderingHints.KEY_FRACTIONALMETRICS,
                             RenderingHints.VALUE_FRACTIONALMETRICS_ON);
        g2d.setRenderingHint(RenderingHints.KEY_ALPHA_INTERPOLATION,
                             RenderingHints.VALUE_ALPHA_INTERPOLATION_QUALITY);
        g2d.setRenderingHint(RenderingHints.KEY_COLOR_RENDERING,
                             RenderingHints.VALUE_COLOR_RENDER_QUALITY);
        g2d.setRenderingHint(RenderingHints.KEY_STROKE_CONTROL,
                             RenderingHints.VALUE_STROKE_PURE);
    }

    @Override
    public void paintComponent(Graphics g) {
        super.paintComponent(g);
        int sumDanger = 0;
        Graphics2D graphics2D = (Graphics2D) g.create();
        increaseRenderingQuality(graphics2D);  // Comment this out to
                                               // potentially make animation
                                               // smoother (if laggy)

        // Draw each individual
        for (Individual individual : individuals) {
            double[] coords = individual.getPosition();
            coords[0] *= xScalingFactor;
            coords[1] *= yScalingFactor;
```

```
102
103             // Set the color depending on the danger level of the individual
104             int dangerLevel = individual.dangerLevel;
105             if (dangerLevel == 0) {
106                 graphics2D.setColor(new Color(204, 229, 255));
107             } else if (dangerLevel == 1) {
108                 graphics2D.setColor(new Color(154, 204, 255));
109             } else if (dangerLevel == 2) {
110                 graphics2D.setColor(new Color(102, 178, 255));
111             } else if (dangerLevel == 3) {
112                 sumDanger++;
113                 graphics2D.setColor(new Color(51, 153, 255));
114             } else if (dangerLevel == 4) {
115                 sumDanger += 2;
116                 graphics2D.setColor(new Color(0, 128, 255));
117             } else if (dangerLevel == 5) {
118                 sumDanger += 3;
119                 graphics2D.setColor(new Color(0, 102, 204));
120             } else if (dangerLevel == 6) {
121                 sumDanger += 4;
122                 graphics2D.setColor(new Color(255, 51, 51));
123             }
124
125             graphics2D.fill(new Ellipse2D.Double(coords[0], coords[1],
126                                                  individual.radius *
127                                                          xScalingFactor,
128                                                  individual.radius *
129                                                          yScalingFactor));
130
131             // Fill the individual with a white circle if not participating
132             if (shouldShowParticipants) {
133                 if (!individual.isParticipating) {
134                     graphics2D.setColor(Color.WHITE);
135                     graphics2D.fill(new Ellipse2D.Double(
136                             coords[0] + individual.radius * xScalingFactor / 4,
137                             coords[1] + individual.radius * yScalingFactor / 4,
138                             individual.radius * xScalingFactor / 2,
139                             individual.radius * yScalingFactor / 2));
140
141                 }
142             }
143         }
144
145         // General Danger indicator
146         graphics2D.setColor(new Color(102, 102, 0));
147         graphics2D.fill(new Rectangle2D.Double(0, 10, 13, sumDanger / 5));
148         graphics2D.setColor(new Color(204, 204, 0));
149         graphics2D.fill(new Rectangle2D.Double(1, 11, 11, sumDanger / 5 - 2));
150
151         // Drawing the policemen
152         boolean[][] monitoredSectors = simulation.getMatrix().isPoliceAtSector;
```

```
153         for (int i = 0; i < monitoredSectors.length; i++) {
154             for (int j = 0; j < monitoredSectors[i].length; j++) {
155                 if (monitoredSectors[i][j]) {
156                     graphics2D.drawImage(image,
157                                          (int) ((i * 10 + 4) * xScalingFactor),
158                                          (int) ((j * 10 + 4) * yScalingFactor),
159                                          (int) (3 * xScalingFactor),
160                                          (int) (3 * yScalingFactor), null);
161                 }
162             }
163         }
164         g.dispose();
165     }
166 }
```

Appendix F: Python Code

F.1: Time Evolution of Participation Rate and Danger

```
# -*- coding: utf-8 -*-
from matplotlib.pylab import *
from numpy import *

colors = array(
    ['dodgerblue', 'darkorange', 'g', 'red', 'purple', 'brown', 'violet',
     'grey', 'y', 'lightskyblue', 'black',
     'magenta'])


def analyse_median_danger(test_set, i):
    to_do = "from %s.counter import *" % test_set

    exec(to_do, globals())

    median_danger_time_evolution = zeros((n - 5, m))

    t = linspace(0, 1, n - 5)
    title('Time Evolution of Average of Median Danger')

    for j in range(0, m):  # iterating over different seeds
        for k in range(0, n - 5):  # iterating over time steps
            filename = 'out_%s_%s' % (j, k)
            exec("from %s.%s import *" % (test_set, filename),
                 globals())  # importing data for given seed and time steps
            median_danger_time_evolution[k, j] += medianDanger
    y = average(median_danger_time_evolution, axis=1)
    ylabel('Median Danger')
    ymax = max(y)
    if (test_set == 'control'):
        linewidth_ = 2
    else:
        linewidth_ = 1.2
    plot(t, y / ymax, colors[i], linewidth=linewidth_, label=test_set)


def analyse_is_participating(test_set, i):
    toDo = "from %s.counter import *" % test_set

    exec(toDo, globals())

    is_participating_time_evolution = zeros(n - 5)
    t = linspace(0, 1, n - 5)
    ylim(0, 1)
    title('Time Evolution of Participation Rate')
    for j in range(0, m):  # iterating over different seeds
        for k in range(0, n - 5):  # iterating over time steps
```

```
            filename = 'out_%s_%s' % (j, k)
            exec("from %s.%s import *" % (test_set, filename),
                 globals())  # importing data for given seed and time steps
            is_participating_time_evolution[k] += sum(isParticipating) / (
            500 * 50)

    if (test_set == 'control'):
        linewidth_ = 2
    else:
        linewidth_ = 1.2

    plot(t, is_participating_time_evolution, colors[i], linewidth=linewidth_,
         label=test_set)
    ylabel('Participation Rate')


if __name__ == '__main__' and __package__ is None:
    import sys, os.path as path

    # Make sure we can import the out.py files
    sys.path.append(path.dirname(path.dirname(path.abspath(__file__))))

    # isParticipating: iterate over the configs listed in configs.sim
    with open("configs.sim") as f:
        next(f)
        figure(figsize=(7, 5))
        k = 0
        for test_set in f:
            analyse_is_participating(test_set.strip(), k)
            k += 1

    legend(prop={'size': 8}, fancybox=True, ncol=3, loc=1)
    xlabel('Time')
    savefig('isParticipating_timeEvolution.png', dpi=600)

    # Median Danger: iterate over the configs listed in configs.sim
    with open("configs.sim") as f:
        next(f)
        figure(figsize=(7, 5))
        k = 0
        for test_set in f:
            analyse_median_danger(test_set.strip(), k)
            k += 1

    legend(prop={'size': 8}, fancybox=True, ncol=3, loc=1)
    xlabel('Time')
    savefig('medianDanger_timeEvolution.png', dpi=600)
```

F.2: Creation of Phase Diagrams

```
import numpy as np
import matplotlib.pylab as plt
from scipy import interpolate


def phase_diagram(x, y, danger):
    # levels to be considered safe/dangerous
    safe_danger = 0.4
    danger1 = 0.9
    danger2 = 1.4

    # interpolates the data to get a full grid
    grid_x, grid_y = mgrid[0:99:200j, 0:99:200j]
    points = (x, y)
    grid_danger = interpolate.griddata(points, danger, (grid_x, grid_y),
                                       method='cubic')

    plt.figure()
    # plots danger diagram
    im_d = plt.imshow(grid_danger, extent=(0, 99, 0, 99), origin='upper',
                      cmap='hot', vmin=safe_danger, vmax=danger2 + 0.2)
    plt.axis('off')
    cbar_d = plt.colorbar(im_d, fraction=0.046, pad=0.04, orientation='vertical',
                          ticks=[safe_danger, danger1, danger2])
    cbar_d.ax.set_yticklabels(['Low', 'Medium', 'High'])
    plt.title('Danger Level')

    plt.show()


# This program shows danger levels in a phase
# diagram as an average of a set of 'out.py' files

# Average function which looks for two equals points
def average_(points2, d2):
    global continuous_danger_level_
    global points
    continuous_danger_level_ = np.append(continuous_danger_level_, d2)
    points_[0] = np.append(points_[0], points2[0])
    points_[1] = np.append(points_[1], points2[1])


# Imports and averages the data-set from the out files
def analyse2(test_set, time):

    # Import the data from the out.py files
    to_do = "from %s.counter import *" % test_set
    exec(to_do, globals())

```

```
    global points_
    global continuous_danger_level_
    exec("from %s.out_0_0 import *" % (test_set), globals())
    points_ = [x, y]
    continuous_danger_level_ = continuousDangerLevel

    # Iterate over the seeds
    for i in range(0, m):
        try:
            filename_ = 'out_%s_%s' % (i, time)
            exec("from %s.%s import *" % (test_set, filename_), globals())
        except ModuleNotFoundError:
            break

        # Average over the seeds
        average_((x, y), continuousDangerLevel)

    phase_diagram(points_[0], points_[1], continuous_danger_level_)


if __name__ == '__main__' and __package__ is None:
    import sys, os.path as path

    sys.path.append(path.dirname(path.dirname(path.abspath(__file__))))

    # Iterate over all the config files in configs.sim
    with open("configs.sim") as f:
        next(f)
        for test_set in f:
            time = int(input('Choose time ->    '))
            analyse2(test_set.strip(), time)
```