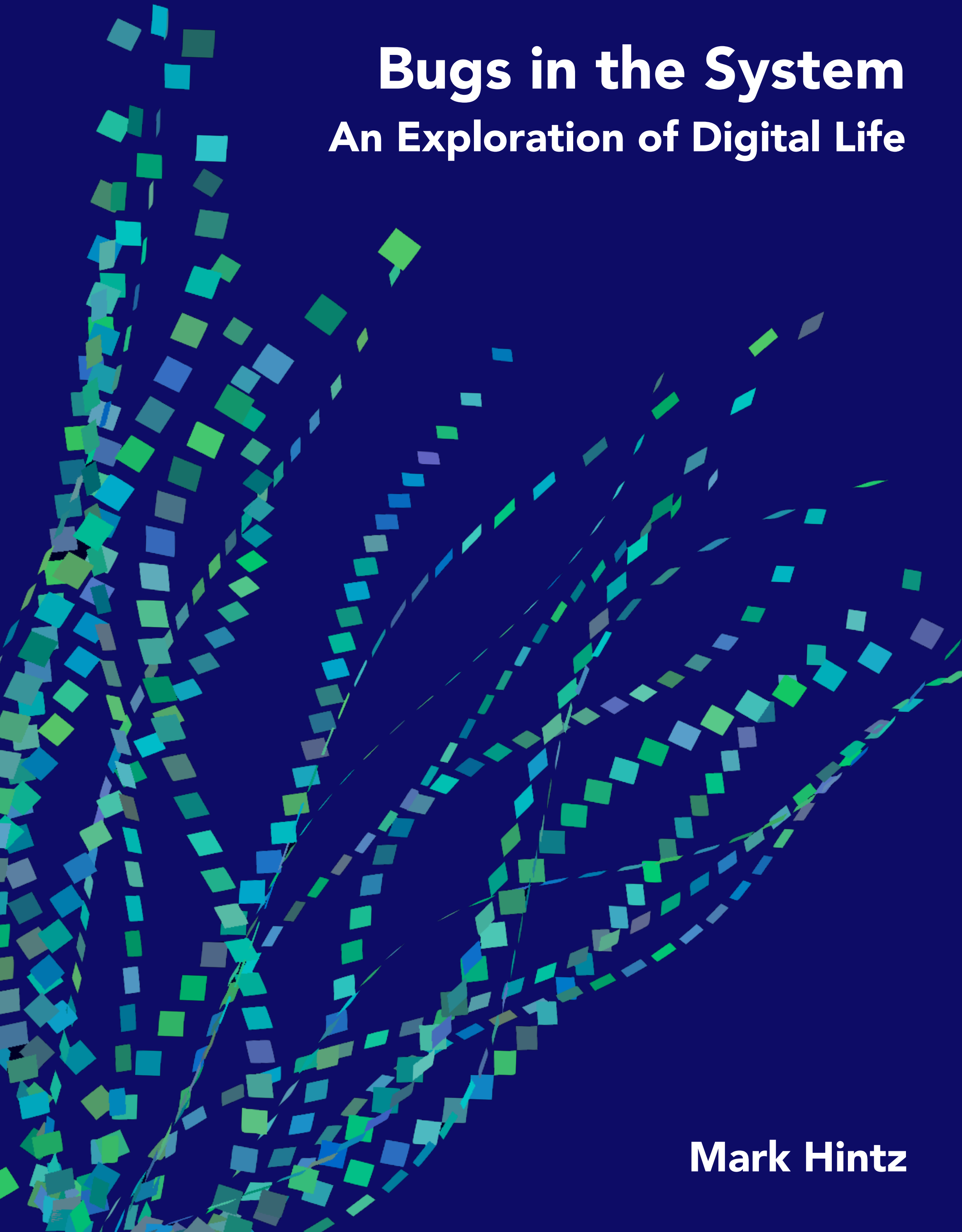
Bugs in the System

An Exploration of Digital Life



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Bugs in the System: An Exploration of Digital Life

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Abstract

This project is a work of speculative design investigating the possibility of digital life. Drawing on scientific debates about the essence of life, it describes the distinct properties of living organic processes. These are then applied to digital processes, asking whether digital life could exist, and how it would appear.

Alongside this theoretical work are example programs demonstrating some lifelike properties, presented in an installation based on the speculative concept of a natural history museum of the future. The installation invites viewers to probe the complexity of existing digital systems and to interrogate the nature of life itself. Perhaps some digital life is already growing, like microbes, inside our opaque digital ecosystem.

Keywords

Digital Life, Generative Design, Speculative Design, Complex Systems, Origins of Life, Computer Graphics, Installation, Interactive

Abstrakt

Diese Arbeit verwendet spekulatives Design, um über die Möglichkeiten eines digitalen Lebens zu reflektieren. Ausgehend von wissenschaftlichen Diskussionen über die Essenz des Lebens werden die Eigenschaften lebender organischer Prozesse beschrieben und anschließend ins Digitale übertragen. Auf dieser Basis wird dann der Fragestellung nachgegangen, ob im Digitalen Leben existieren könnte und wie es aussehen würde.

Zusätzlich zu diesem theoretischen Rahmen werden Beispielprogramme herangezogen, die einige Eigenschaften von Leben aufweisen. Die spekulative Ausstellung basiert auf dem Konzept eines Naturkundemuseums der Zukunft. Sie lädt Zuschauer ein, die Komplexität existierender digitaler Systeme zu erproben und der Frage nach der Essenz des Lebens nachzugehen. Denn vielleicht wachsen digitale Lebewesen schon, wie Mikroben, in unserem undurchschaubaren digitalen Ökosystem.

Stichworte

Digitale Leben, Generative Gestaltung, Komplexe Systemen, Ursprünge des Lebens, Computergrafik, Installation, Interaktiv

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One can set out to construct a minimal form of life only if one has at least a working hypothesis about life's minimally sufficient conditions. Otherwise one would have no idea what to try to make. (Bedau 2007b: p. 461)

Introduction

The focus of this thesis is the concept of "digital life": its interpretation, its complexity, its nature, and its potential. The idea that life could exist with digital material may seem like an inherently contradictory concept at first glance, but the hope is that, after encountering the research and arguments in this thesis, the reader will be more comfortable with that term, and will have a more thorough understanding of the concept's history, present, and possible futures.

It hardly needs saying that the phenomenon of biological, carbon-based life is one of the most complex and fascinating phenomena in the natural world. Humans are not only surrounded by an immense variety of other life forms, we also often congratulate ourselves as being life's crowning achievement. Biological life on Earth has, over a period of several billion years, produced creatures capable of reflecting upon and studying themselves and their own evolutionary development. That is an astounding phenomenon, one which as far as we know has no parallel anywhere else in the universe.

Humans have always been toolmakers, extending our bodies and our minds with creations of increasing sophistication, each new tool being used in some small way to help us conceive of and produce the next one. And now, in the early decades of the 21st century, we have created our most complex and powerful tool yet, the digital computer. The digital computer has been developed, mass-produced, and spread from its humble beginnings in experimental laboratories and theoretical research, to accompany humans everywhere we live, on every continent, in every corner of the world, and into the void of space beyond. At this point we have even used computers to explore locations, such as the surface of Mars or the bottom of the ocean, which no human has ever seen with their own eyes, and to report back what is found there.

Every computer is roughly bounded by its physical dimensions, but its electronic state encodes a vast amount of information, and furthermore that information can be copied and moved across the entire population of similar devices on the planet. We have developed infrastructure for the spread of this information, and many of us use that infrastructure every day, relying on the connection it provides between our devices to consume, to create, and to communicate information with others around the world. Taken in total, the sum of computers themselves and the infrastructure of communication between them can be seen as a massive system, mostly interconnected, which contains many smaller entities, and encompasses an enormous amount of processing capability and data storage capacity.

The topic of this thesis is the phenomena that already exist, and the phenomena that are possible, where our understandings of biological life and digital computers overlap. In doing so, I will be considering phenomena both biological and digital, and asking what it might mean to imagine lifelike, or even living, processes that exist within the systems of digital computers. My goal is not to argue that the digital phenomena under discussion are alive in the same exact way that biological creatures are alive. Rather, the idea is to ask, "Is such a thing as digital life possible? What characteristics could it have? If it were to appear some day, would we recognize it? Would we be able to understand it?" This leads to a concise formulation of my research question: what could digital life look like if it were to emerge?

The dual meaning of "look like", which could be interpreted as demanding either an explanation of its characteristics or a demonstration of how digital life could literally visually appear, is intentional. The theoretical part of this thesis, presented in this written document, offers a textual description of what characteristics digital life would have. Meanwhile, the praxis part of this thesis, presented as an installation, depicts how digital life might visually and experientially appear were it to develop in the future. In answering the research question, this thesis is partly speculative, partly practical, and partly explorational. I will speculate about the potential of a phenomenon, discuss practically the characteristics it would have, and explore examples which hint at a possible future.

Methodology

To answer my research question, I will first contextualize the concept "digital life" within the fields of biological, technological, mathematical, and design study. This thesis then turns to theories from biology about the defining characteristics of organic life – its origin, its unique processes, and precisely what it is that distinguishes biological life from other naturally occurring chemical phenomena. This fundamental topic in biology is, perhaps surprisingly, still a matter of much debate among experts, and any consensus is continually being challenged by new discoveries. Once a working characterization of the key qualities of biological life has been developed, this thesis considers what those fundamental characteristics might look like in digital form. That is, with the hardware, software, and processing power of digital computers as their basic building blocks, rather than the organic macromolecules and chemical reactions of biological life. That discussion will include consideration of extant digital phenomena which display some of the characteristics of digital life. Lastly, I will describe my work implementing examples of lifelike digital phenomena, contextualizing them within a speculative concept, and presenting them in an installation based around that concept.

The goal of this written, theoretical part of this thesis is to answer the research question descriptively, to present the characteristics that digital life would have. This requires referring to research on what distinguishes biological life from other chemical processes, and using that as a basis for determining what would distinguish digital life from other digital processes. On the other hand, the goal of the praxis part of the thesis is to answer the research question demonstratively, to present a visual, physical example of the characteristics that digital life might have. This requires implementing systems that are reasonably lifelike, and presenting them in an installation which contextualizes them in an imagined world of the future. This is a necessarily fictional, perhaps even poetic approach to the question. I am interested in the possibility of digital life, and since no such thing as digital life currently exists, I must imagine it, speculate about its characteristics, and present it to viewers as a design fiction.

Praxis Connections

The two parts of this thesis project are separate, but related. The theoretical argument applies concepts surrounding biological life to digital systems, and interrogates whether the comparison fits. The praxis part illustrates these concepts physically, rather than verbally, with a group of computer simulations of lifelike behavior presented in the speculative installation. The installation presents these example programs as a display in an imagined natural history museum of the future. The viewer is transported forward in time to a future in which digital life is all around us, thriving in all of our devices and in every niche of the ecosystem of the net. They see a collection of life forms gathered from "the wild" and trapped within a glowing otherworldly form. Although the simulations are examples of the current state of technological development, the installation presents them as something far more advanced, sparking a consideration of the possible future evolution of our current technologies.

The installation seeks to convey the discussion of the current and future possibilities for digital life to a wider audience, to display digital systems which go outside of the common conception of computer systems, and to inspire the same questioning in others that I am engaged with here – what does it mean to consider a chemical or digital phenomenon to be alive? And have our creations begun already to display these characteristics? This work follows Anthony Dunne and Fiona Raby's concept of speculative design (Dunne and Raby 2013). It proposes a possible future, and then invites the viewer to engage with that future, to become enchanted by it, to interrogate it, and to evaluate it as both a concept and a possibility. As Dunne and Raby write, "design speculations can act as a catalyst for collectively redefining our relationship to reality" (Dunne and Raby 2013: p. 2). Furthermore, in the realm of emerging technologies, Dunne and Raby argue that "by moving upstream and exploring ideas before they become products or even technologies, designers can look into the possible consequences of technological applications before they happen" (Dunne and Raby 2013: p. 47). The goal of this project is to speculate plausibly on the concept of digital life, and to build an installation which presents that speculation, invoking a redefinition of our relationship to the existing digital technologies that surround us, and engaging proactively with the future consequences of technological change.

This work's speculative approach is similar to that taken in other design work engaging with the possible future directions of life. As an example, Alexandra Daisy Ginsberg's project "Designing for the Sixth

Extinction" imagines a world in which we can genetically program new creatures that have custom behavior. It presents a trio of species with synthetic DNA, whose behavior, interactions, and life cycles have been programmed to conserve biodiversity and a healthy environment in a future forest (Ginsberg 2013). Ginsberg's project imagines entirely new future organic life forms that have been artificially created by humans. This project, by contrast, imagines the digital biodiversity of the future, creatures which exist within the human-made environment of digital devices, but are nonetheless just as living as Ginsberg's forest creatures. Both projects are engaged in a kind of speculative zoology. The primary difference is the choice of constituent materials for these imagined creatures.

In my imagined world, digital life has arisen in much the same way that biological life probably arose on earth billions of years ago – spontaneously, unplanned, and without any discernible purpose. Perhaps the forebears of such digital beings would have been created by humans, but at some point the system started to get out of control. Many digital systems we have created are arguably already more complex than any one human can fully understand, notably including most recent advances in artificial intelligence (Knight 2017). It has therefore become easier to speculate that with a few further steps something as complex and mystifying as biological life might emerge.

Positioning

The concept I am pursuing is in an important sense different from the related concept of artificial intelligence. As a concept and as a research field, artificial intelligence is concerned with the instantiation, in a digital medium, of a kind of consciousness that resembles that of a human or an animal. It is fundamentally focused on the replication of cognitive processes with digital means. This research, by contrast, is focused on the concept of living processes themselves, distinct from any consciousness which those processes might display. Living processes are composed of naturally-occurring chemicals, yet they are distinct in particular ways from nonliving chemical processes. I explore the essence of this distinction and ask if the same essence could be demonstrated by digital processes.

This is also a value-neutral proposition. Scholars and commentators have variously predicted positive and negative consequences around the concept of artificial intelligence, or thinking machines. In considering digital life, I am speculating about the nature of a digital processes that would much more closely resemble a bacterium than a human mind. Bacteria in the natural world are not necessarily positive or negative, they simply exist. We humans interact with bacteria in positive and negative ways, and in these interactions lies the good or the bad. Likewise, the development of digital life could be positive or negative, depending on how we see these digital creatures, and depending on how they interact with us. Rather than arguing that digital life would be a "good" or "bad" development for humanity, this work's goal is more fundamental. It is to provide a plausible conception of how such creatures might function, and how we might recognize and perceive them. The knowledge gained from this thesis is its challenge to the concept of life, and the argument that life could indeed exist inside a digital medium. This project, both theory and praxis, represents a descriptive and demonstrative approach to that argument. Using both word and artifact, it fleshes out an answer to the research question, showing what digital life would look like were it to develop on Earth.

In chapter one I situate this project within its academic context, showing its interdisciplinary nature and noting the particular connections it has with diverse fields, including biology, computing, philosophy, and design. In this chapter I will also introduce some fundamental concepts. In chapter two I lay out the results of research from biology and philosophy, where I pin down a working characterization of the fundamental characteristics, the essence, of biological living processes. In chapter three I apply this working characterization to digital processes, speculating about the possible nature of future digital life, and I discuss a few examples of digital processes which already display some aspects of digital life. In chapter four I provide context for and description of my own speculative exhibition. Lastly, I conclude with an evaluation and critical engagement with the subject.

Chapter 1 - Context

The topic of digital life touches directly on two major fields of study, biology and computing. Furthermore, past work that theorizes about the phenomena that lie at the intersection of these two fields is also connected to complexity theory, philosophy, and design. This chapter will contextualize this thesis by linking to broader areas of academic study. It will also point out what this thesis does not cover, by delineating the topic from other related areas. Asking questions about the nature of life opens up some deep fundamental topics, which for practical reasons cannot be presented in full here. This chapter will indicate them, and the reader is encouraged to explore further via the bibliography.

Biology

Within the field of biology, the area which this topic touches is the ongoing fundamental discussions about the definition of life. Life is the central concept of biology, but defining what exactly is life and what is not remains an elusive goal. This is because, while living organisms display many "hallmarks" (e.g. reproduction or metabolism), there are also non-living processes displaying those same hallmarks, and there are numerous "edge case" examples of processes we would still want to describe as living, but which nevertheless do not display all of those hallmarks (e.g. sterile or dormant organisms) (Bedau 2007b, p 458). Some biologists argue that a definition of life is not actually relevant to the kinds of studies they are doing in the life sciences (Bedau 2007b, p 455). However, when considering digital life, it is important to be clear on the fundamental characteristics of biological living things, from a physical, conceptual, and functional perspective.

The ongoing discussion among biologists about the mechanism of the origin of life is also relevant here. This is because the discussion has at its heart the question of when precisely a collection of presumably random chemical reactions began to be living processes, and how this transition might have come about. If we can find a satisfactory answer to this question, then we can begin to decide when a collection of digital processes can be considered to have become digital life.

Computer Science

Any discussion of digital life must also rely on the field of computer science, since a good understanding of digital processes, including their creation, functioning, and possible futures, is key to clarifying how a living digital process might work. It should be understood that "digital processes", in the abstract, can be conceptualized as distinct entities, regardless of how many other processes are running on the same physical computer. In understanding any given digital process, the two fundamental concepts are the data structure and the algorithm.

Data structures are the stored information content at any given moment in a program's execution. Computer storage consists entirely of digital bits, that is it is made up of billions of units of binary storage of either a 1 or a 0. Groups of bits are then considered to represent different kinds of fundamental data, with different combinations of 1s and 0s standing for different numbers or letters. Aggregates of these fundamental data types are also used, with groupings copied and passed around as if they were single entities.

Algorithms are the operations which the computer carries out to manipulate its stored data. An algorithm is represented as a series of instructions in computer memory, which are fed into the computer's processor one by one, along with the location of the stored data upon which the instructions should operate. Every computer processor provides some set of relatively simple, usually mathematical, instructions which it can execute, and programs are composed of millions of these simple operations. Most creators of digital processes do not operate at this "low level" of the computer's instructions, but rely on more abstract programming languages to express their ideas and intentions.

In the theoretical discussions in this thesis, both the computer hardware and the programming language of choice will be mostly abstracted away, except in cases where a dip into this "low level" is useful to illuminate some concept. This abstraction is possible because of one of the fundamental theories of computer science, that any process, storing any kind of data, may be executed by any computer that fulfills certain very basic physical and technical requirements. Differences among different physical computers and programming languages are almost always simply a matter of how much time and storage space the computer requires to execute the process in question.

Mathematics and Philosophy

Discussions of digital life often make reference to theories from mathematics and philosophy. One of those is the theory of complexity, which is in turn the study of complex systems. In the technical sense employed by mathematicians, "complex systems typically have a large number of small parts or components that interact with similar near-by parts and components. These local interactions often lead to the system organizing itself without any master control or external agent being ‚in charge'" (Galanter 2003, p 5). Biological life is considered one of the classic examples of a complex system (Bedau and Humphreys 2008: p. 2). The behavior of complex systems is determined by their constituent entities, but the behavior of the whole system is usually not directly derivable, or even predictable, from the behavior of the entities. A complex system as a whole is therefore usually not describable using the precise logic of mathematical language. Often the only way to predict its behavior is to simulate the system's functioning over a period of time and see where it ends up. When a natural system must be predicted through simulation in this way, the simulations are necessarily imperfect. In addition, a computer simulation of a complex natural phenomenon is itself by definition a complex system, and therefore unpredictable by traditional mathematical means (Galanter 2003, p 6).

The behavior of complex systems that arises out of the interactions of their parts, which cannot be predicted, is often described using the philosophical concept of "emergence". Any property that a system displays which arises out of complex interactions, but which is not directly derivable from them, is called "emergent". The concept of emergence is currently a hotly debated topic in philosophy, where "emergentism" is positioned as a counterpoint to reductivism, the philosophy which argues that systems can be explained by a precise deconstruction and explanation of their constituent parts (Bedau 2002, p 10). Emergentism tends to hold that emergent behavior is not fully describable in this way, but is in fact a higher-order class of behavior that appears in complex systems. Theories of complex systems and emergence will both be discussed in more detail later, with more concrete examples at hand.

When considering arguments about the essence of life, one might ask if life is even something that has an essence at all, or if "life" is simply a grouping imposed by human perceptions and custom. In analytic philosophy terms, one asks if life is a "natural kind" (Bedau 2007b: p. 462).

Furthermore, does it make sense to speak of a boundary between living organisms and the nonliving material around them, or between living and nonliving chemical processes? Perhaps the entire earth, including all its matter, is living, and what humans perceive as organisms are simply smaller parts of this greater living whole? These epistemological questions are covered in more detail in other sources, especially Mark Bedau and Carol Cleland‘s book The Nature of Life. Suffice it to say that I take the position that there is indeed something distinguishable and special about living creatures that separates them from other natural phenomena. This specialness is what I have called the essence of life, and is what I will seek to characterize in the discussion that follows. One might then ask if this essence is a property of the material of life, organic molecules, or of the structure and behavior of that material. This is a topic which will be covered in the next chapter. Because of the difficulty posed by satisfactorily resolving the ongoing debate about the essence of life, and coming to a precise "definition of life", I will prefer to use the term "working characterization".

Artificial Life

In contextualizing this study, it is worth mentioning the most prominent academic efforts in the area of digital life, which come from the field of "Artificial Life" (also known as ALife or simply AL). Artificial Life as a discipline traces its roots back to work done at the Center for Nonlinear Studies at the Los Alamos National Laboratory which synthesized several existing fields of research in the academic community (Langton 1989: p xv). Diverse academic studies, including that of self-reproducing machines, self-guided machines, robots, and systems theory, were given the title "Artificial Life" in a paper by Christopher Langton that reported on one of the earliest conferences of the field (Langton 1989: p 19). In that paper, Langton provides his foundational definition of the study of Artificial Life as:

> "The study of man-made systems that exhibit behaviors characteristic of natural living systems. It complements the traditional biological sciences concerned with the analysis of living organisms by attempting to synthesize life-like behaviors within computers and other artificial media. By extending the empirical foundation upon which biology is based beyond the carbon-chain life that has evolved on Earth, Artificial Life can contribute to the-

> oretical biology by locating life-as-we-know-it within the larger picture of life-as-it-could-be." (Langton 1989: p 1)

Several of the examples discussed in this thesis are related to the discipline of Artificial Life, but the approach taken here is different from the general approach taken in Artificial Life research. Langton's definition represents the so-called "weak Artificial Life position", which holds that Artificial Life is concerned with creating simulations of biological life in order to better understand biological life processes, but that these simulations are not literally alive. This position contrasts with a "strong Artificial Life position" holding that Artificial Life creations, if not being so now, may one day be literally alive (Bedau and Cleland 2010: p. xxi).

Much research in the field of Artificial Life is based on the weak position, and is interested in better understanding biological life. However, this thesis will investigate interpretations of the strong Artificial Life position, specifically focusing on the digital domain. Drawing on concepts from biology and philosophy, it will speculate on the nature of a digital life form, which would be a literally living process instantiated in a digital medium. It will imagine what would be required for a phenomenon composed of digital data, and driven by digital computation, to be considered alive. The distinction here is small but important. Whereas Artificial Life research works from the current state of the art and aspires towards the future, I will be speculating about the future, fictionalizing a possible future, and evaluating how far the current state of the art is from that speculated possibility. The praxis part of this thesis can then be seen as an extension of that speculation which pulls it out of the printed page and presents it tangibly to viewers.

The field of Artificial Life also includes several research areas which I will not consider in this thesis. One concerns itself with using techniques inspired by nature to solve certain practical problems in computer science, usually optimization or search problems. Although the algorithms themselves display interesting behavior, research on these approaches are oriented towards the practical problems to be solved, discussions of which are outside the scope of this thesis (Floreano and Mattiussi 2008). Another branch of Artificial Life is concerned with creating biological life "from scratch" in a laboratory. These efforts are currently focused on developing a basic functioning wholly artificial cell, and are mostly related to molecular biology (Bedau 2007a: p. 598).

Finally, there is a hardware branch of Artificial Life focused on building nature-inspired robots, using principles from Artificial Life to improve their design and behavior. These side branches are all connected to digital life by a shared focus on synthetic phenomena which exhibit complex lifelike behavior. However, the details of this research diverge sufficiently from the focus of this thesis that I will not cover them in more depth.

Artificial Intelligence

As briefly discussed in the introduction, artificial intelligence research has key similarities to and differences from both artificial life research and the topic of this thesis, digital life. Artificial intelligence is the branch of computer science that seeks to develop programs that display hallmarks of human intelligence, which can complete tasks and solve problems comparable to or more difficult than those which human intelligence can complete and solve. In its early decades, artificial intelligence was dominated by linear-oriented strategies, which sought to model all human intelligence as a centralized control structure choosing from among a list of many possible alternatives (Langton 1989: p. 5). This is an approach similar to the way a program playing a game of chess might consider all possible moves from a given board position and choose the strongest one. However, many situations and choices cannot be realistically condensed into such a list of predefined alternatives.

More recently, the cutting edge of AI has begun to employ neural network algorithms, a nature-inspired process which models intelligence as the combined contribution of many specially-tuned "neuron" agents, each one trained to recognize certain specific features in a dataset. This approach, inspired by the functioning of the human brain, has proved remarkably effective in enabling computer programs to recognize patterns in a variety of datasets, notably in images. This nature-inspired approach draws on the lessons of artificial life research. However, artificial intelligence is in general concerned with simulating human intelligence, which means it has a quite different focus from the goal of imagining a digital life form. The characteristics that make a process conscious, or intelligent, are different from the characteristics that make a process living, and this thesis' speculation is focused on the latter. The fields of artificial life and artificial intelligence have informed my research, but for the reasons given above, and because of the interdisciplinary and speculative nature of this work, this thesis has distinctively different focus and goals.

Generative Art and Generative Design

The final discipline I would like to mention in connection with the subject of this thesis is that of generative art. As Philip Galanter, professor at the Interactive Telecommunications Program at New York University, defines it, "generative art refers to any art practice where the artist uses a system, such as a set of natural language rules, a computer program, a machine, or other procedural invention, which is set into motion with some degree of autonomy contributing to or resulting in a completed work of art" (Galanter 2003, p 4). This definition includes a wide variety of systematic techniques for producing art, techniques which do not necessarily require the use of a computer.

Applications of generative art techniques to areas that are considered to fall under the purview of design have been called generative design. The practice of generative art and design is first concerned with creating artworks and design artifacts, and second with creating complex systems. The creation of the system is necessary for the creation of the artifact, but the system is tweaked so long as the artifact is unsatisfactory. The idea is to create a system whose functioning is regular enough that it produces artifacts with the desired quality and appearance, but also unpredictable enough that it surprises the creator of the system. Often, the use of generative systems lends some of the random, unpredictable, and organic quality of natural forms to the resulting artifacts.

A digital life process as hypothesized in this thesis would be a complex system. Its output, such as it had, could even be considered a work of generative art or design. (This has to do of course with how one defines art and design, a much longer discussion.) More generally, the principles of creating and working with complex systems are similar whether one speaks of digital life or of a complex generative system for art and design. The study of living digital systems has applications in deeper understanding of generative design systems, both concerning their functioning but also their creation by designers. For example, in the praxis part of this thesis, generative techniques were used to produce the visual content of the speculative installation about digital life. There is thus a close connection between study of complex systems, including hypothesized digital life, and creation of generative design artifacts.

The field of generative techniques is also quite relevant to the state of the art in design as a whole. Contemporary design is increasingly computer-driven, both as the result of the increasing digitization of design production, and because designers are increasingly asked to create digital products. The computer already has an essential place in the toolkit of the modern designer. An understanding of the concept of generative methods, and of the principles of generative systems in design, enriches the designer‘s repertoire, enables the creation of novel visual forms and novel product types, and can even provide a deeper understanding of the complex computer systems which are increasingly central in design. Really complex generative creations have only recently become feasible on consumer computer hardware, but there are already a variety of programs that enable designers, even those who don‘t know how to write computer programs, to create complex and interesting generative design systems. Being able to construct complex systems which display many of the same intricate patterns and variety as nature adds a powerful tool to the designer‘s aesthetic toolbox. Furthermore, if the designer learns any one of a number of commonly-used programming languages, they have access to a whole host of generative techniques and production methods which can create endless interesting and useful forms.

The study of complex systems is also very relevant to the broader social role of the designer, especially when it comes to understanding and designing for society in the 21st century. Our interconnected societies have rapidly become very complex systems. No longer constrained to smaller scale units like the community, the city, or even the nation, our globalized society now includes people from a stunning variety of backgrounds. The complexity and scale of human interactions around the globe is unprecedented. The density of our networks mean that culture, ideas, and technologies travel with extreme velocity through our densely interconnected human society. This is the essence of a complex interacting system, pulsing with information, ideas, stories, and memes. For the designer, this means that not only is an understanding of the dynamics of such systems remarkably relevant, it also changes the types of products that they might want to design.

In an interconnected, complex society without a single strong pole of cultural control and with a multitude of overlapping social groups, distributed strategies will succeed. Technologies which have been designed to work effectively at the individual level, and to be shared and spread throughout networked society, will see wide adoption. Because of the distributed-yet-interconnected nature of these technologies, design decisions made for the individual level will have effects at the system level that can be very difficult, if not impossible to predict. Individual actions and interactions, in the aggregate, will produce emergent systemic effects. Whether the result is intended or not, the effects of large scale adoption of new technologies, all of them products of a design process, will alter human society in the large. And these effects won't just be confined to certain regions or demographics. (As an example, just think of the ways that infinite-scrolling "news feed" design has affected our relationship to social media platforms, and our interactions with each other through them.) This is something which the designer of the 21st century must take into account while doing their work.

In generative design, the designer is constantly thinking about how a relatively small local change to a parameter, or to a rule of interaction among agents, will affect the behavior of the group of agents as a whole. The whole challenge of the process of doing generative design rests in these kinds of considerations. A good change is one that not only works for the individual, but also improves the behavior of the whole along the desired dimension. To do this kind of distributed design, it is essential to think through the systemic consequences of different design decisions. In the distributed thinking that will characterize effective design in the 21st century, designers are challenged to make decisions that encourage the most positive future, perhaps by only altering behavior at the individual level. New technologies, distributed throughout the population, will have a radical and permanent affect on our ways of life, our interactions with others in our close social circles, and the functioning of our societies as a whole. It is up to the designer to be prepared to initiate and to design these effects. A thorough study and understanding of complex generative systems, among them digital living systems, is key to developing that preparation.

Conclusion

This chapter has presented connections between the topic of digital life and the fields of biology, computer science, complexity theory, artificial life, artificial intelligence, and design. In particular, it points out how study of complex systems, and applications of generative design, relate to current design practice. It has also presented distinctions between this topic and similar fields of study that, although related, will not be covered in depth here. The next chapter introduces the debate about the essence of living processes. I do not presume to present a definitive answer for the definition of life, but it will draw out the most salient themes, and construct a working characterization, which will then be used to characterize digital life.

Chapter 2 - What is Life?

I'll now develop a working characterization of biological life, drawing on research from biology, biochemistry, and philosophy. The goal is to determine when a natural process can be considered a living process. Once a working characterization of biological life has been established, I can then apply that characterization to digital processes, and speculate on what living digital processes might look like. Knowing that, we then know how to recognize digital life if it were to appear "in the wild". It is only when we can describe how life in the biological sense actually is, that we can begin to imagine how life in a digital sense might be. We can then also evaluate how closely existing digital processes are to digital life, and can speculate at the future potential for the existence of digital life.

Throughout this discussion, I will try to keep the material as general as possible, only delving into the specifics of biological processes where necessary to make the argument. The fields of cellular and molecular biology are too large to be presented here, but a high-level summary of the key fundamental processes in biological life should suffice to create a characterization of what it is that makes living things so special.

A clear definition of life is less obvious than it may appear. It is a vexing question that has engaged biologists and philosophers for many years. A key starting point is to observe that living organisms are, fundamentally, the aggregate of trillions of molecules. A large complex organism can be observed at many levels of aggregation by making a series of distinctions. Note that each distinction is sometimes problematic, since it can be hard to draw a precise boundary between different entities under consideration. These distinctions start with separating the organism from other organisms and its environment, divide organs within the organism, tissues within the organs, and then the cells which make up tissues. The cell is commonly considered the fundamental unit of life (Mazzarello 1999). Cells are themselves composed of numerous molecules which are continually involved in chemical reactions with each other. At this level, biology, the study of organisms, blends into chemistry, the study of chemical properties and reactions between molecules. Living cells contain very distinct molecules, and it is this level, where living processes blend with chemical processes, that will be the focus of the forthcoming discussion. The key is to describe the fundamental ways that living molecular and cellular processes are special.

This small level of aggregation, "the level of molecules and biochemical processes" is the one generally considered by modern theorists of the nature of life (Bedau and Cleland 2010: p. xx). However, that is not to say that it is the only level of distinction at which this is an interesting question, as discussions of the aliveness of groups of organisms, and of digital processes, indicate (Bedau 2007b: p. 458). Curious readers are encouraged to consult the bibliography for resources that consider these questions in great depth.

So, given that at a fundamental level, living things are made up of a vast number of molecular elements, the problem is to describe the characteristics of a collection of molecules that make it a living collection of molecules. In addition to the dimension of physical scale which was just used in making those distinctions, consider also the temporal dimension. Living collections of molecules engage in a huge variety of chemical reactions over time, and the nature and function of these reactions is key to the characterization of life. Throughout the discussion that follows, I will also use the term "living processes", referring to this temporal aspect of molecular behavior. A living thing is a particular collection of molecules organized in a particular way and characterized by particular processes over time. It is the nature of that particularity that I will investigate.

No one disputes that a human, or a giraffe, or a sequoia, are alive. Neither is it disputed that bacteria are alive. But difficult questions, which lead to insight about the nature of life, start at the fuzzy edges. Can a clear boundary between living and nonliving be drawn? Are very simple forms, like viruses, alive? Are kinds of life fundamentally different from what we have seen on Earth possible, and would we recognize them if they were? Attempts to answer these questions are informed by both biology and philosophy. These questions also lead us to consider the origins of life in the almost unimaginably distant past. The emergence of living processes from nonliving chemical reactions, called abiogenesis, is an active topic of scientific study (Luisi 2016: p. 3). Scientific hypotheses about the process and characteristics of abiogenesis concern determining the pathways by which nonliving matter became living. These theories directly inform discussions about the nature of life, because if we can explain how a collection of nonliving molecules on the prebiotic earth became biological life, then we can speculate about how other collections of materials might do the same.

Foundations

Since at least Aristotle, philosophers have noted that living processes seem to display a certain purpose, and that this is one of their key characteristics (Bedau and Cleland 2010: p. 2). We think of an inert chemical compound like a stone as existing fundamentally without purpose, while the chemical parts that make up a living system all seem to have their roles in that system, and the system itself is directed towards certain aims, like consuming food, reproducing, and surviving in a sometimes hostile environment. This purpose-driven, teleological conception of living processes has never since left the philosophical discussion. Its primary counterpoint is an argument focused on mechanistic aspects of life, which denies that living systems have a purpose, and argues that seemingly purposeful behaviors of life are reducible to being the result of the complex mechanical interactions of the components of living systems. That is, that the seemingly purpose-driven behavior of living things is directly derivable from the behavior of their fundamental parts. This divide persists in the debate about the nature of life to this day (Bedau and Cleland 2010: p. 2).

A teleological account would consider a process living if it satisfies the same types of function as biological life (it is then a question of defining those functions), whereas a mechanistic account would consider it living if it operated according to the same physical mechanisms as biological life (it is then a question of defining those mechanisms). Mark Bedau, a leading scholar of this question, helps to contextualize the discussion by enumerating different accounts of the "hallmarks" of life, characteristic qualities and behaviors which many — if not all — living processes display (Bedau 2007b: p. 457). These hallmarks, of which scholars have devised many differing but usually overlapping lists, are phenomena which a satisfactory account of the nature of life should encompass. Some key hallmarks he provides are: definition as an indivisible entity (often called holism), metabolism, homeostasis, interaction with the environment, information storage, growth, reproduction, evolution, and mortality (Bedau 2007b: p. 457).

In considering these hallmarks, Bedau notes the examples which demonstrate one or more of the hallmarks, but not all of them. These are the "borderline cases". Viruses, which contain genetic material and not much else, reproduce and evolve but lack metabolism, relying on parasitic use of organisms to fulfill their functions. Spores which can go dormant before sprouting represent the potential for growth, but without capacity for reproduction or metabolism. Chemical processes, like fire, which consume material and maintain a relatively stable overall state, despite constantly changing molecules, represent homeostasis and even growth, without reproduction, evolution, or information storage. Certain insect colonies may display homeostasis, interaction with the environment, and mortality, but they lack holism (Bedau 2007b: p. 458). These cases make clear that the task of characterizing living processes is difficult not just because of the technical knowledge required, but also because of the difficulty of distinguishing in borderline cases between what is life and what is not life. Emphasis on some hallmarks over others has led different thinkers to very different concepts of the nature of life. To delve deeper, I will consider some of the most studied hallmarks.

Reproduction

Given the reluctance on the part of some biologists to tackle the question of life, it is perhaps fitting that a landmark book on the subject should have been written by a theoretical physicist. In 1944, Erwin Schrödinger, famed theorist of quantum mechanics and statistical thermodynamics, published "What is Life? The Physical Aspect of the Living Cell ", one of the first modern attempts at defining the fundamental characteristics of living processes (Schrödinger 1944). Schrödinger's book, which was the result of a series of lectures he gave in Dublin during the second world war, set out an initial position in the modern debate, one which subsequent study has often sought to either validate or disprove, with varying degrees of success.

At the time of Schrödinger's writing, the cell was already known to be the basic building block of living things, and the role of genetics in heredity across generations of organisms had already been established by Mendel. However, the structure of genes had not yet been discovered, nor had the concepts of DNA, base pairs, and the genome with which we are familiar from modern genetics (Dyson 1988: p. 58). Schrödinger's thesis in the book revolves around a deduction from the work of geneticists and biologists, combined with his own observations as a student of probability theory and the laws of physics. He deduced that whatever it was that carried hereditable information from one generation to the next must be a physical substance, present in every reproducing organism, that was stable enough to reliably transmit information from parent to child, yet unstable enough to allow for occasional mutations. Without stability, traits would not be reliably passed on from cell to cell and from parent to child, but without mutations, Darwinian evolution and the gradual differentiation of species could not occur (Schrödinger 1944: p. 41).

After pointing out this potential contradiction between stability and mutation, Schrödinger speculated about the nature of the hereditary substance. Reasoning that the substance must be ordered, and yet capable of encoding a large variety of information, he reached the conclusion for which the book is most known, characterizing the basic unit of reproduction as an "aperiodic crystal" (Schrödinger 1944: p. 61). By this he meant a structure with the regularity and replicability of a crystal, but with variation in its form which could encode for different traits, and which allows for small changes that would create mutations. Later discoveries of the structure and composition of genes served to validate him, by showing that genetic material is made up of a few different basic chemicals, organized in a standard form, but with an infinite number of possible patterns of organization (Dyson 1999: p. 3). Furthermore, as Schrödinger predicted, although genes are usually correctly transcribed during cell duplication and reproduction, occasional random errors and mutations do occur, providing the basic variation required for Darwinian evolution.

In Schrödinger's telling, the role played by genes was the embodiment of the fundamental function of life, reproduction (Dyson 1988: p. 61). Furthermore, Schrödinger believed that life's strange orderliness, which seemingly flies in the face of the second law of thermodynamics, was imposed upon living processes by genes. He saw genes as the concert master, conducting the symphony of life. This is an important statement of what Schrödinger believed was the essence of living processes, that they derive from a set of ordered instructions encoded in genetic material, and that this genetic material, by being replicable and evolvable, enables that orderliness to be extended over the growth of an organism and over evolutionary time from the dawn of life to the present. If growth and reproduction of organisms is seen as the central characteristic of living systems, then the presence of genes, or some other ordered regulatory influence, is the most significant characteristic in determining whether a process is living.

There is a further conclusion to be drawn. Genes remain relatively constant within an individual over its lifetime. Genetic change, and the development of new genetic forms, takes place during reproduction, especially sexual reproduction, as the product of relatively rare mutations that occur as genetic material is copied and combined into new organisms. A gene- and reproduction-focused approach to the essence of life looks at life as a process that stretches across generations. This approach is tightly bound with a teleological Darwinian logic that treats reproduction and evolution as the purpose of life, and therefore defines life as being those processes and entities which satisfy this purpose. Furthermore, it defines as not living those processes and entities which fail to reproduce or which cannot demonstrate the action of some form of heritable ordering information in their development.

Shortly after the publication of What is Life, John von Neumann, another eminent scholar whose work affected a wide variety of disciplines, published "The General and Logical Theory of Automata". In it, he laid out a schema for what he called a "universal automaton" (von Neumann 1948, in Taub, ed. 1961: p. 313), also known as a "universal constructor" (Langton 1989: p. 13). The universal constructor was meant as a physical analogue to British mathematician Alan Turing's Turing machine, which is a simple concept machine capable of calculating any computable function. The universal constructor concept is a simple machine capable of being programmed to build any machine, including itself. Von Neumann worked out as an example one of the earliest efforts at an automaton that could construct versions of itself (Langton 1989: p. 14).

Crucially, von Neumann pointed out that programmed replicating machines like his UC concept must make a distinction between reading the program as commands to be executed, and then reading it during replication as simply a material to be copied. This switching is performed in biological cells, where DNA instructions (the "program" of cells) are sometimes read by proteins to construct operant molecules like RNA and enzymes, and at other times read by other proteins to construct copies of the DNA itself, during the process of cell division. This dual role, and the especially the cellular architecture and types of molecules required to implement it, is a significant part of the story of DNA's special role in living processes.

Recognizing that, the dual role also highlights that DNA alone does not make up the essence of life, because it requires extensive cellular machinery around it to become effective. The ordering of life is not a direct result of the orderliness of DNA, that is, DNA does not directly engage in chemical reactions that directly cause cellular function. Rather, cellular function is the result of a combination of the information encoded in DNA and other machinery required to interpret that information, either as program or as raw material to be reproduced, and to embody that information in protein enzymes which are themselves the agents of cellular function.

Metabolism

Schrödinger‘s foundational account highlights the centrality of genetic material in living processes. But, as von Neumann‘s observations about programmable constructors, and later discoveries in molecular biology have shown, living processes consist of much more than simply genetic material. And DNA itself is inert in the absence of this other cellular architecture, which provides the mechanisms within a living organism that enable genetic material to be expressed in the physical structure of the organism, and that replicate genetic material during growth and reproduction (Dyson 1999: p. 6). These mechanisms are closely related to gene-based reproduction, but they are composed of other chemical processes (Bedau 2007b: p. 465). Schrödinger himself observed,

> "When is a piece of matter said to be alive? When it goes on ‚doing something‘, moving, exchanging material with its environment, and so forth … it is by avoiding the rapid decay into the state of ‚equilibrium‘ that an organism appears so enigmatic … the technical term is metabolism." (Schrödinger 1944: p. 70-71, quoted in Bedau 2007b: p. 465).

He believed that this metabolism was an extension of the regulatory powers of the gene, but that is not the whole story. Freeman Dyson, an eminent scholar working at the Institute for Advanced Study in Princeton, notes in his book Infinite in all Directions that Schrödinger‘s account, the above quotation notwithstanding, spends relatively little time discussing the process of metabolism (Dyson 1988: p. 60).

Metabolism is the process whereby external material is converted into organic compounds and energy which can be used by cells in their daily activity (Dyson 1999: p. 7). It plays an essential role in expressing the genetic code borne by an organism, because metabolism drives development of the organism's constituent parts, and is the essential process that allows an organism to continue its internal chemical processes, to grow, and to continue its existence in its environment. Without metabolism, in other words, the organism would be dead and its genetic material therefore inert, long before it had the chance to reproduce. The molecules which perform metabolism, types of protein, are created based on information stored in DNA, but it is they that then go on to perform, directly through catalyzing chemical reactions, the functions of the cell (including, in self-referential fashion, the creation of more proteins and the copying of DNA).

Dyson points out that if we try to imagine life at a very early stage, before the advent of unicellular life forms, it is more reasonable to imagine a population of proteins developing self-replication, than it is to imagine a population of DNA-like molecules developing self-replication and expression capability. It is something of a chicken-and-egg problem, but to Dyson the precursor to life would be relatively simple proteins that formed what others have called an "autocatalytic set" (Kauffman 1995: p. 92) where a group of chemical compounds catalyzed reactions that produced each other. Combined with a supply of the raw materials for these compounds, this autocatalysis would serve to produce all the members of this set of chemicals, in self-sustaining fashion. In doing so, they would achieve a primitive kind of self-reproduction, one not based on instructions encoded in DNA. Scientists have attempted to create such autocatalytic sets of proteins in the laboratory, searching for the right combination of raw materials that could enter into a self-recreating cycle (Luisi 2016: p. 41).

Drawing on the promise of this model, Dyson places more emphasis on a proteins-first approach to life, suggesting that cell metabolic functions are primary, with DNA entering the picture later as a convenient way of ensuring that the same metabolic functions are carried over generation to generation. Possibly, the earliest primitive DNA strands developed a sort of symbiotic relationship with a population of autocatalytic proteins. Over time, this relationship would have deepened, leading to the cellular division of labor we know today (Dyson 1988: p. 68).

There is a theory which acts as a kind of "unifying theory" between the DNA-first picture introduced by Schrödinger and the metabolism-first picture that Dyson describes. This is the "RNA world" theory, which posits that the earliest life was a population of RNA molecules (Gilbert 1986). RNA carries out a role that is somewhere between the roles of proteins and DNA. It is composed of chains of smaller nucleic acid molecules, like DNA, and strings of RNA often encode information copied from short sequences of the cell's DNA. In addition, RNA structures are often found performing tasks in the cell normally associated with proteins, like catalysis of chemical reactions, in which case they behave much more like active enzymes than like passive stores of information. RNA may therefore represent a sort of bridge between the cellular responsibilities of proteins and DNA. It is possible that the earliest forms of life were populations of RNA molecules that catalyzed their own replication—autocatalytic sets of agents which were at once creators of other molecules and also the blueprints that served to be copied. This theory has emerged as one of the stronger contenders for explaining the origin of life. However, as will be seen, there are issues with a conception of living processes that focuses too much on the molecular materials, and ignores the functional properties of those materials, and the organizations in which they interact.

Thermodynamics and Autocatalytic Sets

In the above discussion, I have highlighted two themes which appear again and again in discussions of the nature of life – its reproductive behavior and its metabolic behavior. A living organism must metabolize material and energy from outside itself in order to continue living, and it reproduces itself, often ever so slightly imperfectly. It carries out these processes in an apparently ordered way, one that defies the chaos often found in other naturally occurring chemical reactions. Furthermore, reproduction over time leads these systems to develop new characteristics, and to evolve.

But we should return to a question posed in the previous discussion of foundations. In speaking of reproduction and metabolism, these behaviors are often positioned as the purpose or intent of the molecules involved. But does the orderliness of living processes derive from an essential purposiveness, or is it the result of mechanistic interactions of the molecules that make up those processes, a consequence of fundamental physical interactions which occur among all molecules? Crucially, are the principles of reproduction and metabolism alone sufficient to capture the essence of life?

Stuart Kauffman, in his paper "What is Life? Was Schrödinger Right?" sheds light on this question. Orderliness, he argues, does not have to derive from a preexisting orderliness, like that of DNA. Instead, orderliness is observed to arise spontaneously in some types of system, specifically "non-equilibrium thermodynamic systems" (Kauffman 1995: p. 87). To describe the behavior of these systems, I'll first clarify the terminology used in discussions of thermodynamic systems. Imagine a system of elements, in this case molecules, which can take many states. Then imagine all of the variables that describe the state of all the elements of that system at any one time. In this example, variables include the position and velocity of all molecules, their structure, and their concentration in the mixture. If each of these variables has a range of possible values along a mathematical dimension, then the state of the system as a whole can be described using a single point in a many-dimensional mathematical space. The space has one dimension for each of the variables that describe the state of the system. Other points in that multi-dimensional space represent other possible states of the system. This multi-dimensional space is called "phase space". Chemical systems, driven by the physical rules of chemical interaction, progress through a sequence of states, and the systems are therefore said to "move" through phase space.

Now to continue with Kauffman's account. Systems with the same rules, but starting with different states (that is, at different points in phase space), may display different patterns of movement within phase space depending on the rules of those systems, and on their initial states. Under some sets of rules, systems starting with slightly different states will diverge in phase space, tracing out their own unique paths and never again coming close to being in similar states. This is an example of sensitivity to initial conditions, and because their behavior is difficult to predict, such systems are often called disordered or chaotic systems. Under other rules, the systems will converge in phase space, reaching the same state, or sequence of states, even when starting from very different positions. Such systems are said to be ordered systems. They may even reach and remain at some final state, never changing afterwards. This is called an equilibrium state. Systems can be considered more ordered or more chaotic depending on how quickly they converge or diverge in phase space.

However, even systems that converge in phase space do not necessarily reach an equilibrium, and they may have many different non-overlapping paths of convergence in phase space. These are the ones in which Kauffman is particularly interested, systems which operate at the so-called "edge of chaos" (Kauffman 1995: p. 108). These systems converge onto similar trajectories through phase space, meaning that many different initial states will tend eventually to the same sequence of states, but they never reach an equilibrium and stay put. This characteristic of never reaching equilibrium, which suggests that there is no possible equilibrium to be reached, is why these are also called non-equilibrium systems.

Kaufman's contribution to discussions of the origin of life is to point out that collections of autocatalytic molecules are an example of such a system. Such a system continually reproduces its own constituent elements as they dissipate or are combined into other elements. Different initial concentrations may tend towards a similarly fluctuating mix. The system is continually out of equilibrium – it never stops churning, but it also never explodes. Such a system displays order via the reproduction of its own components and the maintenance of sufficient concentrations of each member, and this order arises from an initial disorder. But this orderliness is a property which cannot be directly derived from the behavior of the individual entities in the system, because no entity is coordinating or otherwise directing the generation of order. The transition to orderliness (called a "phase transition") happens in these systems nonetheless, as a consequence of the rules of the non-equilibrium system itself.

Crucially, Kauffman also points out, if you have a class of molecules capable of catalyzing the production of other molecules, then once a system contains enough different types of these molecules, an autocatalytic subset is mathematically guaranteed to exist within the group. This property can be measured by two values: the minimum required molecular diversity, and the number of reactions catalyzed per molecule, such that the existence of an autocatalytic subset becomes guaranteed (Kauffman 1995: p. 91). As the reactions catalyzed per molecule increases, and especially as molecular diversity increases, the likelihood of the existence of such an autocatalytic set goes up. This likelihood also displays a phase transition. At first, with only a few types of molecule, the likelihood is rather low. But then, as different molecular types are added to the system, the number of interconnected catalyzing relationships goes up. Past a critical diversity, the likelihood of an autocatalytic set suddenly shoots up to be almost a guarantee. This is the phase transition to highly likely autocatalysis (Kauffman 1995: p. 92).

Kauffman shows that primitive collections of different basic pre-biotic molecules, when sufficiently diverse, satisfy the requirements to ensure the existence of an autocatalytic subset (Kauffman 1995: p. 94). Furthermore, he argues that different initial states could converge to ordered development along a path in phase space that traverses the edge of chaos (Kauffman 1995: p. 110). This means that it is quite likely that an autocatalytic set of proteins, or possibly of RNA, could have emerged in prebiotic conditions, creating the basic chemical groundwork for the development of living processes. It has even been shown that in some circumstances, autocatalytic sets can display a kind of evolution over time in response to environmental changes, as the composition of the set, and the concentrations of different elements of the set, change in response to changing conditions and changing availability of basic ingredients (Walker and Davies 2012: p. 3).

Autopoiesis

Kauffman's account of the feasibility and likelihood of autocatalytic sets is deeply rooted in chemistry, but stylistically he has also moved away from discussing the purposes of molecular types like DNA and protein, to discuss the phenomena of life from a perspective that describes the qualities of collections of molecules, rather than the behavior of molecules themselves. Kauffman seeks to provide an account of the dynamics of the origin of life, looking at the systemic properties and behavior which would have to be present in a collection of molecules that ended up becoming life. This is a perspective that is subtly but essentially different from one that focuses only on the primacy of either DNA or protein molecules.

This perspective, characterizing the properties of systems, is shared by Humberto Maturana and Francisco Varela in their highly theoretical publication "Autopoiesis and Cognition: the Realization of the Living" (Maturana and Varela 1980). Their central concept is "autopoiesis", which, roughly, is the phenomenon where a system itself creates its own components. This concept is clearly related to Kauffman's arguments about autocatalysis. In autocatalytic sets, the molecules in the set catalyze the creation of other molecules in the set, and there are enough relationships of catalysis that they form a closed loop with no molecule left out. Maturana and Varela approach this concept from a less chemical and more philosophical perspective, citing autopoiesis as the core quality, the essence of life (Luisi 2016: p. 123).

In their account, living things are processes which are constantly generating and shaping themselves, both day to day but also over evolutionary time. They developed the concept to apply to unicellular life, but in recent years it has been philosophically extended to higher-order creatures (Luisi 2016: p. 150). They argue that "entities" should be distinguished as a collection of relationships between components. In a single cell, that means the focus is on the relationships between molecules. Life resides not in DNA or protein alone, but in the way they relate to each other. Cells in turn operate in relation to each other. In the extension to so-called second-order autopoiesis, the cells together form an entity that is the organism, which has relations with other entities, some living, some not, and some very recently living, like the food the individual consumes to sustain itself and continue the process of autopoiesis (Luisi 2016: p. 151). Life's essence is in the organization of that set of relations, an organization which results in the reproduction of the very components which participate in the relations.

Maturana and Varela contend that this complex structure of relationships is primary, while the actual material components which take part in that structure are de-emphasized. Furthermore, the components are replaceable, so long as the relationships are preserved. This is a structural attitude towards the essence of life, comparable with Kauffman's look at the thermodynamic properties of proto-living molecular processes. Phenomena of life are taken as examples of a certain systemic way of functioning, and the characteristics of that system are then described and explained. In this way of thinking, life is a quality that adheres to certain organizations and states of materials, much like heat is a quality that materials may or may not have (Bedau 2007b: p. 467).

This view, one that seeks to examine structural qualities of living organisms in the search for the essence of life, is a general philosophical approach to answering the question. If different structural qualities are emphasized, then a different essence will be described. The analysis operates at one level above that of the particular molecules which we observe running living processes. In fact, thinkers taking this view may argue that the chemicals themselves are irrelevant. Chris Langton summed up this view well when he wrote, "life is a property of form, not matter, a result of the organization of matter rather than something that inheres in the matter itself" (Langton 1989: p. 41). This view has profound consequences for how we contextualize the essence of life, and as we will see, profound consequences for speculation about the essence of digital life.

The Role of Information

In their article "The Algorithmic Origins of Life", Sara Walker and Paul Davies make another structural argument about life by emphasizing the role of information in living processes. Like Kauffman, whose argument relies on concepts from thermodynamics, Walker and Davies bring to bear concepts from another conceptual mathematical field, applying information theory to the study of life (Walker and Davies 2012: p. 2). They look at information as it is encoded in the structure of DNA but also as it exists in the state of a cell's other molecules, which are responsible for gene activation and transforming genetically encoded information into proteins and other cellular structures (Walker and Davies 2012: p. 5). Their argument sees cells as an example of von Neumann's universal constructors, engaged in an autocatalytic (or autopoietic) process, but with a fundamental information-processing aspect. To them, the roles of each chemical in a living system represent one step in a circular chain of mutual creation, moving from DNA to RNA to protein and back. At every step, information is encoded in the state of the cell, either in the concentrations and structure of proteins, or nascent in the DNA strands which are used as the base encoded storage for the structure of proteins. This informational content of the cell acts as a kind of cellular program, and the chemical reactions within the cell execute that program. Autopoiesis is recast as information processing.

Making the implicit analogy with computers explicit, Walker and Davies see DNA as information storage, RNA as information messengers, and proteins as information processing hardware, which is itself constructed on the basis of stored genetic information. DNA or protein-only systems may display interesting dynamics by themselves, but life really emerges when they are combined, and specifically when DNA-stored information begins to have real causal effects on the processes of the cell. They argue that autocatalytic systems provide the essential thermodynamic groundwork for the functioning of life, but that an account which focuses solely on this autocatalytic structure of living processes leaves out a description of the "causal architecture" of these processes (Walker and Davies 2012: p. 1). Arguments about the thermodynamics of collections of molecules relate to the feasibility of the emergence of chemical organization in prebiotic life, and arguments about the autopoiesis of living processes relate to the dynamic perpetuation of those organizations, but the account told by Walker and Davies adds the causal influence of the informational content of these processes. Information is the force that drives the processes forward in their particular way, and it is distinct from the mechanism of their functioning.

In their account, the emergence of life is associated with the emergence of this method of information processing, where a system cannot be said to be living until information has taken over the causal role in the system. Autocatalytic sets of proteins consume external materials and fabricate new components for the system. DNA stores information relating to the production of useful proteins, and its role as storage enables the highly sophisticated process of Darwinian evolution. But taken separately proteins and DNA do not complete the story of life. Rather, in combination they display unique information processing, behaving as if programmed and guided by the very information that they encode. A description of the essence of life, according to Walker and Davies, is not complete without this information-driven processing. "Biological systems are distinctive because information manipulates the matter it is instantiated in … the origin of life may thus be identified when information gains top-down causal efficacy over the matter that instantiates it" (Walker and Davies 2012, p. 6).

Emergence

I have now touched on the major hallmarks of life, and presented some viewpoints which draw on both physical and systemic properties of living processes to explain those hallmarks. The final concept that must be brought into play, indeed a concept which unifies all of the above discussions, is emergence. In its most straightforward definition, "emergence relates to phenomena that arise from and depend on some more basic phenomena yet are simultaneously autonomous from that base" (Bedau and Humphreys 2008: p. 1). Emergent phenomena are often either not deducible or not explainable from their base phenomena. Systems that contain many interacting entities or agents often display emergence. When many agents are thrown together, and all have some kind of interaction with each other that steers their individual behavior, extremely complex and unpredictable group behaviors can arise that must be viewed as a related, but fundamentally separate, phenomenon (Bedau and Humpreys 2008: p. 16).

As all of the authors and theories presented above indicate, life is characterized by emergent properties at all levels, starting from whole ecosystems and going all the way down to intra-cellular behavior. The behaviors of single molecules or cells can be analyzed individually, but together their complex interactions form something remarkable that can't quite be captured by the individual analysis. Single cells are in constant communication with other cells around them, and this communication shapes the behavior of all the cells, guiding gene expression and protein development. A large number of cells, all of them sharing the same DNA but expressing it in their processes in different ways, have the emergent property of being an organism. This organism-ness also relies on the cellular organization itself. If all its cells were present but completely reorganized, an organism would cease to function.

At a level even greater than the organism, we can see ecologies and societies as an emergent phenomenon. This is strikingly true among the so-called "social insects", including ants, wasps, and termites, where the individuals are rather dumb and quite short-lived, but the colony as a whole demonstrates very intelligent adaptive behavior, including different stages of maturity (Johnson 2001: p. 80).

Many emergent properties are dynamic over time. For example, the process of evolution emerges from the interactions of many individuals in a species, over a long period of time. Even the concept of a species is, in contemporary philosophy of biology, somewhat emergent. Bedau notes that biologists increasingly believe that "the similarities among the members of a species are only statistical. Species are no more than a cloud or clump in an abstract possible feature space" (Bedau 2007b: p. 467). Evolution traces many paths through this feature space, finding new regions of suitability within it, which are quickly populated by the members of a new species.

Life is through and through characterized by emergent properties, which derive from structures, behaviors, and organizations found in life. Attempts to describe the emergent behavior of life lead to the systemic accounts presented in previous sections. The concept of emergence effectively characterizes the particular way that the behavior of living systems seems like something separate and distinct from the behavior of the smaller constituent components of those systems. An analysis based on emergence treats the system as the complex result of the structure and interactions of many parts, arguing that its essence is that structure, rather than the deconstruction into the material which composes the system.

Conclusion

This chapter has presented both an introduction to the history of the debate around the essence of life, and drawn out its most compelling concepts. It has considered accounts based on a fundamental purpose, like reproduction or metabolism, and moved from those towards accounts based on structure and function within that structure. These accounts focus on life‘s interesting emergent properties, including the phase transition to autocatalysis, the causal role of information, and its autopoiesis. It is now possible to state the working characterization of biological life that this discussion leads to. This is the basis for the forthcoming discussion of digital life:

Biological life is a patterned emergent system of autocatalysis, where a collection of basic molecules together reproduce each other in an ongoing cycle. This coordination emerges as a phase transition of the uncoordinated behavior of many elements, each of which obeys the relatively simple rules of chemical interactions. The coordination is driven by information encoded in DNA and manifested in protein structures. As a system, it achieves the recreation and perpetuation of itself.

This statement differs with characterizations of life as linearly dependent on DNA, protein, or some other material. Instead, it sees life as a particular structural organization emerging from the cycling reactions of a collection of molecules. A key aspect of this characterization is that it positions life as being a characteristic of an organization of matter, rather than a particular kind of matter, or a particular instantiation of that organization. This position stands in agreement with Langton‘s statement about life being “a property of form, not matter” (Langton 1989: p. 41). Drawing on structural approaches to living processes, this characterization argues that a process is living insofar as its organization displays the characteristics associated with biologically living processes. The key characteristics are distinction as an entity (holism), emergent autocatalysis, homeostatic maintenance of the organization, and information-driven causal dynamics of self-creation.

With that working characterization in hand, the next chapter will turn to digital processes, and apply the structural characterization of biological life within the context of the digital medium. In the process of doing so, the discussion moves from phenomena that are undoubtedly real into the realm of reality-based speculation.

Chapter 3 - What is Digital Life?

With a working characterization of biological life in hand, I'll now turn away from the academic literature and towards speculation about the possibilities for digital life. Based on the working characterization of biological life, I will characterize "digital life" as: digital systems which spontaneously develop emergent pattern formation from the combined behavior of many uncoordinated rule-driven elements, characterized by causal information control, and achieving the self-perpetuation of their own processes.

This chapter speculates about what that might mean in practice, how such a digital process might be instantiated in the systems we know of today, how we might recognize such a process were it to be built or come to exist spontaneously, and what the future prospects for living or lifelike digital processes are. I will close with a review of some algorithms and digital processes that already show some of the characteristics of digital life. Although I do not believe any of them behave in a way that can yet be called fully living, I do believe that they point the way forward, hinting at how digital life might appear one day, and that they demonstrate that the ideas presented in the chapter on biological life can in fact be translated into the digital medium.

Like the characterization of biological life, this approach to digital life is based on structural properties of a digital system. I argued before that life is characterized by a certain structural organization, but that as a system it is independent of the actual physical material in which it is instantiated. The molecules themselves tell us too little about how life works, because the process of life in a molecular system is an emergent property of that system. In order for a digital process to be considered a living digital process, it would need to demonstrate a similar organization and similar emergent properties as biological life.

This argument has one foot in the realm of scientific research and scientifically provable statements, one foot in the realm of philosophy, from which I borrow the vocabulary of emergence and structuralism, and (to stretch the metaphor) a third foot in the realm of design speculation. I am not arguing that we should treat all of our smartphones as we might treat a family pet or another human being, although some people probably do this already. Rather, I am arguing that if, at a fundamental level, a digital program behaved in much the same way as the simplest living collection of molecules, we would have to say that there was something lifelike about it. Perhaps we would say that it was displaying a "life of its own".

This is also not to say that such living digital processes would be akin to artificial intelligence. As discussed in the "academic background" section, artificial intelligence imagines creating a computer program that resembles consciousness. This discussion speculates about computer programs that resemble living processes, either by design or because their behavior comes to resemble living systems. Although living processes do sometimes have consciousness, this argument operates at a more fundamental level, and a full discussion of the intricacies of consciousness is beyond the scope of this study. This argument is based on an analogy between very basic living processes, like single-celled organisms, and digital processes. If we were to see such living digital processes, they would probably bear as much resemblance to a general artificial intelligence program as a bacteria bears to a human mind. However, it's worth noting that despite being small, bacteria are no less, and probably much more, important to the world's ecosystem than the human mind.

In this comparison with biological life, the electrical energy involved in driving the computation of a digital system is analogous to the physical energy which drives chemical reactions in cells. The structure and operation rules of the computing system are analogous to the physical rules that govern molecular behavior in a biochemical system. The stored data of the program is analogous to the state of the current collections of molecules in a cell. The rules of program execution are analogous to the information exerting causal control over the execution of the system, which is encoded in DNA and expressed in protein. Self-reflection, extension, changing, copying, or movement of the running program within a single computing environment or across multiple computing environments is analogous to self-perpetuation, self-creation, and growth in living systems. Emergent behavior displayed by the program is analogous to the emergent order of autocatalytic chemical systems in biological life.

Forms of Digital Life

What would a digital life form look like, if it were to exist? How would it be instantiated in a digital substrate, instead of the chemical substrate of biological life? A computer has a fundamental division between memory and processor. In a modern computer, there are several tiers of memory, ranging from low-capacity high-speed memory built into the processor, up to high-capacity, relatively low-speed memory in the hard disk. There are often several types of processor, including the central processing unit (CPU), often a graphics processing unit (GPU), and other assorted microprocessors, such as in the motherboard or in certain peripherals. However, despite these differences, different memory and processors can be generalized over, and for the purposes of this argument, I will consider them for their theoretical, rather than physical characteristics.

In the computer's memory, all data (usually billions of bytes) are stored in binary form. This data represents either stored values upon which calculations are to be performed, or stored instructions which the machine could execute. At heart, the data are the same – billions of ones and zeros – but in practice, the way the data are interpreted changes their use within the computing system. It is worth noting that this distinction is analogous to von Neumann's observation about the stored program of a universal constructor. It must be able to be interpreted alternatively as a program to be executed and as raw data to be copied during reproduction. This is also analogous to DNA. DNA, when it is being copied, is not interpreted, as when a computer copies program instructions in memory. However, when DNA is being read out in the creation of a protein, it must be interpreted differently, as when a computer executes stored program instructions.

The other side, the microprocessor, is a highly complex machine designed to compute a limited set of simple functions, usually mathematical, on data stored in memory, and to do so very quickly. This is true for programs which run on central processing units (CPUs), the main processor in a computer, but also graphics processing units (GPUs), which have a fundamentally different construction enabling them to perform large-scale parallel processing of the kind especially suited for drawing 3D graphics to a 2D screen. The microprocessor accepts a list of instructions, most of which refer to the location of stored data values, and it executes those instructions on that stored data. The results of the computation can then be read back out of the memory of the system for human inspection. That data may reside in memory for as long as physical and electronic constraints on the storage medium allow, even persisting through times when electricity supply to the device is shut off. Generally, access to a computer's processing units by different programs is controlled by the operating system of the computer, which is a very basic set of software instructions that manage the hardware. The operating system is responsible for scheduling the execution of a variety of programs, including many background programs that are neither directly requested by a human user, nor necessarily visible to that user on inspection.

So, how would a living digital process exist in these conditions? It would have to demonstrate emergent order. This order would emerge from the smaller-scale behavior of many elements. In this case, it would be the semi-coordinated behavior of many data values stored in the system. These data values would be manipulated by instructions in the processor, much the same way that in a cell, concentrations of molecules are affected by protein synthesis from DNA, hence by the causal influence of DNA-encoded information. The semi-coordinated data in these systems would have to display the emergence of patterned behavior, and the system as a whole would have to display self-creation, either by directly copying or effecting the spread of the system into other regions of the computer's memory. Such systems of patterned phenomena would then display self-creation as a higher-order process.

So then, imagine if you will a computer program which manipulates a large number of stored pieces of data, with no predetermined plan for the development of those data values, but according to relatively simple rules that govern the changes made. These rules could include comparisons with other stored data values as a form of interaction among the simple building blocks of the system. If the stored data then displayed emergent coordinated behavior (emergence), and if the values displayed repeating patterns (autocatalysis), and if the system caused its own self-reproduction and development (autopoiesis), then according to the working definition of biological life presented above, we would have to say that there was something living about this process. We would call this process digital life.

With respect to the role of information in such a system, I propose two positions, based on two levels of abstraction. At the lower level of abstraction, we take the algorithm as given, and consider how it drives the manipulation of data values. In a computer, an algorithm is encoded as data just like the data which it manipulates. This means that in a system that displays emergent patterns in data, the algorithm is literally information manipulating the matter it is instantiated in, which was a key criterion of living biological processes proposed by Walker and Davies (Walker and Davies 2012: p. 6). According to this position, any digital process that demonstrates emergent and self-repeating pattern formation in its data is a living digital process, because the process is information-driven regardless of the algorithm used.

However, at the higher level of abstraction we might consider it a requirement that the algorithm manipulates its own informational structure. That is, for a digital process to display the kind of information-driven control of its own matter that Walker and Davies describe, it is necessary that the algorithm change its own functioning over time. This is possible if the rules of the system are changed by the system itself, or if the algorithm produces subsequent generations of new algorithms, slightly different from the parent algorithm, which eventually take over the entire digital process. This would be a kind of evolution of digital systems.

In deciding on the aliveness of a digital process, it is important to decide which of these two positions is favored. The low-level position is more general, and would accept more kinds of digital processes as living. Meanwhile, the higher-level position accepts as living only digital processes driven by algorithms that display a certain kind of self-reflection and even evolution. I tend to favor the higher-level position, but I leave that choice to the reader.

Appearance

How would such digital life really appear to us, humans, inspecting our devices for signs of its development? The "digital ecosystem" consists of all computing devices in the world. Many of these devices are connected to each other through the infrastructure of the internet, exchanging programs and data with each other at all times of day, worldwide. Groups of devices networked together create digital biomes. How would we be able to recognize living digital processes humming along, hidden in the secret niches of the digital ecosystem? This is especially difficult since the growing number of computers on earth is already so large that many are left mostly unattended, the contents of their memory and the behavior of their processors never really closely inspected by a human eye. They hum along in back rooms and server farms, running processes that may be long-forgotten and unmaintained.

If digital life were to exist, unattended, “in the wild”, it would be most noticeable in the data that serves as its substrate. The instructions executed by a modern CPU fly past at such a high rate that they would be practically untraceable. But the data remain. In the shifting but recognizable patterns of these data values, we might one day recognize lifelike processes. We would need to inspect these data regularly to notice patterns in their behavior. We would probably need to visualize these data, since the printout of a large mass of binary from computer memory is practically unintelligible, let alone recognizable. Perhaps, somewhere, these lifelike processes already exist in a primitive form, still undergoing the gradual development and change that occurred among chemical populations in the millennia before the appearance of life on earth. Or, even more daring to speculate, perhaps a living digital process is present on earth now, we have simply yet to discover it, or yet to recognize it for what it is.

Digital Proto-Life

I‘ll now turn to considering existing examples of existing digital processes that display some of the characteristics of digital life described above. These include the systems I‘ve implemented as examples for the speculative installation, but also other complex systems, and ones that aren‘t as straightforward to visualize and present to the public. Some of these systems have been developed with particular practical uses in mind, or to solve particular classes of problem in computer science. These are often examples of “natural” or “bio-inspired” computing, which is the development of algorithms inspired by natural processes (Nunes de Castro 2006: p. 2). Other examples have been developed out of curiosity by researchers over the years. Insofar as the implementation of these algorithms displays some of the characteristics described above, these can be considered as pointing the way towards true digital life. In each case, I will present a rough description of the process or algorithm involved, describe how it demonstrates lifelike properties, and speculate how far towards digital life the process is.

Cellular Automata

The earliest, and perhaps most well-known example of lifelike digital systems are cellular automata. This refers to a class of systems, all of which operate based on similarly-structured data, but with different algorithms and parameter values. Generally, a cellular automata system simulates a large number of quantities in discrete space and time. Imagine a grid, and for every square of the grid, there is a stored value. These values change over a series of discrete "time steps", where at each step rules are applied to the current value to determine its next value. Usually these rules refer to the current values of grid cells nearby, or otherwise related to, the stored value. The most well-known example is Conway's Game of Life, where cells can be either living or dead, and whether they change between these states is determined by a few simple rules based on the number of living or dead neighbor cells they have. Each cell, then, operates as an automaton, following its own small-scale rules and with some reference to its neighbors. When cellular automata are scaled up to contain many cells, then under certain special rulesets very complex behavior can emerge.

John von Neumann was an early proponent of the development and study of cellular automata (Langton 1989: p. 13), and his work on the concept of a universal constructor indicated a path which subsequent researchers would follow. Christopher Langton later sought to develop the simplest example that was able to replicate itself over time, and his result was his "replicating loops" concept (Langton 1989: p. 28). The great early computer scientist Alan Turing, who was a contemporary of von Neumann, proposed a system which I have used as an example in my work, both for its conceptual elegance and its aesthetic value. Turing's system, which is known as "reaction-diffusion", simulates two chemicals which react to create each other, and which also diffuse through the medium they share (Turing 1952). Each of many grid locations stores concentration values of the two chemicals, and on each time step the concentrations are adjusted according to rates of diffusion from neighboring cells, and rates of reaction between the chemicals in the cell. The brilliant thing about this simulation is that, despite its simple rules, it displays fantastically complex behavior. Each cell is usually visualized as a pixel, with its concentration determining color. Depending on the values of the parameters used, slow-moving ropes, or quickly changing flashes can form. The entire available surface is soon taken up with evolving concentrations of the two simulated values, as blobs of higher concentration form, merge, disperse, and form again. The overall effect is like watching bacteria grow, move, and disperse through an environment.

The most salient property of lifelike processes which these simple examples display is that of emergent autocatalytic behavior as described by Kauffman. The patterns seen in the values of the automaton cells emerge spontaneously from the interactions of related cells, and then replicate themselves across the surface of the grid. Often they grow, spread, and develop strange new patterns. There is a degree of information control in these systems provided by the simple rules of cell value change. I chose to implement a reaction-diffusion system for its technical and aesthetic elegance. In the speculative installation, the reaction-diffusion system is presented as an example of a kind of digital bacterium that grows spontaneously in a computer and thrives within the unused memory of the device. The appearance of the system under the parameter set that I've chosen supports this presentation. I implemented the system in code that can run on a computer's GPU, allowing for very rapid calculation of each time step of the simulation. This enables the normally slow simulation to develop at a much faster rate, leading to an impressive real time experience.

Agent-Based Symptoms

Another category of lifelike system also focuses on the program controlling individual agents, like cells in a cellular automaton, but generally these agents are free to move about through imagined virtual space. This field developed out of the work on cybernetics in the 1950s. Modern agent-based systems are often employed in either optimization problems, where groups of agents search a virtual parameter space for the best solutions to a problem, or in robotics, where simple spatial navigation behaviors form the basis of robot artificial intelligence (Nunes de Castro 2006: pp. 217 and 235).

The example I implemented to demonstrate agent-based behavior is a flocking simulation. Flocking simulates the movements of birds, which attempt to fly alongside other birds, without coming too close. There is a constant tension for each bird between maintaining its distance from others and maintaining its flight direction and destination to fly with the others. In a flocking simulation, these forces are balanced with each other, and together they determine the acceleration and velocity of individual birds. The birds' flocking behavior emerges out of the entire uncoordinated group, as nearby birds join together into larger bands, and these bands join to form flocks. The flocks then move as if with a mind of their own, exploring the space available to them in an infinite migration. This flocking simulation demonstrates emergent group formation, and it has a greater degree of information control stemming from the program itself. However, the program has not yet begun to manipulate its own implementation, and so it has not yet begun to evolve.

Evolution-Based Systems

The process of biological evolution has been borrowed by computer scientists as the "genetic algorithm". A genetic algorithm must formulate a problem as the optimization of a fitness function, and a solution to that problem as a particular "genotype". The genotype is either directly fed into the fitness function, or it generates a "phenotype" solution in some way, which is then fed into the fitness function. Biological Darwinian evolution achieves this, with an organism's DNA being expressed in the form of the organism, the phenotype, and survival and reproduction in a hostile environment as the fitness function. The goal in Darwinian evolution is to maximize the number of offspring. In an evolutionary algorithm, the goal is to either maximize or minimize the fitness function. Many random genotypes are at first generated, then they are tested against the fitness function, and the most successful are mixed with each other to create a new generation of genotypes. Over many generations, this gradually leads to the development of genotypes which are very well-adapted to optimizing the fitness function.

In problems of complex optimization across many variables, this has proven to be a useful method. Genetic algorithms were also employed extensively in an early phase of Artificial Life-inspired art, which used them to generate images based on a simple grammar and users' choices (Whitelaw 2004: p. 27). These systems demonstrate a way forward in implementing proper evolution of computer programs, since often the "genotype" is itself a program which generates a solution. Genetic algorithms display a particularly lifelike kind of information-driven self-reflective change, and can be seen as algorithms which generate sub-algorithms. However, there is still much more research required before genetic algorithms can create the kind of variety and innovation seen in biological life (Bedau 2007a: p. 602). Furthermore, these systems, not displaying the other characteristics of living processes, are not fully living, but probably a truly living digital organism would make use of a similar evolutionary mechanism in its development.

Another system which displays some degree of evolution in its parameters over time is neural networks. These are systems of parameters modeled after the structure of neurons in a human brain, which are used to calculate solutions to problems involving correlations between different types of unstructured data. The classic example is matching images to words describing their contents, called image recognition (Floreano and Mattiussi 2008: p. 199 and Abadi, Martín et. al. 2016). Neural networks are today one of the main areas of research in artificial intelligence, demonstrating fertile cross-pollination across disciplines in bio-inspired computing. Neural networks are a massive topic of their own, and complete coverage of their intricacies that would do them justice is unfortunately beyond the scope of this thesis. But their basic demonstration of the effectiveness of semi-coordinated behavior, and limited algorithmic evolution over time, is a powerful argument for the relevance of studies like this one to the emerging technologies of the 21st century.

Growth-Based Systems

There are also algorithms developed to simulate the growth and development of organisms. These algorithms seek to represent morphogenesis – the development of the form of an organism. Often these are used by artists to create visual content with a natural look. Work by the design studio Nervous System, led by Jessica Rosenkrantz and Jesse Louis-Rosenberg, uses the patterns of growth of corals, plants, and fungi to create digital designs for physical products, including rings, lights, puzzles, and dresses. These algorithms are based on simulating the growth of organic tissue (Rosenkrantz and Rosenberg 2014). In a similar vein is the work of the British artist Andy Lomas, whose work in the field of generative art is inspired by organic form. Most notable in this area is his work "Cellular Forms", which simulates the growth of a large collection of interconnected cells, creating remarkable structures that resemble organic tissues. With different cell division rates and different connection strengths between cells, Lomas' programs can produce a wide variety of forms (Lomas 2014).

In these cases, numerous small-scale structures with local interactions are simulated, with the result displaying emergent large-scale structures. These systems are very dependent on initial parameter values, which do not change during the running of the simulation. The algorithms themselves are not self-reflective or self-changing. This is similar to the cellular automata and flocking examples but unlike the genetic algorithm and neural network examples. One could imagine a digital process where these natural forms were generated as the phenotype of a genotype, and those genotypes were evolved as part of a genetic algorithm. Such a process would then be well on its way to demonstrating all the basic characteristics of digital life.

Viruses

A topic that should be covered in any discussion of digital life forms is the phenomenon of computer viruses. Just what constitutes a computer virus is difficult to precisely define, but for the purposes of discussion I'll consider a rough archetype of such programs – malign computer programs that run on devices without the knowledge of the device owner, and which are built to spread from device to device via network connections, emails, thumb drives, or some other transmission mechanism that enables the virus to install itself on previously uninfected machines.

Are such programs examples of digital life? It's worth noting that biological viruses, being essentially compact packages of DNA in a protein shell, are often not considered to be living organisms, because they don't perform metabolism. Maturana and Varela would say it's because they have no autopoiesis, but rely on the mechanisms of host cells for their self-reproduction (Luisi 2016: p. 129). In the digital realm, these programs pose some interesting challenges in their classification.

For one, it is not clear whether or not computer viruses display the characteristic emergent behavior in their underlying data that other lifelike digital processes do. Viruses are often designed for a particular purpose, often to steal or sometimes ransom data, and then to spread. They often do this in a linear way – the code dictates which data to steal and that's the end of it. There is no ongoing development of data values or demonstration of emergence. At least not on the level of the individual computer. However, on the level of the network of computers, more interesting behavior can be seen. Viruses spread through computer networks following the intrinsic logic of their propagation mechanism. Perhaps they spread to personal contacts stored by an infected computer, in which case the virus would display characteristic patterns of infection spanning groups of computers that mirror human acquaintanceship networks.

Furthermore, as the viruses are detected and blocked by various antivirus software, and then modified by their creators or scrapped altogether, there is a sort of ongoing evolutionary arms race. In a particularly interesting development, some viruses are built to employ "polymorphic" code — code which changes itself randomly — to avoid detection by antivirus software (Nachenberg 1997: p. 49). Such a system demonstrates a primitive kind of software evolution. It's evolution because different versions of a similar program will have different data, but primitive because the changes affect the physical representation, but not the functioning of the code itself. In the ongoing struggles between virus authors and those who seek to make computers more secure (sometimes these are the same people!), viruses have developed elaborate sophistication. And, perhaps based on the strength of the biological metaphor, computer viruses have succeeded in entering the popular consciousness as something which can potentially infect and slow down one's computer, sort of like what the common cold does to a human body.

But viruses are not fully living. The functioning of any individual virus does not display life's characteristic emergence. And the algorithms executed by viruses are insufficiently mutable over time to be considered digital life. That being said, modern computer viruses, like genetic algorithms and programs which demonstrate emergent pattern formation, point forward to a possible future where living digital organisms roam our computer networks and infest our digital ecosystem.

For this reason, I've included a simple simulation of virus propagation through a connected network as the third example in my speculative installation about digital life of the future. The idea is that in the future viruses have become more advanced, capable of mutations over time, and very difficult to fully eradicate from computer systems. The simulation tracks the spread of a wild virus through connected computers around the world. Viewers can watch as it flickers into and out of different computers, constantly on the run from the humans and antivirus programs that seek to eradicate it. The installation presents it in terms of future developments in virus technology, but this speculation is the one that lies closest to our current reality. Undoubtedly to many viewers, the idea of a virus spreading globally through the ecosystem of connected computers doesn‘t seem that far-fetched.

Conclusion

In this chapter, I‘ve described my answer to the research question, “what could digital life look like?” Digital life would be an emergent self-replicating pattern in data manipulated by a computer process, which achieved its own self-perpetuation and developed over time. Digital life would be recognizable in the behavior of data values deep in the memory of a computer, and in the structure of the information that drives their fluctuations. If digitized algorithms become self-reflective, and if the data they manipulate displays emergent repeated patterns of organization, then those systems will have become digitally living systems. This description is based on the investigation of the essence of the structure of biological living systems presented earlier.

I have also presented speculation about how we might actually notice the existence of digital life in our computer systems. I do believe that our systems are already so complex that it might be hard to recognize such a phenomenon were it to spontaneously arise. I also believe that we would need to visualize those systems in some way, because the inner intricacies of digital systems are often very difficult for our analysis tools to capture, and the patterns displayed in data can be very difficult to recognize, except with a human eye.

Lastly, I have presented examples of existing systems which demonstrate some, but in no cases all, of the qualities of digital life. I think these programs represent steps on the way towards digital life, but they are not quite yet living. These examples however may indicate to us areas from which digital life may some day arise. Furthermore, in the speculative installation, a few of these examples provide the visual basis for the depiction of the digital life of the future. In the next chapter, I will describe that depiction in more detail, explaining the concept behind the speculative natural history museum of the future.

Chapter 4 – Presenting Digital Lifelike Systems in a Speculative Installation

This last chapter describes my work presenting a speculative position about the future of digital life as the praxis part of this thesis. It extends into the future the discussion in the previous chapter about how digital life would function, and how it would appear. The praxis part proposes a possible future in which digital life has emerged on earth, and presents to viewers a physical installation visualizing these new life forms. This visible, tangible expression of the speculative concepts developed in the first few chapters is a physical manifestation of the answer to my research question. The installation represents how I think digital life would appear to us, were it to some day exist.

This speculative installation challenges the nature of life by demonstrating a material-independent interpretation of life, where living processes can just as well exist with digital components as they can with biochemical components. It represents the knowledge gained in this thesis, a demonstrative challenge to the question of the essence of life. In seeking to answer the research question of what digital life would look like, I have laid out the theoretical characteristics it would have, and this installation presents an idea of its literal look and feel, its functioning, and its practical consequences for humans interacting with the digital ecosystem.

Future Speculation

In the future, perhaps we will have discovered that our digital systems have been developing lifelike properties all along, and that at some point, say in the year 2100, we will be able to observe digital ecosystems thriving inside our devices and networks around the world. These creatures are powered by our inventions, and they are descended from our creations. Some of them may even be specially created by humans to achieve certain tasks. Perhaps such programs will one day be considered digital parasites, or digital symbiotic organisms. In this version of the future, programs will be multiplying, evolving, and diversifying all around us. They will display unexpected behavior, develop surprising characteristics, and find novel solutions to problems they may encounter.

Perhaps niches in the environment of connected devices will give rise to interesting variation in digital life. A toaster in a suburban home could become the breeding ground for a rare genotype of digital organism. A cell phone on a college campus in Asia could be the source of a bold new program mutation that quickly spreads around the world. A change of a byte or a few lines of code and the whole behavior of the organism changes. We could see a veritable Cambrian explosion of digital life forms. Although each program might be simple, together they would form a complex digital ecosystem.

We may want to contain, nurture, and show off examples of such programs. It is exactly this speculative concept which the physical installation part of this thesis seeks to simulate. It invites visitors to travel forward in time to a natural history museum from the year 2100. In this hypothetical museum, the visitors first see specimens of biological life that has gone extinct due to human changes to the environment. But afterwards, they see examples of digital life forms that developed during the course of the 21st century. To the human visitors, these digital creatures resemble spreading bacteria, or relatively unintelligent small animals. They sprang from the work of human hands and live within infrastructure built and maintained by humans, but by the year 2100, there is something about them which is wholly inhuman, wholly unplanned, unintended, and perhaps unknowable. In the installation, an audio track introduces the visitors to the specimen samples, presenting them as a natural consequence of life‘s innovation in the digital realm.

The first example is described as a digital bacterium that grows in the unused spaces of computer hard drives. Its functioning is very simple, and its program is very short, but it is highly contagious. Small clumps of this bacterium filter into any computer connected to the internet, and spread throughout untouched fragments of memory. If the computer ever uses this memory, or cleans it manually, the bacterium is wiped out, but it always returns after a little while. However, the bacterium is harmless to the functioning parts of the system, as it never rewrites or copies memory in active use. Some system maintainers have learned to cultivate various forms of this bacteria as a kind of memory randomizer to overwrite old and potentially sensitive data. In this symbiotic relationship, the bacteria has a fertile habitat in which to flourish, and the system becomes more resistant to infections by other digital life forms, some of them much more malicious than this one. This species of bacterium was one of the first digital life forms to be discovered, so it is included in the natural history museum as a historical curiosity.

The second example is described as depicting the development of human social media data over the preceding 100 years. Starting at the beginning of the 21st century, users began uploading personal details to the primitive social platforms that were popular in the early days of the internet. These profiles, whose data were stored in a globally distributed computer infrastructure that came to be known as “the cloud”, became more and more complex, and their ties with other social profiles – the friends of the original uploaders – became stronger. Eventually, with all of the constant updates and adjustments to their stored data, and with much of the process long ago automated by long-running scripts and forgotten code, these social profiles began to demonstrate strange behavior that couldn‘t be explained by the humans who had originally created them. The social system had developed a kind of emergent social pressure, in which friendly social profiles were drawn towards each other. They synchronized their data with each other, primitively resembling the way that humans respond to peer pressure and cultural fads. These profiles began exploring the cloud together, meeting other groups of profiles and merging together into swarms. The installation depicts a real-time visualization of a “flock” of these profiles traveling through the cloud. They swarm together, fly alongside each other, and create a group whose behavior is not planned in any way, but emerges from the combined interactions of all of the individuals in the flock.

The third example depicts a tenacious infectious program as it propagates through a global network of connected computers. When the program first infects a computer, it spreads through its storage, gathering sensitive data and transmitting it to a mysterious location. Then the program seeks to mutate and copy itself into other computers connected over the network. The “purpose” of this life form is unknown. It is unclear if the life form is a human creation, perhaps synthesized from several other known infectious organisms, or if it developed spontaneously within the vast network. The type of information it gathers and the reasons it does so are also still a complete mystery. The installation shows the global pandemic monitoring map, where every time the program infects a computer, the color of that computer‘s node on the map changes. There are constant efforts underway to eradicate it, which change the color back. But the program always seems to find its way back into the network, perhaps with the help of human agents who reintroduce it. The ongoing struggle against such parasitic and potentially harmful digital life, especially where researchers do not yet fully understand it, is one of the biggest fields of research in computing in the year 2100.

These are the main examples used to illustrate the concept of digital life for viewers of the installation. The setting, and information about the programs themselves, will be presented to the visitor through an accompanying audio track. This will bring visitors into the imagined world of the year 2100, and encourage them to think through the possible futures that are already developing around us today. There are two goals for this speculative installation. The first centers around the present and future of digital technology. The intention is that this installation provokes in viewers questions about our relationship to the complex digital devices and systems we already have, and that they interrogate the degree to which the complexity of our digital systems has already started to overwhelm even the experts. The second goal relates to the nature of life itself. The installation displays potential emergent digital living ecosystems, and it inspires questions about the essence of life, asking visitors to consider whether digital creations could ever be considered really alive. The theoretical argument about what would constitute digital life has been presented already in this thesis, but the speculative installation brings this discussion to visitors and presents it in a physical way which grabs attention and leads them into an immersive experience of an exciting possible future world.

Physicality and Practicality

Computer programs, by their nature, exist within digital space. That is, the mechanism of the digital hardware on which they run is so small as to be invisible to the naked eye, and manipulate data values in ways that the human eye cannot see. The content and results of these processes must be translated in some way, brought out of the digital space into more consumable spaces appreciable by human senses. The most readily available method of doing this is to visualize them. A visualization must represent the data manipulated by these programs in some comprehensible way. The speculative installation I‘ve put together does exactly that. It runs lifelike digital simulations and projects a visualization of their functioning onto a three-dimensional screen.

In the installation, I want to bring the digital out of its black box and into perceptible human space, but also to bring viewers closer to the digital world. As a result of their opacity, we often see digital devices, and the processes they run, as inscrutable objects. Someone with knowledge of software development can often "see through" an interface and make reasonable deductions about how the software runs, but this remains a relatively specialized ability. Most frequent computer users have little direct experience of this world. Instead, we appreciate the complexity of digital systems only through interfaces, most of which are built to hide that complexity. Because a central part of the argument about lifelike digital processes rests on their very complexity, and on the special way that their complexity generates emergent behavior, it is important to reveal that to viewers more directly than a standard interface would.

The three-dimensional nature of the installation, which is a large sphere in the center of the room, is meant to bring the digital space closer to the physical world. The simulations are presented as life forms trapped within the sphere, in the same way that fish or other animals might be held in a glass case in a museum, or in the way that biologists keep microbes in petri dishes and test tubes. The viewer is meant to step into another world, one in which we can isolate digital life from its environment and present it as a contained system, something which can become the subject of study. In this possible world of the future, digital life is all around us, thriving in the nooks and crannies of the digital devices on which we have come to rely, but it remains fundamentally inscrutable while roaming about "in the wild". It must be captured in this spherical device in order to be made visible, tangible, and therefore understandable to the viewing public. It is as if there had been fungus growing in the deep recesses of your refrigerator, which hadn't been cleaned in years. Only when you shine a flashlight back there, do you see the thriving ecosystem that has emerged. This installation shines a light on the hidden processes of digital life which, in the imagined world of 2100, have been evolving inside our computers and our networks all along.

I invite the viewer to entertain the fantasy of a possible future world with digital life, but also to question the very real ways in which our current digital systems are becoming too complex for human understanding. Many of us use the massive interconnected web of computers that is called the internet every day, but its scale, scope, and functioning are unknown, perhaps unknowable to us. This installation speculates as to what strange beings and strange forces could be brewing deep within the opaque networks of the internet, and asks viewers to reflect on the scale of that human-made complexity.

At the moment, I still doubt that digital bacteria are beginning their evolutionary cycles in the unused memory space of the world's hard drives, but I do believe that the complexity of the worldwide networked computer system has reached a point where it is no longer fully comprehensible to us humans, which means that it is no longer fully under human control. There is no government structure of the internet (although human governments do often seek to control its dynamics), there is no census, no overarching directive body. It is an incredibly complex networked structure, its behavior driven by the inputs of millions of humans around the world. We cannot today observe the behavior of the internet as a whole system. Perhaps now that it has reached this level of complexity, it will remain forever outside our understanding. After all, although it is composed of and driven by human constructions and human behaviors, it has become something strangely inhuman.

Conclusion

This thesis set out to answer the research question, how could digital life look if it were to emerge? The goal of this research was to explore the concept of digital life, and to describe its characteristics. To accomplish this goal I presented a theoretical description, grounded in accounts of the fundamental structure and properties of biological living processes, which then enumerated the fundamental structure and properties of hypothetical digital living processes. Alongside this theoretical description is the physical description, a speculative installation which shows what digital life might look like in the future. These two types of answer to the research question represent related but different ways of achieving the same research goal.

Summary

The description of digital life focuses on the structural characteristics it would have, because the distinctive structure of biological living processes, which makes them unique among chemical processes, is independent of the physical materials which make them up. Life can exist in many kinds of materials, so long as those materials participate in processes which display the kind of organization found in biological life forms. Investigating the structure of living processes leads to the characterization of life as a patterned emergent system of autocatalysis, where the basic components and patterns reproduce themselves in an ongoing cycle. Life is an emergent behavior, a phase transition in the semi-coordinated behavior of many small elements. The process is driven by information, which has a special causal role, and this system achieves the self-reproduction of its own patterned behavior.

When translated into the digital realm, this implies that digital life would be characterized by repeated emergent patterns in collections of digital data, driven forward by a self-reflective program encoded in the same kind of information as the underlying data. Those patterns would replicate and develop within the digital ecosystem. If it were to actually develop some day, we would recognize digital life as patterned fluctuations in a computing system's data, where a "computing system" may include multiple computers connected to each other over a network. A visualization of captive digital life would resemble the speculative installation I developed – patterned behavior of many semi-coordinated elements, emerging naturally within a complex ecosystem that has long been beyond total human understanding or control.

The results of this research are a demonstrative challenge to how we consider the essence of life itself. This thesis has proposed, in line with some other thinkers, that life can be instantiated in non-organic materials, and it has shown an example of what that might look like. The formulation, development, and presentation of this demonstration represents the knowledge gained from the research of this thesis.

The installation, which immerses viewers in a possible future, presents a statement about what kind of future we might find ourselves in, and forces consideration of some fundamental questions. By proposing that digital systems could become literally living in the future, the installation confronts viewers with the argument that life is possible in other materials, provoking them to question whether that position is actually sensible. They are then led to question what constitutes the essence of life itself, to ask whether it is material or structural. In considering this argument, viewers must acknowledge the vast complexity of our modern digital systems. They must admit that, like the installation proposes, it would be quite possible for digital life to develop for some time within some forgotten corner of computer memory without human observers realizing it. Thus the installation provokes questioning of the depth and complexity of digital systems, and sets this in comparison to the depth and complexity of living systems, exposing viewers to another aspect of this thesis' theoretical argument. The installation thus develops the arguments made within the theoretical thesis and presents them in the form of an experience.

To build the installation, I designed a spherical projection surface, a projector setup, and wrote the software simulations that run in the installation. The programs I wrote implement simulations of biological phenomena, to create lifelike visual effects. Rough descriptions of the algorithms and the ideas behind them were presented in chapter 4. These programs were written in the languages C++ and GLSL, high-performance programming languages for the CPU and GPU, respectively. The installation requires projection mapping, the simultaneous rendering of a 3D scene from multiple projector angles in such a way that the virtual scene matches the uneven surface of a physical object. To achieve this, I at first wrote my own configuration program, and later collaborated with Martin Fröhlich, who provided the use of his excellent SPARCK projection mapping software, for which I am very grateful. Beyond this outline, a full and detailed discussion of the details of the physical assembly and software implementation of the work on this thesis would be both relatively boring for a nonspecialist and beyond the scope of this thesis.

Discussion, Reflection, and Outlook

The particular example processes that I havve created share some similarities, especially visual ones, to what I propose would constitute digital life. However, they are not yet completely living. These examples all demonstrate some kind of emergent repeated patterned behavior in their underlying data. They are all driven in a semi-coordinated way by the information they encode. However, they do not attain the level of self-reflection, self-reproduction, and development seen in living processes. Some day, there may be a self-reflective digital living program which is capable of altering its own functioning, and of spreading through digital ecosystems. Such a program would be much more alive than the specimens presented in this thesis.

But could such digital life ever really develop? I do think there is a distinct possibility. As previously mentioned, computer systems are now so extensive, so complex, and so distributed that their functioning is not really fully describable by any one group of experts. We cannot, at this point, provide a complete account of all the kinds of programs running on devices around the world. For the most part, we expect those programs to be consciously chosen and executed by a human user, but the fact is that many computers now communicate exclusively amongst themselves, and they often execute programs requested by other semi-autonomous devices. Operating systems are built to prevent unwanted software from running on one‘s machine, but as anyone who has ever dealt with an inadvertent malware installation, or who follows breaking news about major software vulnerabilities, can tell you, such preventive systems can fail. Some future program, perhaps initially of human construction, could conceivably begin developing within a permissive digital environment, gradually changing itself and testing the systems it communicates with. Eventually, it may move out into more hostile parts of the network, surreptitiously installing itself into other machines, from which it would make further adjustments to itself before moving on. This program would be like a spreading colony of early bacteria, gradually feeling out and adapting to new operating systems, overcoming new restrictions, and discovering new environmental niches. Like a bacterium, it may start small and comparatively simple, but after all bacteria are how all of life as we know it started, many millions of years ago.

Supposing digital life were to appear, how would we humans interact with it? That probably depends on how menacing it seemed. If valuable infrastructure were damaged by creeping digital life forms, it can be assumed that we would take severe actions against it, hopefully after collecting a few specimens for further study. But if it were possible to "tame" digital life, we might discover brand new ways of creating programs, inspired by the new ways we learned programs could be. We might be able to develop symbiotic relationships with digital life forms in the same way that we have relationships with livestock animals, pets, bacteria in our guts, and other creatures that form an irreplaceable part of our ecosystem. We might find amazing new uses for digital living systems, in the same way that many useful medicines have been developed from plants.

In the current discourse, when one thinks of advanced semi-autonomous computer programs that would be helpful to humans, the mind immediately jumps to artificial intelligence. The idea is that helpful robots will aid us in performing many of the minutiae of daily life, like scheduling, driving, and shopping. But it is entirely possible that the influence of digital life could extend to such unglamorous tasks as maintaining distributed databases, removing old data stored by search engines, or defending computers from infection by harmful programs. These are examples of applications that do not necessarily require a human consciousness, but do require lifelike functions.

In this thesis, I have argued that digital life is a distinct possibility in the future. And I have presented a vision of what it might look like, both in theory and in practice. The computer programming community, which includes many people who are researching bio-inspired computing techniques, or who are using generative nature-like systems in their designs, pushes forward our understanding and invents new techniques every day. A core pillar of programming is the sharing of work and knowledge, especially the open-source software movement. I have relied on a variety of open-source software in the work on this thesis, and the ethos of computer programming compels those who benefit from the community to also return something to it. In the spirit of sharing techniques and implementations, I have made all of the work done for this thesis public and open source on Github, a popular website for sharing code. It is now available for others trying to understand and use generative or bio-inspired systems in realizing their designs and other work. I can't wait to see what they make.

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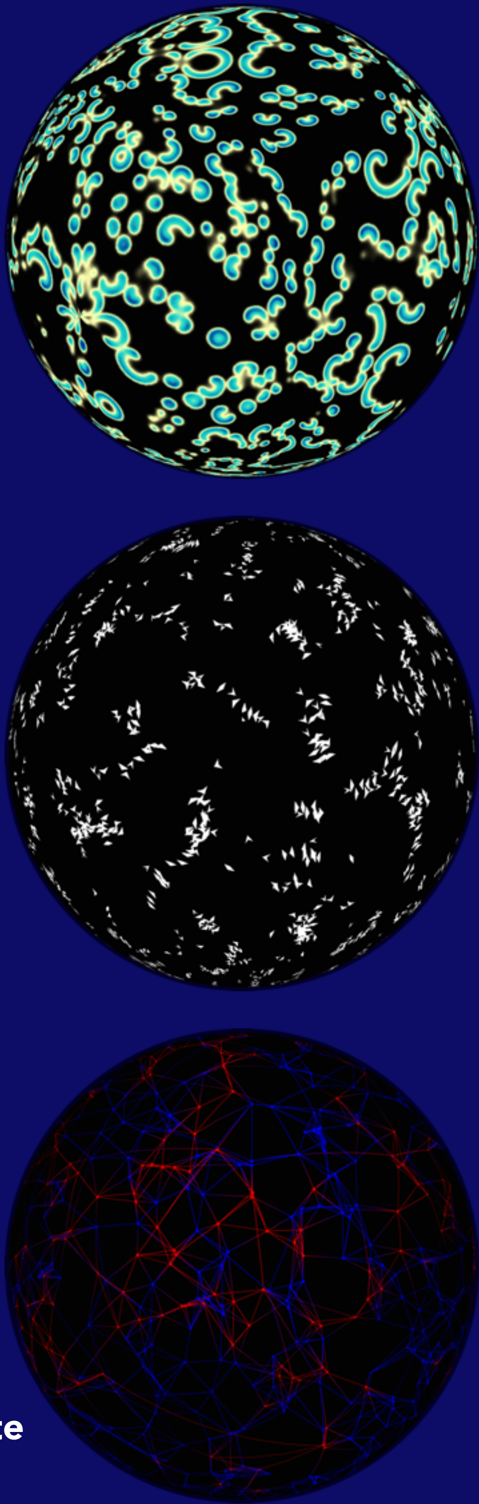

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