MICROCOSM

MICROCOSM

a playful neural network
by Hart Sturgeon-Reed

A thesis exhibition presented to OCAD University
in partial fulfillment of the requirements for the degree of
Master of Design in Digital Futures

OCADU Open Gallery
49 McCaul St, April 16-19th
Toronto, Ontario, Canada, April 2016

Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I authorize OCAD University to lend this thesis to other institutions or individuals for the purpose of scholarly research.

I understand that my thesis may be made electronically available to the public.

I further authorize OCAD University to reproduce this thesis by photocopying or by other means, in total or in part, at the request of other institutions or individuals for the purpose of scholarly research.

Signature ____

MICROCOSM

Hart Sturgeon-Reed
Masters of Design, Digital Futures, OCAD University, 2016

Abstract

Microcosm explores the potential of responsive, evolving games through the lenses of play theory and cybernetics. It aims to provide an engaging play experience while supporting the exploration of dynamic networks. It is inspired by biological models of cell signalling and neural networks. Building on the framework of play theorist James Carse, *microcosm* is an attempt to create an infinite game that is played not to be won, but to keep all participants in play by continually shifting the relationships and boundaries that constitute the game. *Microcosm* is populated by virtual organisms that play with the boundaries between organic and artificial, component and whole, human and non-human.

Keywords

Play theory, infinite games, cybernetics, ecology, artificial life, neural networks, evolution, companion species, symbiosis

Dedication

This project is dedicated to:

The rich tapestry of living organisms whose infinite play has created the world I live in.

All of my companion species, large and small: for allowing me to participate in this complex communal game of ours.

My dog friend Pepper, whose play is just beginning: for all her inspiration, wisdom, and companionship.

My parents, who taught me to play with words and ideas: for always taking my play seriously in a society which all too often assumes play is frivolous.

My advisors and teachers: for helping me learn the rules of play without losing that original spirit of curiosity and playfulness.

My friends and classmates: for playing along and continually surprising me; may our game never end.

Table of Contents

List of Figures

Introduction

> No one can play a game alone. One cannot be human by oneself. There is no selfhood where there is no community. We do not relate to others as the persons we are; we are who we are in relating to others. (Carse, 1985, p. 45)

Microcosm is a project that invites an attitude of boundless and infinite play while exploring the entangled nature of our biological and computational models. It is informed by questions and insights from a range of interdisciplinary fields including biology, philosophy of mind, neuroscience, science studies, play theory, cybernetics, and artificial intelligence.

Models of mind are often based on technological accomplishments, and conversely technology is frequently inspired by insights derived from observing biological systems. Rather than puzzle over the seemingly paradoxical nature of this linkage, *microcosm* embraces the messy, interwoven web of bio-computational understanding to present a model of intelligence as playful relation. Play theory and material-semiotics provide rich contexts to explore the extraordinarily diverse relationships of biological and computational intelligence.

This project would not have been possible without the work of Gregory Bateson, James Carse, and Donna Haraway. Their expansive notions of ecology, play, and companionship have irrevocably changed the way I think about myself and the worlds I inhabit; their visions of tangled interspecies play are the seeds from which *microcosm* has sprung.

Carse describes two distinct kinds of play in his book *Finite and Infinite Games* (1985). Finite games are played to be won and must have fixed rules and agreed upon conditions for victory. In contrast, infinite games are played for the purpose of continuing play for all participants. For an infinite game to continue indefinitely it cannot have fixed rules; the act of repeatedly altering the context and relationships of the players is what allows play to continue. Play can be very serious business; it can even be a matter of life and death, as in the case of warfare. For Carse, all social interactions and structures exist to support one form of game or another.

Infinite play is ubiquitous. It is an inherent part of the structure of the universe, and all animals engage in it. Finite play is an obsession of humans and particularly human societies, a desire to fix the fluid nature of the world into a form more easily understood and less threatening to our fear of the transience and boundlessness of all things. Carse (1985) says that "Finite players play within boundaries; infinite players play with boundaries" (p. 12).

Microcosm plays with the boundaries between component and whole, artificial and natural, human and nonhuman: critical dualities threatened by what Haraway (1991) calls the cyborg myth. Carse (1985) believes that "myth provokes explanation but accepts none of it," (p. 165) while Haraway (1991) states that “the boundary is permeable between tool and myth" (p. 164). *Microcosm* then is both myth and tool; it tries to provoke explanation without seeking any fixed conceptualization of meaning or method. *Microcosm* is a tool for exploring boundaries and creating worlds.

Microcosm is built around Haraway’s notion of *becoming with*, which suggests that no organisms are ever truly separate; they can only exist through the relationships and interactions between them. This is a central notion to Carse's infinite play; no one can play a game alone.

Microcosm is an attempt to design a virtual world and play experience while holding in mind the concept of *becoming with* as the continuous performance of dynamic relationships between mutually constitutive organisms.

I set out to create *microcosm* with a number of goals in mind. As a web developer with a long-standing interest in game design, I wanted to see what kinds of games were possible with current web technologies. It was also an opportunity for me to try building a game engine, which taught me a lot about what goes on behind the scenes in a complex game. I wanted to try to make a framework that was maintainable enough that I could keep using it for many projects in the future, so it was also an experiment in writing clean, modular, performant code.

As a game, I wanted *microcosm* to contain both finite and infinite layers. The finite layer would be a traditional game, while the infinite layer had to allow enough flexibility for players to substantially shape and change their play experience. Finally, I wanted the gameplay of *microcosm* to help its players think about the complex interdependencies that make up the ecological networks they are a part of. I wanted a game that would highlight Bateson's notion that it is the entire ecological context — the sum of all relationships — that evolves, not the individual organism.

Form: Overview of the Work

I call *microcosm* a playful neural network. Unlike traditional artificial neural networks built to be research tools for neuroscience or modelling tools for engineering, it is designed primarily to be engaging and aesthetically pleasing, inviting playful experimentation with and observation of its dynamics. Because of this it does not attempt to be wholly biologically accurate or optimally efficient; instead it aims to be as easy to observe, understand, and engage with as possible. *Microcosm* is a biologically inspired system that replicates some of the characteristics and patterns seen in both biological and artificial neural networks.

In this document, I use *network* not to mean a fixed topology or structure, but rather the sum of all interactions and relationships among a community of agents. This is a dynamic, temporal network that must be *performed*, similar to the use of the word network within actor-network theory (ANT).

Each network in *microcosm* is made up of a central hub component called the nest, a handful of agents that resemble cells, and a set of flowers that produce resources. The 'goal' of the system is for the cells to collect as many resources as possible and transport them to the nest, while also distributing resources among the cells to improve their performance. A variety of kinds of networks can be created, from generalized systems where each cell moves and collects resources independently to highly specialized networks in which cells must communicate and cooperate closely to relay resources between each other.

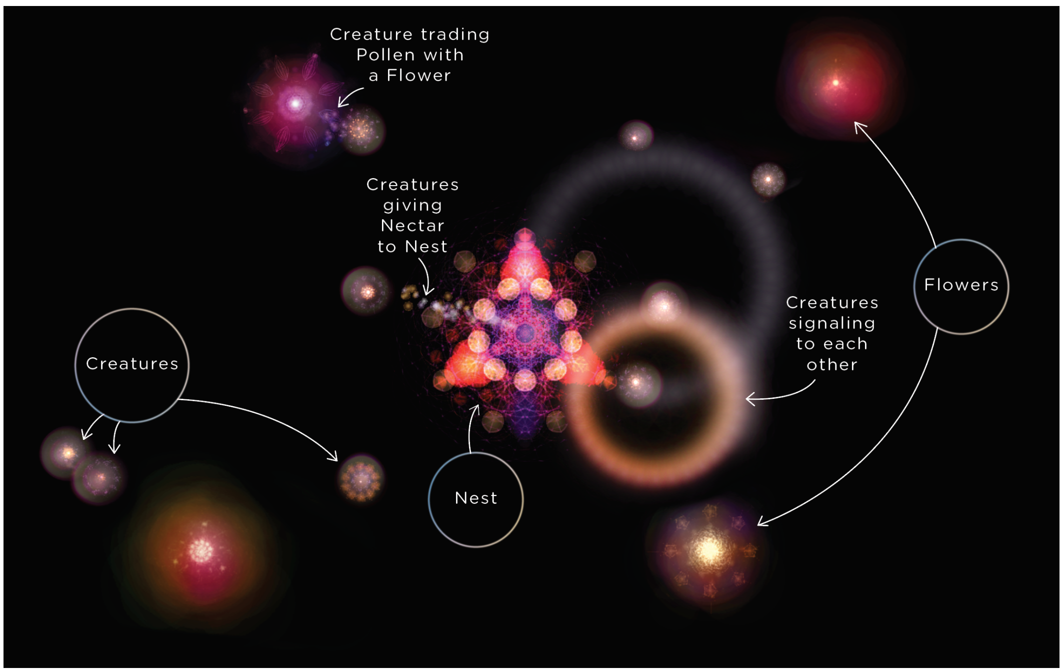

Figure 1: A network in microcosm *showing nest (center), flowers (corners), and cells (in between)*

Microcosm allows the player to explore the dynamics of the system by directly controlling one of the cellular agents and contributing their own dynamics to the network. This makes it easy to see how different actions can affect the autonomous patterns of the network and disrupt or enhance their functioning.

The agents in *microcosm* resemble cells in some ways, but are intentionally abstracted and simplified in order to make them more relatable and easier to observe. Abstraction in this sense means the substitution of the part for the whole; components in *microcosm* are inspired by biological systems and show some of the same patterns, but do not capture the full complexity and messiness of living organisms. Cells can request and offer resources by sending messages to each other, mimicking the behaviour of neurotransmitters in a very abstract way.

The networks in *microcosm* intentionally blur the metaphors used in their construction, drawing inspiration from many kinds of cooperative systems including brains, single cells, bacterial biofilms (McDonald, 2015), and colony animals like ants or bees. Rather than attempting to be wholly authentic to one specific set of phenomena *microcosm* tries to generalize some of the patterns observed in all of these kinds of systems and present them in a fun and accessible way.

The terminology for the elements of *microcosm* was selected to try to make the organisms and their interactions relatable on human terms. Much of what is explored in *microcosm* is the behaviour of communal organisms, but often these creatures (bacteria, ants, jellyfish) are not seen as particularly charismatic. Bees are colony animals that have been highly valued by human societies for a very long time. It may be unfair to ants, but the fact that bees produce something of value to us (honey) has given them a better reputation. *Microcosm* therefore uses terms like *pollen*, *nectar*, and *flower* to describe its structures -- even when they more closely resemble parts of eukaryotic cells or bacteria. Nectar is a bit of a play on words; literally defined it means 'overcoming death,' and its distribution among the organisms of *microcosm* is what keeps them alive. Nectar also is a relatable example of the importance of mutualism in ecologies: plants use it to recruit pollinating insects to help them reproduce.

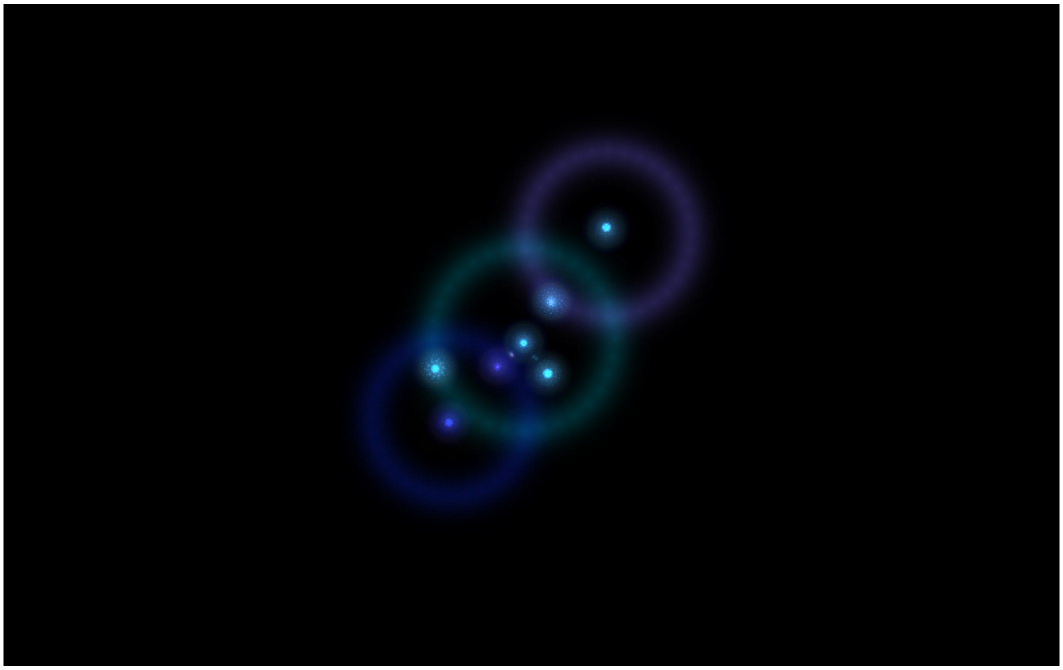

Figure 2: Agents in a network signal to each other

Vibrant visuals and procedural audio are used to allow players to easily see the rhythms and patterns that develop in the communications between cells. Because signals tend to provoke responses from other cells, communication cascades through the network, sometimes creating recurring oscillations of behaviour. Bright colours and audio cues help observers see the synchrony and disruptions that affect the functioning of the network over time.

Play is a wonderful way to explore a complicated system because it encourages experimentation and intuitive observation. Digital game players are used to uncovering complicated networks of cause and effect in their interactions with a game system simply by trying things out and observing the feedback provided. In a similar way, *microcosm* allows players to ‘touch’ the networks and see how they respond, helping them build rich understandings of the relationships between agents.

Players can repeatedly attempt a particular network configuration to try and figure out what additional behaviour they can provide to maximize (or minimize) the efficiency of the system. Depending on how the network and the individual cells are set up, this strategy is likely to be slightly different for each network. This helps players build up an intuitive understanding of the dynamics of complex networks.

Currently, networks in *microcosm* are procedurally generated from ‘seeds,’ so every network is different. In the future I hope to provide the capacity for the player to determine some of the parameters of the network themselves, tweaking them and even building their own networks to test them out.

Because networks are created from seeds, each network can be mutated to create variations that still bear some similarity to the original. This allows players to explore similar themes while still generating new experiences and dynamics.

Each network is composed of several parts: the world seed, which determines the visual appearance of the whole system; cell genomes, which determine their basic behaviours; cell orbits, which determine the paths of movement each cell follows; and flower placement, which determines where resources are available on the map. Each of these elements can be mutated and cycled independently, allowing users to vary many different aspects of each network.

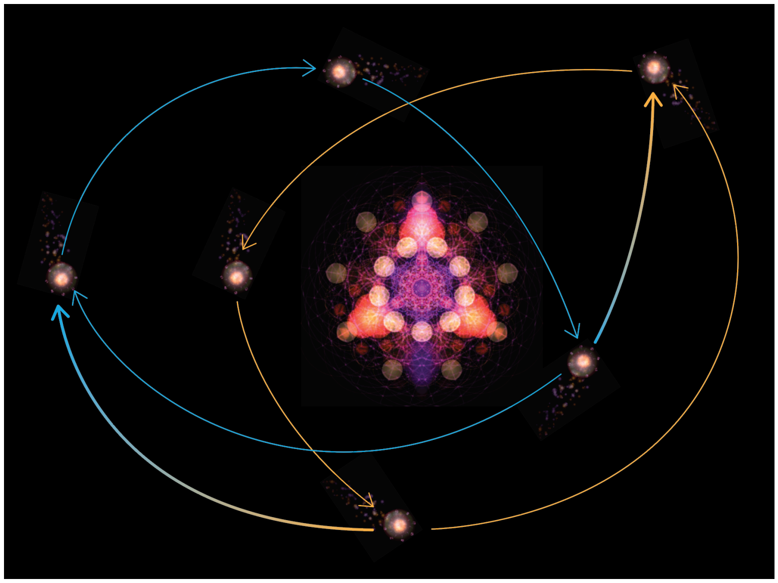

Figure 3: Cell orbits. The orange and blue paths represent sequential points the cell visits over time. Internal changes in state or external events can cause the cell to switch orbits.

Unlike most genetically inspired artificial systems, *microcosm* doesn't really have a defined goal or optimal state. Although the game can evaluate particularly efficient runs of the system to determine which autonomous networks are most successful at collecting resources, players may not necessarily find these to be the most desirable characteristics for play. It may be that assisting a community that functions less efficiently on its own is actually more fun for the player and provides a more interesting challenge or a surprising insight.

Over many runs of the system, players constitute a kind of selection force that places value on the configurations that they find aesthetically or interactively interesting and fun. This can be leveraged to help the overall system adapt to the interests and desires of its users and learn to provide a more enjoyable experience over time. It also allows the game experience the flexibility to change continuously, so that no two sessions are ever quite the same.

Elements of microcosm

The *microcosm* framework is made up of several different components, which share some design patterns.

Nest

The nest is the central element of the community of creatures. At the start of a round, each cell starts in the nest, and collects a small amount of 'nectar,' the energy used by cells to move and act within the world. Cells collect 'pollen' from flowers in the environment and bring it back to the nest, where it is converted into nectar. This means that successful networks in *microcosm* must allow for the flow of resources in two directions: nectar is distributed outward from the nest to cells to keep them alive, while pollen is distributed inwards from cells to the nest so that more nectar can be created.

This pattern can be seen as a metaphor for a single cell, in which proteins flow to and from the nucleus; as a metaphor for a complex organism, in which nutrients flow to and from central regions like the stomach, heart, or brain; or as a metaphor for bounded societies, in which resources and services flow to and from a centralized government.

Pollen

Pollen is the basic resource in *microcosm*. While the main goal for a community is to transport pollen to the nest, some actions taken by cells also require pollen, so cells may trade pollen with each other to make sure they all have a balanced supply. Different flowers will produce different kinds of pollen in different amounts, and nectar production at the nest requires all of the varieties.

Flowers

Flowers are randomly placed around the world, and their placement largely determines the patterns of movement and resource flow that a community of cells needs in order to survive. Flowers produce pollen at a fixed rate, and have a maximum capacity, so efficient networks need to adapt to this rate of change and harvest flowers periodically.

Cells

Agents in *microcosm* resemble colourful abstract cells. Each cell contains its own genome, which is mutated from a seed genome for the nest; each cell is therefore similar but still unique. Some communities may have cells that all display the same general behaviour and are functionally identical while others may have much more specialization, with some cells primarily collecting resources while others are responsible for transporting resources through the network.

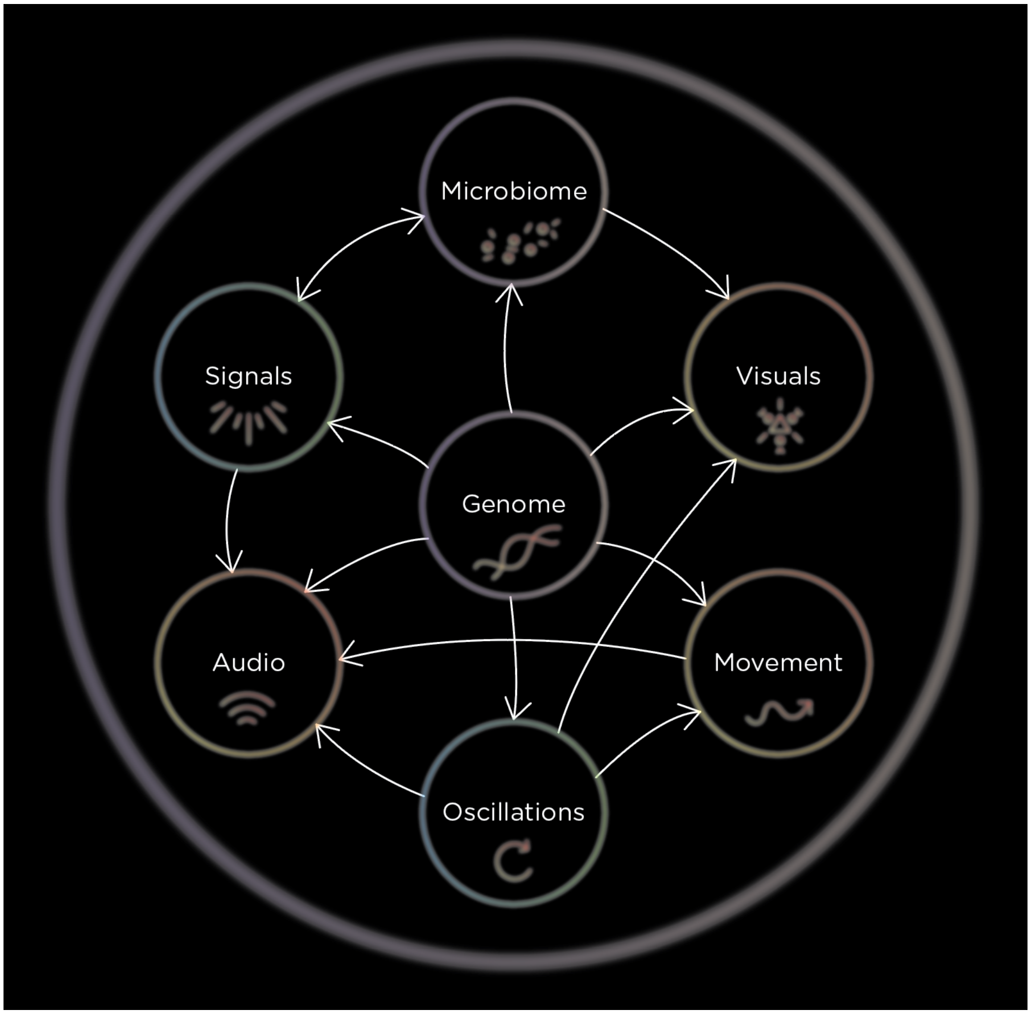

Figure 4: Components of cells in microcosm

All subcomponents of the cell are built from the cell genome. Many of the components are linked together; the component that generates oscillating loops is used to create animations for the visuals, orbits for cell movement, and loops of actions and decisions the cell uses to choose behaviour during each time step.

Because each cell has a maximum capacity for both nectar and pollen, it is often more efficient for a cell that is near a pollen source but already at capacity to transfer resources to another cell closer to the nest than it would be for it to return to the nest itself.

Cells can communicate with each other through simple signal pulses, conveying information on resources they need or that they have a surplus of. Signals can act like a wave, propagating outwards to all cells within a certain area, or they can be specific: explicitly targeting one other cell. These two behaviours are inspired by biological cell signalling, which can be modelled as a chemical gradient (like hormones) or as directed transmission, such as when a neuron triggers another neuron to ‘fire’ through an exchange of neurotransmitters.

Signals are usually requests for or offers of a resource. For example, a cell that is low on nectar may send out a signal pulse asking nearby cells to send it nectar. The strength of that pulse depends on how critical the cell's shortage of nectar is, and cells which have a larger amount available may respond by sending back a pod containing nectar. Similarly, a cell that has reached capacity for a certain type of pollen may advertise this surplus, attempting to recruit other cells to take some of the pollen and allowing it to harvest more.

Mites

In order to communicate, cells send waves or bursts of 'mites' to each other. Mites are like smaller organisms and are constructed by cells out of pollen. Mites can be seen as analogous to signalling proteins in cells or symbiotic microbes in larger organisms.

In addition to allowing cells to exchange messages, mites can also enhance the abilities of cells, allowing them to move faster, hold more pollen, or giving them larger signalling or receptive fields. Each cell produces its own varieties of mites as determined by their genome and environmental contact, so sharing mites between cells can help improve the fitness of the whole community.

Links

Agents that exchange mites frequently can be observed by the flow of brightly coloured mites and pollen between them. This helps the player easily see which cells in the network are linked closely and which are largely independent.

Mandalas in microcosm

The graphics for all of the components in a round of microcosm are constructed from the same visual elements. A 'world seed' mandala is first constructed which contains all of the sub-elements.

Simple components of this larger visual are then selected to represent the different kinds of pollen.

Each mite is made of a combination of the graphics for the types of pollen it is fed on.

Flowers contain the graphics for all the species of mites that live on them, as well as their own unique petal layers.

Cells will display different parts of the overall mandala as they collect pollen and mites.

If the nest has a balanced supply of all types of pollen, it will come to resemble the initial world seed mandala.

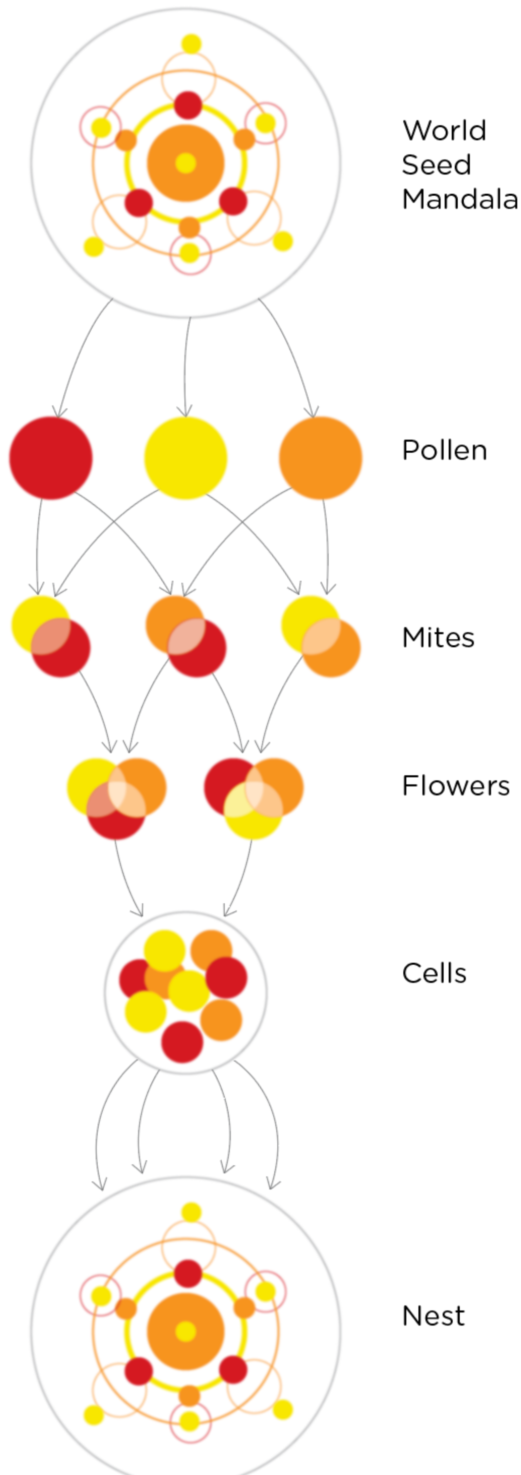

Figure 5: Mandala visuals in microcosm

Sequence of Play

Each round starts with the player selecting a seed pattern for their organism. This seed can be mutated to allow the player to evolve the design and find something aesthetically pleasing.

Once selected, the seed is used to generate the visuals for all the components. The player then starts in the nest with six friendly AI cells.

The cells are given an initial supply of nectar from the nest, and must return to collect more if they run low.

The player moves to flowers and collects pollen to transport back to the nest.

The player and AI cells can exchange nectar and pollen to distribute resources through the community.

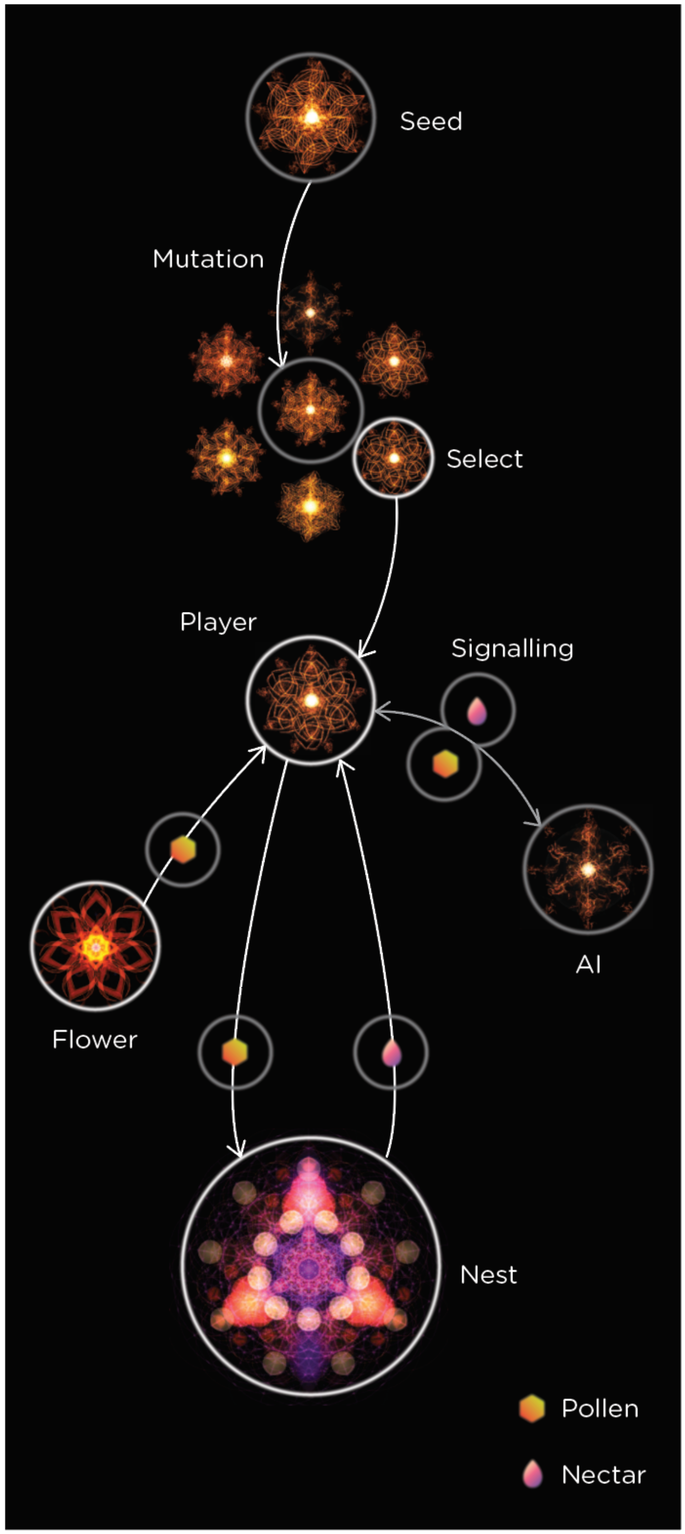

Figure 6: Sequence of play in microcosm

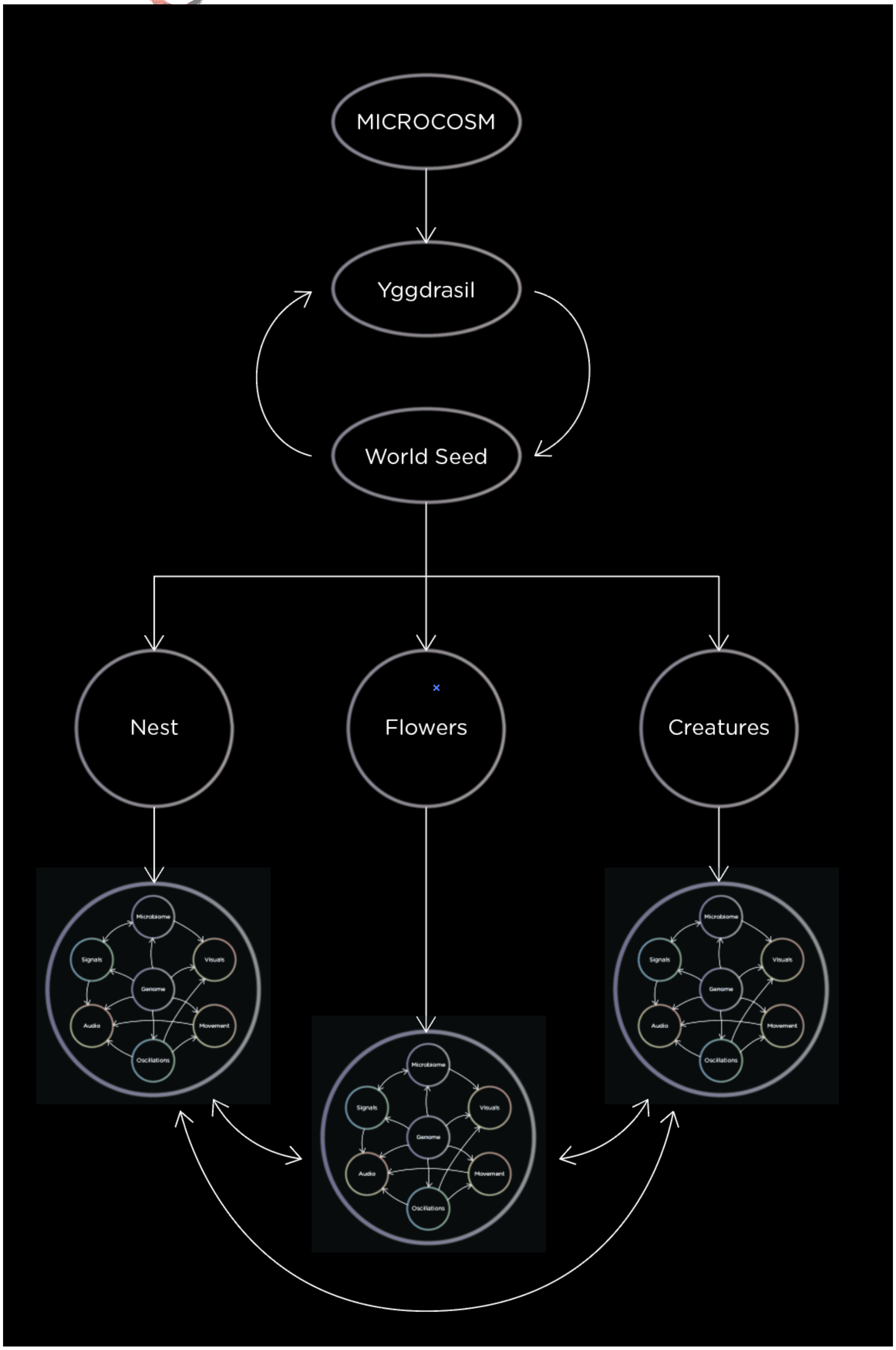

Figure 7: Game components

Game Components Diagram

The main *microcosm* game element is the top level component of the whole system. It contains many utility functions to connect with input devices and handle different implementations of the system.

The main component for managing the genomes and the gameplay is called *Yggdrasil*. Within the game, *Yggdrasil* contains the database of genomes which are used to create each world in the game. These are called world seeds, and they are mutated and cloned to create the nest, flowers, and creatures for each round of the game. *Yggdrasil* was the world tree in Norse mythology; it connected all of the different realms and worlds into one structure, so it makes a good metaphor for a branching tree of possible worlds.

Yggdrasil is the key component for the evolution of play experiences because it allows each seed pattern to be instantiated, tested, evaluated, and then compared. This allows players to shape the patterns they like playing with over time. It also means that the system can play the game entirely by itself and rank seeds to find ones that are most successful at collecting nectar. The system even keeps a tree-like representation of the genomes viewed as players mutate and select genomes.

The nest, flowers, and creatures are all permutations of the same class, called *Soma*. *Soma* means body, and it is the top level component for the game objects. Each *Soma* is instantiated with a list of options that determine its subtype, positioning, genome and characteristics. From the genome a number of subcomponents are constructed, each using a different chunk of the total genome pattern. These subcomponents include *Visuals*, *Oscillations*, *Movement*, *Signaling*, *Audio*, and *Microbiome* classes. When the *Soma* interacts with an input device or another *Soma* it will delegate responses to the appropriate subcomponent of the system. Most interactions between *Soma* utilize the *Microbiome* and *Signaling* components.

It is in the interactions and relationships that come out of creatures signaling to each other that the dynamic play experience of *microcosm* emerges. A single creature on its own doesn't really do much, but the patterns of a group working together are substantially more complex.

The way that creatures in *microcosm* are built up of independent subcomponents also mirrors composition in biological organisms. Eukaryotic cells are composed of many specialized organelles that each have their own function, although at some point in evolutionary history they were almost certainly separate organisms.

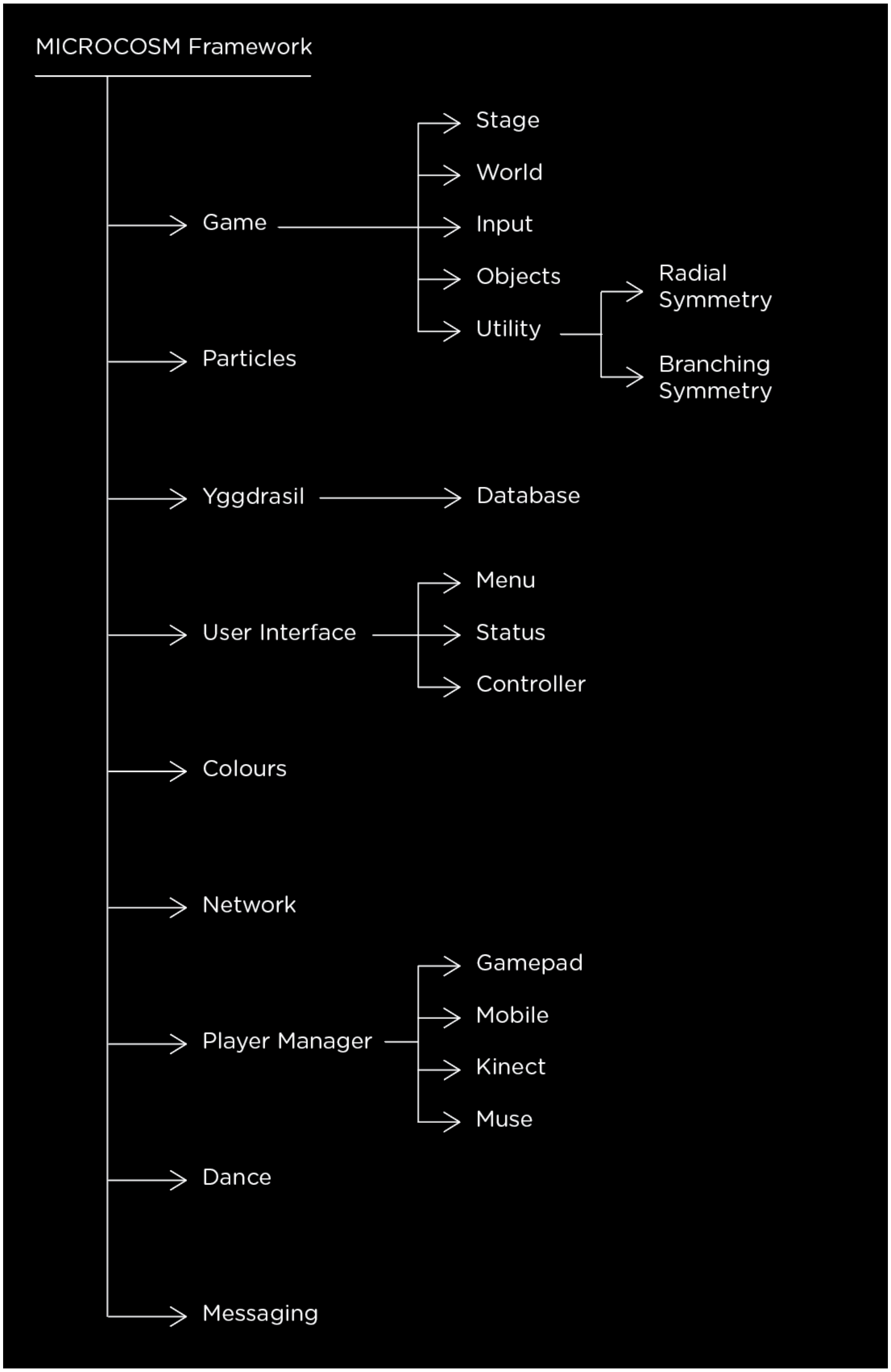

Figure 8: Framework components

Framework Components Diagram

Microcosm and *Yggdrasil* are the two main pieces of this particular game, but many other components are necessary to support all of the different interactions and input devices. *Microcosm* is an instantiation of the *Game* class, the central part of the engine. This includes subcomponents that handle rendering sprites, managing layers, adding and simulating physics bodies and basic input. In the future many of the components built specifically for *microcosm* like the particle system will be decoupled and integrated into the engine instead.

This diagram lists some of the other parts of the system, including the user interface, input handling for keyboard and mouse, gamepads, mobile devices, the Microsoft Kinect, and the Muse EEG headset.

Context: Theory and Inspirations

Microbes are everywhere. They can be found inside us; in the sky, soil, and sea; even miles below the earth's crust (University of Georgia, 1998). Each of us has a microbial cloud as unique as our fingerprint that overlaps and interacts with everyone we meet (Miller, 2015). Unfortunately, microbes are not charismatic megafauna. Microorganisms are essential to all life on Earth, and yet they get relatively little popular attention for their efforts; they are hard for us to relate to as hulking, language-bound primates.

Microbes are worth looking at, because they point toward the importance of cooperation and symbiosis in the development and persistence of life. Microbes understand how to get along. Bacterial biofilms on our teeth communicate in order to ensure that nutrients are transferred evenly to all members of the population, including those stuck in the center (McDonald, 2011). Strange bacteria embedded in the sea floor -- consuming energy directly from electrons without an organic intermediary -- form long 'wires' of hundreds of thousands of organisms to enable electrons to flow from rocks in the Earth's crust to the oxygen-rich seawater (Brahic, 2014).

These complex acts of communication and cooperation were major inspirations for the signalling behaviours of the creatures in *microcosm*. Evolutionary theorist Lynn Margulis calls this kind of cooperative behaviour *symbiogenesis*, and says that:

> The creative force of symbiosis produced eukaryotic cells from bacteria. Hence all larger organisms--protists, fungi, animals, and plants--originated symbiogenetically. But creation of novelty by symbiosis did not end with the evolution of the earliest nucleated cells. Symbiosis is still everywhere. (quoted in Haraway, 2008, p. 31)

Margulis is referring to the well-supported idea that eukaryotic cells, which have complex differentiated components, evolved when simpler prokaryotic cells started living inside one another. Speaking of Margulis, Haraway (2008) says that “I get the idea that she believes everything interesting on earth happened among the bacteria, and all the rest is just elaboration” (p. 31).

I’ve tried to use the gameplay and visual aesthetics of *microcosm* to make the behaviours of bacteria and other microbes a little more relatable and accessible. Creatures in *microcosm* communicate and cooperate in much the same way as colonies of bacteria. They are an attempt to create charismatic microfauna: drawing a bit more attention to the fascinating tiny friends that allow us all to exist in the first place. The organisms in *microcosm* are made up of several layers of smaller critters: mites are contained within cells, and cells collectively make up the behaviour of the nest. Haraway (2008) describes this notion by saying that “The basic story is simple: ever more complex life forms are the continual result of ever more intricate and multidirectional acts of association of and with other life forms” (p. 31).

Microbiomes and Holobionts

Humans are not exempt from this process of encapsulation and interconnection. The human microbiome -- the collection of all microbes living on and inside us -- comprises a huge and diverse population of organisms. As Haraway (2008) puts it:

> I love the fact that human genomes can be found in only about 10 percent of all the cells that occupy the mundane space I call my body; the other 90 percent of the cells are all filled with the genomes of bacteria, fungi, protists, and such, some of which play in a symphony necessary to my being alive at all, and some of which are hitching a ride and doing the rest of me, of us, no harm. (p. 3)

Biologists have coined the term *holobiont* to describe complex organisms that rely upon communities of symbiotic microbes to survive. Evolutionary theorists must now contend not only with the genomes of single species, but with the notion of a *hologenome* comprising all the genetic variation of a host and its symbionts.

This increasing recognition of the importance of our microbial symbionts has resulted in a partial comeback for Lamarckian evolution, which assumed an exchange of traits between an organism and its environment as well as horizontally between living organisms. Haraway (2008) states: “Bacteria pass genes back and forth all the time and do not resolve into well-bounded species, giving the taxonomist either an ecstatic moment or a headache” (p. 31). The more we observe bacteria and sequence their genomes, the more we realize that life does not play by the rules we have set in trying to differentiate and separate organisms into well-defined species. Each time we exchange bacteria with our environments and one another we alter our hologenome.

This horizontal gene transfer is represented in *microcosm* by mites. Depending on the level of abstraction, mites can be seen as the chunks of RNA that bacteria swap back and forth, or as the bacteria and viruses that facilitate gene transfer between larger organisms like us. Mites are consumed but not digested by cells; instead they trigger behavioural changes within the cell microbiome and may result in additional transfers of mites or pollen back to the original host.

Becoming With

This continuous exchange of traits is what Haraway speaks of when she talks of species *becoming with* one another. She says that “The partners do not precede the meeting; species of all kinds, living and not, are consequent on a subject- and object-shaping dance of encounters” (Haraway, 2008, p. 4).

Species cannot exist alone; they are mutually constituted by their entangled relationships with each other. A species can only be defined through the recognition of differences and similarities with another, and as bacteria show, this is not solid ground but continually shifting play.

The organisms of *microcosm* try to respect this entangled web of relationships in the formation of their own play. A single cell in *microcosm* displays almost no interesting behaviour; it is only in its interactions with other cells and a human player that complex, playful action can arise. Haraway (2008) prefers Karen Barad’s term *intra-action* to interaction because it better demonstrates the mutually constitutive nature of these relationships (p. 17). “To be one is always to *become with* many” (Haraway, 2008, p.4).

Companion Species

"The partners do not precede their relating; all that is, is the fruit of becoming with: those are the mantras of companion species" (Haraway, 2008, p. 17). These notions of *becoming with* and *intra-action* demonstrate the importance of interspecies relationships to all complex organisms. When these relationships are robust and long-lasting, Haraway speaks of *companion species*: organisms whose intra-active play has changed each other so thoroughly that they have become inextricably linked. In her essay "Unruly Edges: Mushrooms as Companion Species," Anna Tsing (2012) says that "Human nature is an interspecies relationship" (p. 141).

Whether looking at microbes in our gut, mushrooms in the forest, or dogs in our homes (a favourite topic for Haraway), humans are surrounded by complex relationships with other species. We tend to speak of domesticated animals as though the dominion goes one way, but how do we know that this is the case? Does it really seem likely that human culture would be exactly what it is today without dogs permeating our societies as pets, working animals, and companions?

Lactobacillus and *bifidobacterium* are two prominent microbes in the human gut that allow us to digest lactic acid (and therefore milk and cheese) into adulthood. Research has shown that these bacteria also happen to assist with the production of GABA and serotonin: neurotransmitters sometimes associated with feeling happy and stress-free (Carpenter, 2012). Around ninety percent of the serotonin used by our bodies is produced in the gut through interactions with bacterial symbionts (Stoller-Conrad, 2015). Is it possible that these bacteria have domesticated us, and not the other way around? Have we been lulled into cheesy bliss in order to create new and better homes for these companion species?

The following graphic shows the interconnections between the microbiomes of different species. As we can see, the microbiomes of ‘domesticated species’ and humans are much more closely linked than those of other animals. The critters we have become human with have irrevocably changed our own ecologies.

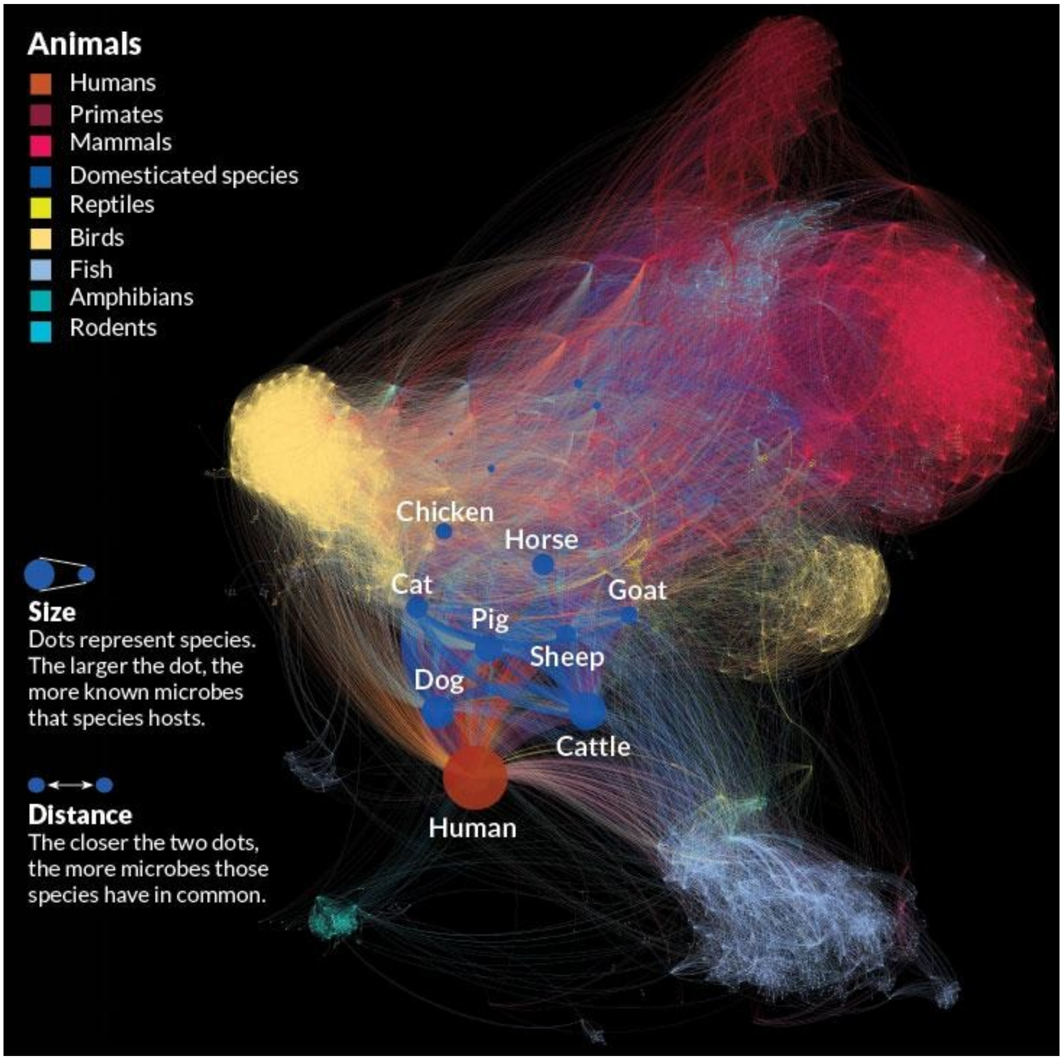

Figure 9: (Rosen, 2015). Mapping microbiomes between species

Haraway says that "Organisms are ecosystems of genomes, consortia, communities, partly digested dinners, mortal boundary formations" (p. 31). *Microcosm* celebrates the complexity and interrelations of our microbiomes and contested bodies with a digital ecosystem of mutually constitutive organisms playing along together.

An Ecology of Mind

Gregory Bateson (1972) coined the phrase 'ecology of mind' to describe the complex interactions that go on between ideas and thoughts in the mind. *Microcosm* reifies that concept rather literally by creating a digital ecology of organisms that collectively constitute a simple 'mind.' I fear that our technological capacity to disrupt the ecological networks that we are a part of has grown far faster than our capability to understand those networks, and particularly to quickly and intuitively judge how our actions may affect them. *Microcosm* uses metaphors from biology and the microbiome, but it is not made up of biological organisms; instead, like the mind, it is an ecology of conceptual relationships.

Bateson's life work was to try to describe and encourage what he called ecological thinking, a state of mind that recognizes the enormously complex tapestries of life humans are embedded within. He believed that we must learn to respect that the ramifications of our actions are often far-reaching and difficult to see, and that if we want to act with responsibility we need to move from thinking about things to thinking about relationships.

His interest in relationships made him one of the founding theorists of cybernetics, which he called the language of relationships. Cybernetics comes from the Greek *kybernētēs*, meaning that which steers. Cybernetics is the study of regulation -- and particularly self-regulation. It focuses on systems that display recursive feedback: where the state of the system in each cycle directly influences the state of the system in subsequent cycles.

Bateson's work helped cybernetics progress from early obsessions with the abstract structures of formal logic to second wave 'biocybernetics,' which attempted to examine and replicate the patterns of regulation found in living organisms (Hayles, 2006, p. 161). This spirit of *biomimesis*, in which technology is inspired by forms and patterns found in nature, was a central focus of the development of *microcosm*. Many of the design structures I chose arose from *Bio-Inspired Artificial Intelligence*, a book collecting a variety of biologically inspired computational approaches to problem solving (Floreano and Mattiussi, 2007). In particular, *microcosm* utilizes artificial genetics, simple neural networks, and a very simple developmental model. The developmental model can be seen in the way that all game components emerge from the same *Soma* class, much as a pluripotent stem cell can develop into many varieties and roles depending on the environment it grows in.

Microcosm grew out of my own desire to better understand some of the overlapping patterns between different kinds of complex networks and organisms. I found myself wanting a responsive way to learn about and question the concepts I was encountering as I read about the intricacies of biological networks from single cells up to massive natural-cultural ecologies (to use Haraway's term).

In my undergraduate education, the topics that fascinated me most were philosophy of mind, neuroscience, and the dynamics of ecosystems. All of these fields involve the study of complex networks, and I became curious about the parallels I started to see between the concepts I encountered on different scales. Bateson (1972) describes how he:

> picked up a vague mystical feeling that we must look for the same sorts of processes in all fields of natural phenomena - that we might expect to find the same sorts of laws at work in the structure of a crystal or the

> structure of society, or that the segmentation of an earthworm might be comparable to the process by which basalt pillars are formed. (p. 74)

I noticed that I was able to grasp concepts best when there were visual representations of the phenomena being described; it is sometimes easier to understand how two complex proteins interact in an animation than it is in writing. Networks that exhibit recursive feedback are by nature non-linear systems so this can make it difficult to describe their behaviour in the (generally) linear structure of writing. Interaction and visualization often allow for richer experiences of a concept. I wanted to take this a step further and allow myself and others to play with the visualization as well, trying different ways of altering the system to see how it would respond. As I tried to find ways to model these concepts in a way that was abstract enough to be simple yet still relatable, *microcosm* was born.

Bateson (1972) says that "as I see it, the advances in scientific thought come from a combination of loose and strict thinking, and this combination is the most precious tool of science" (p. 74). A concept must first be imagined and explored intuitively. Many important scientific breakthroughs have come from seeds planted by dreams or metaphors, like the chemist Kekule’s dream of an ouroboros leading to the discovery of benzene rings or Crick dreaming the helical structure of DNA as a spiral staircase.

That initial inspiration leads to a stricter analysis and examination: the formulation of a model. Crucially though, once we have strict models in place, Bateson (1972) believes that we must return to questioning and expanding upon those models with loose intuitive thinking so that we aren't trapped within the logical structures we create (p. 75). I see this as an invitation to always continue to play with the boundaries we create.

Bateson (1972) sees this as the role of art, to continually engage in a discourse with the conscious and unconscious forces that shape our scientific and cultural models (p. 137). This can be described as a process of play with ideas. For me, play is all about the exploration of relationships: from a baby playing with building blocks to discover the relationships of basic physics to a chess master playing to discover the complex relationships of their opponent's mind and strategy. Learning is always a process of play with ideas in order to discover new and surprising insights into their relationships.

Play and Learning

How exactly is it that so many different forms of life manage to create such complex webs of mutually constitutive relationships? Haraway (2008) says that: “species interdependence is the name of the worlding game on earth, and that game must be one of response and respect. That is the play of companion species learning to pay attention” (p. 19).

Play is crucial for development and learning in many animals. The human somatosensory cortex, which allows us to control and plan our movements, is developed through a kind of play. In the brains of babies random neural firings lead to muscle twitches and simple movements. These movements result in corresponding signals from the sensory neurons that track our bodies in space. This feedback loop leads to the development of the relationships that describe the somatosensory cortex: the coupling of action and sensation. Without that first experimentation and play however, we would have no way to map these motions into meaningful patterns (Busáki, 2011).

All sorts of animals play (Sharpe, 2011), and there must be some useful advantages to it, because it is a costly and risky behaviour; a baby mouse engrossed in play is quite likely to be snatched up by a predator for its distraction. Research into animal play suggests that play is essential for helping animals learn to better manage their relationships with others and to encourage development of the brain (Sharpe, 2011).

According to Carse (1985) finite play and infinite play both inherently involve taking on roles and performing them for an audience (p. 20). While roles within finite games tend to be fairly fixed, infinite games are defined by the fluidity with which participants exchange and mutate their roles and relationships. Infinite players understand the nature of their performance and are never overly attached to the roles they take in the moment (p. 18).

I see this aspect of infinite play quite clearly when watching my dog at the park. The goal is never for one dog to 'win,' because that would bring the play to an end. Instead the goal seems to be to exchange roles effortlessly to prevent any kind of conclusion. One dog chases and then suddenly becomes chased, or possesses a particularly excellent stick and then must pursue it; it is precisely the fluidity of the roles that permits play to continue without one dog gaining a conclusive advantage.

It seems to me as an observer that it is the *surprise* of the sudden role reversal that makes play fun for dogs. For my dog, nothing tops the look of goofy exhilaration she displays when she has been chasing another dog and suddenly has the tables turned on her. That moment of recognition that the game has changed seems to be what produces ecstatic joy. Carse notes that this is another difference between finite and infinite games; "surprise causes finite play to end; it is the reason for infinite play to continue" (p. 22).

Microcosm is inspired by this fluidity of roles and was expressly built to allow for extreme flexibility in the relationships between its cells. It aspires to create surprise on the part of its players, to give them that moment of exhilaration that comes from a sudden unexpected shift in the game they are playing.

Magic Circles

In Bateson's (1972) framework, play can be seen as a kind of framing around behaviour, a change of context. Bateson discusses the importance of play in the development of communication as well. He uses dogs playing as an example. Within the context of play, actions do not denote what they usually would; the playful nip is not a bite (p. 180). This is important because it demonstrates *metacognition*, or thinking about thinking, without verbal language. In order for dogs to engage in play fighting, both animals must understand the shift in context and recognize that their behaviours mean something else. In dogs this change is usually conveyed through exaggerated body language: the play-bow. One dog invites the other to play, and if an appropriate response is received they co-create a context of play.

The early play theorist Huizinga (1955) called this change of context a 'magic circle,' and considered it to be a central feature of games and play. Games are played in virtual spaces demarcated from the everyday world, in which behaviours and relationships are not quite the same as they would be outside of those boundaries. This magic circle creates a context where exploration and experimentation are encouraged and risks are reduced; chess may simulate the relationships of war, but no one is likely to die from a game. Finite games must always exist within the same carefully defined boundaries, but because of their play *with* boundaries, infinite games continuously recreate and alter their context.

Games seem to encourage thinking about thinking, and particularly thinking about relationships; they ask us to consider the effects of our actions and observe the reactions they provoke from our companions in play.

Games and Artificial Intelligence

Artificial Intelligence (AI) can also be seen as thinking about thinking. AI represents an attempt to describe how it is that we perceive the world and solve problems and to replicate those abilities in the things we build. Games and AI have nearly always been closely linked. Game theory was central to many of the early formulations of AI, and as our capacity to build robust AI has improved, AI players have tackled games of increasing complexity from tic-tac-toe (1957), to checkers (1994), to chess (1997), to the recent mastery of DeepMind's AlphaGo system over the game go (AlphaGo, 2016).

AI simultaneously reflects and shapes cultural representations of our own cognition. The flawed 'expert system' approach to AI of the 1980's reduced all thinking to logical, linguistic rules -- essentially assuming that conscious, verbal thought was the only kind of thinking that mattered. More recent AI research has focused on so called 'deep learning' techniques that can be seen as an attempt to create 'machine intuition.'

Much of our thinking involves knowledge that we cannot describe, what Michael Polanyi (2009) calls 'tacit knowledge.' A master of Zen archery may be able to tell you some of the things they experience when they practice their skill, but they cannot transfer that knowledge to you verbally; it must be built intuitively through experimentation, learning, and somatic experience.

Artificial neural networks (ANNs) can be seen as AI systems that attempt to replicate this kind of tacit learning. A neural network 'learns' to solve a particular problem through repeated training and feedback. One of the issues with a neural network compared to an expert or procedural system is that it is very hard to 'extract' the lessons learned by the system after training. An image recognition network can tell you what is in an image, but not how it knows what is in the image. A major difference with biological neural networks is that we do have total information about the system. It's not that we don't have enough data to understand how a neural network has solved a problem, but rather that the relationships it describes are too complex.

Microcosm aims to explore some of these questions by providing much simpler models of neural networks. The hope is that this makes it easier for players to both logically and intuitively relate to the tacit knowledge of the network. Many of the dynamics of interest in complex networks operate mainly on a very large scale. By simplifying the networks, core concepts like recursive feedback and self-generating oscillations can be demonstrated much more clearly. Oscillations in *microcosm* can be seen in the movement and signaling patterns that appear over time between creatures. Because these features are temporal, they can only really be seen and understood in a dynamic, interactive experience.

Following the progression of tackling more and more complex games, neural networks have recently been used to explore digital games as well. In fact, DeepMind, the company Google acquired to build AlphaGo, developed their technology (called a deep Q network) by teaching neural networks to play Atari Games (Mnih et al., 2014).

People have been building AI systems that play digital games for quite some time, but what made this attempt unusual was that rather than exploiting the total information available in a virtual world and passing data about the game state directly to the AI system, the network learned to play solely with the array of pixels produced by the game's visual output (Mnih et al., 2014). In other words, the network learned to play Atari games in the same way and with the same information as a person would.

A similar approach is used with Microsoft's AIX platform, an open-source AI system that is built to explore different AI learning tasks in the digital game *Minecraft* (Walton, 2014). The AIX researchers highlight some of the advantages digital game environments provide for AI research. For one, training a robot to climb a hill in the real world is much more costly and risky than doing so in a virtual environment. If your AI agent messes up and falls into a river in *Minecraft*, you don't have build a new robot -- you simply reset the state and try again. I find the second advantage more interesting: virtual worlds allow for better study of 'embodied AI' (Walton, 2014).

Embodied AI

Embodied cognition is a cognitive model that reflects the importance of the environment on the formation of intelligence, a concept central to biocybernetic theory. Unlike traditional cognitive models which assume that the agent and the environment are entirely separate components, embodied cognition tends to talk of one system consisting of the agent embedded within the dynamics of the ecosystem.

One good example of this is that primates and birds have similar kinds of problem solving abilities despite not sharing a common ancestor with those same abilities (Güntürkün, 2016). Moreover, the neurological structures that provide these problem-solving skills seem to be similar across both groups despite wildly different brain structures (Güntürkün, 2016). This is called convergent evolution, and it suggests that specific kinds of intelligence develop in specific kinds of situations; if you put a biological neural network into that kind of environment, it's going to come up with a relatively similar strategy every time.

Haraway coined the term *situated knowledges* to describe the contextual nature of all understanding. Knowledge is always shaped by the natural and cultural environment the knowers find themselves in. One experiment used virtual reality technology to demonstrate this rather literally. In a study on the 'doorway effect' researchers found that participants were less likely to remember information about a task after walking through a doorway than if they walked the same distance in a connected space (Brenner & Zacks, 2011). Interestingly, this effect held for both physical and virtual rooms and doorways. It seems that working memory is often directly tied to our spatial models.

Cognition can never be fully detached from context; knowledge is always situated, and thinking always involves an agent embedded within an environment. As Bateson (1972) puts it, form and pattern always evolve together, but ultimately it is context that guides change over time (p. 155).

Microcosm attempts to highlight this blurry boundary between agent and environment by providing multiple levels of organization and cognition. While each agent in the system can be seen as a distinct entity, the whole network can also be seen as a single cognitive network attempting to solve the task of resource distribution. Viewed in this way, both the cells and the flowers simultaneously constitute the environment *and* the intelligent agent. Mites provide another layer of complexity, because they can be seen as intelligent agents in their own right, but the player mostly sees them as component of the cells. In this way *microcosm* plays with the solidity of the relationship between whole organism and biotic component.

A limitation I see with older approaches to AI is the almost exclusive focus on mind as if it were a separate component from body. Futurists often speak of transferring the mind from the body into a machine, escaping the 'prison' of instantiation in 'meat.' I see this as a dangerous oversight of the fact that minds are emergent properties of bodies and are therefore never fully separable. Cartesian dualisms still haunt the field.

If we wish to create artificial minds, we will need to do so through the creation of artificial bodies. These bodies need not be constructed whole cloth however, as we already have wonderfully complex organic bodies for our virtual bodies to augment, deconstruct, overlap, and interrelate with. This is the true beauty of an inter- or intra- active interface: it allows us to extend our bodies across the permeable boundary of the virtual and into new worlds, to create new relationships and new possibilities in the process.

Infolding

All technology reflects our own biology and perception. Haraway (2008) quotes the phenomenologist Don Idhe as saying that "insofar as I use or employ a technology, I am used by and employed by that technology as well… We are bodies in technologies." She goes on to explain that "technologies are not mediations, something between us and another bit of the world. Rather technologies are organs, full partners, in what Merleau-Ponty called 'infoldings of the flesh'" (p. 249). As just one example of this relationship, Haraway (2008) states that "infolded into the metal, plastic, and electronic flesh of the digital apparatus is the primate visual system [we] have inherited" (p. 5).

In her essay "Unfinished Work: From Cyborg to Cognisphere," Katherine Hayles emphasizes that Haraway's notion of companion species encompasses not only human or biological actors, but artificial machine cognizers as well. She refers to the total network of these intra-active relationships as the *cognisphere*, and states that "As inhabitants of globally interconnected networks, we are joined in a dynamic co-evolutionary spiral with intelligent machines as well as with the other biological species with whom we share the planet" (Hayles, 2006, p. 164).

Artificial Life

In addition to providing a rich environment for AI agents to explore, virtual worlds have another excellent resource for AI research: they are built to support interaction with human players. If cybernetics is the study of relationships, then cybernetic agents must have something to *relate to*. This can be the environment around them or other AI, but if we want to understand our own cognitive systems, eventually our AI needs to interact with us.

Digital games have long required different kinds of AI and encouraged their research and development. In order to support meaningful play, we want our AI to be 'lively.' In some ways I feel that digital games reflect a human desire to create artificial organisms that are capable of play. Haraway (1991) speaks of the way in which "our machines are disturbingly lively, and we ourselves frighteningly inert" (p. 152).

If the organisms of *microcosm* constitute a part of the cognisphere, then they too can be seen as companion species co-evolving along with their human players. The structures of *microcosm* that encode the history of intra-actions between player and organism help the larger infinite game to change and adapt over time. The creatures of *microcosm* are an artificial companion species learning to play with us. “People and things are in mutually constituting, interactive touch” (Haraway, 2008, p. 4).

I feel that the field of artificial life (a-life) owes much to games and play. Conway’s *Game of Life*, one of the first cellular automata, was developed after Conway spent an extensive period of time researching the game go. *The Game of Life* is a very simple representation of life, inspired by single celled organisms as much as go, but it produces an essential quality of living systems: self-generated replication.

Strange Loops

The biocyberneticists Maturana and Varela (1998) consider replication through time to be the single most fundamental element of living systems. They refer to this process as *autopoiesis*, or self-creation. Haraway (2008) says that:

> Autopoesis is self-making, in which self-maintaining entities (the smallest biological unit of which is the living cell) develop and sustain their own form, drawing on the enveloping flows of matter and energy. (Haraway, 2008, p. 32)

A living cell continually produces and replaces the components that constitute it. It persists as a discrete entity (at least in our minds) throughout time despite the fact that the components that constitute it are always changing. It is unquestionably an infinite player, not a finite one.

Crucially, Haraway points out that no living system is *solely* self-producing, it always acts in relation to the organisms and environments around it. Autopoesis then is the process of using the dynamics of interaction to generate and maintain a self.

Any a-life system must also implement this; in *microcosm* each cell persists throughout the simulation despite the fact that the pixels that represent it are continually changing. This is not necessarily a specific property of a-life; nearly all computation involves recursive loops. Digital games rely even more heavily on recursion. Any kind of interactive digital system must continually loop through a set of procedures that maintain and modify the world and elements it represents.

Douglas Hofstadter (2007) highlights a specific kind of recursive structure that he calls a ‘strange loop.’ Strange loops are feedback structures that cross multiple hierarchical levels of organization. Escher’s *Drawing Hands* is one of the examples he provides, in which a pattern at one level is suddenly recognized as a pattern at a higher level before dissolving back into the first level again. The dynamics of a cell also constitute a strange loop, as DNA is inscribed into RNA, translated into proteins, and then used to construct DNA again.

Programming frequently involves recursive structures that cycle through multiple levels of abstraction, and *microcosm* is specifically built to take advantage of this. A strange loop can be seen in the way a seed genome is translated into the behaviour of a cell and then the behaviour of that organism in the system results in the eventual evaluation and modification of the genome, which in turn is passed on to the next generation.

Many structures within *microcosm* are also reused at multiple levels of abstraction. The code that generates visual representations from a genome creates the graphics for a cell, but then is reused in part to create visuals for the mites and pollen. Depending on what mites and pollen the cell ends up collecting, the visuals of the cell will change to reflect the incorporation of the smaller elements.

The oscillations of communication between cells can also be seen as a strange loop. The signalling between the elements of the system comprises the overall success and behaviour of the community as a whole, but those dynamics will also end up constraining and affecting the behaviour of the individual elements. In many ways it is the oscillations of the overall network that are interesting to players, but their only method of altering or probing those dynamics is by affecting individual cells and watching those changes propagate through the whole system.

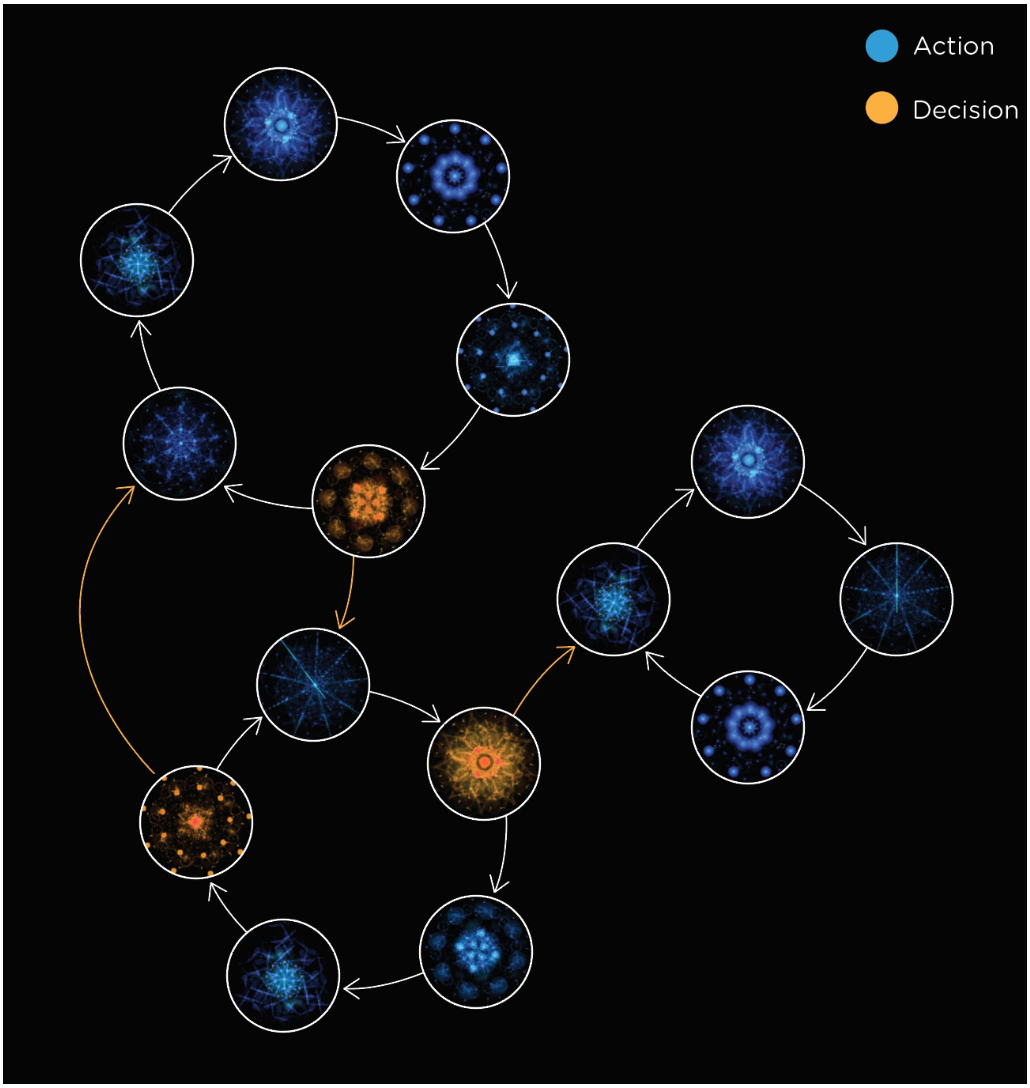

Figure 10: Cell Behaviours. Blue nodes represent actions the cell can take, orange nodes switch between loops of behaviours.

Cell behavior ‘trees’ are also entangled loops. The genome produces several sets of looping actions, which the cell steps through in sequence. Decision nodes in the tree can switch between loops depending on the internal state of the cell's microbiome or signals received from other cells.

This mirrors some of the oscillatory dynamics of brains, as processing in the brain seems to involve recursive feedback loops between individual neurons. These oscillations reinforce their own relationships, leading to the development of structured networks, just as in the earlier example of the development of the somatosensory cortex (Buzsáki, 2011, p. 222).

These oscillations also seem to cross multiple levels of hierarchy, as demonstrated very well by visual processing (Buzsáki, 2011, p. 178). Input from sensory neurons in the eye is routed to visual processing networks in the thalamus, which then send that information to 'higher-order' visual processing regions for more complex forms of feature and motion detection. Interestingly, these higher-order networks are connected back into the 'lower-level' processing regions and so the dynamics of the two levels of processing are intertwined. In fact, only about one tenth of the inputs into the low level processing regions come from sensory neurons, the rest are all recurrent loops from other regions of the brain (Buzsáki, 2011, p. 177). This seems to highlight the importance of these kinds of level crossing recursive structures in perception and cognition. Haraway (2008) says that “the shape and temporality of life on earth are more like a liquid-crystal consortium folding on itself again and again than a well-branched tree” (p. 31).

Recent AI models like the deep learning networks discussed before are starting to resemble these cognitive models more and more. As stated before, it is always somewhat hard to tell whether our ideas about how brains work are structured by our AI systems or vice versa. Haraway and Hayles suggest that the answer is probably both.

Networks like those used by AlphaGo and the *Minecraft* AIX use a technique called ‘reservoir computing’ that combines some of the attributes of biological neural networks and traditional recurrent neural networks (RNNs). They tend to consist of two components, a ‘liquid state network’ and at least one RNN (Lukoševičius, M., Jaeger, H., 2009).

As outlined by Lukoševičius and Jaeger, (2009) liquid state networks, unlike traditional networks, never resolve into a fixed topology. Instead, they continually shift and alter the connections between neurons. While they can't be used for binary classification like a traditional network, they are very good at autonomously producing oscillations. Reservoir computing is often used to respond to visual input. Here, data is first fed into the liquid state network, which is already producing its own continuous activity. The input perturbs the autonomous patterns of oscillation and alters the dynamics of the network. Traditional recurrent networks are then hooked up to the outputs of this continual oscillation and used to determine behaviour.

In some ways the networks in *microcosm* bear more similarity to liquid state networks then they do to traditional artificial neural networks. Rather than explicitly solving a problem, they are designed to create continuous patterns of oscillation. This makes them more like an autopoietic entity in that they are capable of both producing their own dynamics and responding to perturbations from the environment or the player.

Across Worlds and Bodies

In *Across Worlds and Bodies: Criticism in the Age of Video Games*, Brendan Keogh (2014) makes the argument that interactive media like digital games allow for a more robust and balanced cybernetic flow than non-interactive media. Unlike film, when engaging with a digital game not only are you observing and reacting to the game but the system of the game itself is reacting to you as well. This kind of observation of the subject is commonplace in interactive technology and much of user-centered design focuses on trying to improve the capacity of our devices to observe and respond intelligently to their users.

Keogh uses the concept of continuous partial immersion to lay out a framework for understanding digital games. It is never enough, he says, to view a digital game as simply the structures and rules that govern it. We can also never discard the technological frame and focus only on the narrative or diegetic elements of the game. Instead, Keogh sees a game as a cybernetic system comprised of the player, the physical interface, the frame of the narrative (the magic circle), and the content of the game itself. To make matters worse (or perhaps better), this whole set of relationships is continuously shifting.

No matter how immersive a game may be, the player is always aware on some level of their physical body and of the unreality of the virtual space. Similarly, even a game that is tremendously abstract and composed mostly of extra-diegetic elements still requires a certain effort on the part of the player in order to extend their self into the game world and interact with the system. We are infolded into our virtual worlds.

Where film may require a suspension of disbelief, Keogh claims that games by their very nature are systems in which players actively create belief structures that facilitate becoming a part of the world. Carse (1985) also speaks of the way that games require their players to voluntarily 'veil' themselves and enter into the roles they play (p. 17). The sense of agency and dynamism that modern digital games provide creates a kind of hybrid frame in which the player is able to simultaneously possess multiple contradictory bodies.

As with most other elements of digital games, these are not necessarily novel practices. All of these practices that blur the boundary between the consumer of media and the artefact itself can be seen in film and quite clearly in postmodern literature. What is different about games is that fact that they are not static, finished products: they are dynamic worlds.

Perhaps more specifically, they are recursive structures where the world and the player continually influence, shape, and constrain each other. I believe that this is a crucial difference between games and other forms of media, because this is exactly the kind of strange loop or entangled system that Hofstadter or Haraway discusses. Our virtual worlds co-create our virtual and real selves. We are engaged in a process of *becoming with* our virtual identities and companion species. This dynamism helps support the kind of infinite play that Carse advocates.

Digital games provide a different temporal experience than other media because the hybrid self of player and game world dynamically evolves in such a way that both are able to constrain the behaviour of the whole. Even in literature we can see a process of dynamic feedback between text and reader, but the text itself never changes in response to the reader; the interpretative process is one way. It's worth pointing out that while this may be literally true, the relationship between a text and any specific reader is always going to be different; it will always be situated in the co-created world of reader and text.

I feel that this model of continuous partial immersion or infolding better emphasizes the effects that our experiences in virtual spaces can have on us. A good comparison can be found in dreams; whatever occurs to me over the course of a dream may not be real, but it is still going to shape my mood, my reactions the next day, as well as many other intangible elements of my neurochemistry. This is especially true because I am acting *as if* my dream self were my waking self. Except perhaps in lucid dreams, there is no frame or context -- no magic circle -- around the events of a dream. Digital games make this separation slightly clearer because we are usually more aware of our virtual selves as distinct entities, but it is by no means complete.

Polanyi (2009) argues that all human tool use and technology depends upon the flexibility of our models of self. This flexibility allows us to both extend ourselves into our tools -- integrating them into our conceptions of our bodies -- and also allows us to deconstruct ourselves into constituent components. This is yet another example of the infolding of technology and flesh.

Digital games and virtual worlds take full advantage of this by multiplying and modifying our sense of self: giving us virtual bodies and virtual tools that we are nonetheless able to integrate into sensory experience as 'ours.' A digital game player speaks of their character's actions as if they were their own, highlighting the hybrid frame in which we are able to simultaneously possess both an organic body and a virtual one.

I emphasize this point because it has forced me to reconsider the ethics of digital worlds. I feel that as a game designer I have a responsibility to consider what kinds of experiences and worlds I am building for my co-players. The virtual worlds and stories we choose to engage with can reshape our social realities to enhance diversity, flexibility, resilience and compassion. Empathy and communication are only possible through the co-creation of shared worlds and the acceptance of multiple perspectives. As Haraway (1991) puts it, "social reality is lived social relations, our most important political construction, a world-changing fiction" (p. 149).

In the introduction I suggested that our technical tools are nearly always myths and vice versa. I want the mythos of *microcosm* to demonstrate the importance of cooperation and the deep relationships that shape the overlapping worlds we inhabit. I want it to help imagine a world where ecological thinking, in Bateson's expansive definition, is at the core of all human activity.

Haraway (1991) suggests that: "A cyborg world might be about lived social and bodily realities in which people are not afraid of their joint kinship with animals and machines, not afraid of permanently partial identities and contradictory standpoints" (p. 154). This is the kind of world that I would like to live in.

Evolution: Development Process

This section follows the evolution of *microcosm* and a related project called *somata* built with the same framework.

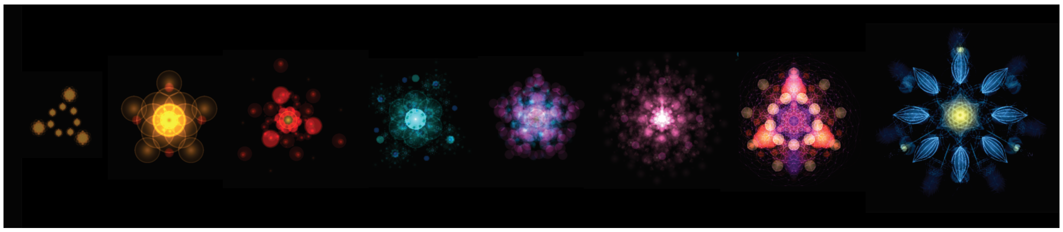

Figure 11: Evolution of mandalas in microcosm*. From left to right, increasing complexity of mandalas as the algorithm improves.*

Convergence

I began developing the framework that would eventually become *microcosm* when I realized that I was writing the same components over and over again in my game projects. I decided that I should try to extract the bits that I found useful and make them a bit more modular, then put them all together into a simple game engine. The framework I built primarily handles the integration between the rendering library Pixi.js and the physics engine PhysicsJS.

Most of the components I consolidated were fairly standard: handling input from devices including the Kinect, mobile devices, and gamepads; organizing the game into a scene graph; object pooling; handling collisions between different game objects. One component that I kept finding new uses for was a small set of functions for generating and animating radial symmetry.

I'd first developed the component when working on a drawing application called *Lightgarden* where users were able to draw on a projected image with a custom controller. I found that different forms of symmetry helped to make the patterns users created more coherent and less 'scribbly.' What had initially been intended to be only one brush mode ended up shaping the entire aesthetics of the system, and it became an application for drawing radially symmetric mandalas in light.

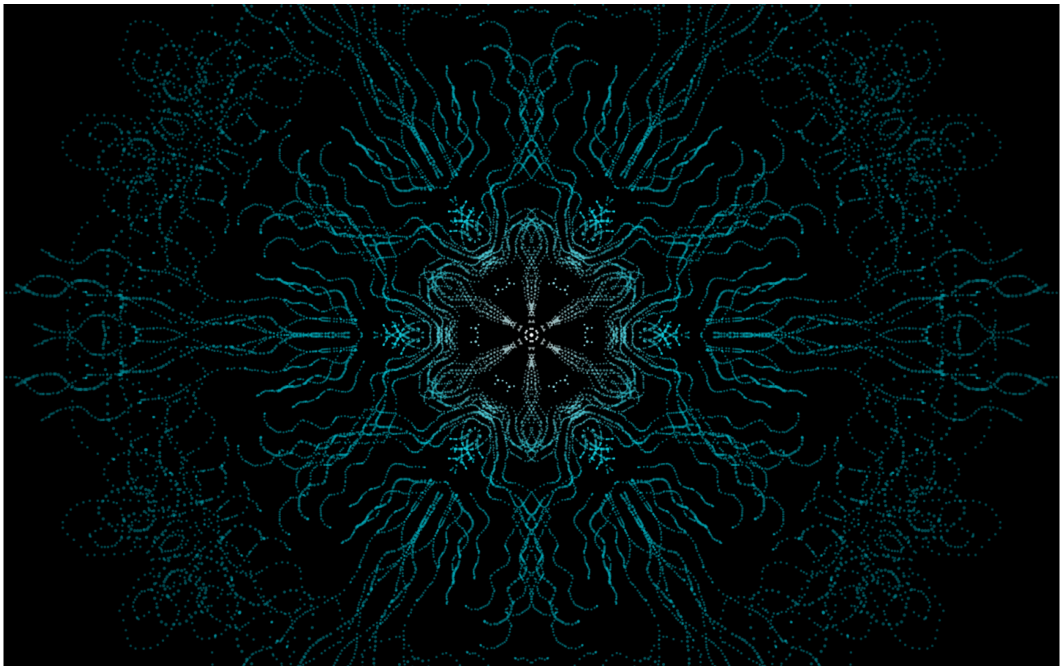

Figure 12: A mandala drawn with LightGarden

Symmetry

Several viewers of the project noted that there was something very captivating about the construction of the mandalas -- particularly when they were scaled up to the size of a wall. I had been reading Jung's memoir *Memories, Dreams, Reflections* at the time, and I remembered that Jung had been fascinated by mandala images and had made them a huge part of his own recovery from psychological breakdown. Mandalas are archetypes of wholeness and balance, and Jung believed that their construction was therapeutic (pp. 195-6).

A bit later, I began working on a project using the Kinect for OCAD's *Mobile Experience Lab,* where I worked as a research assistant for Dr. Paula Gardner. The goal of this project was to map the body in motion in a somewhat abstract way. It was heavily inspired by Barad's notion of intra-action. I pulled the same radial symmetry code and used it to create a visualization, this time mapping the joints of the Kinect skeleton to radially symmetric rings of sprites. This was interesting because the mandalas moved and shifted along with the user and the end result looked very organic. In some ways it resembled a stylized cell.

Recursion

By this point, I knew that I wanted my thesis work to resemble cellular automata and I knew that I wanted it to highlight the way that living systems are built up from progressively larger and larger collections of cooperating individuals. The previous mandala visuals were a perfect metaphor for this because each mandala could be constructed of recursively-nested elements. These elements would be symbolic representations of the proteins making up the structure of the cell, surrounding the focal point of the nucleus.

First the system would generate a set of base sprites by layering simple geometric components in a radial pattern, then those sprites would be arranged into radially symmetric rings, and then those rings would be layered and animated to produce a complex final shape. In initial versions, I used only a base set of grayscale circles, which were tinted and applied with varying scale, position, and opacity. The final mandalas were fractal patterns, with each component constructed of smaller, visually similar elements.

Even in these early experiments, I was struck by the staggering complexity that could be created out of such simple shapes just by recursively nesting them. I was encountering a perfect visual metaphor for *emergence*, the way that complex behaviour can arise from the interactions between simple components that do not display that same behaviour.

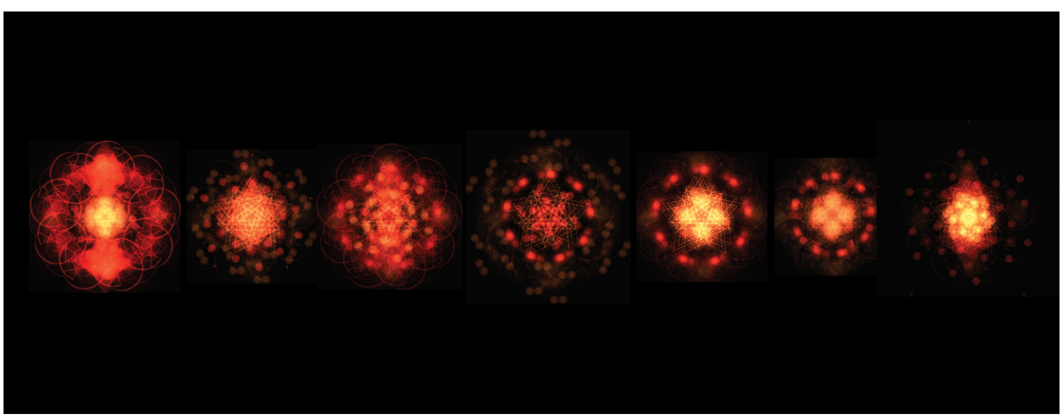

Figure 13: Animation sequence of a cell

By giving each layer a randomly generated animation, the patterns became complex in time as well as space. Because each animation had a random period the loops didn't sync up perfectly. This lead to visual beat patterns that resulted in even greater complexity; some of the animated mandalas wouldn't loop for five or ten minutes. Watching the animations I was reminded of Hofstadter's strange loop; my perception alternated between perceiving the individual components and the patterns produced by their overlapping relationships.

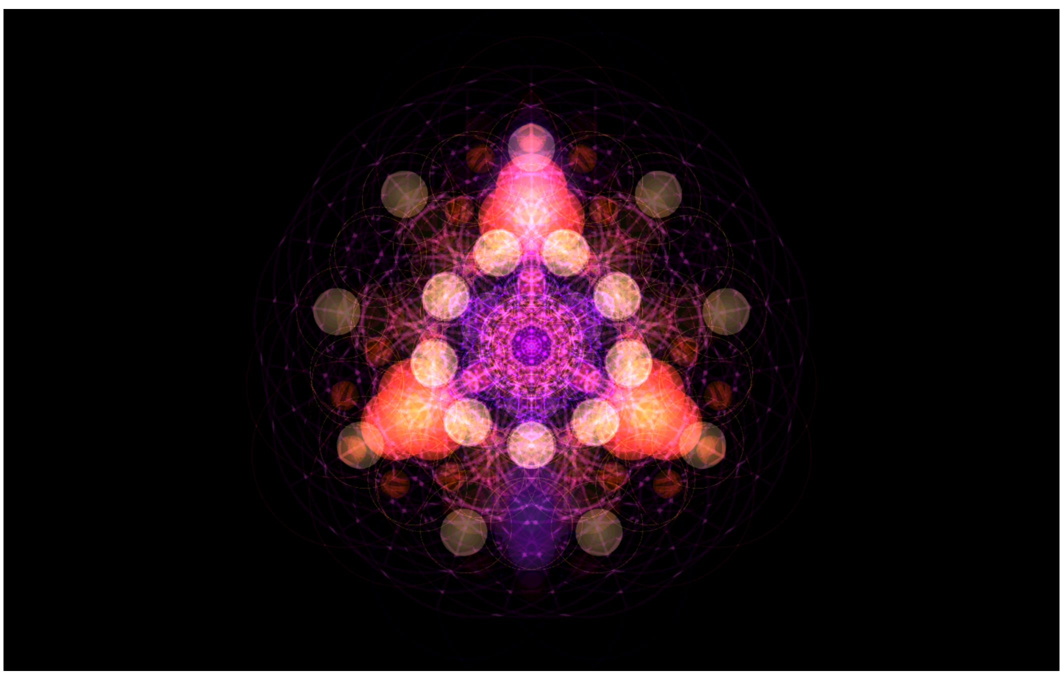

Figure 14: An early mandala generated only from simple circles

This newfound respect for the power of recursion became a central theme for the project. As I developed the other visuals and mechanics for *microcosm*, I tried to replicate the nested structure of the initial mandalas. In the current iteration, all of the graphics for a single network are generated as one very complex multilayered mandala. Layers of this are then selected and used to represent the smaller components, so cells and the nest will actually grow in complexity over time as they collect parts of the overall pattern. A completely balanced and well-stocked nest will thus come to resemble the original seed pattern.

Figure 15: Microcosm *logo, design by Tarik El-Khateeb*

The logo for *microcosm* reflects this focus on recursion with a symbol that combines the *ensō* of Zen Buddhism and the *ouroboros* of western mysticism. Both are symbolic representations of the centrality of recursion to all of life and mind.

Drift

While I was building out the basic interactive elements of *microcosm*, work started again on the Kinect project that had inspired it. The interface was re-tasked as an interactive visualization for an improvisational dance performance, and the Muse EEG headset was added to track brain activity.

It became even more important for the link between the performer's movements and the visualization to be obscure but still intuitively understandable because a simple one-to-one relationship resulted in the dancer focusing too much on how they were controlling the mandala rather than how they were dancing. The solution we found to this was to create randomized links between the body-mapping generated by the Kinect and Muse, and the animations of the mandala.

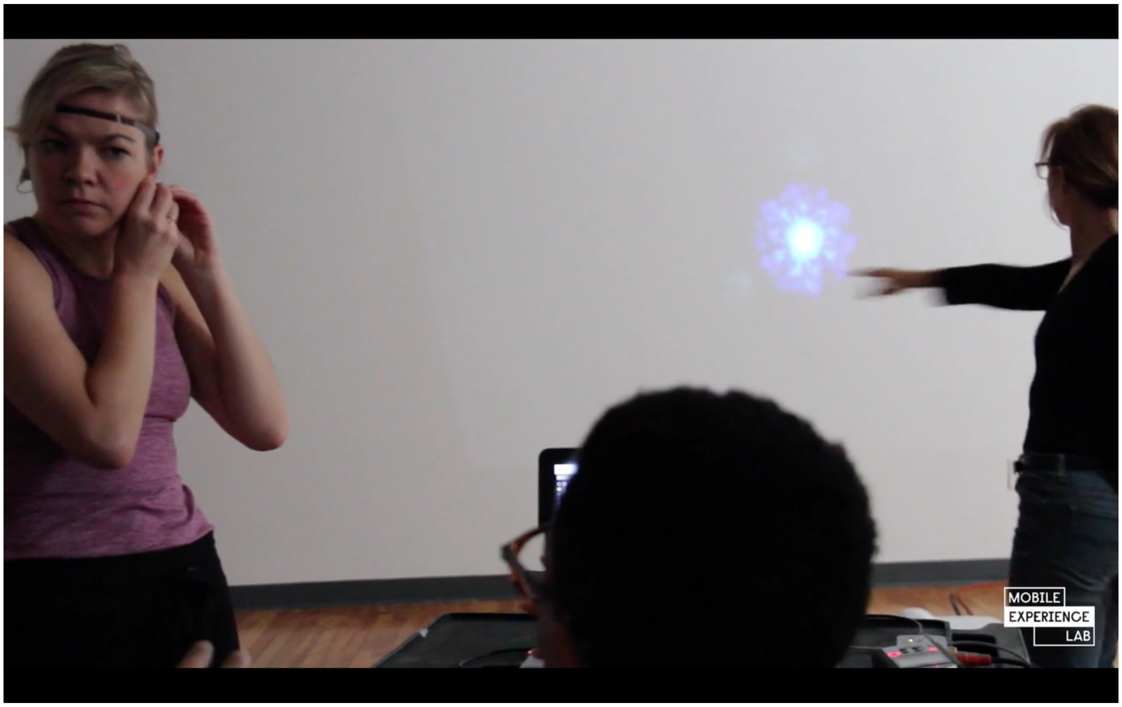

Figure 16: A dancer sets up the Muse headset, the mandala begins to grow

This worked much better because while it was obvious that the performer's actions triggered changes in the visualization, it was much harder to pick out exactly what the relationship was between input and output. In addition to the linked animations, some of the animations were left untouched so that the mandala still moved and shifted a bit even without any input. This gave the dancer something to respond to and resulted in what one performer described as a 'duet.' As Haraway (2008) says:

> all the actors become who they are in the dance of relating, not from scratch, not ex nihilo, but full of the patterns of their sometimes-joined, sometimes-separate heritages both before and lateral to this encounter. All the dancers are redone through the patterns they enact. (p. 25)

We called the system *somata*, meaning ‘bodies.’ Somata are the main body sections of neurons, where the activity of the dendrites and axons that link neurons together converge. *Somata,* therefore, reflects the convergence point of complex relationships between infolded human and machine bodies. *Somata* supports dance visualization precisely because of the continuous partial immersion that Keogh describes.

The dancer might initially start moving in response to an autonomous rhythm of the mandala, but as they move the system observes them and responds. This generates additional visual activity and further constrains and shapes the flow of the performer’s movements. It is a two-way cybernetic system: both observing and observed. Ultimately, it allowed the performer and the visualization to play -- exploring a set of rich possibilities together.

Mutations

Around this time I began developing the components that handled the genetics for *microcosm*. This meant that each mandala was no longer randomly generated, but instead based on a genetic seed (or a part of one). Genomes could be stored and recalled, so interesting patterns could be saved for later use. Once this was in place, I began experimenting with mutation.

Mutation gave the user much more control over how the graphics developed. When an interesting seed was found, the user could mutate it -- creating similar but slightly different mandalas. If one of the mutations was better, you could select that instead and it would become the next seed for mutation. In this way the user could 'evolve' patterns that they found personally aesthetically appealing.

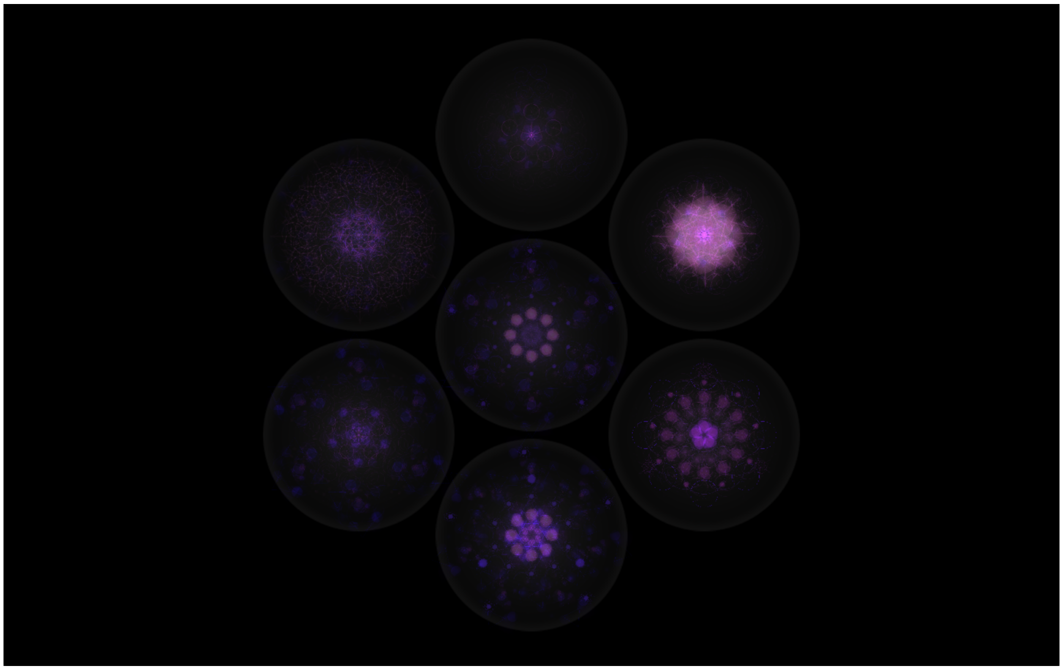

Figure 17: Examples of genetics in Microcosm*. The six outer 'cells' are mutations of the center organism.*

This framework was eventually applied to both *microcosm* and *somata*. It added quite a bit to *somata*, because the dancer could now select the visuals they wanted to perform with. Rather than the dancer explicitly creating them however, it was a process of exploration: a kind of play with the genome to get it to produce what the performer had in mind. Importantly, the randomness of the mutations also allowed for elements of surprise; you might start going for one pattern and then suddenly be struck by a permutation of it you hadn't expected.

In *microcosm*, this element was even more robust because the genome was used to create much more than the visuals. The genome constrained the behaviour, movement patterns, particle effects, and attributes of each cell. It also affected patterns, resources, and positions of flowers, ultimately shaping the environment as well. Eventually the genome was split into multiple components allowing different aspects of the network to be evolved and mutated separately.

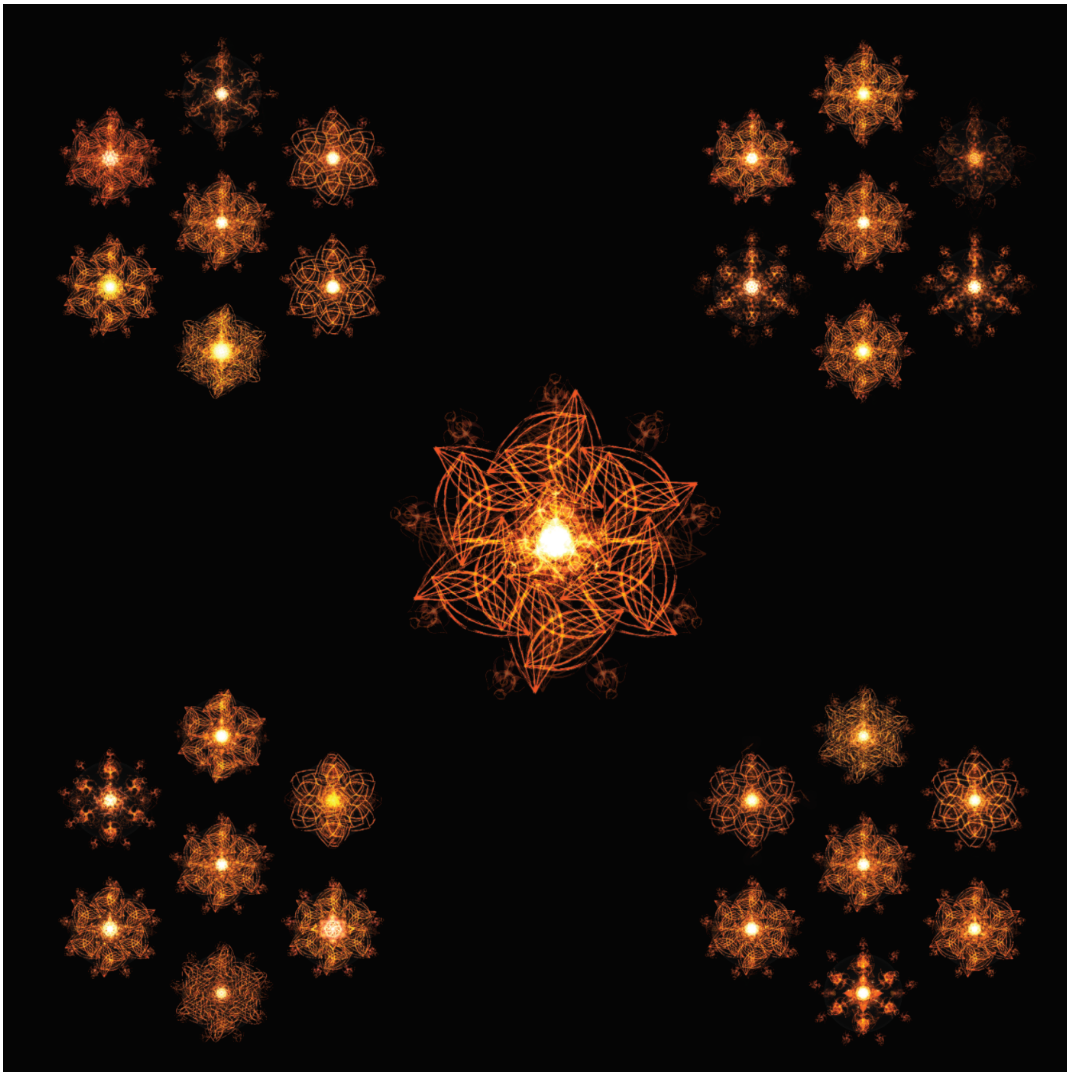

Figure 18: Variety in mutations. All four sets of mutation are based on the center genome.

Play

Once these base components of the system were in place, I began experimenting with different game mechanics and interfaces. An earlier project had used smartphones as networked controllers, utilizing both the touchscreen and device tilt to control characters. I liked the idea of bringing that support back into the system as it would allow for a wide variety of future interfaces to be constructed quickly and easily

I also wanted to bring in more traditional input devices though, so initial versions of the game used Sony's Dualshock 4 controller, which was been designed for their PS4 console. This had the advantage of being immediately familiar to console gamers and providing a large number of controls.

The first version of *microcosm* had significantly simplified game mechanics. A single player would try to cooperate with the AI to collect pollen from flowers and bring it to the nest to keep it alive and keep the game going. In this scenario each world seed of the game would produce different AI behaviour. The AI would follow certain paths and patterns, and players had to learn how best to fill in the gaps within this pattern.

Although the goal and interactions were quite simple, response from players was good, and a number of users said that they enjoyed the meditative simplicity of just going back and forth from flower to nest. It also became apparent that the smoothness of the player movement was key to the experience being satisfying. Down the line I ended up limiting some of the graphic choices to try and keep gameplay feeling fluid.

A second iteration of the game was built for the Emerge conference at Arizona State University. The largest additions here were multiplayer, procedural audio, and a more complex ecological metaphor. Instead of players bringing pollen to the nest, each flower would produce one kind of pollen, but needed the other kinds of pollen to make nectar. Players would take pollen between flowers and trade for nectar, then bring the nectar back to the nest to sustain it. I liked this mechanic better because it made the flowers a more prominent part of the system, and better illustrated the idea of mutual dependency. Each flower relied on the diversity of other kinds of flowers to survive, and neither the creatures nor the flowers could exist on their own. To me this was an accessible way of pointing to Margulis' notion of *symbiogenesis*, the importance of mutualism in evolution, while using a relatable biological metaphor.

For this version I implemented support for using mobile devices as controllers. Players would use a Nexus 7 Android tablet to control their creatures. By tilting the tablet left, right, up, or down, players could move their character in the same direction. The controls were further simplified from the initial version so that only two buttons were needed. Players could tap the left side of the screen to exchange pollen or nectar with other creatures or flowers, and tap the right side of the screen to jump in whatever direction they were moving. This interface seemed much easier and less threatening for non-gamers to grasp, although the tilt controls also took a bit more getting used to.

My lab-mate from the *Mobile Experience Lab*, Stephen Surlin, created a procedural audio component in Max MSP that would trigger different audio samples as creatures collected pollen, signalled to each other, and collided with one another. This helped illustrate the dynamics and patterns of the system and also made the creatures seem much more lively and playful as they chirped and twittered back and forth.

The final iteration of the game I tested combined systems from both versions to allow for cooperative gameplay for up to 7 simultaneous players. One player could use the dualshock controller while 6 others (potentially more) could use tablets or mobile phones. This social element seemed to make the game much more appealing, as groups of friends had to communicate and work together to keep all the flowers producing nectar.

The game's abstract metaphors proved useful for sparking discussions about ecological systems on different scales. Some players saw the creatures as microbes and wanted to talk about microbiomes and cell signalling. Other players saw the creatures as bees, which led to discussions about pollinator collapse and human hubris around controlling and modifying ecological networks. Still other players saw the game as a metaphor for economic systems, and wanted to use it to explore the dynamics of supply and demand. To me, this variety in experience showed that the game had at least partially achieved its goal of sparking dialogue about scale-free patterns of dynamic networks. I hope to bring more of these elements directly into the gameplay so that all of these ways of considering the system can be accessible to players.

Possibility: Future Directions

Both *microcosm* and *somata* have proven to be fruitful prototypes and the lessons I have learned along the way make me excited about their potential as art pieces, as learning and teaching tools, and as playful experiences.

Imagining Future Worlds

For me, one of the critical functions of art is to playfully explore possibilities. I have a long-standing fascination with science fiction as a tool to analyze current societies and relationships and to imagine what they may become. Moving forward, I would like to develop *microcosm* into a more complete game experience, and embed it within a fully realized fictional world.

Narrative Themes

I have always imagined the play experience of *microcosm* as a game-within-a-game. The larger fictional world would take place about a hundred years in the future and would focus on corporations mining and developing the asteroid belt between Mars and Jupiter.

Within that world the exploration and testing of the networks currently implemented in *microcosm* would be a game designed to help AI systems discover useful ecologies of bioengineered organisms and nanites. Ecologies that functioned well could be used to generate food, synthesize chemicals, or extract resources from asteroids. There would be additional game mechanics in the larger world, but much of the player-driven value would be generated by discovering and constructing ecological networks in the asteroids controlled by the player. Effectively, within the game world corporations would be crowdsourcing research into nanotechnology and bioengineering through a game interface.

Crowdsourcing Research

This idea of using a game interface to crowdsource research is not science fiction; it's in use today. While crowdsourcing research computations through distributed computing has been a long-standing practice, only recently has distributed computation been applied to tasks that still require human interaction.

Some kinds of classification or analysis tasks are still out of easy reach of our computational models; visual identification of objects in a photograph is a good example of this. Some, like determining what is aesthetically pleasing to a specific individual, may never be solvable by computation alone. This kind of distributed human input can be leveraged to create remarkably complex calculations. Amazon refers to these as 'human intelligence tasks' in its Mechanical Turk distributed computing system.

Zooniverse is one excellent example of this framework, collecting many projects that require human input to process large data sets (Zooniverse, 2016). Users can help out ecologists by tagging the type and behaviour of species in photos captured by automated trail-cams, or identifying plankton in slides. Recently the massively multiplayer game *EVE Online* took this a step further and integrated a crowdsourced research project as a game within their existing game world (It's Science, 2016). While waiting for other in-game actions to complete, players are able to spend their downtime identifying cell structures in slides captured for the *Human Protein Atlas* project.

By placing user interaction with the research system within a game environment, human input can lead to the recognition of interesting dynamic behaviours, aesthetic choices, and system dynamics. One great advantage is that users see their evaluation as fun rather than work, making them much more likely to participate regularly and persistently. In the case of *EVE Online*, in-game items and currency are used to reward players for contributing to the project.

While *microcosm* may not currently support distributed research of this kind, at the very least it can help spur the discourse around the development of these kinds of crowdsourced game-like systems. The narrative frame of science fiction provides a way to discuss the possibilities of our complex play with machine intelligences and ecologies.

Bio-Inspired Economies

Much of economic and state policy has been based upon (frequently misleading) biological metaphors. Free-market capitalism uses the supposedly natural idea of individuals competing for personal gain (nature as ‘red in tooth and claw’) to legitimize the modern nation-state, yet observations of ecologies show that this dynamic is extremely minor compared to cooperative strategies. By and large, any kind of complex system requires regulation, communication, and sophisticated social dynamics.

Free-market fundamentalism believes that growth is the only metric of value. There is a name for unregulated growth in biological systems; it's called cancer. I believe that economic and political systems should strive to create ecological equilibrium instead, or better yet what Bateson refers to as 'dynamic disequilibrium,' when self-regulation leads to balance while still supporting continuous change. If we're going to turn to biology for inspiration then I want to help shift the metaphor.

The larger scale world of *microcosm* could simulate the dynamics of a procedural economy by trading resources and the knowledge generated by the ecology exploration mini-game. Corporations would be AI controlled agents and could engage in a variety of interactions and strategies with one another, from cooperation to all out war.

The goal of the overall system would be to test out different kinds of economic systems and see which ones were most resilient and flexible. Ideally this could help to shift player's ideas about how 'natural' or inevitable free-market capitalism really is. There would also be an interesting symmetry in the dynamics of the small ecologies (nanites and cells) and the dynamics of the large ecologies (asteroids and corporations).

The Future of *somata*

Somata will continue development as an ongoing project in the *Mobile Experience Lab*. I will be participating in a workshop held at the Nova Scotia College of Art and Design, where our team will collaborate with an interdisciplinary performing arts class to brainstorm and experiment with new features and directions for the project.

One direction I would like to pursue is bringing more transparency and visibility to the links the system generates between the input and the output. Using a similar visualization to *microcosm*, inputs could be displayed as nodes in a network, with normalized activity resulting in changes to opacity or color. This would allow the input to be visualized in an aesthetically pleasing way.

Additionally, this kind of layout would allow inspection of all the components and even user modification to fine tune the animations of the mandala.

To make this even more like a neural network each node could be given an activation threshold. When it exceeds this threshold it can fire, activating linked nodes and triggering corresponding visual changes. This would allow for motion and brain activity to be visualized as a randomized linked network and may even serve as an alternate aesthetic visualization to the main mandala.

The Future of *microcosm*

As with *somata*, one of the first goals for future work on *microcosm* will be to make more of the tacit parameters of the system visible to users. I'd like to use the same network visualization to allow users to examine and tweak the behaviour trees that individual cells use to select their actions.

Once these behaviour trees were editable by players, *microcosm* could be used to teach basic programming concepts by allowing users to combine the building blocks of the trees into modular chains. This would both give players a better sense of the dynamics of the system, and allow for much greater customization and variety in the interactions between cells.

I'd also like to make better use of the networking abilities already built into the system, allowing users to share world and creature seeds with each other and perhaps even to play within the same world. *Microcosm* could easily be used to explore more complex network dynamics by allowing multiple nests and communities of organisms to exist in the same environment. This could open up the possibility of competition between cells for resources as well as allowing for more complex, large-scale cooperative behaviour.

Situating the gameplay of *microcosm* within the fictional world described above would also allow for much more persistence and narrative experience. Players could develop specific colonies of organisms over time, customizing them to support different tasks in the larger game world.

Ultimately, players could discover and evolve strategies of AI that were enjoyable to play with or against, and then share those with each other to create a rich spectrum of possible game experiences.

Conclusion

The blessing and curse of an infinite game is that it requires infinite development. I've stated some of the ways that I hope to continue to expand the possibilities for play within *microcosm*. As I discovered while building it, some features can be planned but others must evolve dynamically through interaction and play. Rather than lamenting this, I hope to allow *microcosm* greater capacities to encode its histories of inter- and intra-action to support growth and change over time.

Adding additional persistence and narrative framing to the world of *microcosm* will allow it to better fulfill its goal of infinite play. I hope that over time it will allow for a variety of finite games to be played within its bounds, as these kinds of play experiences can help add complexity and nuance to the overall world. If, as Carse (1985) believes, societies are constructed out of many overlapping finite contests (p. 50), then it is only by replicating some of the contests of power, politics, and economics that constitute a nation-state that *microcosm* can enter into play with them.

Ultimately, as I build more tools to explore and interact with *microcosm*, I hope to open up its evolution to many players, allowing it to be guided by the infinite play of many participants. Together, I hope to co-create a world of possibilities where we can have “pleasure in the confusion of boundaries” and “responsibility in their construction” (Haraway, 1991, p. 150).

I feel that the surest sign of success in building the framework for *microcosm* is the fact that I am still excited to work on the project, even after many tangled iterations and revisions. The combined code of engine and game represent the largest codebase I have ever worked on, and it was quite surprising to me to get this far and not feel like I wanted to start over from scratch. Along the way I have learned a lot about keeping code modular and maintainable, and I look forward to adding to and improving both game and engine.

I’ve decided to separate out many of the elements that handle evolution and genetics into the engine and try to release it as *Symbio:* an open-source framework for making bio-inspired games and educational tools. *Symbio* would be different from other evolutionary toolkits because it would focus on co-evolving organisms together in ecological networks and supporting playful interactions with the evolving systems. I hope to use the engine to build a number of other small games and demos to help explore the potential of such a framework.

The fact that a game as simple as *microcosm* was able to start discussions among its players about ecological interdependency and mutualism encourages me that *Symbio* could be a useful tool for educators and game developers alike. The more games we can get out into the general public that get people thinking about the ecologies they are a part of the easier it will be to start discussions about how humans can change our relationships with the complex overlapping worlds we inhabit.

Microcosm succeeded in supporting both finite and infinite play, but there are still many opportunities to improve and expand the flexibility of the infinite layer. Adding layers of gameplay and customization should give players much more power in shaping both the organisms they control and interact with and the overall dynamics of the gameplay itself. I see the current version of the game as a single seed from which a whole tree of play experiences can be cultivated and explored.

References

AlphaGo: Using machine learning to master the ancient game of go. (2016, January 27). Retrieved from https://googleblog.blogspot.ca/2016/01/alphago-machine-learning-game-go.html

Bateson, G. (1972). *Steps to an Ecology of Mind*. New York, NY: Ballantine Books.

Buzsáki, G. (2011). *Rhythms of the Brain.* Oxford, UK: Oxford University Press.

Brahic, C. (2014, July 19). Meet the electric life forms that live on pure energy. *New Scientist, 2978*. Retrieved from https://www.newscientist.com/article/dn25894-meet-the-electric-life-forms-that-live-on-pure-energy/

Brenner, C. B., Zacks, J. M. (2011, December 13). Why Walking through a Doorway Makes You Forget. *Scientific American.* Retrieved from http://www.scientificamerican.com/article/why-walking-through-doorway-makes-you-forget/

Carse, J. P. (1986). *Finite and Infinite Games*. New York, NY: Ballantine Books

Carpenter, S. (2012, September). That gut feeling. *APA Monitor, 43,* (8), 50.

Floreano, D., Mattiussi, C. (2008). *Bio-Inspired Artificial Intelligence*. Cambridge, MA: The MIT Press.

Güntürkün, O. (2016). Some birds are just as smart as apes. Retrieved from http://aktuell.ruhr-uni-bochum.de/pm2016/pm00026.html.en

Haraway, D. J. (1991). A Cyborg Manifesto: Science , Technology , and Socialist- Feminism in the Late Twentieth Century. *Simians, Cyborgs, and Women: The Reinvention of Nature*, 149–181. New York, NY: Routledge

Haraway, D. J. (2008). *When Species Meet*. Minneapolis, MN: University of Minnesota Press

Hayles, N. K. (2006). Unfinished Work: From Cyborg to Cognisphere. *Theory, Culture & Society*, *23* (7-8), 159–166. http://doi.org/10.1177/0263276406069229

Hofstadter, D. (2007). *I Am a Strange Loop*. New York, NY: Basic Books.

Huizinga, J. (1955). *Homo Ludens; a Study of the Play-Element in Culture.* Boston, MA: Beacon Press.

Jung, C. G., (1989). *Memories, Dreams, Reflections*. New York, NY: Vintage Books. (Original work published 1961)

It's Science! EVE Online Players Contribute to Human Protein Atlas in Project Discovery. (2016, March 9). *Gamasutra*. Retrieved from http://www.gamasutra.com/view/pressreleases/267641/ITS_SCIENCE_EVE_Online_Players_Contribute_to_Human_Protein%20Atlas_in_Project_Discovery.php

Keogh, B. (2014). Across Worlds and Bodies: Criticism in the Age of Video Games. *Journal of Games Criticism, 1* (1)*,* 1-26.

Lukoševičius, M., Jaeger, H. (2009). Reservoir computing approaches to recurrent neural network training *Computer Science Review, 3* (3), 127–149.

Maturana, H. R., Varela, F. J. (1998). *The Tree of Knowledge: The Biological Roots of Human Understanding* (2nd Edition)*.* Boston, MA: Shambala

McDonald, K. (2015). Biologists Discover Bacteria Communicate Like Neurons in the Brain. *UC San Diego News*. Retrieved from http://ucsdnews.ucsd.edu/pressrelease/biologists_discover_bacteria_communicate_like_neurons_in_the_brain

Miller, S. G. (2015, September 22). People emit a unique "microbial cloud" of bacteria, study finds. *CBS News*. Retrieved from http://www.cbsnews.com/news/people-emit-a-unique-microbial-cloud-of-bacteria-study-finds/

Mnih, V., Kavukcuoglu, K., Silver, D., Rusu, A. , Veness , J., . . . Hassabis, D. (2014). Human-level control through deep reinforcement learning. *Nature*. Retrieved from https://storage.googleapis.com/deepmind-data/assets/papers/DeepMindNature14236Paper.pdf

Polanyi, M. (2009). *The Tacit Dimension*. Chicago, IL: University of Chicago Press. (Original work published 1966)

Rosen, S. (2015, November 14). Diagram captures microbes' influence across animal kingdom. *Science News, 188* (10)*,* 32.

Sharpe, L. (2011). So You Think You Know Why Animals Play… *Scientific American*. Retrieved from http://blogs.scientificamerican.com/guest-blog/so-you-think-you-know-why-animals-play/

Stoller-Conrad, J. (2015, April 9). Microbes Help Produce Serotonin in Gut. *Caltech*. Retrieved from http://www.caltech.edu/news/microbes-help-produce-serotonin-gut-46495

Tsing, A. (2012). Unruly Edges: Mushrooms as Companion Species. *Environmental Humanities, 1*, 141-154

University Of Georgia. (1998, August 25). First-Ever Scientific Estimate Of Total Bacteria On Earth Shows Far Greater Numbers Than Ever Known Before. *ScienceDaily*. Retrieved from www.sciencedaily.com/releases/1998/08/980825080732.htm

Walton, M. (2016, March 14). Microsoft is using Minecraft to train AI and wants you to help out. Retrieved from http://arstechnica.com/gaming/2016/03/microsoft-minecraft-aix-artificial-intelligence/

Zooniverse (2016). About us. Retrieved from https://www.zooniverse.org/about