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Research Report

Emergent Behaviours in Evolutionary Simulation

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Abstract

Evolution gives rise to complex behaviours and outcomes, the motivations for which may be difficult to reason about based on the result alone. This difficulty can be attributed in part to the immense timescales required for evolutionary changes to occur. The aim of this research is to expose this enigmatic process visually, and show that incremental change can give rise to complex outcomes.

Ars Anima is a generative artificial life simulation, visualising the process of evolution. In the work, abstract virtual creatures live and die in an accelerated genetic struggle to be the fittest survivors. Through interacting with the work, curious audience members can explore unexpected behaviours that emerge as the creatures adapt to a changing virtual environment. The work employs practices of representation though visualisation, interaction design, and artificial intelligence, specifically the field of Evolutionary Art (EvoArt).

This report documents experiments in emergent behaviours, used as a device to visualise evolution and challenge audience's preconceptions on agency and the potential for life within virtual worlds. The conducted research has led to the production of a work that animates life in a struggle for survival, allowing the audience to discover actions that will impact a virtual ecosystem.

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Notes on nomenclature

"Agent" refers to an entity embodied with an AI procedure.

"Creature" is used to refer to the virtual agents appearing within *Ars Anima.*

"Boid" is an agent which moves with respect to a set of calculated forces, detailed in Craig Reynolds paper.[1]

"GPU" refers to the Graphics Processing Unit, a piece of computer hardware used for rendering graphics.

[1] C. Reynolds, 'Flocks, herds and schools: A distributed behavioral model'. *ACM SIGGRAPH computer graphics*, 21(4), 1987, pp. 25-34.

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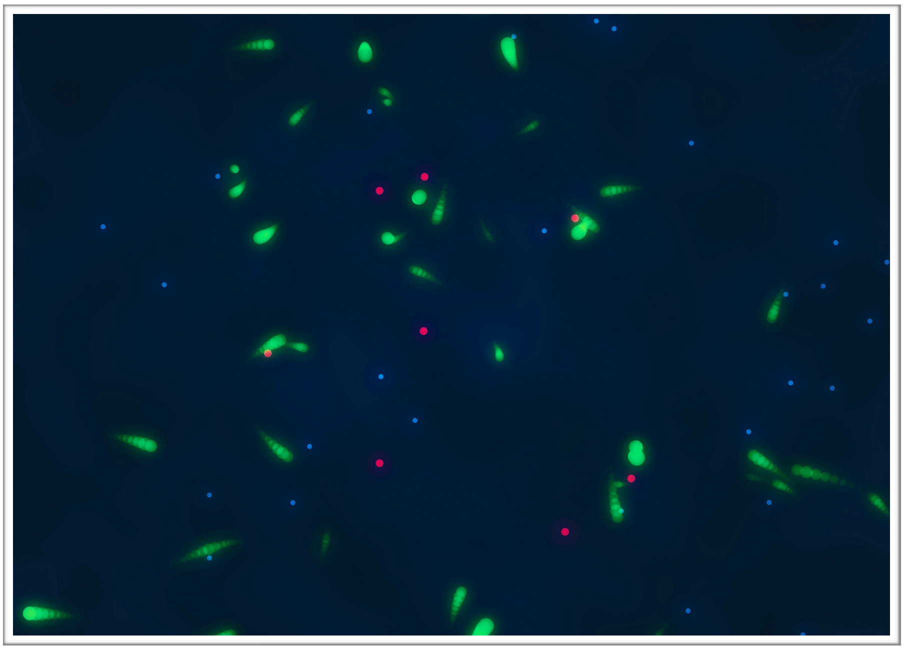

Figure 1 Ars Anima

1.0 Introduction

Over time, the incremental process of evolution in living organisms is capable of giving rise to complex behaviours. To possess life, an organism must have the capacity for growth, reproduction, and be functionally active prior to death.[2] In this report, these attributes are recreated in simulation, proposing that life may exist in virtual worlds and providing visual evidence in support of the potential for complexity to arise.

The topic of evolving ecosystems invites interpretation through the thematic lenses of theistic ontology, social darwinism, behaviouralism, climate change and the cultural implications of artificial intelligence, however focus of this report will be in emergent behaviours and the representation of evolution through interactive art. To achieve this there will be three areas of focus: visualising evolutionary progression, interacting through environmental manipulation, and engaging the audience through emergent behaviours.

Ars Anima is an ecosystem wherein artificial creatures are simulated and interact with their environment, having the capacity for autonomy and decision making. Species may compete or cooperate, rapidly adapting and devising strategies for survival. Only the most fit will have the chance to procreate and pass on their virtual genetic legacy.

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[2] Anon, *Oxford English dictionary online*. https://en.oxforddictionaries.com/definition/life, (accessed 10 October 2017).

1.1 Research and core literature

The following is a review of select precedents from the fields of research. They provide context for further discussion in following sections.

Black Shoals contains simulated life forms that gain energy from stock market trading data. The work is presented such that the audience is passive. They engage by empathising with the organic movements and struggles of the creatures to survive. The creatures "strive to survive, competing with each other in a world whose complexity they are too simple to fathom."[3] This is a metaphoric link to the world of financial trading. The mechanics of the artificial ecosystem are quite advanced, with capacity for changing morphologies (as seen in Karl Sims' *Evolving Virtual Creatures*), the capability to retain memory (through use of recurrent neural networks), and a reproductive isolation mechanic which allows multiple species to co-exist without merging into a single conglomerate species.[4] Additionally, the genotype mapping considers epistasis, enabling retention of dormant components as well as redundancy within the encoding for features of high importance. With this, more compelling behaviour can be presented to the audience.

The installation is positioned to afford an upwards gaze, also a symbolic metaphor for discovery and exploration. One of the key themes explored within the work is how the creatures experience their world. They will form beliefs about their work based on what happens to them, but they never know that their world is controlled completely by financial markets. This mirrors the speculative bets placed by traders from which the work is inspired.

There are many parallels between the *Black Shoals* project and my own research. One common key aim is that the work seeks to engage with the audience through generative narratives. It attempts to reveal an appreciation for the vitality found in non-living systems.

With his work *Iconica*, Troy Innocent aims to establish a self perpetuating virtual world constructed with information and symbolic language.[5] *Iconica* is an ambitious project, broad in scope. It is more complex than some other evolving genetic simulations, where entities might simply eat and die. Entities in *Iconica* have digestive mechanics, can have moods, communicate with the interactor and each other, and even upload themselves to the internet. Innocent discusses several ideas relevant to the direction of my own work. The evolving entities in this abstract world have digestive

[3] C. Hoile, 'Black Shoals: Evolving Organisms in a World of Financial Data', 2014, p. 7.

[4] K. Sims, 'Evolving Virtual Creatures'. *Proceedings of the 21st annual conference on Computer graphics and interactive techniques: ACM*, 1994, pp. 15-22.

[5] T. Innocent, 'The Language of Iconica', *Leonardo*, 34(3), 2001, pp. 255-259.

systems, moods, a symbolic language for communication (with each other *or* with an interactor), and they can even upload themselves to the internet.[6]

As Innocent alludes to, it seems the complexity of the interaction is intimidating to the uninitiated "casual" audience. A significant cognitive investment is required to be a non-passive participant and appreciate the full scope and mechanics of the work. Innocent recognises that the merit of the work is to be found in the novelty within a gallery installation scenario, rather than in an in-depth understanding and engagement as would be ideal.

Karl Sims' paper, *Evolving Virtual Creatures* discusses in detail how to implement the genetic optimisation system resulting in the automatic generation of complex behaviours in a physically based virtual 3D space.[7] Sims broke new ground by using 3D, but also in performing this algorithm on armatures that were not fixed by a predetermined design, meaning the creatures could evolve new forms or "morphologies". Through separating the concepts of genotype and phenotype, the creatures gain the capability to add additional sensors and or effectors to their structure.

1.2 Research methodology

My practice-led research has several components. First there is Generative Art, visuals generated and animated through computational rules, and logic. The second component is interaction design, seeking to create meaningful, engaging and intriguing interactions, in which the audience may express themselves through the medium.[8] The third component is artificial intelligence, specifically in the area of emergent behaviours in artificial life (ALife). In this section I summarise how each of these components were combined and applied to my creative practice.

The practice-based methodology I employ involves creating iterative prototypes through programming, and then assessing and reflecting upon their ability to fulfil their desired purpose. I inform these incremental experiments with theory from a range of topics from related disciplines, including Evolutionary Art (EvoArt), animation aesthetics, genetics and neural networks.[9] By connecting my researched theory and precedence back to my practice, I refine the form of the final work, and discover new avenues for exploration.

To conduct experiments I reflected and reasoned upon how compelling the visual aesthetic, animation, and interaction is. This interactive visual communication can be summarised as what I

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[6] Innocent, op. cite., pp. 255-259.

[7] Sims, op. cite., pp. 15-22.

[8] D. Rokeby, 'Transforming Mirrors', *Leonardo Electronic Almanac*, 3(4), 1995, p. 12.

[9] R. Antunes, F. Leymarie, and W. Latham, 'Two decades of evolutionary art using computational ecosystems and its potential for virtual worlds', *Journal For Virtual Worlds Research*, 7(3), 2014, p 2.

term “intrigue” which may be exhibited by an audience. Apart from these elements, I also conducted experiments with behavioural mechanics. To do this, I selected from a number of virtual contraptions designed to induce specific behaviours within the simulation. They are inspired by natural biological occurrences, and adapted and simplified to work within the bounds of the simplistic virtual world. For example, a squirrel stockpiles nuts for the winter, when food will be scarce. This behavioural mechanic can be replicated virtually by giving creatures a “locker” where food may be deposited for later consumption. Cycles of famine are introduced where food becomes scarce. The only way for the simulated creatures to thrive is to adapt, however the creatures are not explicitly programmed with this behaviour. They must adapt through genetic mutation and a “survival of the fittest” selection process. Though the outcome is designed, the way in which the creatures adapt may be unexpected.

It is important to note the tools used in creating experiments for this project, as the choice of tools and medium affects how the work was developed, and the quality of interaction that is achieved.[10] Cinder is a high-performance C++ framework for displaying OpenGL graphics. Xcode is used for programming to allow for a modify, build, test workflow cycle. Schematics and diagrams for design of behavioural experiments are drawn by hand on an iPad (included in appendix). The final work, *Ars Anima* is presented on a 27-inch touchscreen laid horizontally, with two-channel ambient audio and sound effects. A larger second mounted display provides an alternate view into the virtual world without any User Interface (UI) elements. The work also supports interaction through personal smartphone devices.

[10] Rokeby, op. cite., p. 12.

2.0 Visualisation of evolutionary progression

2.1 Visualising temporally abstracted data

There are many natural occurrences that go unobserved, as they only becomes evident when viewed at a specific levels of abstraction. It is the task of visualisation to take data and transform it in such a way that relevant aspects are made apparent.[11] Drew Berry's animations depicting microscopic molecular activity is a notable example of abstraction in order to visually communicate pertinent features.[12] Not only does it communicate information that would be more difficult convey in non-animated mediums, but it *shows* instead of telling, allowing the audience to learn from their own deductions. In my work the candidate aspect for transformation is time. The background simulation and the visualisation can be thought of as two components that make up what is seen. An advantage of simulation is that it is fairly straightforward to adjust the speed, however doing this for the visualisation component is more involved. In early experiments I found simply increasing the speed would cause noisy erratic looking motion and it would become difficult to track objects from frame to frame. Additionally, a single still frame alone was not sufficient to determine the velocity and bearing of moving objects in the scene.

Figure 2. Hollow animation by Drew Berry

Figure 3. Agents have tails in the game Boids, indicating bearing and velocity

By considering precedents which tackled these problems, I settled upon a suitable animation strategy. In *Boids*, a trail is drawn behind each agent which gives an indication of bearing and velocity.(*Figure 3.*) Notably it is not a solid trail, but a redrawn circle with decreased size. This shows direction and speed for the length of the tail, in a similar way to contour lines showing elevation. I experimented by tweaking the physics model's boid particle parameters and forces to achieve visually appealing arabesque motion curves. Animated NEAT particles also have a similar trails indicating motion.(*Figure 4*) Constant movement was still observable in all regions of the

[11] J. McGhee and N. Johnson 'Alternative Ways of Seeing the Inner Body: an Arts-Led Approach to Visualising MRI Scan Data', *Leonardo*, 47(1), 2014, pp. 90-91.

[12] *björk: hollow* [music video], Director D. Berry, 2012, https://youtu.be/Wa1A0pPc-ik (accessed 5 May 2017).

frame, but the animation was less chaotic overall. With this I had satisfied my criteria, having a clear frame-to-frame read at high speeds, visually appealing motion, and animation that draws the eye. These traits are desirable as they can provide the initial visual intrigue necessary to engage the audience further.

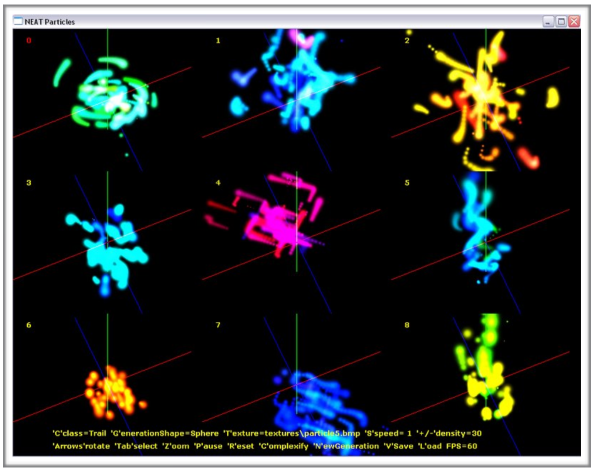

Figure 4. NEAT Particle Samples

2.2 Creating a visual aesthetic inspired by natural organisms

Single cell organism flagellates are somewhat similar in behaviour and morphology to the organisms I have created. They appear to be simple reactionary creatures that can propel themselves around their environment. Typically they are observed as flat 2D creatures on account of them being observed in flat photography. Depth is apparent only through how sharply focused the organisms are —organisms that are closer or farther away will not appear in sharp focus.

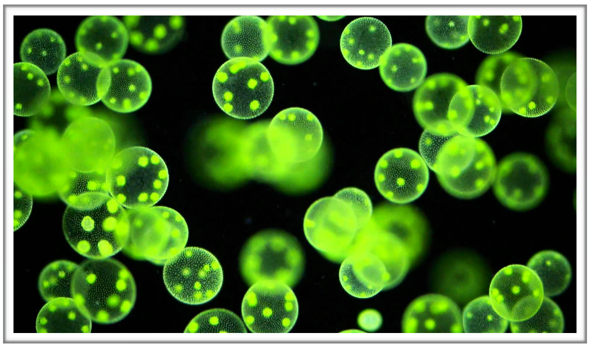

Figure 5. Volvox aureus

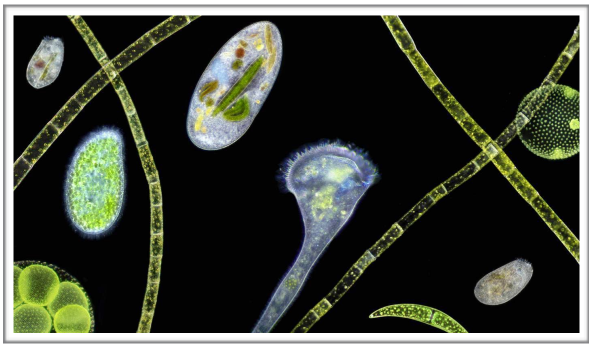

Figure 6. Eukaryotic flagellates — single cell organisms, macro photography

The *Volvox* is an algae observable in macro photography as seen in *Figure 5*, which can be seen tumbling and drifting lazily in video footage. The spherical transparent cells have a fresnel effect, making the cell walls brighter around their perimeter. The colour pallet seen here is a striking and vivid green, saturated and bright against the dark background. The cells have a soft glow, adding to their neon, otherworldly aesthetic. The visual style of *Volvox* as captured with macro photography was used as inspiration in the game *Osmos*.[13] In the game the slow animation within the sprites distills a sense of life and conscious will within the creatures. These have been influential on the animation and visual style employed in *Ars Anima*. Food and corpses appearing in the virtual world were inspired by macro photography of human cells (*Figure 7*).

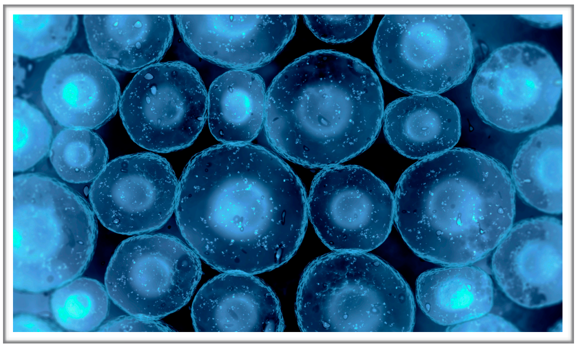

Figure 7. Stained human cells

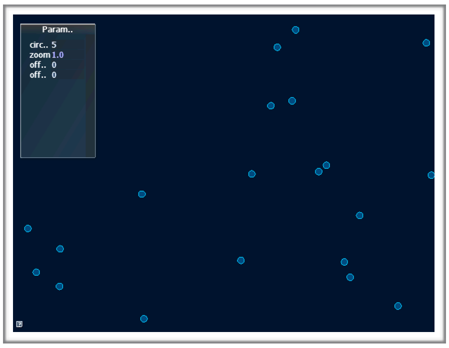

Figure 8. Prototype replicating colour pallet

The visual style used was also informed by the inherent constraints of the medium. It is the role of the artist to push against the boundaries and disrupt the expectations associated with it.[14] At the same time, the tools and medium used here is enabling in terms of the visuals that can be achieved. Utilising a GPU accelerated particle system, graphics programmer and artist Robert Hodgkin was able to create a simulation with 40,000 flocking birds. Each bird is affected by the birds around it. This particle simulation technique was pioneered by Craig Reynolds in an artificial life program called *Boids*.[15] Simple rules involving forces of separation, alignment, and cohesion as well as others allow for complex, organised movement. I have utilised some of these techniques to achieve the animation and movement seen in the creatures in *Ars Anima*.

[13] *Experiment: volvox-style, with 200 small particles* [online video], Osmos, Hemisphere Games 2009, https://vimeo.com/3515917, (accessed 10 October 2017)

[14] D. Rokeby, 'The Construction of Experience: Interface as Content', *Digital Illusion: Entertaining the future with high technology*, 1998, p. 34

[15] C. Reynolds, 'Flocks, herds and schools: A distributed behavioral model'. *ACM SIGGRAPH computer graphics*, 21(4), 1987, pp. 25-34.

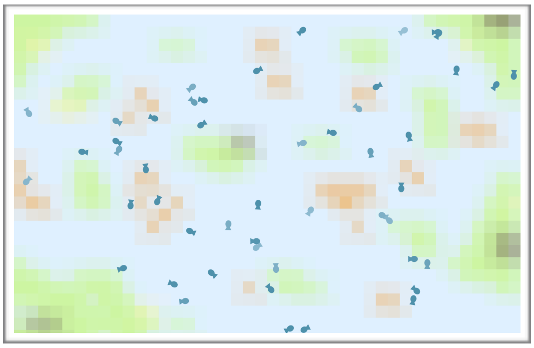

Figure 9. Early prototype with generated landforms and fish-shaped agent silhouettes

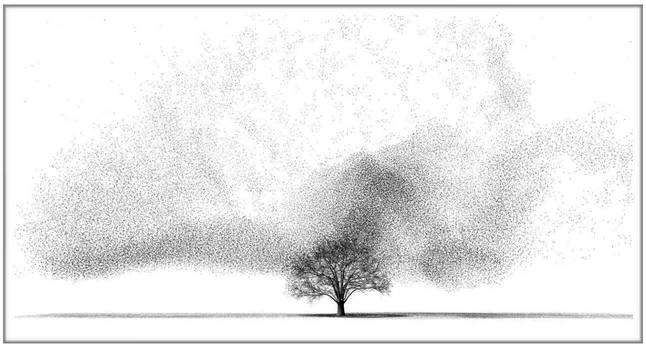

Figure 10. Murmation, realtime flocking simulation

Initially I used a fish-like outline for the agents, as the wedge shaped tail could be used to indicate the bearing. Using the trailing tails allowed for a more minimal and simple look. This way they could more closely match the look of the *Volvox* algae, and have a simpler visual read. This was also conducive to a better performing simulation, as the agents could be considered as a particle system — each agent represented as a point in 2D space with forces acting upon it, rather than as a polygonal shape requiring more computationally expensive object collision calculations. Implementation of cell deformation upon impact with different surfaces is desirable in order to achieve a more organic look. This would be a “faked” visual effect, convincing enough to display without computationally expensive soft-body physics being factored into the simulation. This must be left for a future iteration, as the methods I researched were intractable at the desired scale due to computational limitations.[16]

In order to visually distinguish agents that are outliers in genotype, mutant variations that deviate from a standard are highlighted, drawing attention to them so they may be observed for differing developed behaviours.

2.3 Creating a physics model for the virtual world

A simulation is necessarily a simplification of the real world phenomena that it models. It must be decided which elements are necessary in the model in order to run an experiment indicative of real world behaviour. For *Ars Anima*, the simulation must be sufficient to expose the mechanics of evolution in real time. As long as it satisfies this, there is no imperative to restrict the physics model and world rules to mimicking the real world.[17] Karl Sims chooses the physics model of a 3D

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[16] Metaballs is one such physics simulation often used as an intensive graphical benchmark.
D. Gorny and R. Madeira, *Cinder Creative Coding Cookbook*, Birmingham UK, Packt Publishing, 2013, p. 171

[17] The evolution component must be genuine to the natural model, not aiming to misrepresent the mechanics. The game *Spore* was criticised for this by the scientific community.
M. Robertson, 'The Creation Simulation', *Seed*, 2008, http://seedmagazine.com/content/article/the_creation_simulation/P1/ (accessed 10 May 2017).

underwater setting affording more options for agent locomotion.[18] In *Iconica*, Innocent fabricates rules that apply within the virtual world. There is much room for experimentation here, even creating a completely abstract physics model is possible. An example of this is the related field of cellular automata, where the world is based on rules applied to a discrete grid of cells.[19] *Black Shoals* is another example of the use of synthesised rules, presenting a virtual world governed by oblivious external forces (stock market trading data).[20] Agents may be given senses that would be impossible in reality, for example the agents could be omniscient and observe everything around them at once, or maybe they could communicate more directly with other agents at any distance, without the need for a transfer medium such as with sound. Even the fundamental laws of biology may be challenged — a child agent genotype may be the result of a combination of three (or even more) parent agent genotypes.

In *Ars Anima*, a flat 2D world was chosen, modelling a petri dish or body of water at microscopic level. Newtonian physics is modelled with agents having mass and momentum, and the population is automatically maintained at a stable level. This means that if the population drops, more agents will be spontaneously spawned (in random locations) to prevent population extinction and leaving nothing to observe. These world properties, the animation, visual style, and physics model were chosen in order to communicate clearly and draw attention to the salient features of evolutionary mechanics.

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[18] Sims, op. cite., pp. 15-22.

[19] D. Shiffman, S. Fry and Z. Marsh, *The Nature of Code*, 2012, p. 323

[20] Hoile, op. cite., p. 7.

3.0 Interaction design

3.1 Audience engagement through expressive interactions

The key to engaging the audience is to capture their attention, and then their imagination. This can be done by allowing for emergent and unexpected behaviour in the simulation. The visualisation, as well as the interface, is responsible for abstracting and exposing the important details within the data, guiding the meaning discovered through them.[21] *Ars Anima* is designed to be observable over an extended period of time, with interactors reengaging with the work to see the compounding impact of their interactions. To facilitate this, the work may be placed in a thoroughfare or foyer, somewhere which would encourage repeat encounters. For engagement, the audience should be able to express themselves creatively through interacting with the work.[22] With *Ars Anima*, the aim was to create a sandbox for exploration, with set preconditions and modes of interaction to afford certain audience behaviours. Providing a virtual canvas to leave marks on allows for spontaneity, curiosity, and creativity from interactors. Interactors are not able to manipulate the creatures within the virtual world directly, instead they are able to modify the ecosystem's environment and see how they adapt.

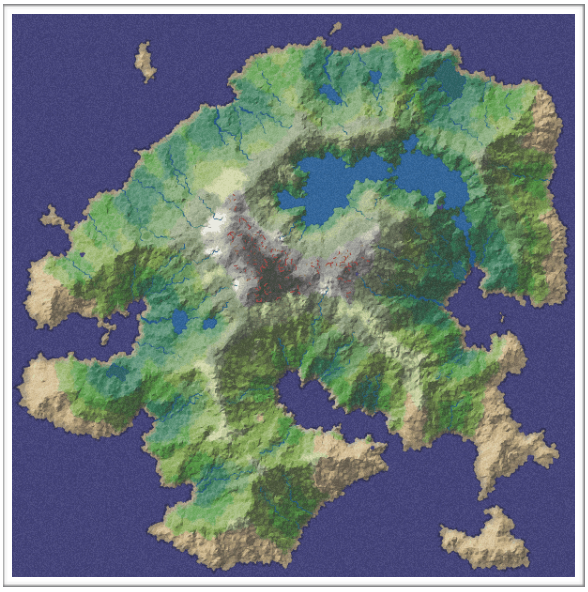

Figure 11. Procedural map generation

Before deciding upon an abstract water based, microscopic environment, I had conducted research into procedural terrain generation. I came across methods for generating realistic climates, landmass formations, and bodies of water. Interactors would be able to sculpt the landmass, and the procedural algorithm would generate rational details around that to adapt.

[21] "Information itself does not create meaning; meaning is created by context and flow, selection and grouping. By guiding us through jungles of content, interfaces are partially responsible for the meanings we discover"
Rokeby, op. cite., p. 9.

[22] D. Rokeby, 'Transforming Mirrors', *Leonardo Electronic Almanac*, 3(4), 1995, p. 12.

Ultimately I decided on a more abstract virtual world, as creating convincing creatures in this environment takes focus away from the important aspect of the work. By designing the creatures to have standard morphologies, I could focus on developing the UI and emergent behaviours. The interactors should be able to partition the population. This would serve to create checkpoints. If the species evolved in a direction that was unsatisfactory or died out, it would be possible to release a corralled population from earlier in the species' evolutionary timeframe. Critically, this interaction is not explicitly stated, but is a possible strategy, discoverable by experimenting with the interface tools provided. Partitioning with barriers also enables populations to diverge into different species. Partitions could then be removed to see how different species interact. Interactors should be able to "paint" food onto the canvas, which would enable the population to be directed (as they would seek the food). Other devices within the virtual world could be used to teleport creatures, store food, or trigger buttons (see appendix for a list of behavioural scenarios where these could be used).

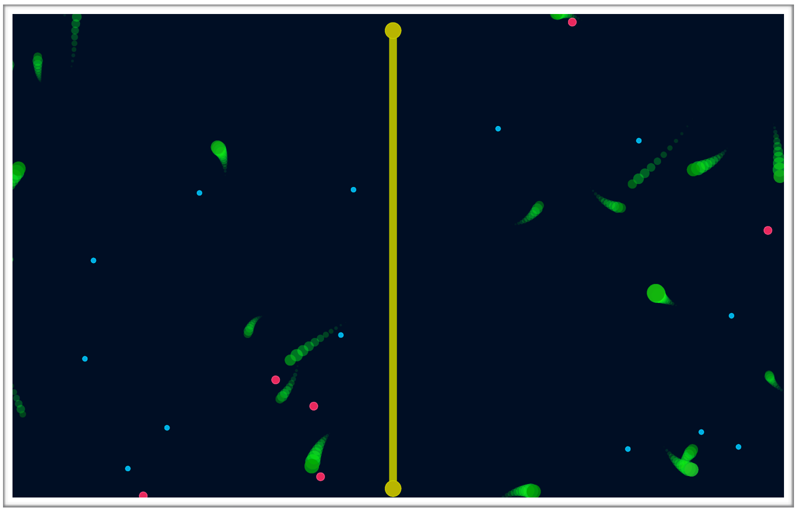

Figure 12. Population partitioned with a barrier in Ars Anima prototype

Figure 13. Camera based "painting" mode of interaction

3.2 User interface considerations

Initially the interaction was painting motions with a light-wand towards a large wall projection. A camera would detect these motions and interpret them for sculpting and pointing.[23] This form of interaction was unreliable and lacked responsiveness. The main mode of interaction became a touchscreen laid flat. Intuitive multi-touch gestures allow interactors to navigate the world by tapping, dragging, and pinching to pan and zoom. User interface elements should be as minimal and non-technical as possible to avoid interactors needing to invest significant effort in order to learn the rules and controls as previously discussed in *section 1.1*.[24] A balance must be struck between overly restricting the interaction, and not providing sufficient freedom. "Constraints provide a frame of reference, a context, within which interaction can be perceived" explains Rokeby, claiming that an interactor will see their impact on an interactive system if the variables that are affected are reduced.[25] He also observes that limiting the interaction can serve to prevent the interactor from feeling as though their behaviour is being judged in their creative expression.[26] To make the interface as minimal as possible, I considered only allowing the ability to drop food, and lead the population of creatures to structures already existing within the virtual world, however this places too much restriction on how the interactors may express themselves through the work. I compromised, allowing a few simple elements to be placed in the world. Large buttons at the side

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[23] This mode of interaction was inspired by description of similar control mechanisms in *Benford*. This method's shortcomings are analysed with a presented design framework for interfaces.
Benford, S. et. al., 2005. 'Expected, sensed, and desired: A framework for designing sensing-based interaction'. *ACM Transactions on Computer-Human Interaction* (TOCHI), 12(1), pp. 3-30.

[24] Predictability is a UI paradigm as referenced in
Rokeby, op. cite., p. 8.

[25] D. Rokeby, 'The Construction of Experience: Interface as Content', *Digital Illusion: Entertaining the future with high technology*, 1998, pp. 27-48.

[26] D. Rokeby, 'Transforming Mirrors: Navigable Structures', *Leonardo Electronic Almanac*, 3(4), 1995, p. 16.

of the touchscreen change the mode, determining which element the interactor intends to add. Barriers used for partitioning can be drawn by dragging across the screen. This mode of interaction was tested informally during development among peers and in the *Share Sydney* exhibition.[27] These tests revealed shortcomings in the interaction expectations that users had for certain UI elements, as well as functionality which was not sufficiently discoverable. These details were iterated upon in order to improve the user experience.

An alternate form of interaction under development is utilising the interactors personal smart-phone device for ongoing engagement. An interactor may be curious to know the impact of their actions. This interface would give users the potential to name an agent, highlighting it within the virtual world on the main display. The act of naming an agent gives the interactor an embodied connection with the virtual world. They may be compelled to root for their champion. On the device, a profile and statistics are visible for their named champion, such as life-span, energy, location, and descendants. Agents within the simulation undergo rapid life-cycles, hence descendants from this agent would inherit the name with an appended suffix. This allows them to track the offspring and see whether there is succession of the champions line or whether it goes extinct.

3.3 Sustaining engagement using curiosity and intrigue

> *"The reward, if one insists on using such a term, is the unfolding experience of exploration and discovery, the collection of points of view resulting in a personal reading of the work."*[28]
> *— David Rokeby, 1995*

Curiosity drives interactor engagement, they will seek answers to their questions within the experience. The claim is made in this report that the work *Ars Anima* depicts evolution, however this could be argued as interaction through environmental manipulation attaches a component of authorship. This is termed Orthogenesis, as interactors may assume the role of omniscient gods presiding over this virtual domain. This is similar to the control a player has in a game, however it is distinct as it does not have points, rewards, or role-playing mechanics. It simply provides an interactive sandbox within which emergent behaviour may occur. Rokeby posits that a game is an ego-gratifying experience devoid of accountability, whereas an interactive experience is about encounter rather than control, and may therefore provide a richer experience. This is applicable to my own work, where I aim to set the preconditions for the interactor to have an encounter, a moment of surprise from an unexpected emergent behaviour that makes them wonder about its

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[27] *Share Sydney* is an exhibition event for experimental interactive works including works in progress, with the aims of receiving feedback and networking. A prototype for testing touch interactions for this project was exhibited on the 4th of October, 2017, Creative Robotics Lab, UNSW Art and Design.

[28] Rokeby, op. cite., p. 16.

metaphoric links with the real world. Though the creatures are virtual, the interactor is somewhat responsible for the evolutionary progress that is made, and accountable in part if a population dies out, dismantling that same progress.

Maintaining engagement should be achieved by giving meaningful depth to the experience, which may be provided in *Ars Anima* by the system of emergent behaviour. This system aims to capture the same desire to observe, seen in ardent keepers of fish tanks or ant colonies, where movement becomes calming and mesmerising as one muses over possible rationales for the various observed actions. Matching these real world analogues is done by implementing and demonstrating a dynamic behavioural system (to be detailed in *section 4.0*).

The best interactions may occur when the user interface does not stand in the way of the desired action. This removes the metaphorical barriers to experiencing the work, allowing for unhindered expressiveness in the interactor's actions. For these reasons, a carefully considered user interface is essential for engaging the audience and allowing exploration of the presented virtual ecosystem.

4.0 Exploration of emergent behaviours

4.1 Behavioural system utilising small neural networks

Behavioural agents are reactionary organisms that respond to certain stimulus. This can be seen in single cell flagellates, and it can be seen in Braitenberg's "emotional" vehicles.(*Figure 14*) These vehicles have the most basic of behaviours. *Vehicle A* has the "fear" behaviour, and *Vehicle B* has the "aggression" behaviour. Two sensors on the front detect light, and power motors they are connected to. In this way, more power will be provided to one motor than the other, causing the vehicles to turn. *Vehicle A* will steer away form the light, "fearing" it. *Vehicle B* is wired differently and will steer towards the light, in an "aggressive" behaviour. Neural networks are a logical extension of this idea, adding a larger network of sensors and actuators.

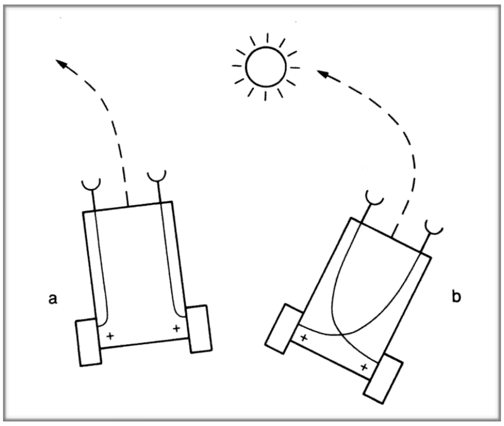

Figure 14. Braitenberg's Vehicles

The neural network component is core to being able to get behaviours to emerge in the work. It functions as the brain for each creature, interpreting sensory input, and making decisions on actions to take. Functionally, a neural network is a graph of interconnected nodes, roughly modelling neurones and synapses. Each node sends a signal to the next node if there is enough "energy" for it to fire. This energy is determined by edge weights. If a creature sees some food on

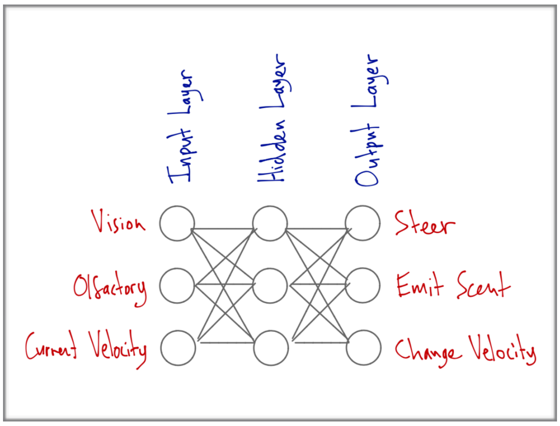

Figure 15. Diagram illustrating an example feed-forward neural network

the left, the network may produce an output which causes the creature to steer left towards the food, just as with the Braitenberg vehicles.

Training a neural network to correctly map the inputs to the corresponding outputs can become a computationally expensive operation. To achieve the best results, the choices of sensors and actuators should be limited to the ones that can make the most impact in creating the desired behaviour. In *Ars Anima*, the agents' sensors and actuators are considered in conjunction with the physics model to maintain an animation style consistent with what is discussed in *section 2.1*.

Another element that was experimented with is recurrence. A recurrent neural network has outputs that are looped back into the inputs in the next time step. This allows agents to perpetuate signals across time, effectively giving them a limited short term memory. This in turn results in more complex and informed behaviour. For example limited object permanence may be possible —an agent may continue to seek a piece of food even if it becomes occluded.

4.2 Genetic algorithm optimisation strategy

The network does not start out with the perfect weights to use. These are not explicitly programmed. Instead, the weights are randomised, and then trained by using a "genetic algorithm". The best combination of weights to satisfy the fitness function will be optimised. The fitness function is a measure of how successful an agent is. An example of a possible fitness function is the lifespan of the creature —the longer it is able to stay alive, the more successful it is. The most successful creature's neural network will be inherited by subsequent generations, but with a small chance of genotype mutation allowing the creature to evolve over time.

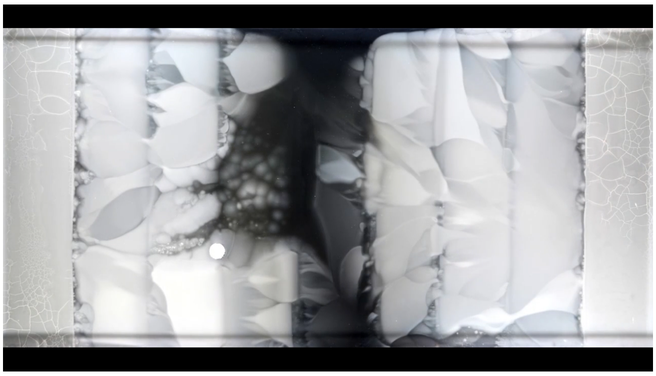

Figure 16. E.coli adapt to stepped concentrations of antibiotics

One rare example of where we can observe real natural selection in action is this time-lapse by Harvard School of Medicine. Here *E.coli* adapt within the space of eleven days to stronger and stronger concentrations of antibiotics.

The genetic algorithm requires three key elements: heredity, selection, and diversity.[29] Heredity describes how the network is inherited by descendants, selection is a maximisation of the chosen fitness function, and diversity is how the population mutates over time. This algorithm is a model for the “survival of the fittest” paradigm observed in evolution.

4.3 Modelling behaviours

Experiments modelling emergent behaviours can be combined to provide a compelling sandbox for exploration. These behaviours range from simple to more complex, and arise in an attempt to optimise the system. A simulation titled *Guppies - Evolving neural networks*, was my initial inspiration for exploring these emergent behaviours. In a video documenting the progression of the “guppy” agents, a creature close to death becomes desperate, performing risky manoeuvres in order to get food before it starves. It is logical that this would occur, as the creature has the choice of certain death, or taking a risk for possible gain. The latter option is more likely to maximise the fitness function (in this case, lifespan).

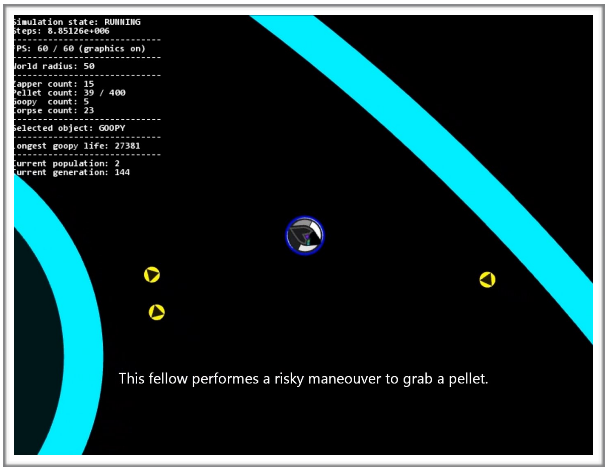

Figure 17. Risk taking behaviour in Paul Oliver’s “Guppies”

I designed a number of experiments and virtual apparatus in order to experiment with a range of behaviours inspired by real world phenomena. A full list may be seen in the *Appendix*. A few key mechanisms that enable these behaviours is the ability for agents to carry food. This effects the physics calculations, increasing the combined mass of the agent, which in turn means more energy is required to accelerate and decelerate. The creatures can choose when to consume carried food. Because the creatures have an energy cap, there is no benefit in consuming food past a certain point. This allows for the creature to make the decision on when it should consume the food. A predated creature will surrender unconsumed food upon being killed. Additionally, carried food can be voluntarily dropped. This could serve as a distraction or diversion for predators. Agents may also duel upon contact, expending energy. The victor is decided by a combination of factors: chance, size, and the energy the agent chooses to expend in confrontation. This enables behaviours including: aggression, predation, cannibalism (with intent) and more.

[29] Shiffman, op. cite., p. 394.

5.0 Conclusion

This report has summarised the research and journey in making Ars Anima, and discussed the mechanisms by which emergent behaviours may arise, proposing the potential for an approximation of life to exist within virtual simulations. This work attempts to authentically represent the fundamental mechanics of evolution through the lens of visualisation and artistic interpretation. There is a body of precedents in each of the domains that this research covers, however this work is unique to the best of my knowledge in combining its mode of interaction, its focus on emergent behaviours, and its aim of presenting these ideas in a visual manner to a wide audience. Possible directions for further work include making a more advanced neural network system and experimenting with different network architectures, devising further behaviours or adapting the visualisation to be an educational tool.

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7.2 Appendix: Behavioural experiments

I have designed some apparatus that may be used to test a variety of behaviours. These are inspired by real world phenomena. I will outline their designs below.

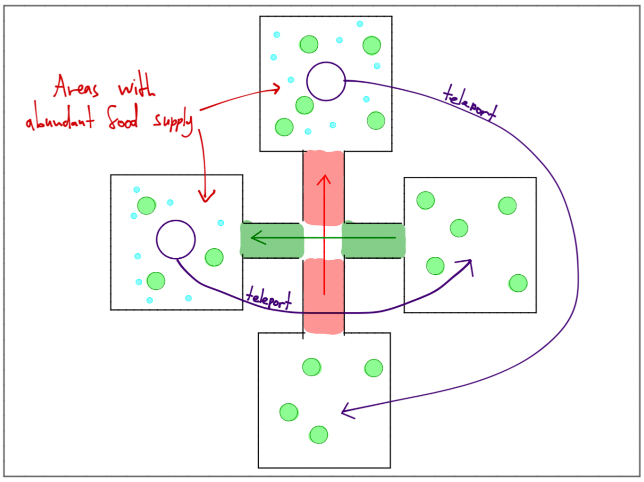

Figure 18. Intersection behavioural apparatus design

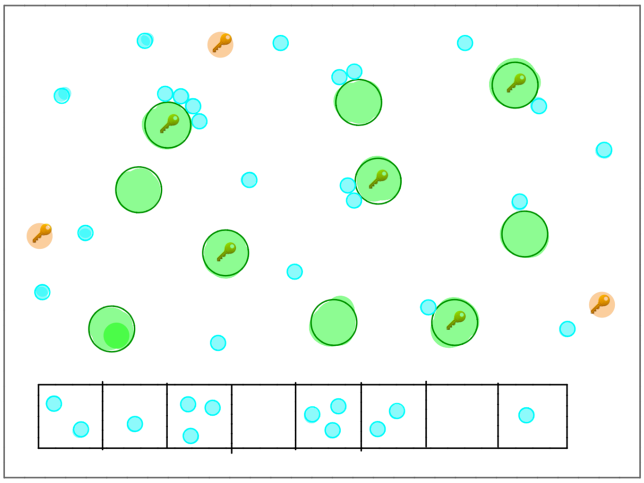

Figure 19. Stockpile behavioural apparatus design

Intersection

After eating food, creatures get teleported. This creates a constricted flow through an intersection. The constricted pathways alternate between red and green, like traffic lights. Creatures can travel more efficiently if they take turns, allowing them to get to the food faster. Will they evolve to use the traffic signals? This behaviour can be seen in nature. There exist crows which have learnt to drop nuts at traffic intersections, allowing cars to crush them. They then read the traffic signals and collect the food when it is safe. It can also be related to the underlying purpose for traffic signals — to allow more efficient and safer travel by organising flow.

Stockpile

There are a limited number of lockers. An agent can obtain a key to a locker. Keys could be inherited, or appear in the environment to be collected. Keys could be inherited, or appear in the environment to be collected. The location of the locker is known from the key. Famine may periodically occur. Will the agents evolve to stockpile food? This behaviour is inspired by squirrels and their behaviour in stockpiling nuts underground for the winter. They remember where they buried it, so they are able to survive even when food is restricted.

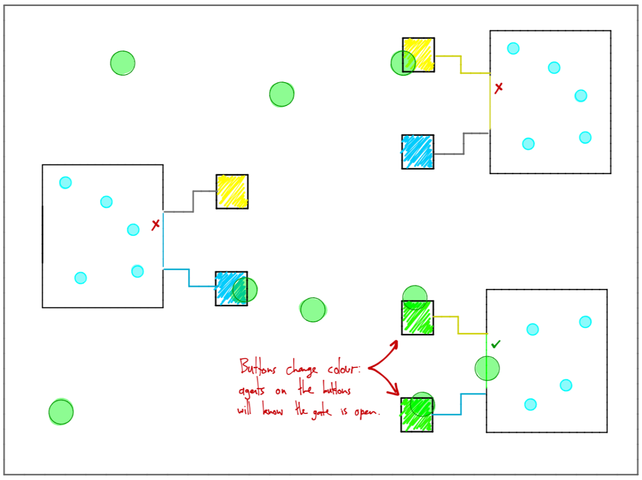

Figure 20. Cooperation behavioural apparatus design

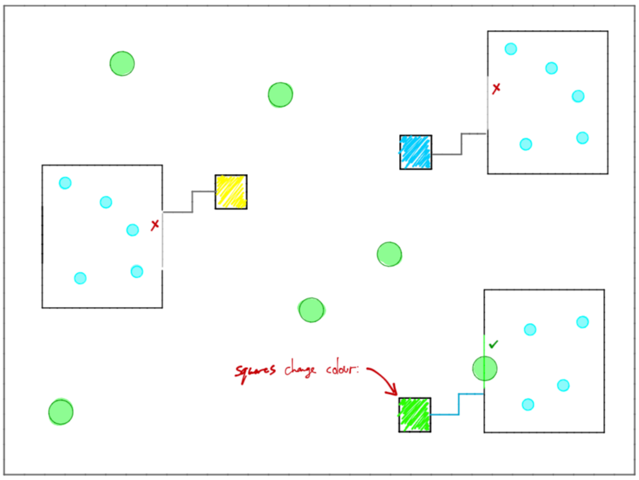

Figure 21. Clock behavioural apparatus design

Cooperation

Agents must cooperate and press both buttons to open the gate. Food only appears in gated areas. Only one agent can be within the gated area. Agents may carry food out. Food takes time to reappear. This is inspired by octopus, who are highly intelligent and can learn to use tools, cooperate and navigate fish traps to steal food. Food taking time to reappear incorporates the idea of a harvest cycle.

Clock

For time to have meaning in a virtual world there must be a frame of reference. Without a frame of reference, the passing of time becomes first hard to perceive, and then, irrelevant. Consider an isolation cell of a 20th century prison. Prisoners loose track of time, unless they have access to regular meals and a wall to mark passing days on. In this experiment, food becomes available only at certain times in a cycle. Coloured square progress in colour from yellow to blue over 24 hours. When the square is green, a gate opens and food can be accessed. The colour can only be queried once per minute. This requires agents to keep track of state internally. The regular food gives meaning to time for the agents.

Flocking

Agents can more easily protect from predation in a group. Will agents flock together for safety in numbers? Will they turn on any who betray the interests of the group? This is an experiment in trust, herd mentality and social contract.

Slavery

An agent oppresses slaves, using them to gather resources and keeping them in a weakened state to ensure they can’t overthrow the slave-driver and escape. Will slavery behaviour emerge? Will slaves attempt to revolt? This is inspired by slave-maker ants, who do just this to other ant species.

Hunting Pack

Will predatory agents cooperate in pack formation to have a more successful hunt?

Funeral

Will agents dispose of corpses to prevent disease? Can agents mourn? This is inspired by ape species, who perform funeral rituals, but also by ants, who clear out waste and dead bodies from the nest to maintain their colony.

Empathy

Agents feel pain, usually indicating loss of energy. Pain is shared by signal to creatures in close proximity (like a scream). Pain fades over time if not renewed. Will agents assist or flee from others in pain?

Queen Bee

A visually distinct maternal agent may occasionally appear. Will agents form a colony with a queen? What if multiple queens appear?

Harvest

Food is more likely to appear upon 'cleared' land. Will agents evolve to adapt their own environment to their benefit?

Others

Parasitic behaviour and symbiotic behaviour. Can these interspecies relations occur within the ecosystem?[30] One key element to implementing this some mechanism to prevent species from merging into one conglomerate.

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[30] C. Zimmer, *Parasite Rex,* New York, Touchstone., 2001, p. 157