How Cellular Automata have contributed to the study of complex systems in todays society

Olivier Hinds

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Abstract

Exploring the historical origins of Cellular Automata, as well as the early pioneers in its' development is important when understanding where CA fit in today's society. In this paper, I lay out and explain the ways in which CA can be classified. I explore how Lenia hand what we should be concerned about regarding the societal implications. This research is incredibly important when trying to maintain a balance between developing CA, and the potential for misuse in high-risk environments such as in fire management. I conclude we need education and law in order to prevent this technology from being misused, and I propose a policy which could be used in this scenario.

Table of Contents

1 The Origins of Cellular Automata **6**

1.1 Introduction 6

1.2 Early Pioneers 6

1.2.1 Why this is so Important? 7

2 A Detailed Explanation **8**

2.1 Conway's Game of Life 8

2.2 Wolfram's Classification 13

2.2.1 Steven Wolfram's Influential Work 13

2.3 Lenia 14

2.3.1 What is Lenia? 14

3 What are the Practical Applications of CA? **19**

3.1 Science, Technology, Engineering and Maths (STEM) 19

3.1.1 Maths 19

3.1.2 Growing Isotropic Neural Cellular Automata 20

3.1.3 Computer Science (Cryptography) 21

3.2 Biology 21

3.3 Humanities 22

3.3.1 Urban Development . . . 23

4 How Cellular Automata are Related to the Study of Complex Systems 25

4.1 Complex Systems . . . 25

4.1.1 Features . . . 25

5 The Societal Implications of CA 27

5.1 Misuse in Simulating Harmful Scenarios . . . 27

5.1.1 Simulating a wildfire with CA . . . 28

5.1.2 Evaluation . . . 28

5.2 Ethical Concerns in Modeling . . . 28

5.2.1 Disease and Viruses . . . 28

5.3 Security Risks and the Unintended Consequences in the use of CA in the automation of processes . . . 29

5.3.1 Example: Traffic Management . . . 29

5.4 Public Misunderstanding . . . 30

5.5 Energy Consumption in Computational Models . . . 30

6 Potential Areas for Future Research 31

6.1 Ongoing Research . . . 31

6.2 Potential for Expansion . . . 31

6.3 Drawing an end . . . 32

6.4 New areas for application . . . 32

6.4.1 CA in AI Training . . . 32

6.4.2 CA in enhancing AI Models . . . 33

7 Evaluation 34

7.0.1 Aims . . . 34

7.0.2 limitations . . . 34

7.0.3 What I would do differently . . . 35

7.0.4 What lessons I have learnt . . . 35

7.0.5 Presentation 36

A Appendix **42**

A.1 Presentation Material 42

A.2 My Stand 49

B Appendix **55**

B.1 Materials Used from external sources 55

B.2 Code for Live Demonstration 55

C Appendix **56**

C.1 Form Feedback 56

List of Figures

2.1 Some creatures which exist in the Game of Life [6] 12
2.2 A well-evolved grid in Conway's Game of Life 13
2.3 Illustration of Differences between Continuous and Discrete Data 15

3.1 Logistic Map of a Feigenbaum tree 20
3.2 A T. lepidus [12] 22

A.1 Important People Poster 1 43
A.2 Important People Poster 2 44
A.3 Important People Poster 3 45
A.4 Important People Poster 4 46
A.5 Lenia Poster 1 (Not Used In Presentation) 47
A.6 Similarities and Differences Poster (Lenia Poster 2) 48
A.7 CA Main Poster 1 49
A.8 Main Poster 2 50

1 | The Origins of Cellular Automata

1.1 Introduction

Cellular Automata, or CA, in their most primitive state, are complex mathematical systems comprised of a grid of cells, which are governed by a set of rules. These rules govern how the grid functions and, consequently, the properties which the CA displays. Ever since the discovery of CA in the late 1950s, they have played a crucial part in our understanding and mathematical knowledge in the 21'st century. Exploring both the historical developments of CA and its diverse applications, such as in theoretical Biology [1] and urban growth dynamics [2] is what led me to write this dissertation.

1.2 Early Pioneers

As mentioned previously, the first Cellular Automaton (CA) system was originally developed in the late 1950s by Stanislaw Ulam and John von Neumann. This groundbreaking system aimed to simulate life processes [3] and represented an incredible achievement given the technological standards of the time. As the technology grew, it was popularised by John Conway, with "Conway's Game of Life" which debuted in Scientific American, in 1970 [4]. It was 1969 when CA were first considered complex systems [5]. With Conway's Game of Life, the rate of development of CA increased beyond the belief of John Conway. It seems like the resulting exposure of CA in the scientific community led to further developments.

6

1.2.1 Why this is so Important?

Learning about the roots of CA, and the people who spearheaded development, it helps us grasp the significance of their work and its far-reaching impact on our modern society. Although this dissertation primarily focuses on advanced forms of CA, such as Lenia [1], exploring their early iterations provides valuable insights into their origins and evolution. This historical perspective enables us to appreciate how basic concepts laid the foundation for the intricate CA systems we study today.

2 | A Detailed Explanation

2.1 Conway's Game of Life

Conway's Game of Life is one of the first, and most popular CA engines. It consists of a 2D grid of cells, each of which can either be a $1 = ON$ or $0 = OFF$ - A Binary system. The simulation is advanced by calculating a new state for the grid depending on the defined rules for the CA system. In the case of Conway's Game of Life, these rules are as follows: ([4])

- Survivals. Every encounter with two or three neighboring counters survives for the next generation
- Deaths. Each encounter with four or more neighbors dies (is removed) from overpopulation. Every counter with one neighbor or none dies from isolation.
- Births. Each empty cell adjacent to exactly three neighbors - no more, no fewer - is a birth cell. A counter is placed on it at the next move.

This can be achieved with Python (The programming language I will be using to represent CA algorithms), using this function:

```
# Function to determine the next state based on GoL rules
```

 8

```
def growth(U):
    return 0 + (U == 3) - ((U < 2) | (U > 3))
```

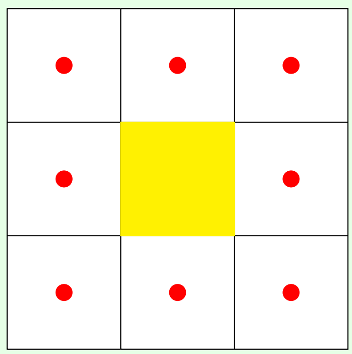
Or a mathematical equivalent

$$\text{growth}(U) = 0 + (U = 3) - ((U < 2) \mid (U > 3)) \tag{2.1}$$

This does not make sense on its own - Here is a more detailed explanation.

Definition

The neighborhood referred to by Gardener in 1970 is a cell's Moore neighborhood. This is referring to the 8 cells adjacent to each cell. As shown below.



This will become very important when I take a look at some of the more modern CA systems, because they all build from this fundamental concept.

The mathematical calculation of the next stage in the system involves the convolution of a Kernel (K) across the grid. The equation governing this convolution operation is expressed as:

$$(f * K)(t) := \int_{-\infty}^{\infty} f(\tau)K(t-\tau)\, d\tau. \tag{2.2}$$

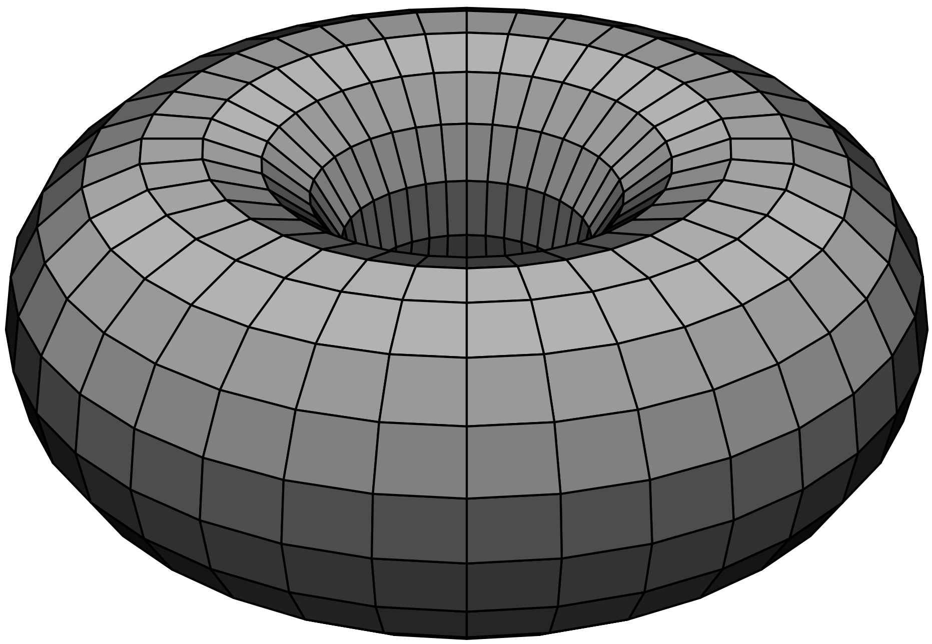
This can be done in a programmatic manner, making use of Python, and some libraries which extend its' capabilities - namely scipy and numpy.

```
import numpy as np
```

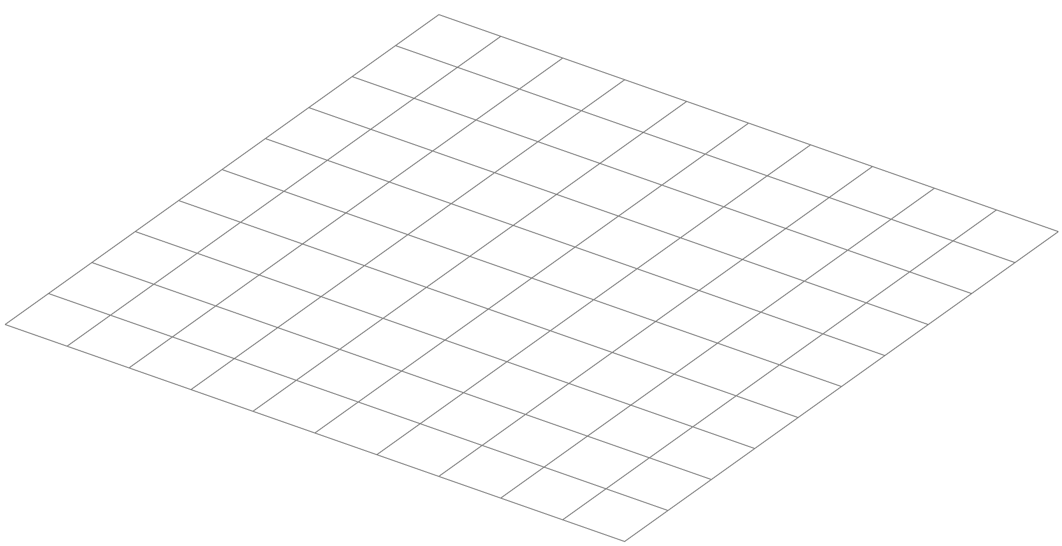
```
from scipy import signal
>>>
self.grid = np.zeros(shape=self.shape, dtype=np.int8)
self.KERNEL = np.asarray([[1, 1, 1], [1, 0, 1], [1, 1, 1]])  # The Kernel to convolve cells
>>>

def next_gen(self):
    self.grid = np.clip(
        self.grid + self.growth(signal.convolve2d(self.grid, self.KERNEL, mode='same', boundary='wrap')), 0, 1)
```

I make use of numpy for efficient array manipulation and scipy's signal module for the convolution operation. The grid is initialised as a 2D array of zeros, and the convolution kernel is set to the Moore Neighbourhood.

You may also notice `boundary='wrap'` parameter passed into `scipy.signal.convolve2d`. This is to define the shape of the grid. In this case, I am treating the grid as a torus, as shown below:



This is especially useful because it means that the grid is seemingly infinite - and the edges can be wrapped around easily, allowing for a more sacrosanct approach to the rules. But a regular 2d grid could also be used. This means that cells on the edges won't have neighbours outside of the grid. Below is an example of a regular 2D grid which can be used:



The core concept of Conway's Game of Life is that complex behaviour can arise from a simple set of rules. Below are some examples of life forms that exist in Conway's Game of Life:

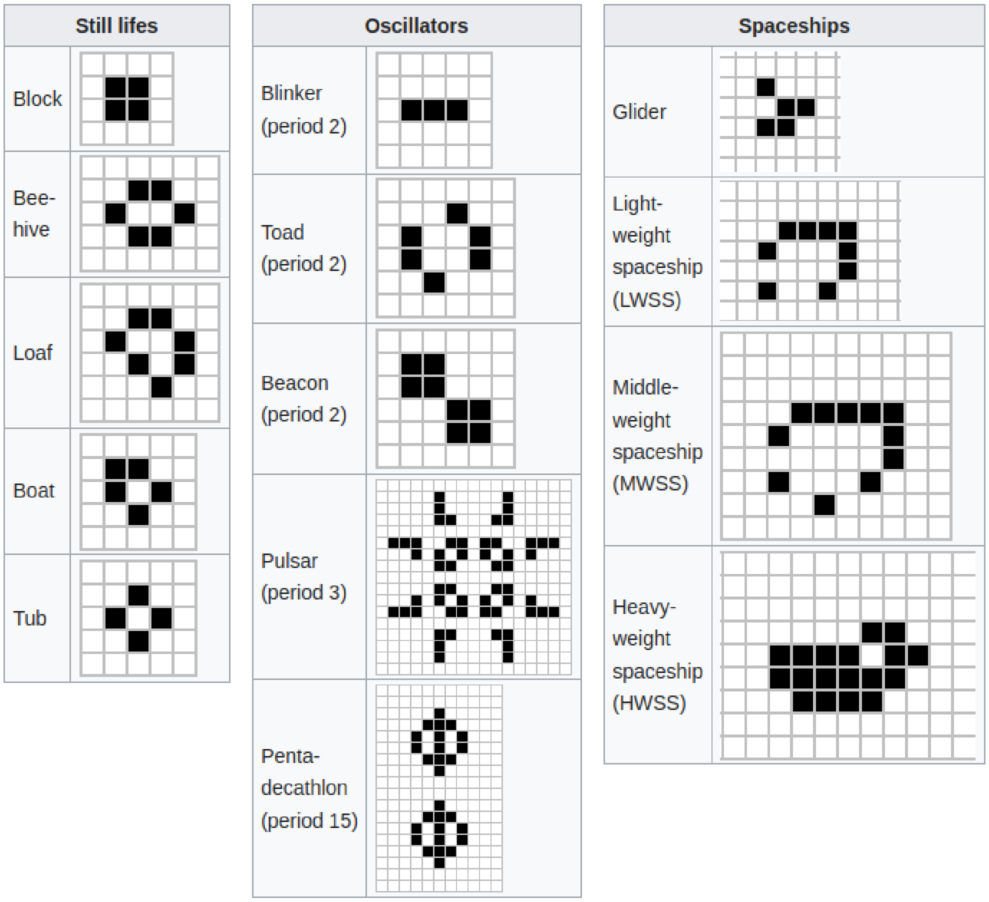


Figure 2.1: Some creatures which exist in the Game of Life [6]

Conway's Game of Life is immensely popular in the Complex Systems space, and it has its' simplicity to thank for that. Below is an example of a well-evolved array:

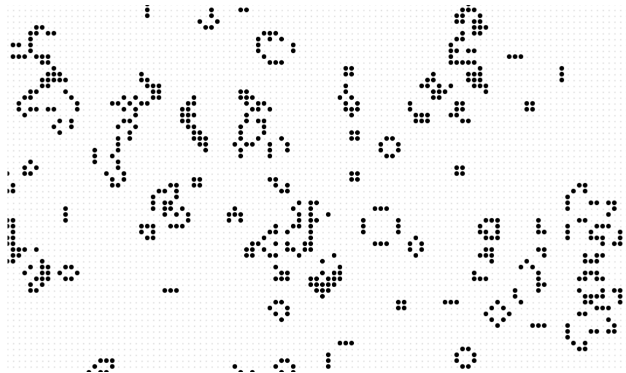


Figure 2.2: A well-evolved grid in Conway's Game of Life

This clearly shows the seemingly random life-patterns that have evolved in Conway's Game of Life, and makes for a fun "*introduction*" to Cellular Automata.

2.2 Wolfram's Classification

The aforementioned exposure of CA in 1969 lead to expanded research in CA, across multiple spacial dimensions. One notable enthusiast of 1-Dimensional CA was Steven Wolfram. In 1984, Wolfram proposed that "*all one-dimensional cellular automata fall into four distinct universality classes*" [7].

2.2.1 Steven Wolfram's Influential Work

Among the contributions Wolfram made in his life; he provided a system for defining and classifying CA. This is known as Wolfram's Classification. Below are the four *classes* of CA.

Wolfram's Universality Classes

Wolfram's classification system categorises one-dimensional cellular automata into four distinct classes. Each class represents a different category of behavior observed.

Class 1: Homogeneous Fixed Points

Cellular automata in Class 1 display homogeneous and stable behavior. These systems often evolve into stable patterns or fixed points. These CA lack much complexity and randomness; as observed in the other three classes.

Class 2: Periodic

Class 2 cellular automata produce simple, periodic patterns without the emergence of complex structures. The behavior is predictable to an extent, but is slightly more complex than Class 1.

Class 3: Chaotic

CA in class 3 often give rise to intricate, non-repeating patterns, and small changes in initial conditions can lead to very different patterns emerging. Most random examples of CA seem to be Class 3

Class 4: Complex

Class 4 CA are characterised by the presence of intricate structures and patterns developing over time.

Wolfram's classification, as you can see, gives us a framework for understanding the diverse behaviors present in 1D cellular automata. It has become an incredibly important part of the history of CA, because of the complexity that can arise from simple rule-based dynamics.

2.3 Lenia

Lenia is one of the most important advancements to Cellular Automata, in my opinion. It's development and subsequent publishing by Bert Chan in 2019 [1] proposed a method of creating CA with *multiple* Kernels. In order to understand the impact this has had on the development of CA, I need to explain how it works.

2.3.1 What is Lenia?

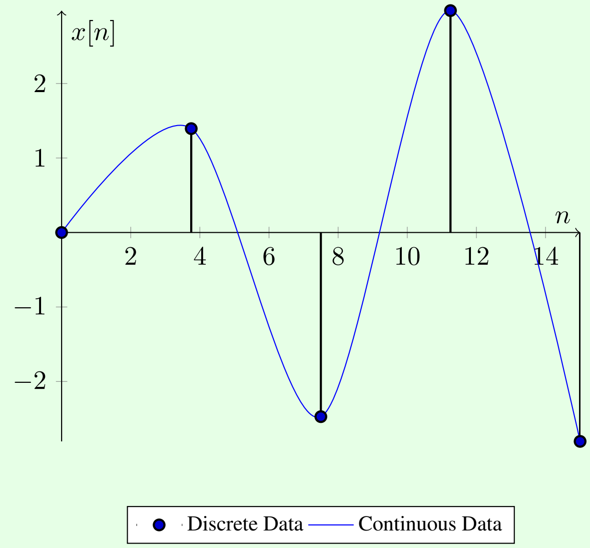
Lenia is "*a two-dimensional cellular automaton with continuous spacetime-state and generalized local rule*" [1]; But, what does this mean?

Lenia are a form of CA which can either be discrete or continuous.

Definition

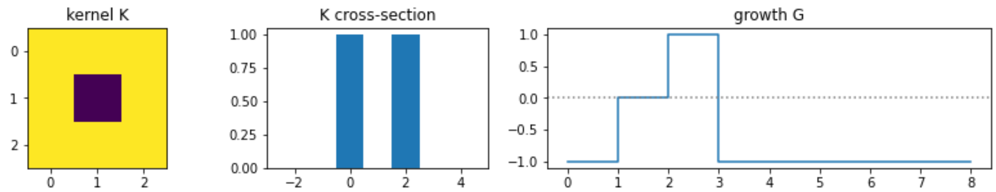
Discrete data consists of a finite number of values. In Conway's Game of Life, the states of cells could either be 0, or 1. This is represented by the blue dots on the diagram below. Lenia, on the other hand, can be continuous - meaning that the value of the cells could be a value between any two arbitrary points. This allowed for much more information to be represented by each cell - like a sort of "intensity" value. This is represented by the blue line.

Figure 2.3: Illustration of Differences between Continuous and Discrete Data



Lenia takes what the stochastic characteristics observed in Conway's Game of Life, and makes it even improves the way in which this is achieved. It expands the state values from a binary system as we have seen; to use real numbers. The "space" which influences the value of a cell has been expanded, and can also change. Lenia can, not only use multiple kernels, but also have these kernels changed depending on the specific variant of Lenia.

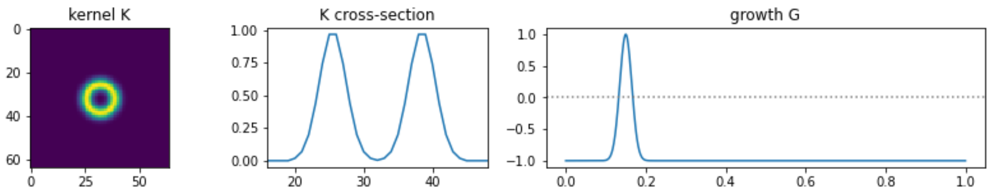
Lenia can even replicate Conway's Game of Life, because we can simply use the same kernel, and the same "weighting" rulle. These weighting rules are similar to the rules of Conway's Game of Life; where a certain value in the neighbourhood will result in a certain value being set at the current cell. This is what the weighting looks like for Game of Life:




```python
size = 64
np.random.seed(0)
A = np.random.randint(2, size=(size, size))
K = np.asarray([[1,1,1], [1,0,1], [1,1,1]])
K_sum = np.sum(K)
''' define growth function with growth/shrink ranges '''
def growth(U):
  return 0 + (U==3) - ((U<2)|(U>3))
def update(i):
  global A
  U = scipy.signal.convolve2d(A, K, mode='same', boundary='wrap')
  ''' use incremental update and clipping '''
  #A = (A & (U==2)) | (U==3)
  A = np.clip(A + growth(U), 0, 1)
  img.set_array(A)
  return img,
figure_asset(K, growth, K_sum=K_sum, bar_K=True)
fig = figure_world(A, cmap='binary')
IPython.display.HTML(matplotlib.animation.FuncAnimation(fig, update,
  ↪ frames=50, interval=50).to_jshtml())
```

From: [8]

As you can see, this graph is directly going from a value of 0 to 1; also known as a step, or step function. This discrete



jump is changed into a continuous form with lenia models; such as the one below:

```python
bell = lambda x, m, s: np.exp(-((x-m)/s)**2 / 2)
size = 64;  mid = size // 2;  scale = 1;  cx, cy = 20, 20
globals().update(pattern["orbium"]);  C = np.asarray(cells)
A = np.zeros([size, size])
C = scipy.ndimage.zoom(C, scale, order=0);  R *= scale
A[cx:cx+C.shape[0], cy:cy+C.shape[1]] = C
''' to use FFT, kernel and world must have the same size '''
#D = np.linalg.norm(np.asarray(np.ogrid[-R:R, -R:R]) + 1) / R
D = np.linalg.norm(np.ogrid[-mid:mid, -mid:mid]) / R
K = (D<1) * bell(D, 0.5, 0.15)
''' pre-calculate FFT of kernel '''
fK = np.fft.fft2(np.fft.fftshift(K / np.sum(K)))
def growth(U):
  return bell(U, m, s)*2-1
def update(i):
  global A, img
  ''' use FFT to perform convolution '''
  #U = scipy.signal.convolve2d(A, K, mode='same', boundary='wrap')
  U = np.real(np.fft.ifft2(fK * np.fft.fft2(A)))
  A = np.clip(A + 1/T * growth(U), 0, 1)
  img.set_array(A)
```

```
  return img,
figure_asset(K, growth)
fig = figure_world(A)
IPython.display.HTML(matplotlib.animation.FuncAnimation(fig, update,
 ↪  frames=200, interval=20).to_jshtml())
```

[8]

3 | What are the Practical Applications of CA?

CA have applications in a vast array of subjects and fields of study. Defining simple rules to how a system functions will enable them to be applied wherever researchers need to model certain phenomena.

3.1 Science, Technology, Engineering and Maths (STEM)

STEM subjects are where CA are most prevalent. They are used in Physics for simulating fluid dynamics and gas mechanics. The main contributors working on the Lattice gas automaton were Jean Hardy, Yves Pomeau and Olivier de Pazzis, with their work on creating a dynamical model of particles which can exhibit behaviours of a gas. It has been able to prove the propagation of sound waves through a viscous body [9]. These kind of discoveries make simulating phenomena much easier than conventional methods, because the relatively simple "rules" that govern CA lead to the most complex subjects scientists research.

3.1.1 Maths

Dynamical models, as you may know, have somewhat similar characteristics to Logistic maps. CA and logistic maps have very similar qualities.

19

To define a system with logistic maps, the syntax is as follows:

$$x_{n+1} = rx_n(1 - x_n) \tag{3.1}$$

This simple definition allows for some particularly elegant maths to take place. This logistic map exhibits chaotic behaviour. As the number of iterations increases, the value of r fluctuates.

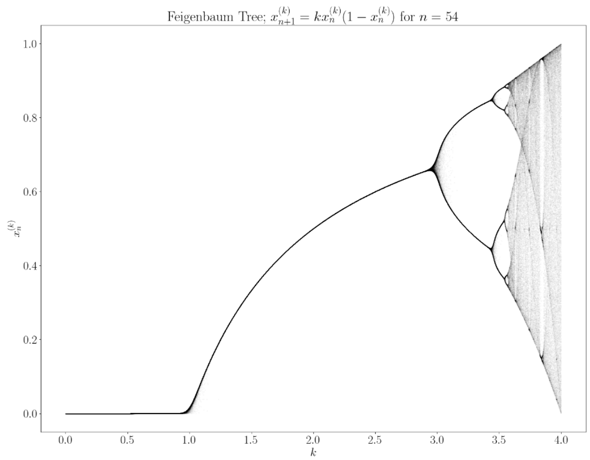


Figure 3.1: Logistic Map of a Feigenbaum tree

Figure 3.1 looks similar to a Bifurcation diagram, which can show how complex behaviours change over time. In Conway's Game of Life, as the evolution progresses, the patterns observed increase in complexity.

Among the uses for Cellular Automata are applications in Computer Science that range from cryptography to image generation.

3.1.2 Growing Isotropic Neural Cellular Automata

Research into growing Isotropic Neural Cellular Automata [10], we can observe an application of cellular automata in computer science which aims to generate a structure, and maintain its form over time. As you destroy the structure, it can rebuild itself based on the initial parameters you define it as. This involves having a seed which will enable this structure to grow and form. These Automata exist on a regular Cartesian grid, and can evolve over time using a stochastically updating pattern. As many chemists know, reactions are Stochastic in nature. This is what enables complex reactions to occur; an asynchronous pattern. These "stochastic fluctuations" has been proven by Michael S Samoilov, Gavin Price, and Adam P Arkin [11] where in fact, biological systems were able to construct complex structures in ways similar to the properties Cellular Automata exhibit. The fact that Cellular Automata exhibit such properties of cells in an entirely simulated environment shows the development of the field over time.

3.1.3 Computer Science (Cryptography)

In cryptography, CA can be used to encrypt messages asymmetrically. Knowing it is easy to determine the next state of a cell given the rule, messages can be encrypted easily using a key generated from a CA after a certain number of iterations. Figuring out the previous states of a grid can be incredibly complex, and insoluble. This insolubility of the problem lends itself to cryptography, where the "key" needed for generating the CA grid can be provided asymetrically, using public-private key encryption.

3.2 Biology

Not only are CA computationally achieved, they are also visible in the real world. A species of European Lizard, the ocellated lizard (Timon lepidus) is a prime example of Cellular Automata being discovered through natural evolution.

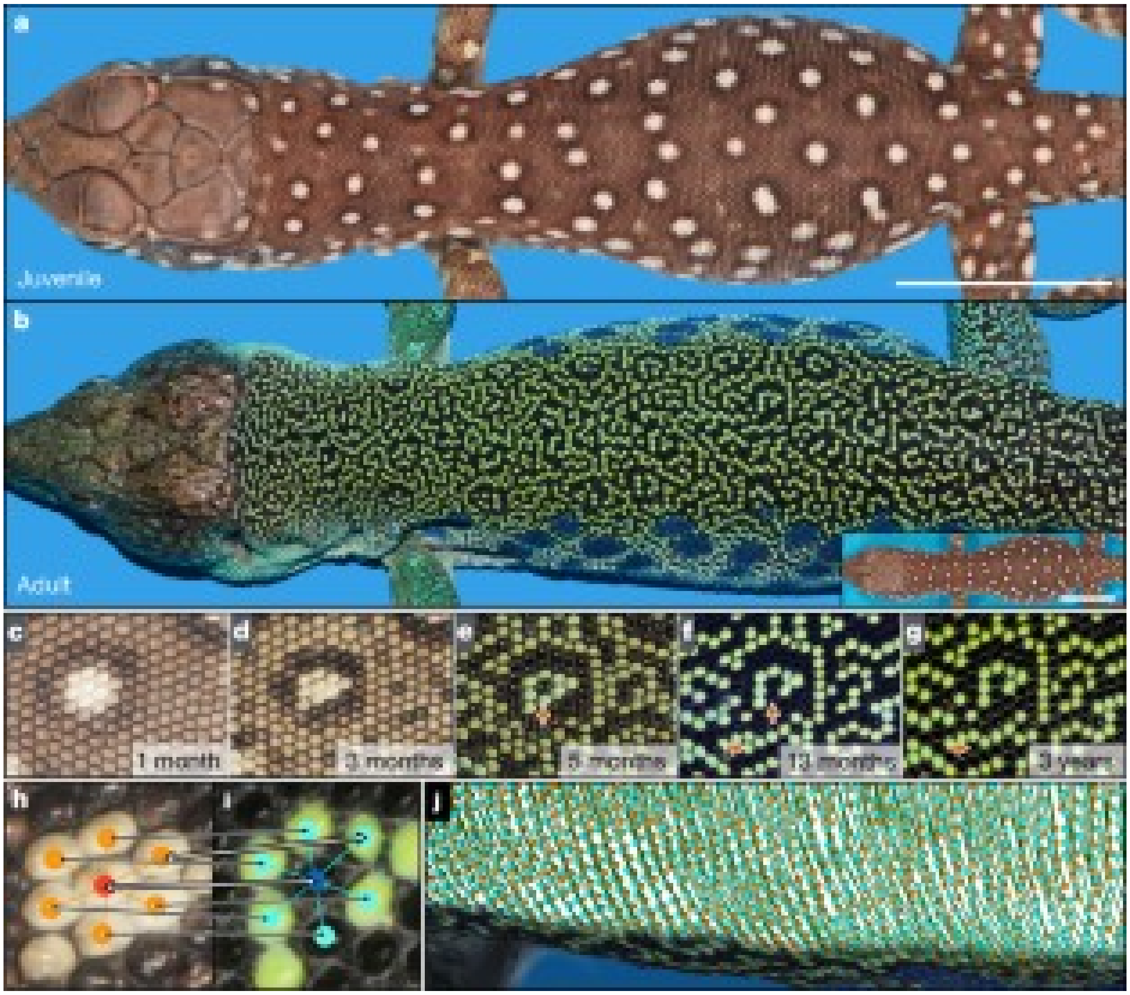


Figure 3.2: A T. lepidus [12]

This stochastic CA shows not only that CA are present in biological life, but are also thriving in our world. This evolution has taken place over a longer period of time than CA have been discovered.

3.3 Humanities

Modelling is a very important part of Geography and History. Humanities as such require a way of simulating these processes. One of the ways this can be achieved is through complex systems; more specifically CA. Modelling population growth dynamics with Cellular Automata is something which has been researched previously.

3.3.1 Urban Development

The use of Cellular Automata in urban development extends to a research paper([2]), outlining its' use to map all of the variables involved with urban growth. This is essentially a manifestation of the different types of human needs and expectations. This min-max of the benefits to an urban population as well as the environmental and economical costs associated with development is what draws my attention to this paper in particular. Cellular Automata provide a framework by which these systems can build on, and develop.

The below workings from [2] takes into account the CORINE Land Cover (CLC), and a certainty factor (CF).

Variable		CF function	
Slope	$\mu(\chi) =$	0.25 $0.25(11-\chi)/9$ $0.25(21-\chi)/39$	if $\chi \in [0,2]$ if $\chi \in (2,8)$ if $\chi \in [8,21]$
Stations distance (from)	$\mu(\chi) =$	$0.58[(\chi+500)/1500]^{0.5}$ $0.58(2500-\chi)/1500$ 0	if $\chi \in [0,1000]$ if $\chi \in (1000,2500)$ else
Intersections distance (from)	$\mu(\chi) =$	0.30 $0.30[(2500-\chi)/2000]^{0.66}$ 0	if $\chi \in [0,500]$ if $\chi \in (500,2500)$ else
Main road distance (from)	$\mu(\chi) =$	$0.45\exp(-\chi/360)$ 0	if $\chi \in [0,3000]$ else
Main road density	$\mu(\chi) =$	0.01χ 1	if $\chi \leq 100$ else
Secondary road distance (from)	$\mu(\chi) =$	$0.40\exp(-\chi/100)$ 0	if $\chi \in [0,2000]$ else
Secondary road density	$\mu(\chi) =$	$\chi/80$ 1	if $\chi \leq 80$ else

[2]

Above is the corresponding CF function for each quantitative input variable to their model. They take variables into consideration such as the slope, distances from main roads, and intersection points.

In the paper, they then proceed to calibrate each of these variables, in order to prevent overestimation or underestimation errors. The model was then able to predict the next year's land cover with "satisfactory" results.

4 | How Cellular Automata are Related to the Study of Complex Systems

After the aforementioned classification of CA being complex systems [5], they have truly made their mark in the field. One of the most important ways in which we can understand their place in relation to complex systems is through understanding exactly what a complex system is, and how CA fall into this category.

4.1 Complex Systems

Definition

> Complex systems are a simple classification of systems that are comprised of many components.

There are a plethora of examples of CA, some of which include weather systems, economic systems and also in maths, with the development of cascading mode interactions [13]. It is very important to understand what makes these similar.

4.1.1 Features

Complex systems exhibit many features similar to those of CA. Below are some of the examples: ([14])

- Emergence

25

- Interdependence

- Self-organisation

What these mean are that the patterns observed in complex systems have emergent properties. That is to say, the fine details of these systems are inter-dependent on the whole picture.

"*A forest has its own behaviors; fires and regrowth are part of the natural behavior of a forest. Of course anything that the forest does is made up of many details of what happens to trees and animals and other plants. Emergence refers to the relationship between the details and the larger view. It is not about the importance of the details or the importance of the larger view; it is about the relationship between them. Specifically, which details are important for the larger view, and which are not?*"

[14]

Interdependence refers to the effect making a change in one variable has to another. This is prominent in CA, because of the Kernel. We can clearly define this property, and change it as we see fit. Interdependence is what leads to a lot of "cause and effect" seen in weather patterns etc.

The last point, self-organisation, is a phenomena seen in Complex systems where we observe specific characteristics develop from a system, of which we did not define. Similar to CA, we don't "define" life in Lenia, but we observe these complex characteristics. This means that CA can be self-organised.

SUMMARY

Complex Systems are the perfect way to classify CA. They are essentially a super set of CA.

5 | The Societal Implications of CA

Even though we have just explored all of these applications of CA, in the realm of complex systems; there are always scenarios where CA can be used wrongly. How a new technology impacts today's modern society is one of the key aspects of its' development. As we have seen with the rise of AI; Society embraces new technologies. I find this to be a double edged sword; Not only is new technology used for good, it can also be used for harmful and potentially damaging events. An example of this could involve Cellular Automata being used to model the spread of a virus. This could, unfortunatley, be used to start a global pandemic. These undesirable events can cause unwarranted panic and fear, which would inevitable lead to the technology either being banned, "*muted*" as such; with the ability to develop it severely restricted. We have seen similar attempts with AI; having global AI leaders wanting to slow down the development of AI [15]. After explaining some more impacts of CA in society, I will explain what I think to be a solution.

5.1 Misuse in Simulating Harmful Scenarios

As we all know, simulations, CA included, can be programmed to simulate scenarios that might have harmful or negative implications. This is often trivial with little to no rules governing the use of CA. An example of using CA in this manner would be using them to model the spread of diseases, or disasters. I want to explore this a little further; seeing just how easy it is to simulate this.

27

5.1.1 Simulating a wildfire with CA

In a model used to simulate wildfire spread in a forest [16]; two opposed processes are simulated: The continuous growth of trees covering the landscape, and the randomly occurring lightning strikes that initiate forest fires. In this simulation, trees can be simulated at each cell, and they can spread based on a statistically evaluated probability (which can be measured in real life). A burning site can ignite neighbouring tree sites. The likelihood of this can also be determined easily based on the types of weather patterns and the frequency and intensity of lightning strikes.

5.1.2 Evaluation

As you can see, this can lead to someone having the knowledge of how, where, and when to light a fire in a forest in order to completely destroy and remove all of the habitat. On the other hand, being able to determine the natural areas of density in your forest can also help create fire evacuation plans and can help optimise the rescue strategies and procedures in a managed forest. The concern is that someone could make use of this technology before it is used for good. This also raises some ethical concerns.

5.2 Ethical Concerns in Modeling

The use of cellular automata to model complex systems raises ethical concerns, especially when dealing with scenarios involving human behavior or societal dynamics. Inaccurate or biased modeling can lead to flawed predictions and misinformed policy decisions.

5.2.1 Disease and Viruses

From the work by Eshel Ben-Jacob et al. in their paper *Generic modelling of cooperative growth patterns in bacterial colonies* [17], I want to consider some of the issues in the misuse of modelling bacterial colonies. Showing that "*a simple model of bacterial growth can reproduce the salient features of the observed growth patterns*" allows researchers to trustingly use current bacteria models to simulate growth patterns. This, in effect, means that we could simulate bacteria precisely, with a very minimal model. Reducing the entry level and access to these technologies could allow for the potential for these models to be used with bias. Bias modelling would lead to predictions based on said models being inaccurate, and potentially leading to decisions based on this model to be misinformed and flawed.

5.3 Security Risks and the Unintended Consequences in the use of CA in the automation of processes

Cellular automata, particularly when used in computational simulations or artificial life experiments, may introduce severe security risks. By exploiting or manipulating the underlying algorithm, someone could affect a simulation which could be used to achieve good, and this could ultimately cause fatalities. The best way to explain this is through an example.

5.3.1 Example: Traffic Management

Consider a city implementing a sophisticated cellular automata-based traffic management system. This system would rely on CA algorithms to optimise, not only traffic light timings, but the general flow of traffic in the city. In this scenario, the security of the CA algorithms would become incredibly important, for the safety and efficiency of the entire transportation network of this city.

A hacker with malicious intent could identify vulnerabilities in the CA algorithms governing the traffic management system. These weaknesses could be exploited easily, and this would lead to the unauthorised access of these algorithms, and the ability to manipulate them with ill intent. Instead of optimising traffic flow, the algorithm could be optimised in a way which "encourages" the simulation of chaotic patterns of traffic flow; causing congestion and disruption on the road network.

These manipulations would then take effect on the road infrastructure. Traffic systems would then not function properly, and this would in turn affect all of the major arteries of the city; blocking off emergency services, and transport infrastructure; grinding the city to a halt.

Hopefully this example shows the extent that an issue could have when regarding CA, and it clearly calls for regulation and policy. When considering implementing policy, there is always a chance that the public will misunderstand it; and public misunderstanding is a large societal impact for CA.

5.4 Public Misunderstanding

As is with any new technology, public understanding (or misunderstanding) can be one of the most important factors to consider before publishing any findings. If the public do not understand the technology well enough, it can lead to concerns or a lack of trust in the scientific community. Making sure that these technologies can be understood for the benefits they bring, and they can be introduced into society in an educated way is what matters. We have seen an example of this go wrong with AI in our current society. AI was made instantly accessible to the wider population with the innovations at Open-AI. This meant that anyone and everyone could access AI directly, and, without proper training, we saw pandemonium break out. I was fortunate to have good experience and knowledge in the field of AI, so I was able to understand common pitfalls, and also the extent that AI could be used in a modern society.

5.5 Energy Consumption in Computational Models

Whenever technology goes large-scale, we have to consider the environmental and ecological impact it will have on society. Some of the specific reasons here are beyond the scope of this project, but one of the important factors is energy consumption. Cellular Automata systems are computationally expensive tasks, which mean that they require a lot of computational processing to be done in servers. This poses a concern regarding the use of data centres and large processing sites.

Having looked at the various aspects of CA that could bring detriment to today's society, it is best to now explore how these problems will be solved, and what we can expect from the future of CA.

6 | Potential Areas for Future Research

6.1 Ongoing Research

Quantum CA are at the forefront of current research, with implementations such as a new paradigm for digital design using Quantum dot CA [18], and the use of Quantum-Dot Cellular Automata in designing the arithmetic and logic unit [19]. Cellular Automata is a technology that has the potential to make big changes in modern society, and the examples I have gone through in this paper only scratch the surface of its' potential. I find it best to treat the scale of potential to be similar to that of AI. As is with AI, these developments have their concerns.

6.2 Potential for Expansion

From the Future of Life Institute [15], They propose this set of recommendations in order to adequately stem the growth of AI.

Policy recommendations

1. Mandate robust third-party auditing and certification.

2. Regulate access to computational power.

31

3. Establish capable AI agencies at the national level.

4. Establish liability for AI-caused harms.

5. Introduce measures to prevent and track AI model leaks.

6. Expand technical AI safety research funding.

7. Develop standards for identifying and managing AI-generated content and recommendations.

6.3 Drawing an end

Assuming this policy is implemented for AI models, I feel like the rate of development of AI will become more manageable, and it will provide a toolkit to help governing bodies manage AI. Establishing AI Agencies will mean that AI can not get into the wrong hands as easily as it can now. Liability and technical AI safety research are two ways in which we can make AI better in our world. I would like to propose that these rules should also apply to CA, because this will allow the development of CA to be better maintained and will, in turn, increase the societal awareness of CA.

6.4 New areas for application

In my opinion, with the rise of AI; Cellular Automata should be developed in order to work in conjunction with other behaviourally emergent systems. Not only can they provide benefits to the people researching in AI, but they can also provide more tangible evidence for the decisions made by these systems. The use of CA in this field would require lots of research to be done, but I think there are some points where this could help.

6.4.1 CA in AI Training

As I was researching this project, I felt that some places where AI could be applied are in the training of AI models, specifically in the back-propagation phase of the process. If AI could be used in order to assist finding local and global minima when training AI, this process could be heavily streamlined and would also mean that AI systems can be trained in fewer iterations; meaning that less power is consumed and it is overall better for the planet. The use of CA in such a way as this would link together AI development and CA. This is definitely some work that CA can be applied in.

6.4.2 CA in enhancing AI Models

GPT-4 is an AI which has the ability to connect with external plugins, such as Wolfram Alpha (On another note, the same person that defined Wolfram's Classification). This plugin connection could be applied to a CA model. If AI were able to interface with CA in this way, it could define the parameters used when running CA, and in turn run its own simulations. This could be beneficial when it is trying to either make a mathematical or logical prediction on the outcome of a situation or simulation. I feel like this would mean that AI can make better informed decisions, and this will improve the quality of results output by these models.

In conclusion, Cellular Automata are incredible models which can be applied to a multitude of problems in our current world. The only problems hindering the expansion of the use of these tools are the regulations and policies that govern them. If we, as a modern society, want to use CA to their fullest extent, we need to embrace both the development of these technologies, as well as the practical implementations. Not only have CA contributed to the study of complex systems, but they also provide a mathematical platform for simulations to be applied in a much broader variety of subjects.

7 | Evaluation

7.0.1 Aims

The aims of my project were to understand more about this rapidly developing technology, and how it has a place in modern society in relation to complex systems as a whole. I feel like I have achieved this aim through my extensive research of resources. I feel like I am very knowledgeable in the subject now, and that my comments made on the feasibility of using CA in systems today are well backed up by fact. Some of the aims I had for myself including writing a fully operational CA engine I feel were too ambitious for an EPQ project, and I did not manage to achieve these to the extent I wished. I have developed a CA system for the purpose of better understanding how it works, but this was used more as an explanatory tool for the user.

7.0.2 limitations

Some of the limitations with regards to my project were both time constraints and general knowledge of CA. If I had more time, I would have read even more resources, leading to scope creep. I would have enjoyed learning more about CA, but I felt that this was unreasonable in the given time-frame. Because of the general lack of knowledge of Cellular Automata in my school community, I have found it to be difficult to learn from other people, and this has led to the majority of my sources being from articles and journals. This method is good in some sense, but I feel like this limited the potential for my project.

34

7.0.3 What I would do differently

If I could go through this process again, I would begin structuring and thinking about my thread of discussion in advance, before even researching topics. If I knew what I wanted to find through my EPQ; Limiting scope creep and other factors would have been easier for me. Admittedly, the thread would change over time, as it does in all projects, but I feel like it would have provided a stronger backbone for the project.

7.0.4 What lessons I have learnt

I have learnt that research is one of the most important parts of academia. If I am not well-read in the subject, any comments I make are not necessarily backed up by facts and proof. I have also learnt several skills along the way, including LaTeX. I feel like the choice to use this method was very bold; and the challenge I set at the beginning to learn this programming language was definitely to improve my skill and push myself as a learner. I have learnt so much about the language and about the community developing it, that I feel like discovering other pathways and methods to write the EPQ should be made clearer from the beginning. Albeit challenging, I have enjoyed working with LaTeX, and I would definitely do it again if I had the choice.

Technological (e)-Skills

LaTeXis a markup language that enables me to have both clear and consistent formatting, and citing abilities, by making use of my own styling code. I can write code for formatting, as well as for diagrams and plots. This entire document was written using LaTeX, and below are some commands I've used when writing more long-form text:

```
\cite{src}
(To cite a source from my bibliography file, using the citing format I defined
in my frontmatter)
\fig{fig:logistic_map}
(To cross-reference a figure I labelled previously in the document)
\acrshort{ca} | \acrlong{ca}
(To reference a variant of an acronym I defined in my acronyms file)
```

I have also been making use of Zotero, in order to keep track of my academic papers, and other sources in one place. This functionality easily allows me to create .bib (bibliography) files from my list of sources, which I can then use in LaTeX.

7.0.5 Presentation

As below in appendix C, I have collected some feedback from the people who I spoke to in my presentation. I feel like this data accurately reflects my ability to respond to questions about CA, and everyone I spoke to felt like I was confident, knowledgeable and had a well presented display. They enjoyed the interactivity, minimalist design and the passion I gave to the subject. One of the key points of feedback I was given involved my ability to tailor the flexibility of my title to different audiences and subjects, which was a point I focused on when preparing for the presentation. Some more critical feedback included having too short a recap, and having my live video presentation running in an overly small section of my stand. This was, unfortunately, due to space constraints, but I do agree with the comments. I could have improved my recap and made the diagrams more fun and included more "interesting" "people".

Glossary

Binary A base-2 numeral system. 8

Cellular Automata A discrete model of computation studied in automata theory. 20, 21, 29

Conway's Game of Life A cellular automaton created by John Horton Conway. 5, 6, 8, 12, 13, 15, 20

John Conway English mathematician, known for Conway's Game of Life. 6

John von Neumann Hungarian-American polymath who co-created Cellular Automata. 6

Kernel A kernel is a small matrix of numbers. 9, 10, 14

Stanislaw Ulam Polish-American mathematician; co-created Cellular Automata. 6

stochastic A random probability distribution or pattern. 20

 37

Nomenclature

$(f * g)(t) := \int_{-\infty}^{\infty} f(\tau)g(t-\tau)\, d\tau.$ Convolution of f and g

$\ker(\alpha)$ The Kernel of α

$x_{n+1} = rx_n(1-x_n)$ Mathematical representation of a logistic map

38

Bibliography

[1] B. W.-C. Chan, “Lenia - biology of artificial life,” *Complex Systems*, vol. 28, no. 3, pp. 251–286, Oct. 15, 2019, ISSN: 08912513. DOI: 10.25088/ComplexSystems.28.3.251. arXiv: 1812.05433[nlin]. [Online]. Available: http://arxiv.org/abs/1812.05433 (visited on 04/15/2023).

[2] L. Mantelas, P. Prastacos, T. Hatzichristos, and K. Koutsopoulos, “Using fuzzy cellular automata to access and simulate urban growth,” *GeoJournal*, vol. 77, no. 1, pp. 13–28, 2012, Publisher: Springer, ISSN: 0343-2521. [Online]. Available: https://www.jstor.org/stable/41431188 (visited on 04/15/2023).

[3] I. BIALYNICKI-BIRULA, I. Bialynicki-Birula, and I. Bialynicka-Birula, *MODELING REALITY: HOW COMPUTERS MIRROR LIFE.* OXFORD: OXFORD UNIV PRESS, Open Library ID: OL22603169M.

[4] M. Gardner, “Mathematical games,” *Scientific American*, vol. 223, no. 4, pp. 120–123, 1970, Publisher: Scientific American, a division of Nature America, Inc., ISSN: 0036-8733. [Online]. Available: https://www.jstor.org/stable/24927642 (visited on 04/15/2023).

[5] G. A. Hedlund, “Endomorphisms and automorphisms of the shift dynamical system,” *Mathematical systems theory*, vol. 3, pp. 320–375, 1969. [Online]. Available: https://api.semanticscholar.org/CorpusID:21803927.

[6] Wikipedia contributors, *Conway’s game of life*, [Online; accessed 02-09-2023], 2023. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Conway%27s_Game_of_Life&oldid=1187705341.

39

[7] S. Wolfram, “Universality and complexity in cellular automata,” *Physica D: Nonlinear Phenomena*, vol. 10, no. 1, pp. 1–35, 1984, ISSN: 0167-2789. DOI: https://doi.org/10.1016/0167-2789(84)90245-8. [Online]. Available: https://www.sciencedirect.com/science/article/pii/0167278984902458.

[8] B. W.-C. Chan, *From conway to lenia*, Jul. 15, 2015. [Online]. Available: https://colab.research.google.com/github/OpenLenia/Lenia-Tutorial/blob/main/Tutorial_From_Conway_to_Lenia.ipynb (visited on 04/15/2023).

[9] J. Hardy, Y. Pomeau, and O. de Pazzis, “Time evolution of a two-dimensional classical lattice system,” *Phys. Rev. Lett.*, vol. 31, pp. 276–279, 5 Jul. 1973. DOI: 10.1103/PhysRevLett.31.276. [Online]. Available: https://link.aps.org/doi/10.1103/PhysRevLett.31.276.

[10] A. Mordvintsev, E. Randazzo, and C. Fouts, *Growing isotropic neural cellular automata*, Jun. 1, 2022. DOI: 10.48550/arXiv.2205.01681. arXiv: 2205.01681[cs,q-bio]. [Online]. Available: http://arxiv.org/abs/2205.01681 (visited on 12/12/2022).

[11] M. S. Samoilov, G. Price, and A. P. Arkin, “From fluctuations to phenotypes: The physiology of noise,” *Science’s STKE: signal transduction knowledge environment*, vol. 2006, no. 366, re17, Dec. 19, 2006, ISSN: 1525-8882. DOI: 10.1126/stke.3662006re17.

[12] L. Manukyan, S. A. Montandon, A. Fofonjka, S. Smirnov, and M. C. Milinkovitch, “A living mesoscopic cellular automaton made of skin scales,” en, *Nature*, vol. 544, no. 7649, pp. 173–179, Apr. 2017.

[13] Himat. Mir, “Cascading mode interactions in discrete dynamical systems. - university of surrey,” Ph.D. dissertation, University of Surrey, 219 pp. [Online]. Available: https://openresearch.surrey.ac.uk/esploro/outputs/doctoral/Cascading-mode-interactions-in-discrete-dynamical/99513038702346 (visited on 06/13/2023).

[14] Y. Bar-Yam, “General features of complex systems,” *KNOWLEDGE MANAGEMENT*, vol. 1, (visited on 10/03/2023).

[15] Future of Life Institute, *Pause giant AI experiments: An open letter*, Letter, Mar. 22, 2023. [Online]. Available: https://futureoflife.org/open-letter/pause-giant-ai-experiments/ (visited on 04/07/2023).

[16] B. Drossel and F. Schwabl, "Self-organized criticality in a forest-fire model," *Physica A: Statistical Mechanics and its Applications*, vol. 191, no. 1, pp. 47–50, 1992, ISSN: 0378-4371. DOI: https://doi.org/10.1016/0378-4371(92)90504-J. [Online]. Available: https://www.sciencedirect.com/science/article/pii/037843719290504J.

[17] E. Ben-Jacob, O. Schochet, A. Tenenbaum, I. Cohen, A. Czirók, and T. Vicsek, "Generic modelling of cooperative growth patterns in bacterial colonies," *Nature*, vol. 368, no. 6466, pp. 46–49, Mar. 1, 1994, ISSN: 1476-4687. DOI: 10.1038/368046a0. [Online]. Available: https://doi.org/10.1038/368046a0.

[18] B. Bilal, S. Ahmed, and V. Kakkar, "Quantum dot cellular automata: A new paradigm for digital design," *Experimental and Theoretical NANOTECHNOLOGY*, pp. 33–43, Jan. 15, 2019, ISSN: 2590-4132. DOI: 10.56053/3.1.33. [Online]. Available: https://etnano.com/index.php/en/article/view/44 (visited on 04/15/2023).

[19] M. R. Gadim and N. J. Navimipour, "Quantum-dot cellular automata in designing the arithmetic and logic unit: Systematic literature review, classification and current trends," *Journal of Circuits, Systems and Computers*, vol. 27, no. 10, p. 1 830 005, Sep. 2018, Publisher: World Scientific Publishing Co., ISSN: 0218-1266. DOI: 10.1142/S0218126618300052. [Online]. Available: https://www.worldscientific.com/doi/10.1142/S0218126618300052 (visited on 04/15/2023).

A | Appendix

A.1 Presentation Material

42

Figure A.1: Important People Poster 1

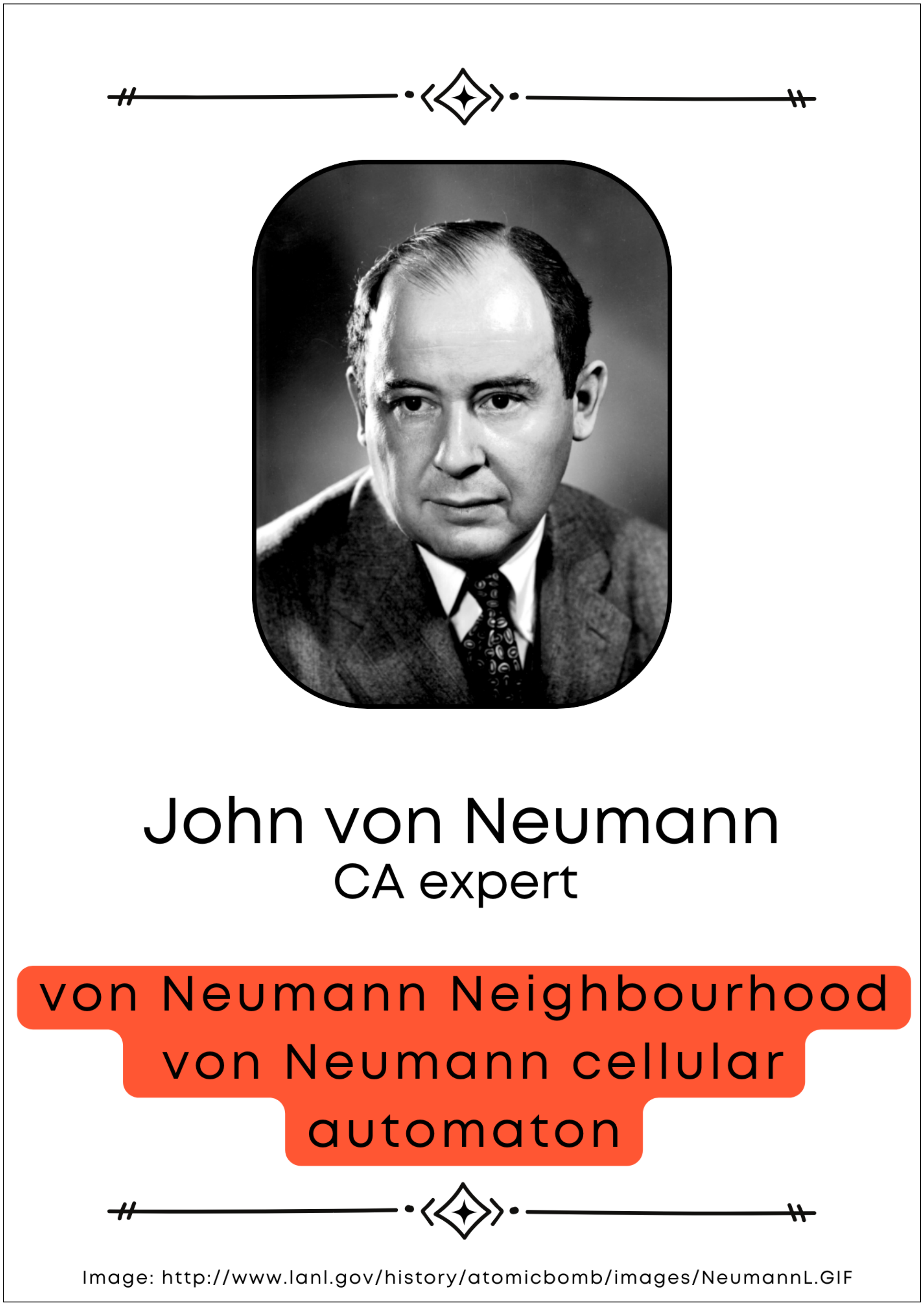


Figure A.2: Important People Poster 2

Figure A.3: Important People Poster 3

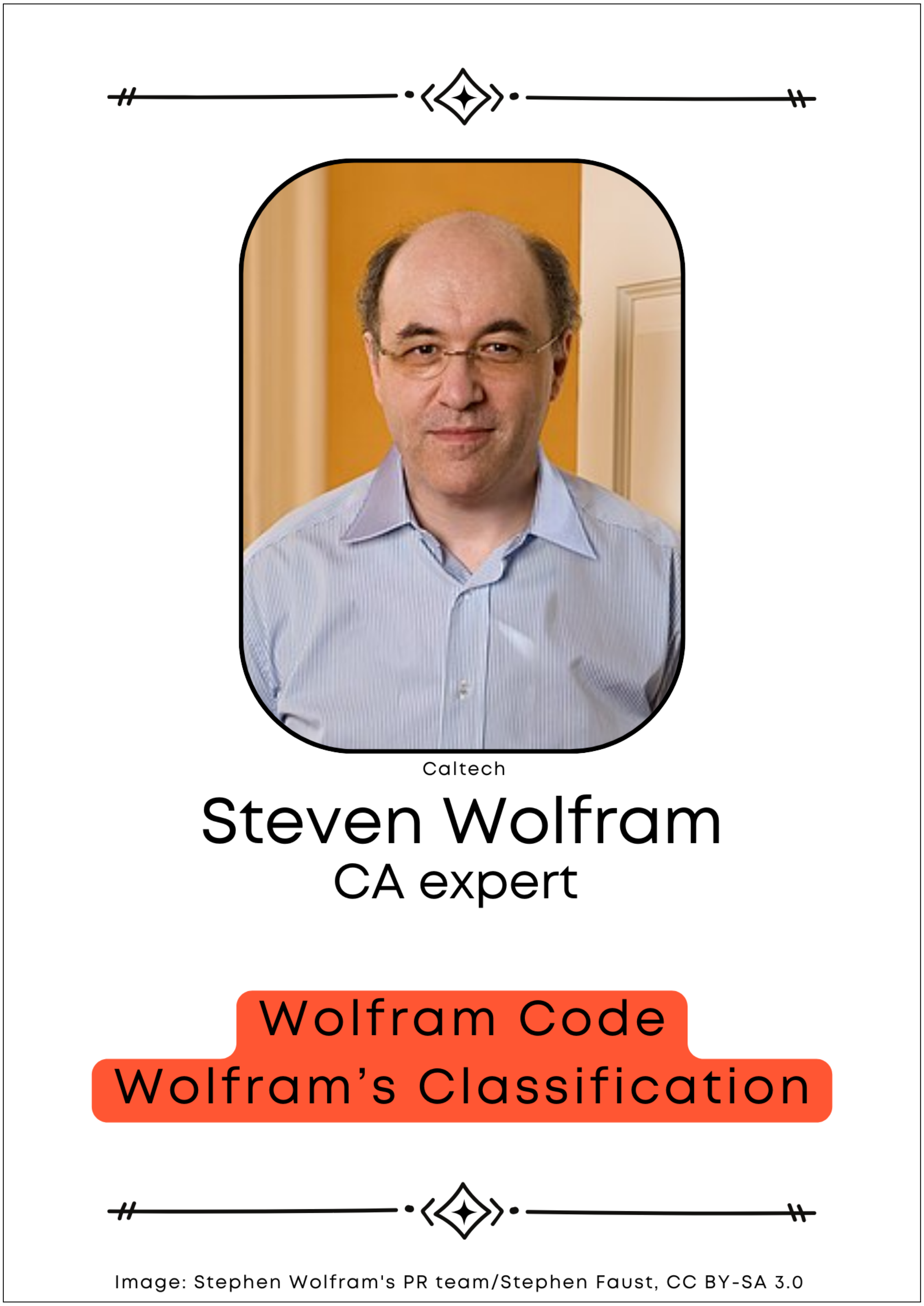


Figure A.4: Important People Poster 4

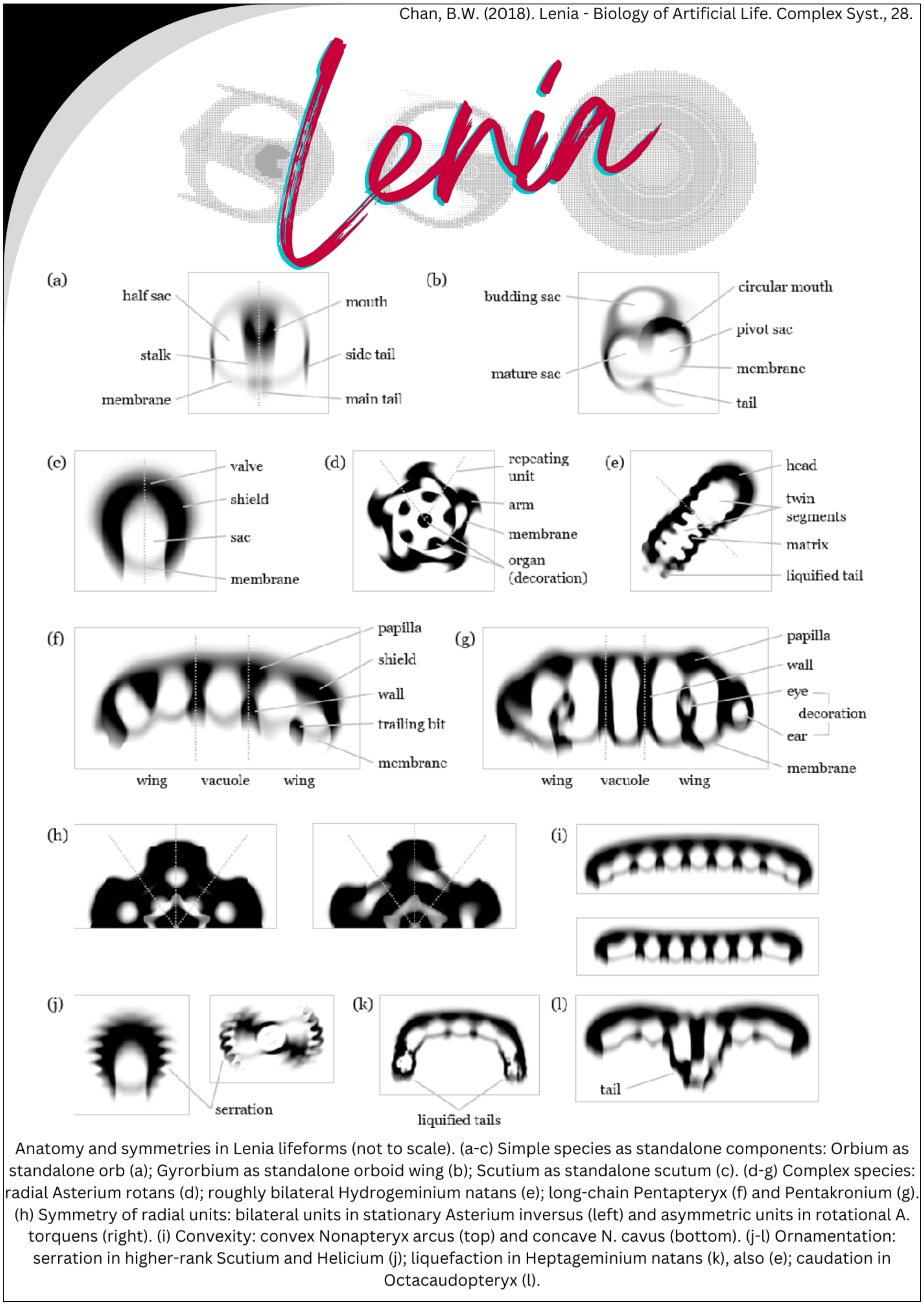


Figure A.5: Lenia Poster 1 (Not Used In Presentation)

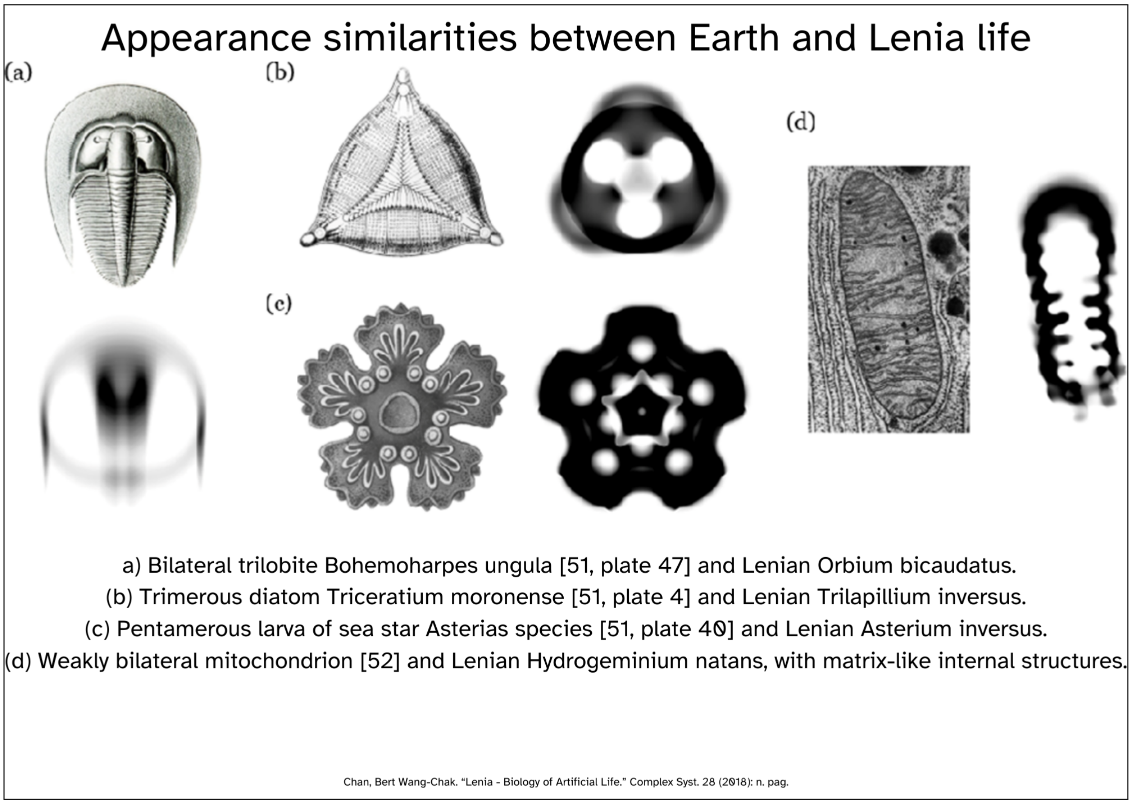


Figure A.6: Similarities and Differences Poster (Lenia Poster 2)

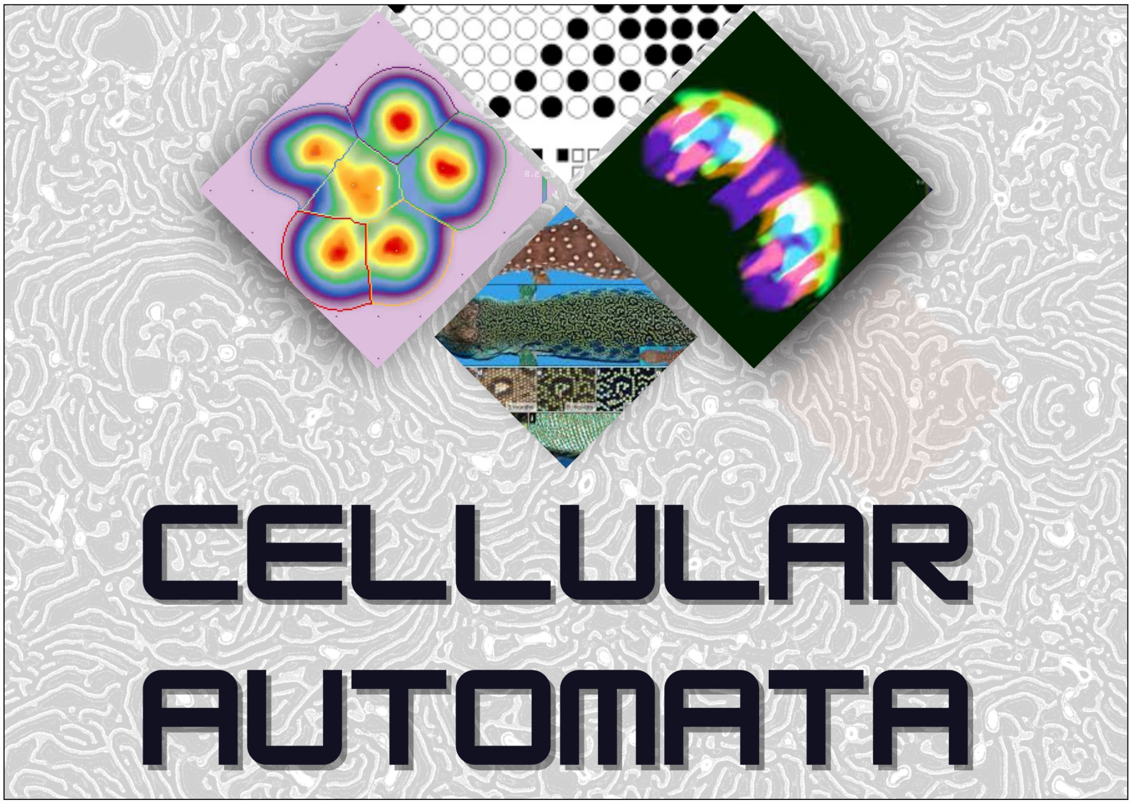


Figure A.7: CA Main Poster 1

https://www.nature.com/articles/s41467-021-22525-1), (https://twitter.com/i/events/1275490076592504833), (https://www.researchgate.net/figure/Memory-in-cellular-automata-A-sixteen-unit-one-dimensional-cellular-automaton-was_fig1_7351309)

A.2 My Stand

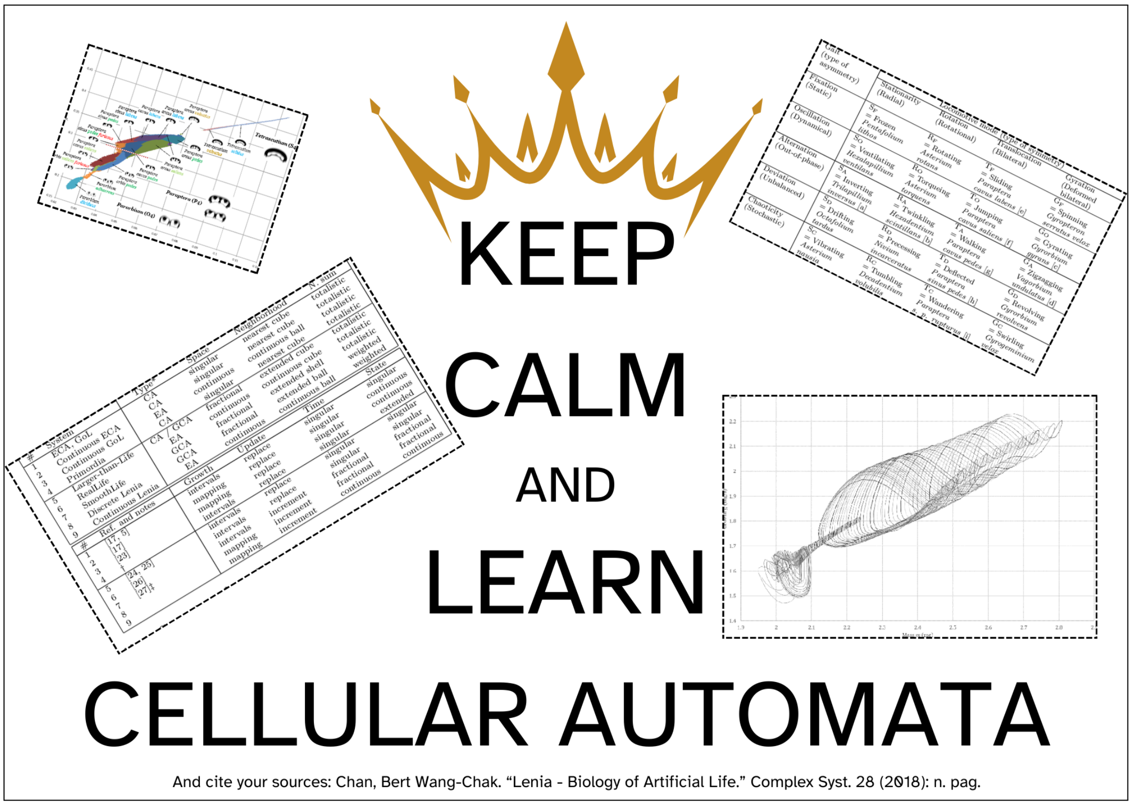
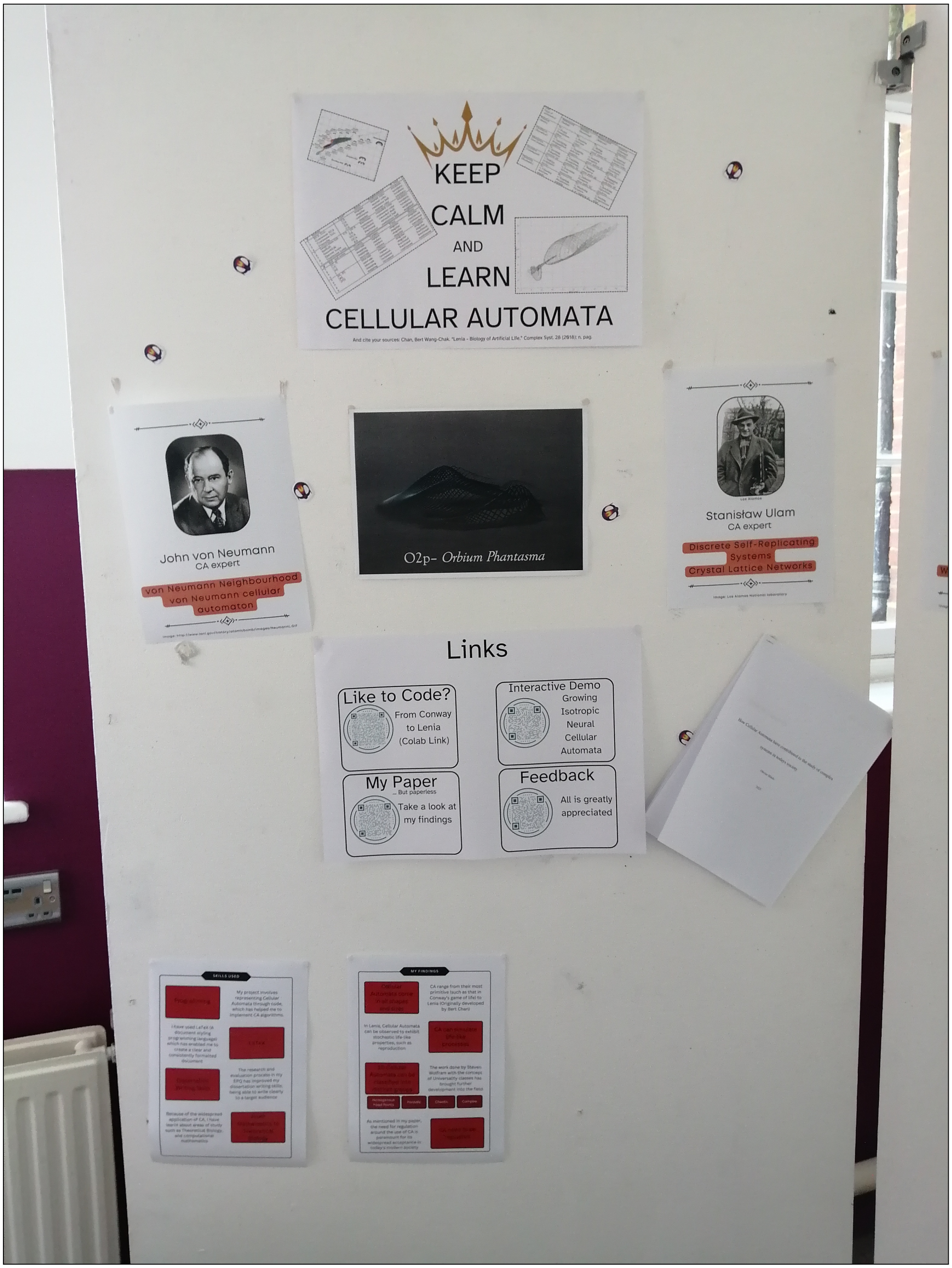
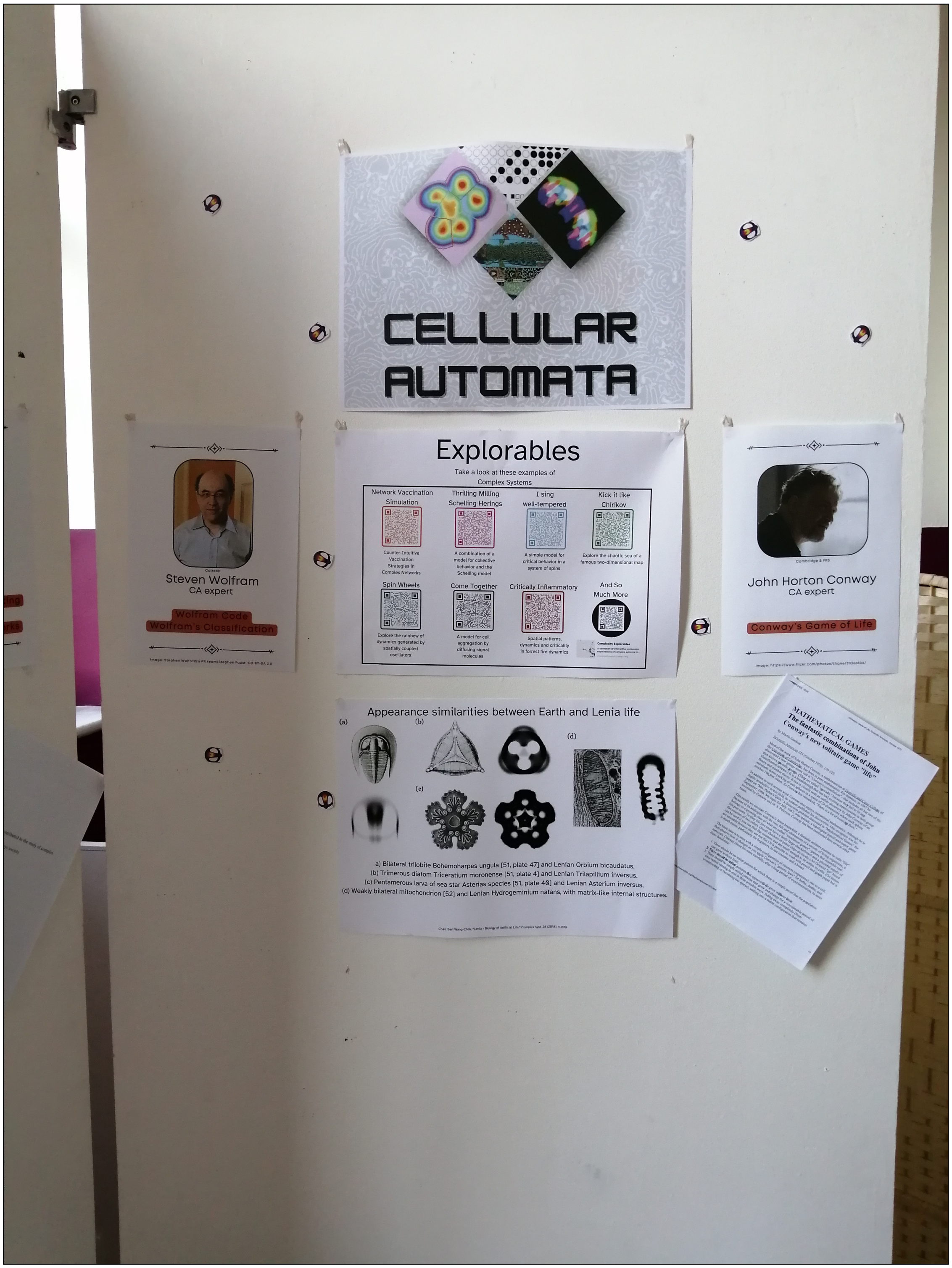


Figure A.8: Main Poster 2


KEEP
CALM
AND
LEARN
CELLULAR AUTOMATA
CELLULAR
AUTOMATA
Explorables
John von Neumann
Stanislaw Ulam
Steven Wolfram
John Horton Conway
Links
Like to Code?
Interactive Demo
My Paper
Feedback
Appearance similarities between Earth and Lenia life
Olivier Hinds
DISSERTATION


KEEP
CALM
AND
LEARN
CELLULAR AUTOMATA
And cite your sources: Chan, Bert Wang-Chak. "Lenia - Biology of Artificial Life." Complex Syst. 28 (2018) n. pag.
John von Neumann
CA expert
von Neumann Neighbourhood
von Neumann cellular automaton
O2p- Orbium Phantasma
Stanisław Ulam
CA expert
Discrete Self-Replicating Systems
Crystal Lattice Networks
Links
Like to Code?
From Conway to Lenia (Colab Link)
Interactive Demo
Growing Isotropic Neural Cellular Automata
My Paper
... But paperless
Take a look at my findings
Feedback
All is greatly appreciated


CELLULAR
AUTOMATA
Explorables
Take a look at these examples of
Complex Systems
Network Vaccination Simulation
Thrilling Milling Schelling Herings
I sing well-tempered
Kick it like Chirikov
Spin Wheels
Come Together
Critically Inflammatory
And So Much More
Steven Wolfram
CA expert
Wolfram Code
Wolfram's Classification
John Horton Conway
CA expert
Conway's Game of Life
Appearance similarities between Earth and Lenia life
a) Bilateral trilobite Bohemoharpes ungula [51, plate 47] and Lenian Orbium bicaudatus.
(b) Trimerous diatom Triceratium moronense [51, plate 4] and Lenian Trilapillium inversus.
(c) Pentamerous larva of sea star Asterias species [51, plate 40] and Lenian Asterium inversus.
(d) Weakly bilateral mitochondrion [52] and Lenian Hydrogeminium natans, with matrix-like internal structures.
MATHEMATICAL GAMES
The fantastic combinations of John
Conway's new solitaire game "life"

Please bear in mind - I did have access to a projector when I was presenting my EPQ, and I have included the code for the presentation graphic in the next appendix

B | Appendix

B.1 Materials Used from external sources

`https://www.complexity-explorables.org` "A collection of interactive explorable explanations of complex systems in biology, physics, mathematics, social sciences, epidemiology, ecology and other fields."

B.2 Code for Live Demonstration

Taken From: `https://www.shadertoy.com/view/7lsGDr`

55

C | Appendix

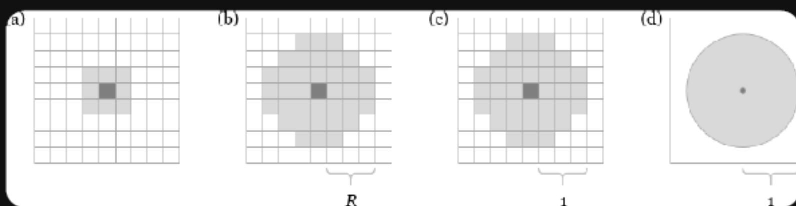
C.1 Form Feedback

This survey was conducted during the presentation of my project. I asked people I spoke to if they could fill it out honestly, and below are the results:

10/12/2023, 20:18 EPQ Feedback Form

EPQ Feedback Form

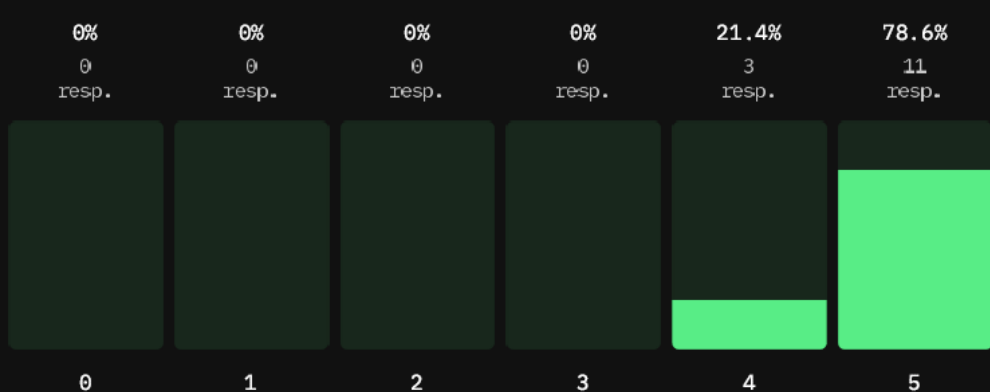
14 responses



From reading my display and listening to what I had to say, how well do you understand the concept of my project?

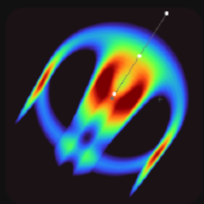
14 out of 14 answered

4.8 Average rating



https://i8rmcxwtm2z.typeform.com/report/BPiNVOKz/4HwHakFQlvnG89Uj?view_mode=print 1/5

What even is... I understand...



Do you think I appeared confident and knowledgeable in the presentation of my project?

14 out of 14 answered

Yes	14 resp.	100%
No	0 resp.	0%

Do you think my display is well presented?

14 out of 14 answered

Yes	14 resp.	100%
No	0 resp.	0%

Please write a sentence or two about any **positive** feedback you may have about my project.

14 out of 14 answered

10/12/2023, 20:18 EPQ Feedback Form

Very interactive and great minimalist design. Very well spoken.

It was very well-presented- you could tell that thorough research has taken place- every question was answered.

olivier seemed very passionate about his subject and he related it to my favourite subject so it made more sense to me. i will continue to keep calm and learn cellular automata forever

Very good

cool video and good explanations

I really liked how you had live examples that we could interact with

It was very well explained especially to those not familiar to the topic

Very clear and engaging

Was very good and informative

Do more like this I want to know more maths

Amazing 10/10

You are really confident and good and showing the information, you also tailor the flexibility of your title to the different audiences

https://i8rmcxwtm2z.typeform.com/report/BPiNVOKz/4HwHakFQlvnG89Uj?view_mode=print 3/5

Is just too good

Interactive and well explained

Please write a sentence or two about any **negative** feedback you may have about my project.

14 out of 14 answered

None

Aside from the answers to the questions, the recap was relatively short.

none at all

Make the projection bigger

more fun diagrams not intresting enough people

No

None :)

N/a

10/12/2023, 20:18 EPQ Feedback Form

No negative all good

Believe in yourself there is no negativity in casa de Rhona

-

It’s a hard topic to understand by just a small convo but you did it really good I don’t really have a negative feedback

Not really

Maybe speak a bit louder but it is very good other than that