Reproduction Strategies
Sexual vs Asexual

Arielle Barouch, Or gold and Dania Odeh

1 Introduction

Complex systems consist of multiple components interacting with each other, when this interaction forms unpredictable complex patterns governed by simple rules for individuals' relationships. [1]

Complex Systems are often characterized by distinct properties arising from such behaviors such as emergence, nonlinearity and feedback loops, and others. When different components of the system interact linearly can create nonlinear outcomes, this change can happen at shift point; when changing a single parameter causes the dramatic shift from one state to another.[2] The previous can happen due to feedback loops between the different components of the system. As a result of a stimulus, shifts the system to or apart from a stable state, a process often defines a negative or positive feedback loop, respectively. [3]
While the complexity of a system can also be manifested by its sensitivity to initial conditions leading to more chaotic behavior.

One of the primary focuses in the study of complex systems, is the property of emergent behavior. When the relationship between system's components yields to collective behaviors of interaction within the system itself and with the environment, which is distinct from the behavior of individuals on their own.[4]

One well-known model of a complex system is Conway's Game of Life, representing a grid of cells each following the same local simple rules, by which creating an initial configuration and observing how the cells interactions evolve, and interestingly shows emergent behavior of interactions. [5]

Inspired by the mentioned, we hope to use this model to investigate the reproduction strategies between different types of cells. The work seeks emergent properties and insights gained from the cell population as a complex system, where each is interacting with another by reproduction and mating rules.

Assuming that, the existence of a winning reproduction strategy; either sexual or asexual, we show that different reproduction rates produce different population interactions and a dependent winning strategy.

2 Implementation and Results

1. Creating the Original Game of Life
   The first stage of our project was implementing the original Game of Life on a python platform and in a way that will be flexible to future changes. The game included the following

classes/code files:
• A cell class with a method to calculate updated life status after each iteration according to game rules.
• A board class that holds a matrix of all cells in the grid and controls the iterations and updates of the board.
• A main file that initializes the board after determining the run parameters. These parameters are:

(a) ALIVE_PROB – the probability of initializing a single cell in the grid to be alive.

(b) ROWS – number of rows in the grid.

(c) COLUMNS – number of columns in the grid.

Our initial game of life board was implemented with walls (as opposed to an infinite grid). We tested our code and observed that the game behaved as expected, for example, the known complex patterns of game of life appeared on board.

2. Designing an Asexual Cell
Since the aim of our project was to compare sexual and asexual reproduction strategies under different circumstances, we designed a new type of cell with the following properties:
• The asexual cell dies if #neighbors >3 or #neighbors <2 (as the game of life original cell)
• The asexual cell reproduces with probability p and chooses the location of its descendant by uniform distribution over its dead neighbors.
For the sake of our experiment, we considered the original game of life cell as a sexual cell, because of the requirement of 3 neighbors for reproduction.
The asexual cell class was implemented as an inheriting child class of the original cell, as it uses some of its methods and all of its class variables.
It should be noted that each cell type counts its neighbors to determine death (from either overpopulation or underpopulation) by considering all cell types, but the sexual cell counts its neighbors to determine reproduction by considering only sexual cells.
In addition, we added to the main code file the TYPE_PROB_LIST parameter, which is a tuple of the probabilities of an alive cell to be of a specific type (sexual or asexual) when the game is initialized.

3. Running the Simulation and Preliminary Results
When running the simulation, we used a 50X50 grid and initialized a cell with probability of 0.25 (ALIVE_PROB), the probability of choosing each type of cell is 0.5.
We studied the way altering the reproduction rate of the asexual cells (denoted as p) influences the dominance of one strategy over another. All the other parameters were fixed to the aforementioned values (The sexual reproduction rate as well, as it depends on the number of neighbors which remained 3).
First, to show the results of the change of the asexual reproduction rate, we plotted per each rate value how many games ended after 500 iterations in favor of asexual cells (figure 1). It can be noticed that there is a clear threshold of the reproduction rate that determines the

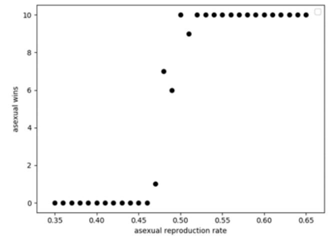

Figure 1: Number of asexual wins out of 10 games as influenced by asexual reproduction rate. This plot presents the initial model.

winning strategy. The value p<0.45 always results in asexual defeat, and p>0.52 always results in asexual dominance. The in-between values results are probably more susceptible to random events.

We sampled a value of the three reproduction values groups (asexual defeat, asexual dominance, in-between values) and observed the unfolding of the game to try to identify important patterns or strategies that appear. To show the results of a single run of the simulation, we plotted the count of each cell type per iteration (figure 2) and identified the following:

• For p << 0.45 (figure 2A) we observe a sharp extinction of the asexual cells while the remaining sexual cells behave as in Game of Life until reaching a steady state. This extinction is probably because the reproduction rate is much smaller than the death rate.

• For 0.45 <= p <= 0.52 (figure 2B, figure 2C) we observe an extinction of the asexual cells in different rates (slower for bigger reproduction rates). The game always started with an initial decline or extinction of the sexual cells. The result changes dramatically between runs and between small changes of p.

• For p >> 0.52 (figure 2D) we observe a sharp extinction of the sexual cells, and after a small number of iterations the asexual cells cover most of the grid (as much as possible with restriction from overpopulation death).

4. Improving the Model – Underpopulation Restriction Removing

Simulating the model always ended in either extinction of the asexual population, extinction of the sexual population, or both. We wished to fix the model in a way that will enable the coexistence of both populations for some reproduction values.

We concluded that the death pressure might be too strong. Therefore, we decided to remove death from underpopulation from our model. Biologically, we assumed that underpopulation death applies less to asexual cells (a colony can begin with a single asexual cell). Also, underpopulation reduces sexual cell reproduction in ways other than death (a cell cannot reproduce with less than 3 neighbors). Thus, removing death from underpopulation would not remove the effect of underpopulation entirely from the sexual population.

We plotted again per each rate value how many games ended after 500 iterations in favor of asexual cells (figure 3), and the shift between the two phases is as sharp as before. However, the threshold has changed from ~0.5 to ~0.2, which indicates that the update was beneficial to the asexual cells.

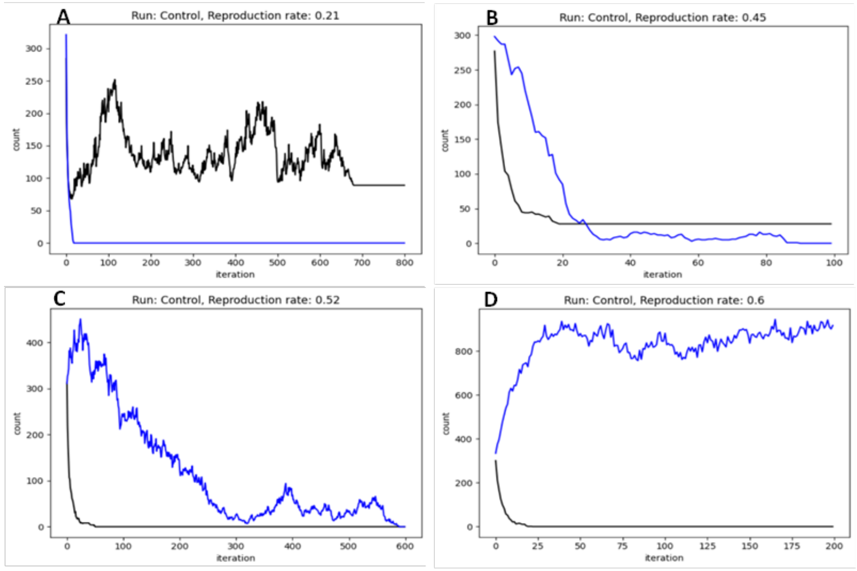

Figure 2: Plotting the count of each cell type (sexual – black, asexual – blue). **A** – asexual reproduction = 0.21 **B** – asexual reproduction = 0.45 **C** – asexual reproduction = 0.52 **D** – asexual reproduction = 0.6

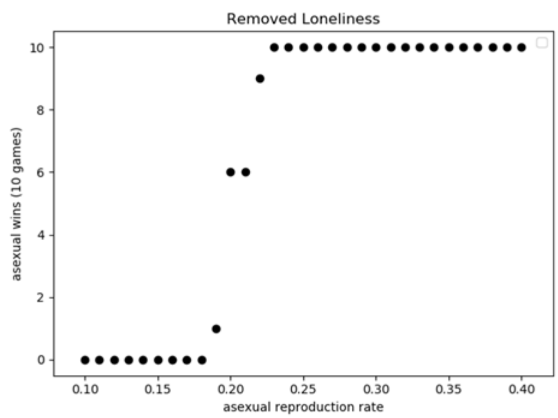

Figure 3: Number of asexual wins out of 10 games as influenced by asexual reproduction rate. The plot presents the model after removing death from underpopulation.

We ran the simulation for different asexual reproduction values as before, and we noticed the following patterns:

• For p << 0.19 (figure 5A) the sexual cells form an intricate maze-like structure (figure 4A) and reach a population of ~1200 cells (out of 2500 cells of the grid) which we assume is close to the possible maximum given the restriction of overpopulation.

• For 0.19<=p<=0.23 (figure 5B, figure 5C) the sexual cells sometimes survive by conquering large parts of the grid middle and creating a long-run stable state, while the asexual cells remain in the edges (figure 4B). This stable state can be broken and lead to almost total sexual cell dominance if they start creating the maze-like structure, which requires conquering an edge first (figure 4C).

- For p>>0.23 (figure 5D) asexual reproduction rate quickly exterminates sexual cells.

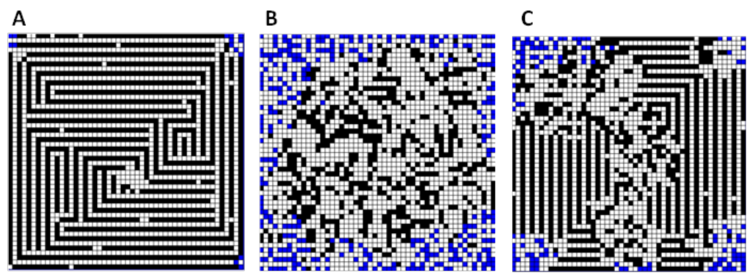

Figure 4: Simulation screenshots (sexual – black, asexual – blue) **A** – asexual reproduction = 0.1 **B** — asexual reproduction = 0.21 **C** – asexual reproduction = 0.21

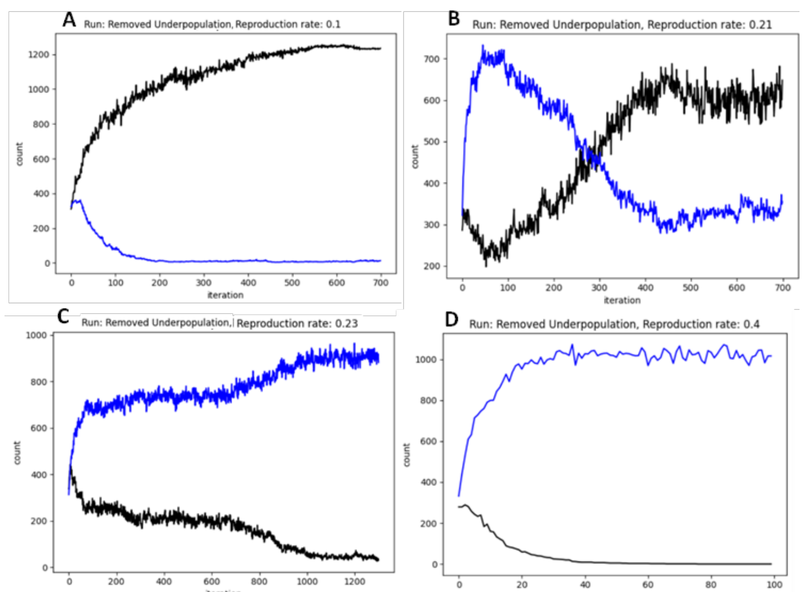

Figure 5: Plotting the count of each cell type (sexual – black, asexual – blue). **A** – asexual reproduction = 0.1 **B** – asexual reproduction = 0.21 **C** – asexual reproduction = 0.23 **D** – asexual reproduction = 0.4

5. Improving the Model - Preventing Immortality

One of the side effects of the previous change to our model was the creation of stable maze-like structures by the sexual cells. However, these structures are practically immortal since an individual cell cannot die (most of the cells in the structure have two neighbors). Therefore, we decided to add a different natural cause of death to our model – age.

This was implemented as follows: any new cell object (either by board initialization or reproduction) has the variable self.life_time that is initialized to a value that we fixed to be 5, and in every iteration, this value is decremented by 1. If this value reaches zero – the cell dies of old age. It should be noted that we tested different values and noticed that lower values i.e.

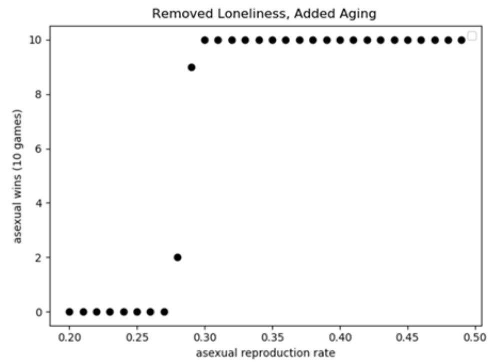

Figure 6: Number of asexual wins out of 10 games as influenced by asexual reproduction rate. The plot presents the model after removing death from underpopulation and adding death from old age.

lower lifespan benefit the sexual cells.

This addition to the model prevented the creation of the immortal maze structures as we intended. It also changed the threshold figure (figure 6) in which the phase change happens for p=0.29 (compared to 0.2 in the previous version). As previously, we looked for the cell's behavior for different values of p:

• For $p << 0.28$ (figure 8A) the asexual cells disappear rapidly. The sexual cells inhabit the whole grid however the maximum population is about ~850 which is far from the numbers the maze-like structure enabled which were ~1200, due to their unordered changing structure.

• For $0.28<=p<=0.29$ (figure 8B, figure 8C) the sexual and asexual cells achieve a relatively steady state in which both types are on the grid. For p=0.28 the sexual cells are dominant, and for p=0.29 the asexual cells are dominant. As in the previous section, we observe that the structure is that of asexual cells along the edges and the sexual cells are in the middle of the grid (figure 7)

• For $p>>0.30$ (figure 8D) asexual reproduction rate quickly exterminates sexual cells.

6. Improving the Model – Adding External Pressure

We wished to make our model more complex and include external pressure to better imitate real life. Therefore, we decided to add predator cells and observe their influence on the dynamics between sexual and asexual cells.

The predator cell class is designed as a child class to the original Game of Life cell (the sexual cell) and implements the calculation of life status and reproduction differently. The rules applying to this cell type are as follows:

• Each iteration the predator cell looks for prey in a radius of 2 (24 neighbors) and randomly chooses a non-predator cell to predate upon. If none is available, the predator cell will die.

• If the cell did not die and another predator cell is available in a radius of 2, they will mate, and another predator cell will be born in an available cell in the same radius.

• These cells do not perish from overpopulation or underpopulation directly, instead, we expect overpopulation to cause a lack of food and therefore death, and underpopulation to cause

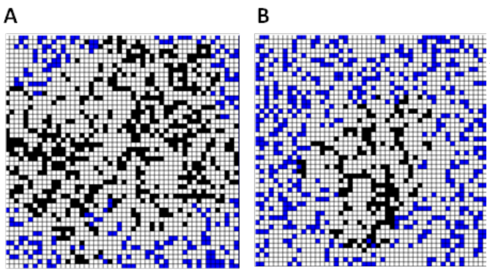

Figure 7: Simulation screenshots (sexual – black, asexual – blue) **A** – asexual reproduction = 0.28 **B** — asexual reproduction = 0.29

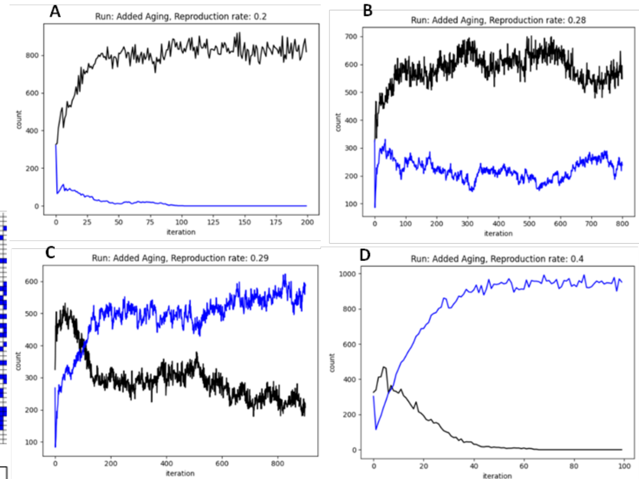

Figure 8: Plotting the count of each cell type (sexual – black, asexual – blue). **A** – asexual reproduction = 0.2 **B** – asexual reproduction = 0.28 **C** – asexual reproduction = 0.29 **D** – asexual reproduction = 0.4

less reproduction and possible extinction.

The probability of an initialized cell being a predator cell had to be much lower than the other cells to avoid quick extinction. Therefore, we chose the probability to be 0.02 and the other cells were 0.49.
The addition of the predators did not influence the dynamics as expected, since the predators were immobile and wiped out all the cells surrounding them until they died of hunger. Occasionally two or more cells were close enough to reproduce leading to a sudden rise in predators' population but shortly afterward they went extinct as well.
To fix the problem, we decided to add movement ability to all the cells. A cell can move in every iteration with a fixed probability (0.5) to one of the empty cells surrounding it. The location is chosen randomly with a uniform probability.
This modification prevented predator extinction, and we observed the formation of groups of predators "chasing" other cell types across the board (figure 9). These groups are probably a result of the abundance of prey and mates for reproduction, and their survival depended on the remaining availability of prey.
Once again, we created the threshold plot (figure 10) and observed there is a notable difference from the last versions of the plot. The phase change is not as sharp as before, and there is a larger interval of reproduction values that can lead either to sexual or asexual dominance. We assume it happens because the introduction of predators added more randomness to the simulation.
Unlike in previous versions of our model, each run behaves entirely differently. The graphs of different runs are more characterized with fluctuations caused by the predator's pressure. We will not pretend to identify global patterns influenced by p, so instead, we will show several run examples and present occurring phenomena:
• p=0.22 (figure 11A) – there is a clear dominance of sexual cells while a small population of

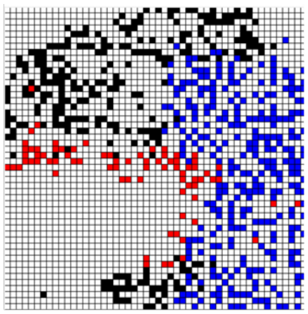

Figure 9: An example of a group of predators (red cells) "chasing" other cell types, leaving behind empty spaces after creating local extinctions on the

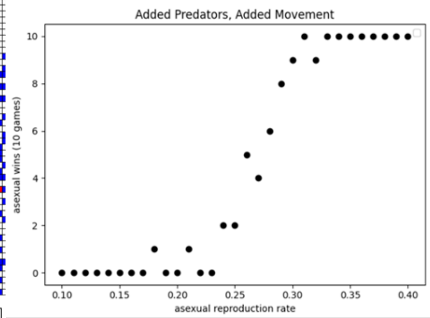

Figure 10: Number of asexual wins out of 10 games as influenced by asexual reproduction rate. The plot presents the model after adding predator cells.

the asexual cell remains. There are periods of growth of the predator population leading to a decline in the sexual cell's population, which leads to a decline in the predators' numbers then sexual cells grow again and repeat.

• p=0.25 (figure 11B) – there is an early shift between the dominance of sexual to the dominance of asexual cells, which was created by an opportunity caused by the predators which dwindled the sexual population significantly, enabling the asexual to spread. Later predators lead themselves to an almost extinction with only a few individuals remaining on board, and after approximately 250 iterations two individuals were able to reproduce by getting close enough and revived the predator population, leading to an immediate decline of the asexual cells.

• p=0.28 (figure 11C) – the predators lead themselves to self-extinction be driving all other populations to almost extinction. After their disappearance, we observe a slow takeover of the sexual cells, in a similar manner observed previously (figure 8C).

• p=0.31(figure 11D) – sexual cells are driven to extinction, we observe a similar pattern of predators revived after only individuals are left.

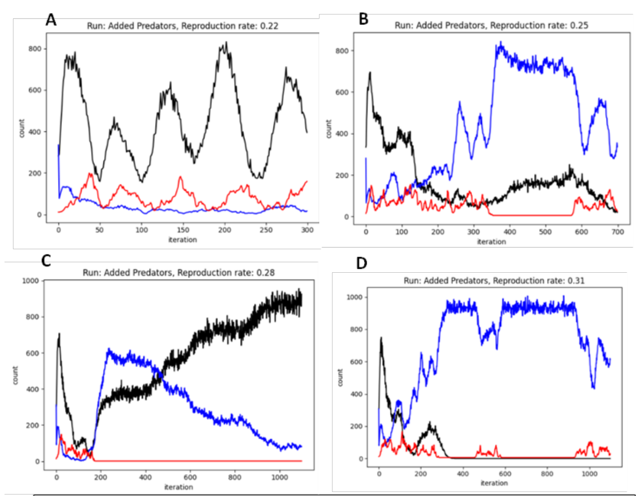

Figure 11: Plotting the count of each cell type (sexual – black, asexual – blue, predator - red). **A** – asexual reproduction = 0.22 **B** – asexual reproduction = 0.25 **C** – asexual reproduction = 0.28 **D** – asexual reproduction = 0.31

7. Improving the Model – Adding No Boundary Mode
   In order to check whether the observed phenomena are unique to the fact there are "walls" in the edges of our board, we implemented a "No Boundary" mode. In this mode, there is no limit of the board, which means that the first row is connected to the last row and the left column is connected to the right one.
   When running our model in all the conditions described above, we observe no dramatic changes in our results. However, there were some minor changes. The sexual cells did not manage to form a maze-like structure. In addition, in our final condition, the predator cells manage to spread more easily through the board instead of staying in the same area.

3 Disscussion

- Steady State:
  Our primary results showed that there is no right way to compare the two strategies if there was no steady reproduction of both. Moreover, there will be no way to compare the two strategies if there will be no mutual steady state of both populations. A steady state which contains mutual life and interactions between the populations will be essential to understanding the differences of sexual vs asexual reproduction. In order to reach that state, we changed some of the model conditions until there was no more total extinction of life or an excessive stable state of one of the populations. In the original 'Game of life' Model, sexual cells, by themselves can reach a steady state, however asexual cells did not reach a steady-state by its starting settings. Therefore, one of our main interests was seeking the conditions that will benefit the asexual cells and makes them become more stable.

- Reproduction Rate dependence
  Throughout all the conditions we ran, it was clear that the reproduction rate of asexual cells was very impactful to the results. However, the reproduction rate is essential for asexual reproduction mainly because it affects the ratio between the number of new living cells to the number of dead cells and thus to the overall balance of the number of cells in the population. In each of the settings parameters, there was a threshold of the reproduction rate. When the rate was lower than that threshold - there was always more sexual cell than asexual cells living on the board after 500 iterations, and when the rate was higher - the opposite. Moreover, in the range around the rate threshold, there was a non-permanent dominance of either one from the strategies. This range provided us the results that enabled us to compare between the strategies.

- Winning strategy
  When trying to determine which reproduction strategy is more successful we need to take into account all the results. Due to the fact that every set of parameters of the model could reach to a state where sexual strategy will always control the board, and to the same for the asexual strategy (depending on the reproduction rate), we could not determine which strategy is the best. However, it is interesting to see that in our primary results the shift between asexual permanent winning to sexual one was ~0.5, which can imply to equality of the two strategies. Moreover, when trying to strengthen the asexual cells reproduction by changing the model,

we reach a lower rate shift like 0.3, 0.25, 0.2 - another implying the preference of the asexual reproduction.
It is important to note that in our project we compared the two strategies only in the context of pure breeding. However, the benefits of sexual reproduction is primarily related to adding variance to the population genetics which creates stability. We did not look into this aspect in our model, and this could be an interesting continuation of this project.

- Complex system
  At each set reproduction rate, we have seen the individual interaction effect on growth rate of the cells population and hence the system whole behavior, when sometimes it affected the growth to be exponentially increasing and others to be decreasing. This illustrates the choatic property of the systems since each starting reproduction rate leads to different dynamics in the system. In addition to , the growth rate weren't linear, as changing a single parameter in the system yields to different population dynamics, hence a nonlinear outcome.
  The nonlinearity effect has been also observed when adding the element of enviromental change; predators. As predators count was increasing the sexual/asexual cells were decreasing and vice versa, due the nonlinear responses of prey and predator cells to their availability. Hence, noting that this change emitated tipping points[6] as the system changes suddenly due to small changes in the environment.
  As a complex system, it is hard to predict its behavior. Therfore observing the changes to the system due to reproduction rate changes made possible at which cases the system is more predictable than others, and enabling when there will be emergent phenomena. When the reproduction rate far from thersholds found, either sexual or asexual cells remained (won), beside those domains (far from threshold), when reproduction rate falls near the threshold, the uncertainty of the system emerged and emerged phenomenas observed, such as the maze cell structure or asexual cells cells surrounding sexual one as observed by Amat et al 2017[7].

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