A Concept of Life as an Emergent Property Originating from the Interplay between Biological Individuality and Entropy

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Abstract

A concept of life as an emergent property, originating from the interaction of two specific interpretations of biological individuality and entropy, will be discussed in this thesis. Biological individuality will be shown to be a specific member of the category of individuality and a notion best interpreted as a relative concept which is hierarchically structured by interrelated nested entities. A specific interpretation of entropy will described as a statistical notion in which entropy is able to locally increase order as a stable dynamic kinetic state in a closed system. The rise of complex organization will be something that can be explained scientifically but is interpreted as a predominant emergentist property. In this thesis I argue that life emerges as a property rising from within the organization of a compartmentalized entity that is able to locally decrease its entropy due to a self-replicating autocatalytic web that jumped into existence. Biological individuality and entropy both relate to a base level of complexity and start to meet at the lowest level of organization. I argue that living biological individuals are not substrate neutral implying life *in silico* will always be fundamentally different from *biological life.*

Contents

Introduction

The biological world is something to wonder about. Life is something to wonder about. Here that wonder will be analysed and discussed. The driving force behind this thesis is the question “What is life?”. It would be presumptuous to assume this question could be answered in this thesis and that won’t be attempted. Instead, the main aim of this thesis is to add a descriptive concept of life that is based on a emergentist view of organization within living biological individuals. In this introduction the living world will be viewed from a distant perspective to get an idea about its characteristics. Then, two views will be briefly introduced that will help in conceptualizing life and the storyline of the thesis is given.

Characteristics of Life

In our daily experience we are able to recognize manifestations of life without much effort, because it is readily available and because of its subtle characteristics. One of the characteristics of life one may be easily surprised about is its complexity. Even the simplest life forms show a remarkable high degree of organization, operating with great accuracy on a scale of nanometers. The accuracy with which specimens make up their life may seem almost impossible to attain without some degree of foresight. Observing any sample taken from the living world one will inevitably come across nature’s impeccable “design” capabilities. Of course it’s known that nature can be extremely creative without the need of an intelligent designer or a supernatural force. In fact, the creativity nature produces is everything but intelligent and nothing gets built for a specific purpose. Nature doesn’t work in a goal-oriented way nor does it try to fulfil a detailed plan.

Not only is the complexity of life striking, so is its diversity. The number of individual forms is very large. The world contains a wide variety of living things we know plenty about, many others about which we hardly know anything, and still others we have yet to discover. Living things occupy the land and the sky as well as the seas, with specimens as big as fire engines or so small they can hardly be seen with microscopes. All these different individual specimens continually come into existence and perish almost at the same time, maintaining its diversity and keeping it highly dynamic.

The availability of individuals makes it relatively easy to start observing living things. Without the need for instruments we can already see many specimens having their own natural agenda. It is such a profound characteristic of life which even toddlers can identify. Although this agenda isn't working towards anything in particular, it does show life has a broad directionality. In fact, this facet of most complex living things is so evident that biologists came up with a special term to address this - teleonomy. Teleonomy is nature's teleology without a well-defined *telos*, therefore lacking any guiding foresight. Because of this absence the term is used to refer to patterns of behaviour such as hunting prey, protecting the young, building shelter, mating and reproduction, etc. This teleonomic character of life is helpful to us for understanding the activity of many biological individuals that constitute the biological world.

Interpreting the Living World

The concept of life has been much debated and a large effort has been put into trying to define life. Some have argued that a definition of life is not helpful or necessary because life is an irreducible fact of nature. Other definitions have followed the line of Descartes' dualism and have viewed life as a mechanism, but this reduction has met a lot of criticism [1][2]. Other attempts have focused on life as organization [3] but failed to explain the complexity of living things. Interpreting organization as (bio)chemical patterns led to the belief that such patterns had special properties [4][1] such as a living systems' ability to metabolize, grow, or repair. Current thoughts about life often focus on its being a process and not a substance and this tends to make definitions more descriptive. The number of different "descriptive" definitions of life is high and each description has most probably been fruitful for the author putting it forward. A common strategy to define life is by listing physiological properties all living things must share. An individual specimen that has all properties is then said to be alive. Physiological properties of life often include adaptation, growth, homeostasis, metabolism, reproduction, and response to stimuli [5][6][7][8][9][10][11]. This strategy will not work because there will always exist living biological things that do not have all properties. For example, a mule is a living thing but sterile and therefore cannot reproduce. In this thesis life will also be conceptualized in a descriptive manner with a focus on its organization and the properties it has. A mechanistic interpretation of life is purely reductionistic whilst an organizational view leaves open the possibility of emergent properties as part of the description. This is why, in this thesis, reductionism alone isn't taken to be sufficient to give a description of life that fits with current thought.

Observing patterns is a method to gather information and gain knowledge about biological systems. The upside of observing behavioural and some morphological patterns is that it can be done from far away, making gathering information and gaining knowledge relatively easy. The downside, however, is that observing such patterns of a living thing will not tell you what makes the living thing actually alive. Observing chemical pattern is also necessary to understand biological systems. To find out what makes a living thing "tick" scientist moved their focus from the point of observation outside the biological individual to a perspective within its physical boundaries. Even though no "elan vital" or "spark of life" is thought to exist these days [12][13], observing and recognizing patterns on a smaller scale has tremendously extended our knowledge of the biological world. Recognizing patterns instantiates explanatory power and often the patterns observed on a large scale can be explained by patterns observed on a small(er) scale. Due to the success of this reductionist approach in science it's no wonder an answer to the problematic phenomenon of life that some have tried to formulate is approached in the same way as many other complex problems. The question "what is life?" has become, besides a philosophical issue, a scientific one and resides within the domain of not only biology but chemistry and physics as well. Looking on the inside of living things has vastly extended our knowledge about what life "does" but the answer to what life "is" is still not clear. Progress within the sciences that study life have produced many insights contributing to our understanding of living systems but a truly satisfying answer to the question "what is life?" remains out of reach. Because of this, doubts are raised whether a complete answer to the question of what life is can be found by a purely reductionist interpretation (if at all). Part of the answer may rely on an emergentist view of life.

One of the reasons for involving an emergentist view besides a reductionist one is that life is easily distinguishable on the scale of a whole system, but isn't necessarily understood best as the mere sum of its parts. Describing the phenomenon of life depends, to a large degree, on the level of observation. The same goes for the concept of biological individuality although there is a slight difference. If one observes one and the same biological individual it could be possible, depending on the specimen chosen, that the parts of which the individual consists are, in a way, biological individuals as well. A dog, for example, a textbook example of a biological individual, is built from many different cells and although each cell isn't an individual dog it is possible to categorize such cells as biological individuals too. To keep things simple for now, if we were to use specific criteria that enable us to characterize a dog as an individual thing then the same criteria could characterize one of its cells as an individual.[1] These are criteria such as: spatial and temporal boundedness, the ability to adapt, clear life cycle, suffering from impaired function if some of its parts were to be removed. The criteria listed here, in this oversimplified example, can be used to pin down what an individual dog is and would single out a dog cell as well. The difference is that a (whole) living thing can somehow be made up of smaller non-living entities (or parts) whilst a (whole) biological individual can be built from smaller biological individuals (or parts).

Depending on both the observer and the level at which the observer actually observes, his/her language, used to describe patterns, may vary. Problems may arise due to ambiguous terms, equivocation, or anthropomorphic language. I want to stress this briefly because if a term, such as "emergent behaviour", is used by A without a proper detailed explanation, person B might interpret this as something mystical or unexplainable. Also, in order to help visualize complex processes specific patterns are sometimes easily described by attributing mental capacities to its components without those components actually having such capacities.

Research Questions and Storyline

In order to build a notion of life two principles for direction are used in this thesis. First, to get a sense of what life is examples are chosen that are thought of as being living things. This domain will be covered by describing biological individuality. Second, to understand what makes living things alive it is valuable to understand how they are organized. In this thesis organization is interpreted as the interactions between parts at specific levels of observation. Here, unpredictability, stability, and most importantly entropy will be of key importance.

The main question of this thesis is: 'How to create a concept of life as an emergent property which originates from the interplay between biological individuality and entropy?'. Maybe scientist believe that such an inquiry belongs to the task of the philosopher. On the other hand, a philosopher might find the inquiry too scientific. The reason to focus on biological individuality and entropy is to try and close the gap a little more between philosophy and science regarding the topic of life.

Two subquestions are put forward in this thesis and build on the two precepts above. The first subquestion is: How to construct an interpretation of

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[1] This does not hold anymore if specific criteria are whole-organism-level criteria. A way to characterize large organism is discussed in chapter 2.

biological individuality that is on a par with the domains in which the scientific community studies living things? With ‘on a par’ I mean that an interpretation of biological individuality needs to correspond with different scales at which biological research is conducted. It will be shown that such an interpretation should take a hierarchical structure of the biological world into account. The second subquestion is: How to construct a scientific relevant interpretation of entropy that doesn’t contradict the description of a biological individual? In other words, can entropy be described so that it can have a realistic presence inside living things without the notion of entropy contradicting the interpretation of biological individuality? The general idea is to form a basis with two specific notions, that of biological individuality and entropy, from which it is reasonable to assume that both biological individuals and entropy are needed for emergent properties to arise that help conceptualize life.

In chapter 1 individuals of any form and/or kind are discussed. The reason for addressing this broader concept of “individuality” instead of “biological individuality” originates from the claim that there can be a specific subset of individuals labelled “biological”. A distinction is made between non-living and living individuals as well as natural kinds. In section 1.4 “Nature of Nature” a small sidestep is made towards intrinsic properties of matter and how it limits interaction. It will become clear throughout chapter 1 why certain individuals are hard to define and why they are special members of the individuality category.

In chapter 2 the subset of biological individuals is discussed. The chapter argues that biological individuality is a relative concept and endorses pluralism about the concept. Nevertheless, some conceptualizations more accurately depict the hierarchy of the biological world and this is done by introducing two (sub)classes of biological things: *Darwinian individuals* and *organisms*. The chapter ends with an interpretation of biological individuality as a multiplicity of nested entities. Levels of organization and relations between nesting biological individuals are argued to be of key importance.

Chapter 3 will discuss notions of entropy. Various physical concepts will be introduced and explained including dynamic stability, compartmentalization, percolation threshold, and autocatalysis. Near the end, this chapter will discuss the basis necessary to understand the relation between biological individuality and entropy. This relationship is shown to be highly dependent on the organizational structure of (pre-)biological things.

Chapter 4 will address the concept of life as an emergent property originating from the interplay between biological individuality and entropy on particular levels of organization. Additionally, artificial life will be discussed and taken to be a special case, but not a paradigmatic example, of life and distinct from any biological living thing but with clear parallels. This chapter will argue against substrate-neutrality and therefore for authenticity of living things.

Chapter 1

Individuality

What do we mean when we talk about individuality? Does it have to do with distinctiveness, identity, unity, or uniqueness perhaps? Yes, would be an appropriate answer to that question since all those terms refer to the same intuitive feeling of what it must be like to be an individual. The quality one needs to possess in order to be characterized as being an individual but what, then, do we mean if we label something as being an individual? Arguably we label "persons" as being individuals, or an individual could be constructed as a being that is separate from other beings, that may hold certain beliefs and desires, and strives for particular goals. Still, this generalization is too narrow for many entities exemplifying individual things. Although persons are great examples of individuals they cannot define "individuality". Specific objects are instances of individual things as well even though beliefs, desires, and goals aren't part of the description.

In order to move forward a definition of individuality is given in this chapter, taken from Thomas Pradeu's "Immunity and the Emergence of Individuality" [14]. In this chapter each criterion of Pradeu's definition will be put to the test by taking borderline cases of individual things that intuitively feel as individuals but are not accurately captured by some of the criteria in Pradeu's definition. The idea behind this is not to show that Pradeu's definition holds no value, because it is possible to make a strong case for his requirements, but rather to show that even with strong criteria it's hard to provide an all-satisfying definition.

There is no universally accepted definition of the notion of individuality, but a preliminary one is chosen: "An *individual* in general is an entity that can be designated through a demonstrative reference (*this* F), is separable, countable, has acceptably clear-cut spatial boundaries, and exhibits transtemporal identity." [14, p.78]. In general this is a definition capable of capturing a large part of the living and non-living world. However, the seemingly endless variety of things always tends to include an exception. The reason for choosing Pradeu's definition opposed to other definitions (of which some will be introduced below) is because it allows us to interpret biological individuals as a subset of individuality. In the next chapter part of the critique of his definition is used to illustrate that biological individuals not necessarily include only living things. This will be discussed chapter 2 but first, problems with this definition of Pradeu are discussed.

1.1 Separate Individuals

The image of a tree as a singular thing consisting of roots, a trunk, supporting branches, and leaves is, in some cases, not adequate. For example, Aspen trees, or *Populus tremula*, look like separate[1] trees but actually form a network of contiguous parts. The trees are all connected underground by multicellular runners which are send out by each tree from their root stocks. These runners fuse underground and also grow upwards to the light forming new trees. Each tree uses their root structure to share nutrients and other resources among other Aspen trees connected to the underground structure [15, p.31]. The connected Aspen trees form a very large and single grove. If "connected" Aspen trees are considered individual things the condition of "separateness" doesn't hold. An even messier example of connectedness and therefore lack of separateness is that of a giant fungus, *Armillaria solidipes*. Like the Aspen trees the fungus grows and spreads underground and, unlike the Aspen trees, the bulk primarily lives underneath the surface. One specimen, found in Malheur National Forest in Oregon, covers an area of nearly 10 square kilometers. The fungus will grow "honey mushrooms" in the autumn, the only (direct) visible part of this "Humongous Fungus". Where it is doable to count single Aspen trees as parts of one single grove or mushrooms of fungus it is considerably harder to count parts of fungus belonging to one single specimen because it is not clear where one part stops and another part ends. A step in the right direction might be Ellen Clarke's advice to pay more attention to critical functional roles in biological individuals, such as (self-)policing and demarcation functions [16]. A little more on functionality will be discussed in the next chapter.

1.2 Bounded Individuals

Separateness strongly depends on the boundary of things, there where you observe a boundary one thing stops and another (or nothing) begins. A bowling ball is separated from other bowling balls due to its boundary made up by its

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[1] I take 'separable' to display a disposition of 'separate' things and consequently test things for displaying 'separateness'.

hard cover, preventing it to merge with other bowling balls and remaining noticeably distinct from the air around it. The boundary at macro-scale seems clear but can only be defined precisely on a micro-scale. For example, human skin functions as a boundary, but what exactly is *skin* and, more importantly, where does it "end"? Basically, it consists of three layers of tissue with the upper layer (epidermis) forming the final boundary. This upper layer of tissue, however, is made from cells. So whenever one wants to locate the boundary more precisely one has to keep zooming in. Unfortunately, establishing an exact boundary is not an easy matter, if possible at all. The answer to the question "Where does the boundary lie?" depends on the satisfaction or acceptance of the observer. But such acceptance is (highly) subjective. If one wants to know the boundary it should be independent of the observer's idiosyncratic satisfaction.

At the cellular level a cell's membrane functions as a spatial boundary separating the internal organization from the external environment, but now the boundary isn't just some passive boundary anymore. Instead, it interacts with its environment. If we zoom in on cell surface receptors, the boundary of three entities will be observable before interaction. These are the boundaries of the membrane-domain of the cell, the receptor of the cell and of an extracellular molecule that is able to bind to the receptor (nutrients, neurotransmitters, hormones, etc). Now, if we take a snapshot in time some may be occupied and others may not. When viewing the snapshot, we could argue that for that specific point in time the molecules occupying the receptors belong to or, more accurately, are "part of" the cell. If we turn time back on again there will be an average occupancy of receptors but then we wouldn't feel as compelled to argue that the average occupancy is part of the cell too. The dynamic aspect of the cell causes problems. To make things a little more realistic (and complicated); some molecules are not the right kind of molecules to bind to receptors but instead move past them and diffuse from the outside environment through the membrane and into the cell. Other molecules cross the boundary in the other direction and move out and away from the cell. Compounds outside the cell are no longer part of or connected to the whole but the cell itself remains one and the same thing.

1.2.1 Level of Observation

If we discuss the notion of boundedness and describe a process occurring at the sub-cellular level it's erroneous to compare it with observations at the cellular level. If we allow continuous switching of levels of observation it becomes impossible to make a valid statement of separateness, or singular things. Trying to find the exact location at which the boundary lies one can zoom in a little further, beyond the sub-cellular to the atomic scale but here boundaries disappear completely. Due to the rapid interactions between atoms it's next to impossible to see what atom “belongs to” or is “part of” which individual thing (unless we freeze time). Interacting atoms do a little dance with one another and then move to another partner and repeat this over and over again until the end of time. It’s no use to try and figure out what particular atoms make up a larger-scale individual for all the atoms making up that one singular thing don’t tend to stay in the same place in space. For this reason atoms can’t be said to “belong to” or be addressed as “part of” anyone or anything, rendering the concept of a boundary meaningless.

The examples above show that it’s rather hard to state that *this* F is a separable, countable entity with clear-cut boundaries unless the location of the boundary is left imprecise. If we now look at Pradeu’s preliminary definition, given earlier, we have to conclude that thus far the conditions fall short or are subjective.

1.3 Discrete Individuals

Most, if not all individual non-living things may be grouped together, portray a sort of “kindhood”, and come in a variety of shapes and sizes, prevalent at different levels of observation.

Going from astronomically large to atomically small we’re able to observe galaxies, solar systems, stars and planets, continents, countries, cities, buildings, rooms, tables, rocks, molecules, atoms, quarks etc. Notice that the examples are instances of real objects and not concepts such as “whiteness” or “pressured”.[2] It should come as no surprise that larger systems may consist of smaller ones that are not miniature versions of the larger assembly but different individual parts on their own.

Living things and non-living things are built from the same elementary particles that make up the matter in our universe. These small entities can be distinguished by their different intrinsic properties making up different kinds. (The ones that share the same intrinsic properties belong to the same kind.) The identity of these entities is independent of time, in other words, taking it out of existence and recreating it again will yield the same entity.

For example, if one of these entities, a gold atom, is taken out of existence together with all those entities sharing the exact same intrinsic properties, i.e. all other gold atoms, no other atom is able to take its place in the periodic table. This is because all other atoms have different intrinsic properties compared to

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[2] It can be argued pressure is considered a real quantity in science. In this paragraph the focus lies on observable entities, but this also is troublesome when instruments are needed and entities are not “directly” observed. Theories about an entity’s characteristics let us believe certain properties are measurable from which we infer its existence [17]. When moving towards scientific domains it is unavoidable to move further without the additional burden of the problems of scientific realism.

gold atoms. In the periodic table gold has atomic number 79 and fills a spot between platinum (with atomic number 78), and mercury (atomic number 80). There are no intermediate levels between platinum and gold or gold and mercury because no atoms exist with 78.5 or 79.3 protons. Likewise no atoms exist with 78.5 or 79.3 electrons. There is no continuous transition from platinum to gold or from gold to mercury. This imposes limits on the possible ways atoms can interact and I will argue the importance of this in chapter 4. If gold is taken out of existence there will occur a gap in the transition from platinum to mercury. That gap functions as a hole which can be potentially filled by an atom with 79 protons if it were created.

Theoretically the transformation from platinum to gold is made if a proton and a neutron are added to the core of a platinum atom and if one electron gets added to its second most outer shell. For mercury one proton and two neutrons will have to be taken out of the core and the most outer shell needs to be stripped of one electron. If such an atom is created, the exact same element *gold* will reappear. Exactly one atom can occupy the gap or “slot” between platinum and mercury, not a tiny bit more and not slightly less but precisely one. The fact that there is one and not an infinite number of slots in between platinum and mercury is a consequence of the fabric of nature.

1.4 Nature of Nature

There is a clear borderline between atoms that we can draw due to the discrete transition from one atom to another, as explained above. This makes atoms categorically distinct. Also, all gold atoms are members of the same “kind” of atom (because they all share the same intrinsic properties) and all mercury atoms are members of a different “kind” and both participate in the laws of nature [18]. Therefore, atoms can be said to be examples of “natural kinds”. Atoms of gold and atoms of mercury are built in distinct ways and although they obey the laws of nature, the way in which the gold and mercury atoms interact with other matter differs.

In this view the number of ways to create new (stable) things is not limitless. It is only possible to fill the “slots” the fabric of nature has installed and because of this constraint the number of possibilities for creation is limited. Atoms are are able to occupy the slots and belong to a specific natural kind which means that they will have the same intrinsic properties before they’re taken out and after they come back into existence. This does not hold for animate matter. For example, each cell is unique, as is every aggregate structure of cells and when taken out of existence that unique thing has ceased to exist. Creating a new cell-like entity will yield a different individual thing for it does not occupy a “slot” in the fabric of nature.

1.5 Changing Individuals

The elementary particles that build matter seem to be relatively stable in time but living things, whether they are small, large, or collectives tend to perish or adapt. The (evolutionary) timescale over which living things change can be extremely long (ca. millions to billions of years, depending on the specimen(s)) [19]. Still this is relatively short compared to the longest timeline known to mankind; that is the estimated origin of the universe until now (ca. 13 billion years) [20].

Evolution depicts change and every living thing studied in an evolutionary timewindow will therefore not exhibit a transtemporal identity. Only under certain time restrictions does it make sense to speak of Pradeu's criterion of transtemporal identity and such a restriction will vary from living thing to living thing. Compared to an evolutionary trajectory a transtemporal identity will only be exhibited when a living thing is observed in a relative short period of time.

An evolutionary trajectory accounts for multiple generations and not the lifespan of one and the same specimen [21]. Therefore, the lifespan of a single specimen is mostly relatively short compared to its evolutionary trajectory. So with regard to that time line a single specimen could be said to display transtemporal identity but this statement becomes flawed because of an unbalanced comparison of timescales. To illustrate this consider a common fruit fly, e.g. *Drosophila melanogaster*, being observed for 24 hours. Although the fly will "look" the same after 24 hours all the metabolic processes going on inside the fruit fly have changed the original body of the fly. The metabolic processes itself could be argued to be the same, and maybe the genetic make up of the fly (although some cells will carry some mutations). The only way to observe the fly while it's not changing is by looking at it in a time frame where all intracellular interactions seem to have come to a (complete) stop. This can only be done if time is frozen but then the term "transtemporal" doesn't seem to mean much anymore.

There is one way to save the claim of transtemporal identity for living things but it is a weak claim especially compared to the transtemporal identity for non-living individuals. Both living and non-living systems are able to persist in time but they do so in quite different manners. Non-living systems tend to uphold a *static stability* which enables them to endure time while living systems maintain a *dynamic stability* to withstand the ticking of the clock.

1.6 Recapitulation

Individuality is a notion that is hard to define. Even a relatively strong definition, taken from Pradeu, has criteria that tend to exclude certain individuals. There exist borderline cases, such as Aspen trees and fungus, that show that the criterion of separateness is problematic due to their connected characteristics.

A boundary generally separates one thing from another but locating the boundary was shown to be troublesome. Different levels of observation are necessary to locate a boundary more precisely. However, scaling too far down will render the concept of a boundary meaningless or a boundary will depend on an observer's personal satisfaction and therefore becomes an subjective notion.

Individuals persist through time, but those that can be characterized as natural kinds do so in a different way compared to others. Non-living things were argued to persist through time by being statically stable. Living things, on the other hand, were argued to persist through time by being dynamically stable and therefore do not stay the same. This led to the idea that the criterion of transtemporal identity doesn't fit either living or non-living individual particularly well.

Some criteria of Pradeu's definition either fall short or rely on the observer's satisfaction. This critique will be shown to have an effect of his definition of "biological individuality" too. The next chapter sets out to construct an idea what the subset "biological" within the set of individuals means and how to construct a notion of biological individuality that matches the hierarchical structure of the biological world. Also, the term "living thing" instead of "biological individual" has been used and for a particular reason: although there is overlap between the two I will argue that they are not necessarily identical to one another.

Chapter 2

Biological Individual

Intuitively it feels as if every biological individual is a form of life. This chapter argues that this is important, because when we try to create a concept of life as an emergent property which originates from the interplay between biological individuality and entropy, we do not take "biological individuality" to equal "life". The main aim of this chapter, however, is to answer the question whether it is possible to construct an interpretation of biological individuality that fits with the different scales at which scientists observe biological things.

The biological world is often equated with the living world, but despite many similarities those two worlds are not identical. I will argue that the biological world spans a space wider than that of the living world because it encapsulates domains below the smallest living thing as well as domains far greater than collectives of living things. Without instruments we are able to observe the richness of life around us and can easily see cats, flocks of birds, fish, and roses. And if we take a closer look we might see ants, fruit flies, or spores. With instruments we can take a look at a whole new world that lies hidden at small scales far beyond our normal visual capacities. With the help of technical devices we can detect single cells, chromosomes, RNA-strands, and genes. Although not every entity listed above would be characterized as a *living thing* they are all suitable for representing some kind of *biological individual* and each one has probably been used as an example as such at some time in the natural science of biology. Biologists recognize many different biological individuals in attempts to better understand, predict, and explain the biological world. These biological individuals can be found on a wide scale-spectrum. This means biologists study biological individuals at the molecular level (genes) all the way up to near astronomical sizes (biosphere). The domains of scientific research regarding biology tend to match[1] the hierarchical structure of the biological world relatively well.

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[1] From a standpoint of scientific realism "match" is a fitting word, however, philosophical objections to this standpoint could argue that the biologists "make" such a hierarchical

In this chapter first the preliminary definition of Pradeu will be rediscussed. This time the requirements of his definition are used to look at a difference between the concepts of *biological individual* and *living thing*. In addition to this discussion the action of defining biological individuality will be argued to be relative. Because some ideas about biological individuality capture the hierarchical structure of the biological world better than others the second part of this chapter deals with two (sub)classes of biological things (because not all are necessarily alive): *Darwinian individuals* and *organisms*.

In section 2.3 the relative interpretation of a biological individual is shown to lead to a view of a multiplicity of biological individuality. This idea is further illustrated by introducing the phenomena of *vertical nesting* and *horizontal nesting*. Lastly, implications of the inherent hierarchy of nested individuals are addressed which have to do with their levels of organization. An interpretation of biological individuality that takes into account the hierarchical structure of the biological world is claimed to stand close to domains of current scientific research.

But let's start with an earlier specific perspective on biological individuality , a preliminary definition from Pradeu.

2.1 Defining Biological Individuality

In the previous chapter we worked with a preliminary definition of individuality listing several requirements (an entity that has demonstrable reference, is countable, bounded and exhibits a transtemporal identity) as to what it must take to be classified as an individual. According to Pradeu a *biological individual* is a **living thing** that fulfills those requirements [14, p.79]. However, there are three main reasons why this does not work. The first reason has to do with the nature of Pradeu's requirements. The second reason deals with entities fulfilling the requirements without belonging to the "living world", and the third reason focuses on the difference between describing and defining.

First, as described in the previous chapter the notions of separateness, clear-cut boundaries, being countable, and transtemporal identity are not tenable (at least not for every biological entity). The last part of the sentence is in between brackets because establishing boundaries is hard when shifting levels of observation regardless of what the boundaries "belong to" or demarcate. Even if no levels of observation are shifted there will remain examples of biological individuals that won't fulfill the requirements listed by Pradeu. The grove of Aspen trees and Humongous Fungus fall short due to their "connectedness" character-

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structure.

istic instead of their "separateness". Another striking example is an uncommon jellyfish: the Portuguese man o' war, or *Physalia physalis.* (Actually, *Physalia physalis* is a "siphonophore" but it looks very much like a jellyfish). The Portuguese man o' war consists of several societies of specialized cell colonies each belonging to an originally different specialized cell, or zooid. Four zooids eventually "built" the jellyfish and are mutually dependent on one another. They can survive only together and form a physiologically integrated whole. Although the Portuguese man o' war starts of as one single zooid it relies on other zooids for its final stage. A fully developed Man o' war has boundaries which are not necessarily clear-cut and, besides that, it exists primarily due to "connected" colonies of different zooids.

Second, Pradeu's requirements may characterize an entity that is not a living thing but nonetheless a biological individual. This is problematic, because Pradeu formulates a biological individual as a "living" thing that satisfies his criteria of individuality. A *bacterium* frozen at -80 degrees Celsius, as stock for research, is an example of a biological individual without being in a state that can be described as being alive. All (sub)cellular processes are put to a stop making it not a viable entity and therefore not a clear case of a living thing. However, one might argue that the bacterium's decay is extremely slowed down making it only *seem* as if life has stopped, while it has only paused.[2] A *virus* raises the same problem in determining whether or not it is a living thing not for slowed down cellular processes, but for lacking them all together. Since viruses don't have their own metabolic processes nor the ability to reproduce autonomously they rely on the cellular machinery of their host to do so. This troubling case arguably isn't a living thing but is in fact a biological individual. And then there are *genes*, clear instances of non-living things, but according to Pradeu biological individuals nonetheless.

In addition to this second argument two other entities display a lack of livelihood but have been argued to be examples of biological individuals. The first of these two entities is a *species.* It was argued by Hull that a concept of species should not be taken to be something that contains a set of intrinsic natural properties that are all necessary and jointly sufficient for the entity to belong to the particular species-kind. It was argued by Ghiselin and Hull that species are individuals due to their role as units of evolution in evolutionary theory [22][23]. Although there are other ways to conceptualize species, such as clusters [24] or sets [25], the notion of species as individuals holds a particular valuable implication: it is a biological individual but not a living thing. Therefore, it ways against Pradeu's definition. The second entity is a *superorganism*

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[2] A frozen bacterium does not grow, metabolize, react to stimuli, actively performs homeostasis, or evolves but once the temperature rises it could.

which is somewhat similar to the Portuguese man o' war but instead of being built from multiple colonies of cells it consist of multiple organisms. Contrary to the jellyfish these individual organisms can be quite similar but do need one another for their survival. They rely heavily on their specialised division of labour. Beehives and ant colonies are examples of such superorganisms often interpreted as a single individual and biological thing. This is a problem for Pradeu's definition because such organisms have been argued to be biological individuals without being alive.

Third, stating what a biological individual is can best be done by giving a description of its properties while giving a definition of "biological individuality" relies on a short[3] explanation of its meaning. Usually a description of something is a detailed conceptualization of the thing's characteristics and functions quite well as background information for the thing's definition. What I mean by this is that a definition tends to be more strict compared to a description. For example, a definition of a mouse will not vary much around the world and most likely state that it is a rodent belonging to a certain family and genus. A description of a mouse, on the other hand, may vary greatly. It should be noted that there's a difference between describing and defining. The biggest difference may be that philosophers and biologists will, most likely, have no dispute about a description of biological individuality (whatever specimen taken) but this generally doesn't hold for defining biological individuality.

Coming up with a definition of "biological individuality" has not been troublesome for philosophers and biologists. However, formulating a definition that is accepted by all philosophers and biologists hasn't been done so far [26]. Part of the reason is the language used to address biological entities where "biological individual", "living thing", and "organism" are often used interchangeably. So far, the term "organism" has been used only few times in order to minimize conceptual vagueness of the term and relational imprecision between "organism" and the two other terms, "biological individual" and "living thing". To prevent obscurity these concepts will be categorized below, but it should be noted that that categorization is not the only possible one.

A second reason why defining biological individuality may be troublesome is that, so far, there have always existed counterexamples in the biological world against current definitions. Coming up with a refined definition has, so far, always led to the same problem. Adding to that, particular definitions suit some biologists well because those definitions happen to correspond to their (current) work better.[4] In general biological individuals are just whatever biologists find

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[3] Although a definition does not require to be "short" it may be more convenient than a definition taking up numerous pages.

[4] Definitions in any field need to be usable for researchers working in that field.

useful to talk about. This suggests that there simply are whatever many kinds of biological individuals are recognized by competent biologists [25] [27]. This implies that attempts to define "biological individuality" is dependent upon the observer's perspective[5] and therefore I move to endorse a form of pluralism [8][28]. Depending on ones perspective different intuitive understandings may arise which can be hard to formalize.

Nevertheless, it is possible to categorize definitions about biological individuality into three sets: a biological individual as 1) the level at which fitness is assigned or 2) the level at which selection is acting or 3) the level at which a response to selection can occur. This categorization is taken from Goodnight [29]. The first class depicts a clear example of being a construct made only for the usefulness of the observer. The second and third class of definitions also put the focus on evolutionary forces acting on the biological individual either by natural selection or evolution by natural selection, respectively [29, p.48]. In most cases, practical constraints or focus of study will force a definition of biological individuality in either one of these categories. It should be noted that, despite this relativistic note, some ideas about biological individuality are more fruitful than others.

2.2 Darwinian individuals and Organisms

Our understanding of the biological world is that it's highly diverse and hierarchically organized with generally 'species composed of populations[6], populations of individuals, individuals of cells[7], cells of organelles, organelles of genomes, genomes of chromosomes, and chromosomes of genes' [30, p.183]. A description of biological individuality that aims to be complementary with our recent understanding of the biological world needs to capture such a hierarchical structure. In the categorization that follows the set of biological individuals is the overarching collection of entities which is subdivided into two overlapping categories: *Darwinian individuals* and *organisms*. This is no new idea and has already been argued for by Peter Godfrey-Smith in his 2014 essay, Individuality

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[5] Biologist seem to capture biological individuals on macroscopic scales up to superorganisms but not higher than that. In the same manner biologist do not seem to characterize biological individuals below the genetic level. Why is that? Because at very large scales the individual doesn't seem to play a role anymore in its organization relative to its smaller parts. At lower levels the descriptions of the trajectory of elementary particles, for example, does not contribute to a clearer understanding of gene activity or influences on any other biological individual for that matter. Levels of observation are used at which biologists can best capture patterns and observe the things that seem relevant to their research of the biological world.

[6] Species can also be argued to be composed of large groups of organisms or by individuals that show similar physical attributes. However, here the focus on a hierarchical structure is what is important.

[7] Buss may have had trouble placing viruses, because viruses are not composed of cells.

and Life Cycles [31]. Although Godfrey-Smith doesn't use the term "biological individuals" for the adjunction of the two sets, which I take over, I do use that term in this thesis, because I believe it provides an opportunity to cover the entire biological world more clearly.

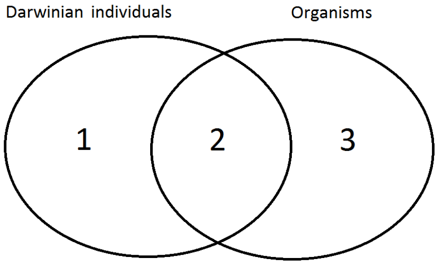

Figure 2.1: Venn diagram of the set of Darwinian individuals (sections 1+2) and the set of organisms (sections 2+3). Biological individuals = (Darwinian individuals) ∪ (Organisms).

The best-known formulations of *Darwinian* in *Darwinian individuals* have been put forward by Richard Lewontin [32][33]. Darwin's theory of evolution by natural selection is contained in three principles: variation, heredity, and differential fitness. Entities or collections of entities of which the three principles apply may be expected to evolve. Simply put: 'Variation, heredity, and difference in reproductive success are the features of populations that give rise to Darwinian change. Any collection that has these features can be called a *Darwinian population*, and any member of such a collection is a *Darwinian individual*' [27, p.19].

Godfrey-Smith's interpretation of organisms is not tied to the theory of evolution but specified as metabolic units. According to this view 'organisms are systems comprised of diverse parts which work together to maintain the system's structure, despite turnover material, by making use of sources of energy and other resources from their environment' [27, p.25]. Part of the elegance of this characterization of organisms is that it doesn't necessarily depicts living things but it can contain large non-living collections of organisms as well, such as superorganisms.

Examples of Darwinian individuals that belong in section 1 in figure2.1 are genes and viruses. Note that these entities are non-living things. Mules and symbiotic bacteria are categorized as organisms that fit in section 3 of figure2.1. The intersection of Darwinian individuals and organisms, depicted by section 2 in figure2.1, contains biological individuals such as trees and dogs (which relate more to textbook examples of biological individuals).

Both Darwinian individuals and organisms are viewed in a gradient way embodying both the clear and more marginal specimens. The gradualness in Darwinian individuals originates from the fact that they are biological things that can "reproduce". Reproductive success is basically a relative interpretation of the number of newly produced Darwinian individuals, or offspring, originating from their parents. In some cases new individuals are reproduced not by means of parents but by being reproduced by "themselves" instead, e.g. cellular reproduction or the reproduction of viruses. In this chapter I recognize three different types of reproducers: elementary, aggregate, and indirect reproducers. Examples of elementary reproducers are bacteria or other unicellular Darwinian individuals that use their own internal processes to make more entities like themselves. Aggregate reproducers are multicellular Darwinian individuals that rely on interactions across levels of multiple cells to reproduce offspring such as dogs and human beings. Examples of indirect reproducers are genes and viruses which rely on either elementary or aggregate reproducers to finally "replicate" themselves. (The concept of reproduction might be more suitable for living biological things and that of replication for non-living biological things such as genes and chromosomes.)

It is possible for evolution to gradually give rise to new types of Darwinian individuals as a Darwinian population evolves. What is meant with new individuals in this case is the rise of aggregate reproducers from elementary ones. When complex biological individuals like swans or giraffes exist, their cells still reproduce themselves (and vary due to mutations along the way). But these cells, that gave rise to a new Darwinian individual, have their own evolutionary activities standing in the shadow of the evolutionary trajectory of the new individual they make up. Due to aggregate reproduction cells rely on collaborative organisation to persist through time. Optimizing collaboration and reducing conflict amongst cells within a multicellular individual enhance the reproductive success and hence the persistence through time of both the (old) elementary reproducers and the (newly formed) aggregate reproducers. This optimization is the result of evolution and a gradual process. This is responsible for both the gradualness in Darwinian individuals as well as degrees of organismality.[8][9]

The categories, *Darwinian individuals* and *organisms*, are able to capture the entire biological world in an unambiguous fashion, containing the smallest biological individuals in the Darwinian category up to the largest in the organism

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[8] 'Significant metabolic integration at level n implies a lower integration of the objects at level $n-1$. More generally, a high degree of organismality at one level in a hierarchy implies lower degrees at others' [27, p.26].

[9] 'At intermediate stages of any transition, there is a group that has some properties of an individual and some of a colony. the view that falls naturally out of this perspective is that whether or not something is an organisms is vague - there are degrees of organismality, corresponding to a group's progress along a transition continuum' [26, p.61].

category, both non-living and living biological individuals. Examples of non-living biological individuals are genes and viruses, belonging to the category of Darwinian individuals, and ant colonies and beehives, belonging to the category of organisms.

2.3 From Pluralism to Multiplicity

These categories function as a broad definition of biological individuality because any biological individual either is a Darwinian individual, an organism, or both. Although this categorization allows for many different individuals there is no set of reasonable necessary and jointly sufficient properties which individuate every type of biological individual. No finite list of properties is able to function as a suitable classification to construct every specimen in the entire biological world. The lack of necessary and sufficient condition has led many philosophers to believe that there simply is not just one kind of individuality but several distinct concepts of biological individuality. Jack Wilson sums it up nicely in his work *Biological Individuality* by stating that 'the assumption that there is only one kind of individuality is as unjustified as the inference that an entity that has some of these properties must have all of them.' [34, p.56]. Due to the lack of necessary and sufficient conditions Wilson opts for an ontological pluralism concerning biological individuality. This idea agrees with the statement that many kinds of biological individuals may be recognized by various biologists.

Wilson's ontological pluralism contains the following six concepts of individuality: particular, historical entity, functional individual, genetic individual, developmental individual, and unit of evolution [34]. This conceptualization proves to be very fruitful for many troubling cases involving some previous examples listed above and in the foregoing chapter. The grove of Aspen trees, as stated earlier, may not be a clear instance of a separate thing but forms a connected functional whole. The same goes for a spider hanging from a leaf by its silk thread (which is genetically distinct from that leaf), or two people shaking hands. According to Wilson this problem is easily solved by checking the functionality condition stating that 'a biological entity is a functional individual if the parts from which it is composed are integrated into a functional organic whole. A functional individual is composed of causally integrated heterogeneous parts' [34, p.89]. The work of Wilson will not be recapitulated here but does form the inspiration for another conceptualization: a multiplicity of biological individuality.

2.3.1 Vertical Nesting

Arguing for a multiplicity of biological individuality does not deny pluralism. In fact, it is compatible or maybe even complementary to pluralism but different in the sense that the concept of multiplicity, set out here, puts the hierarchical structure of the biological world central by focusing on part-whole relationships between nested individuals. According to James Elwick it was Herbert Spencer who first situated individuals in a hierarchy with individuals being able to be part of larger individuals. Spencer created a hierarchy by introducing first-, second-, and third-order individuals. In this way biological things could be visualised as “compounded out of elementary structural elements, added separately as first-order individuals; added in groups as second-order individuals; or added in groups of groups as third-order individuals” [28, p.98].

In extension to this line of thought the relationship between individuals is established by the hierarchy of the biological world itself. Instead of viewing each and every biological individual in isolation it becomes possible to view each biological individual as (a) part of a larger individual. This concept, of individuals constructing larger individuals, will be further referred to as *vertical nesting*. Spencer’s definition of an individual, either a low “first-order” vertically nested individual or an aggregate of such (second- or third-order), is characterized as ‘an organized and structured unit that is able to persist in its environment whilst continuously distinguishing itself from its surroundings’ [28]. According to Elwick this definition was further generalized by Spencer and he later described a biological individual as ‘any organized unit capable of maintaining a “dynamic equilibrium” between its internal and external environment’. Nowadays this “dynamic equilibrium” is simply referred to as “homeostasis”.

Spencer did make a mistake, or at least has led himself astray, when he tried to understand the degree to which vertically nested individuals kept their autonomy whilst being part of a larger thing. Spencer put the emphasis on lower nesting parts following their own “interest” [28]. For Spencer this made sense since he wanted to switch back and forth between the physical order and the social one but biologically this understanding is flawed. Consider a human being who is an employee in a large organization. From a social perspective this human being can be understood as being a nested individual integrated in a larger body which is the entire organization. As an employee certain tasks need to be fulfilled to benefit and safeguard the success (and hence the persistence in time) of the organization. On the other hand the person we’re considering also has interests of his or her own and these may be interests on which he or she occasionally acts. Those interest do not necessarily have to benefit the company. Now if we consider the cells that make up this person “acting on their own interests” a mentalistic fallacy is made. There is no “will” of the cells nor is there any conscious decision-making taking part at the level of the cell. This intentional stance from the perspective of cells makes it seem as if the idea of retaining autonomy on a low level is acceptable while in reality it is not. In this example the only individual able to act on its own interest is the employee. Besides vertical nesting there is another form of nesting that is hardly ever mentioned: horizontal nesting.

2.3.2 Horizontal Nesting

Another phenomena of “nesting” is related to reproduction too but does not focus on “direct” parent-offspring lineages. Instead horizontal nesting introduces phenomena that deviate from this standard (direct) way of thinking. These phenomena involve more complicated life cycles that interfere with the standard idea of reproduction but are, nonetheless, a common biological feature. It’s the biological process of *alternation of generations*.

Alternation of generations is the primary cause of horizontal nesting. It is present in fungi, plants, and even some animals. In general the process of alternation is part of a life cycle where genomes double and halve in size [31]. A classical case are ferns. Take the *sporophyte* for example, this is a regular fern-shaped and diploid plant. By the process of *meiosis* sporophytes are able to produce *spores*. Contrary to the sporophyte the spores have only one set of chromosomes and will therefore grow into haploid plants. These haploid plants, named *gametophytes*, function perfectly well but are clearly different and distinguishable from the diploid sporophytes. The life cycle continues when gametophytes produce their own ”spores” but now they are called *gametes* and are not (cannot be) produced by meiosis. These gametes are sex cells and are therefore either egg-cells or sperm-cells. When the sperm-cells swim to the egg-cells and fuse together fertilization occurs. The fused sex cells will eventually develop into a brand new *sporophyte* completing the life cycle. To recapitulate: A diploid sporophyte *asexually* produces haploid spores that grow into gametophytes. Then those gametophytes *sexually* produce sporophytes.

Note that this sporophyte-to-gametophyte transition is not just a metamorphosis. It is a different process. In case of an actual metamorphosis, like the transition from caterpillar to butterfly, only one butterfly can originate from one caterpillar. In general terms, only one B can occur from one A. In case of the fern, however, many Bs can come from one single A and on top of that many As can come from one single B as well. A further dissimilarity arises due to the bottleneck stage through which the fern goes whereas a butterfly doesn’t narrow down to a single cell during its transition from the caterpillar phase. Passing through a single-cell bottleneck stage isn’t necessary for As to produce Bs and/or Bs to produce As. For example, in the life cycle of one of the most common jellyfish (the *Scyphozoan* jellyfish) two forms (*medusa* and *polyp*) alternate between generations. The medusa creates sex cells from which polyps arise but polyps, on their turn, produce medusae in a multiplicative manner without passing through a single-cell stage.

Focusing on the diploid fern-shaped plant again, imagine that dogs were all clones and not distinguishable by sex. The dogs would produce something like egg-cells and sperm-cells that grow into female and male horses, or mares and stallions. The mares and stallions would be able to copulate and give birth to same-sex dogs. Since both the dogs and the horses function as metabolic units they are easily characterized as organisms. Reproductive success of the dogs and horses depend on one another. It's the entire life cycle that matters in variation, heredity, and reproduction making it rather difficult to "choose" the Darwinian individual between dog and horse. Fortunately, there is no reason not to interpret both dog, or *sporophyte* and horse, or *gametophyte*, to be two organisms nested as one Darwinian individual.

2.4 Hierarchy of Nested Individuals

One thing has been purposely left out when describing vertically and horizontally nested individuals: degrees of complexity. Here degrees of complexity correspond to different levels of organization by means of vertical nesting. And vertical nesting follows from the hierarchy of nested biological individuals. Note that in biological individuals undergoing alternation of generations vertical nesting is also apparent. This idea of vertical nesting inside horizontal nesting can become complex on its own terms but that is not of importance here. The focus lies on different levels of individuality.

What is meant by this is certainly not that some biological individuals are more a biological individual than others. Any biological specimen is either an individual or it is not. Depending on the measure of activity as well as the kind of activity a biological individual displays, small individuals nested in others might be dominated by the larger individual (which might be dominated by yet a larger one, etc.) [35]. Whether a biological individual dominates or is dominated by another individual depends on its activity in the organization of the highest-order biological individual it is nested in.

For example, consider a human, a cell of the human, and a gene of the human. Generally, the cell is dominated by the activity of the person and has no will of its own.[10] Its activity depends on the internal organization of its surrounding cells which are all dependent on the (physical) state the human is in. The level of activity of the humans' cells depend on the activity of the person, they demand less energy if the human is in rest, they burn a lot of energy

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[10] Cancerous cells can be argued to not be dominated by the activity of the person. Also Clarke argues collectives sometimes encourage (instead of suppress) evolutionary processes in their integrated parts [36].

when the human is active. If the person were to fall ill energy production goes up as well. The point is that in this case the activity of the cells is dominated by the higher-order biological individual. Intuitively it makes sense that lower-order individuals are dominated by the higher-order individuals they are nested in but this need not hold true for every case.

This is nicely captured by the interplay between "human" and "gene of the human". Richard Dawkins makes a great effort of making the gene central in his book *The Selfish Gene.* He argues that "our bodies" are used by "our genes" as mere vehicles. Our genes use our bodies as if they are nothing more than survival machines. This view makes it seem as if there's nothing more to a person than his or her package of genes [37]. In many scientific disciplines concerning biology it is useful to place the emphasis on the importance of genes but this does not entail that genes are the only relevant players. We as "survival machines" do in fact have the ability to influence the package of genes we carry. The point here is that there is no center that instantiates linear causality but rather a network causality [38]. The interplay between human and its genes consists of both an upward and downward causation.

Besides degrees of complexity due to different levels of vertical nesting, another thing follows from the hierarchy of nested biological individuals. Biological individuals are partially characterized through their relations to other biological individuals [35]. Perhaps this characterization holds for relations between biological individuals in general but for now the focus lies on nested individuals. The hierarchy is important to the biological individuality of each nested individual because the relations between them lock in their essential roles. This means that the "individuality" of each biological individual is established through their place in the organization composed by other biological individuals as well as the relations it bears on the other individuals.

2.5 Recapitulation

Defining biological individuals as individuals that are living things, as Pradeu suggested, fails for three reasons. First, there exist (living) biological individuals that do not fit the criteria for individuality well. Second, there exist non-living things that are biological individuals and third, a (strict) definition is most likely to reject current and future living things as biological individuals event though biologist might characterize them as such.

A descriptive definition of biological individuality is given that consist of Darwinian individuals and organisms. This characterization includes both clear and marginal specimens and includes most, if not all, of the specimens in the biological world. The sets of Darwinian individuals and organisms are likely to include all biological individuals put forward by competent biologists and embraces pluralism.

The notion of biological individuality put forward in this chapter argued for a multiplicity of nested individuality. Nesting can be both vertical and horizontal and match the hierarchical structure of the biological world. It also showed that although higher-order biological individuals are capable of dominating lower-order biological individuals there is both upward and downward causation. This implies there is not one favored level of organization.

The hierarchical biological world is then represented by biological individuals which belong to the set of are Darwinian individuals, organisms, or both and display different degrees of complexity. The display of different levels of complexity depends on the biological individuals' activity and its specific place in a (large, multi-level) organization. This organization is constructed by vertical and occasionally horizontal nested biological individuals. The stability of this order is evident, as is the complexity, but in order to understand how biological entities are alive the organizational order should be better understood.

Chapter 3

Unpredictability, Stability, and Entropy

A hierarchy of nested individuals portraying different degrees of complexity raises the question where the first forms of complexity came from and how current forms can be explained. These questions fuel, in part, the challenge of constructing an interpretation of entropy that doesn't contradict the description of biological individuality. That construction is complicated because it cannot lean too heavily on reductionism and because the notion of entropy is ambiguous.

What follows in this chapter is a technical and condensed story about organization. Where necessary, some concepts and processes of physics and biochemistry will be discussed in a bit more detail. Analogies are included to get the message across but are simplified examples of the real thing. The philosophical aspects about biological individuality will be merged with the scientific depiction of complex organization of viable entities near the end of this chapter and continue in the next.

After having introduced the idea behind emergent properties I will discuss the "power" of unpredictability. Emergent properties do not need prediction in order to be explained and understood. Unpredictability is sometimes an inherent property of nature. Physics knows three branches that deal with probability instead of predictability, quantum mechanics, chaos theory, and statistical mechanics. These disciplines are briefly introduced to explain how a statistical approach can give a reasonable understanding of a complex system without the need to know every single detail.

The third topic covers different notions of entropy. Complex biological living things are stable and highly ordered, and remain ordered. However, according to physical laws everything should get only more and more disordered. According to Erwin Schrödinger's ideas put forward in his written lectures *What is Life?* a statistical understanding of entropy shows that a stable state is still in accord with physical laws. However, his ideas are both promising in understanding living things and at the same time show how our understanding remains limited. Also the problem of all things moving towards thermodynamic equilibrium (the biological equivalent of death) except for living things is examined.

3.1 Two approaches: Reductionism and Emergentism

Subdividing a system in smaller parts and explaining the entire system solely by its parts lies at the heart of a reductionist approach. It is undeniable that reductionist strategies have been fruitful in the scientific enterprise but sometimes the whole cannot be properly explained by the mere sum of its parts. In some cases natural phenomena require more than a detailed description of their interacting parts because relevant aspects of the phenomena appear only at the level of the whole system. The appropriate level of description that captures the properties of the whole system cannot be found in its parts due to those constituents parts lacking the properties being described. To list a few examples, 'the properties of H_2 and O_2 do not allow us to predict the properties of H_2O; understanding the molecular properties of H_2O does not allow us to derive the Navier-Stokes equations; having the Navier-Stokes equations does not give us a prediction and description of Benard cells' [8].

In these examples properties (or substances) emanate from more basic entities and cannot be subdivided with respect to those entities. Higher-level properties which are not reducible with respect to their parts are called emergent properties [39][40]. Emergence contrasts reductionism in the sense that from a reductionist perspective the whole can (and needs to) be explained solely by the sum of its parts whilst from an emergentist' viewpoint the whole is more than the sum of its parts. It should be noted that nothing mystical is meant by this for the properties can still be rationally explained, that is, without the help of an unknown force. In other words: 'Emergent properties provide the recognition that nature can be creative while denying the occurrence of miracles or inconsistencies' [8].

There is another word that accounts for higher-order properties that are caused by, though not present in, lower-level organization of parts: epiphenomenon. Often the term "epiphenomenon" is defined along the lines of 'a secondary phenomenon that arises as a byproduct of a primary phenomenon' [41]. It's not particularly clear how the term "secondary phenomenon" and "byproduct" should be interpreted but it cannot be taken to be completely separated from the "primary phenomenon". A good example is Brownian motion, the random motion of a non-organic particle in a liquid or gas. Without a proper understanding of what Brownian motion is it seems as if the particles move on their own which is physically not possible. This mystery was solved by Einstein and Brownian motion is now known to be the movement of non-organic particles in a liquid or gas due to the constant bombardment by atoms coming from different directions. When the particle is hit on one side more often than any other side the net force of the bombardment pushes the particle in a specific though random direction. Brownian motion is a probabilistic process, a secondary phenomenon that arises as a byproduct of the random motion of other particles and is one of the simplest emerging phenomena of interacting particles. It can be described as ‘a phenomenon that emerges independently from the underlying phenomena that bring it about’ [42]. In this thesis “emergent” and “epiphenomenal” are therefore taken to be synonymous.

Emergent phenomena are the result of descriptions of properties that refer to real and often complex processes in nature. The trouble with these processes is that they can often be explained but not predicted since they arise as “novel” functions. Inability to predict a process does not mean that it is poorly understood. In fact, unpredictability can itself be predicted as is the case in quantum mechanics and chaos theory. Because unpredictability is of great importance in dealing with emergentism it is wise to pay a little more attention to it.

3.2 Unpredictability

There are parallels between emergence and quantum mechanics, chaotic behaviour, and statistical mechanics: all involve unpredictability. With emergence, (real) observers are unable to predict higher-level properties of complex systems by studying the parts and their interactions that make up the whole system. In case of quantum mechanics, a fundamental indeterminism forbids us to gain knowledge about specific atomic events [43] and with chaos unpredictable behaviour arises due to extreme sensitivity to initial conditions [8]. In statistical mechanics there exist an inability to know the details of every particle’s trajectory. However, this lack of knowledge about the parts that make up the system does not prevent us from making valuable statements about the system as a whole.

Uncertainty can lead the way to a statistical interpretation of complex systems. Especially in statistical physics interactions within a two-state system or between two separate systems can easily be described by calculating their most likely *macro*state instead of all independent *micro*states [44, p.59]. Apparent characteristics of such macroscopic systems like temperature, energy fluctuations, and stability can be derived without knowing the details of every microstate. The most likely macrostates are energetically more favourable and account for the *static* stability of the system(s) and although these systems are non-living a similar path for living systems is reached but by means of a *dynamic* stability.[1] This dynamic stability will play a major role in constructing the idea behind what makes living systems alive. This will be explained in detail below but it is of importance to introduce another concept first, the notion of entropy. On the one hand, dynamic stability is a form of a well organized system in equilibrium. On the other hand, entropy tells us it's most likely for a system to become more disordered. This tension, between the likelihood of order and disorder, needs to be addressed and solved.

3.3 Notions of Entropy

The concept of entropy has been linked to living things ever since the (written) lectures of Erwin Schrödinger's *What is Life?*. There exist, however, many notions of entropy besides a statistical interpretation Schrödinger uses. Therefore, using the expression "the" notion of entropy is already at fault. Here, the problem of the ambiguous notion of entropy will be discussed as well as Erwin Schrödinger's interpretation in *What is Life?*.

The first to mathematically define "entropy" was Rudolf Clausius around 1850 and the formulation went through some transformations to finally become how it is known now in science (although as a classical interpretation of entropy). The first formulation described the transfer of heat from one body to another:

$$S = \frac{Q}{T},\ \Delta S = Q(\frac{1}{T_2} - \frac{1}{T_1}),$$

where S denotes entropy, Q denotes heat, and T denotes temperature. Later Clausius would state that for every cyclical process the expression

$$\int \frac{\delta Q}{T} \geq 0$$

would hold, even in an idealized system where an energy loss due to friction could be excluded. He coined the term "entropy" and stated that 'The entropy of the world always strives towards a maximum', which is now often cited as the *Second Law of Thermodynamics* [45]. After this "classical" formulation of entropy in thermodynamic physics other formulations are present nowadays in statistical thermal physics and information theory. In these fields also different

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[1] Imagine a fountain in a pond. If the fountain is turned off the pond is in equilibrium. This equilibrium is *static*. If one were to make a picture of the pond at t = t1, t2, and t3 all pictures would be similar whilst depicting the same water particles. If the fountain is turned on and there is no loss of water the system is also in equilibrium. This equilibrium is said to be *dynamic*. Now if one were to snap a picture of the pond at t* = t1*, t2*, and t3* the pictures would be similar whilst depicting different water particles.

formulations of the Second Law of Thermodynamics have sprouted.

Common thoughts about entropy include statements as ‘entropy always increases’, ‘a system always tends towards a more disordered state’, ‘a system is most likely to be found in its most probable macrostate’, ‘an ever increasing measure of entropy determines the arrow of time’. All have been used at one stage or another because a definition of thermodynamic entropy is difficult to make precise and there are numerous ways to approach that. There is no room for those strategies in this thesis but a detailed discussion can be found in Uffink’s work [45].

The formulation put forward by Clausius did not make clear what entropy *is*, only what a simple thermodynamic system *does*. In the 1870s Boltzmann developed a statistical interpretation of entropy:

$$S = k_b \ln(\Omega)$$

with k_b Boltzmann’s constant and Ω the number of microstates corresponding to a specific macrostate. It paved the way for the study of systems comprised of large numbers of particles and studying different interactions associated with derivatives of entropy. Depending on the system of interest, notions of entropy governed either interactions associated with energy and temperature, volume and pressure, or particles and chemical potentials [46].

A statistical interpretation of entropy sometimes led to error whenever the newly updated Second Law of Thermodynamics was treated as a fundamental law. This is theoretically incorrect. It is a probabilistic notion which seems to hold true in practice due to astronomically large numbers being fed into the statistical formulation. The lower the number of states, the more incorrect it tends to become. A second problem was the difficulty in understanding the qualitative nature of evolved mathematical equations of entropy, such as:

$$S = k_b N \left(\frac{3}{2} \ln \left(\frac{4\pi m U V^{3/2}}{3 h_o^2 N^{5/3}} \right) + \frac{5}{2} \right)$$

with N the number of gas particles, h_o Planck’s constant, U equals internal energy, and V denotes volume. This formula is an expression of entropy of a pure classical monatomic ideal gas. Two qualitative arguments concerning the dependence of S on m can give opposite results [46].

The ambiguity of the concept of entropy was not all bad as it was used in mathematics as a relatively flexible concept that could have multiple meanings [47]. In time the concept of entropy even found its way to information processing, cosmology and economics. The first of these is worth pursuing as it may have strong links with the question whether it can demonstrate the consistency of statistical mechanics. Both the probabilistic nature of entropy is questioned as well as the validity of the Second Law of Thermodynamics that states that entropy always increases.

First, when only partial information is available there still exist ways to assign numerical values to probabilities. However, setting up rules or consistency requirements to do so is subject to debate and controversy [48]. Part of the problem is the meaning of probability itself. A more general statement of a statistical notion of entropy regarding information is Shannon entropy:

$$H = -K \sum_{i=1}^{n} p_i \log(p_i)$$

with K a positive constant and p_i the probability of event i. In order to assign numerical values to its probabilities constraints need to be set. Justification of constraints, however, seems hard on the basis of partial information but there are various ways to construct constraints from empirical data [49]. For example, if one uses Boltzmann's equation for entropy to describe the change in entropy after a constraint on a specific variable is removed (e.g. removing a partition in a box that contained an ideal gas on only one side of that partition) then one is left with a number of microstates, Ω. After the moment the partition is lifted but before an equilibrium state is reached, the probabilities corresponding to each microstate are not (yet) equal to $1/\Omega$. In theory the assumption that all microstates have the exact same probability could be false. That being said, the overwhelming body of experimental data concerning states of systems indicates that the assumption is extremely reasonable [44]. Exceptions in numerical values of probabilities between microstates corresponding to a specific macrostate may still be observed in the future but even if probabilities are shown not to be equal the differences are "most likely" unable to influence outcomes of systems composed of large numbers of particles. The practical side of systems being composed of a large number of particles puts a strong constraint on assigning numerical values to probabilities because the probabilities are defined as being frequency dependent.

Second, validity of the mechanisms of statistical mechanics has been put to the test by Maxwell's Demon, Szilard's engine [50], and Landauer's principle. The literature on this is extensive and touches upon many subjects but for the sake of space in this thesis the focus will be on the relation between possible ways to violate the Second Law of Thermodynamics by means of intervention. The idea behind intervention in a predetermined thermodynamic system, either by a demon, mechanism, intelligent being, or computational entity, is that with certain knowledge about the system it is possible to decrease the entropy of that system and violate the Second Law of Thermodynamics. It can be argued that acquiring the necessary information about the system brings about an entropic cost that more than offsets the decrease in entropy by utilizing that information. In other words, a local decrease of entropy is possible as long as the entire system (which includes the demon, intelligent being, etc.) still increases the total entropy. Up to this day there are still problems with the combination of knowledge and thermodynamic entropy [51].

The reason for stating this second problem relating to information and thermodynamic entropy is the possibility of locally decreasing entropy. This is what Erwin Schrödinger called *negentropy* when he used the concept to describe order in biological systems [52]. His interpretation and use of the concept of entropy in biological systems is discussed below.

3.3.1 Schrödinger's Interpretation of Entropy in Biological Systems

Erwin Schrödinger set out to answer the questions about a physical and chemical basis within living things in a series of lectures that were later published as *What is Life?*. The actual question 'What is Life?' was changed and consisted of two separate questions: "What is the physicochemical basis of heredity?" and "How does order arise from disorder?".

These two questions both strongly fused the development of molecular biology and anticipated its ultimate explanatory inadequacy. Inspired by the first question, the basis for heredity was conceptualized and later found to originate from a lower level of organization. In the Central Dogma of molecular biology it was thought that DNA was the master molecule and the only source of information [53]. Causality was thought to be all upward from lower levels of organization to higher ones. Plausible answers to the second question changed this conceptualization and showed that levels of organization must be taken seriously for new properties could emerge at each level of organization and influence lower ones. 'This showed there was no privileged level of examination or explanation' [53].

Schrödinger's efforts in answering how order could arise from disorder focused on the thermodynamics of living things. Schroödinger's answer was constructed to deal with the problem how living things could display order whilst the Second Law of Thermodynamics stated that disorder always increases. Here "disorder" does not relate to macroscopic properties of a system but to its specific microscopic description instead. Schrö dinger's concept of entropy was Boltzmann's mathematical description and thus a statistical interpretation.

Although his work may have fused the development of molecular biology his ideas also limited it. A close inspection of his work shows that plausible answers to his two questions that should answer the bigger question 'What is Life?' are paradoxical [53]. Also Schrödinger wondered if additional laws might be necessary to explain life but did not found reasonable ground to support this any further [54]. Some even found his book unoriginal and claimed it contained untrue statements, which could have been prevented if he hadn't largely ignored the science of chemistry [55].

Nevertheless, his idea about interpreting living things as thermodynamic entities that locally reduce entropy in order to maintain and establish order and prevent their decay could be fruitful in constructing an idea of complex organization. If a move from chemistry to biology can be made by means of local reduction of entropy, where entropy is considered to be a measure of disorder, it may be possible to accept the conceptualization that levels of organization are important.

3.4 Stability: Static and Dynamic

An energetically favourable state is a stable state and although it relies on the system's parts it is actually the whole system that is taken to be stable. In case of a system consisting of a glass of water with a droplet of ink the stable state will be the one where the ink molecules are evenly distributed throughout the water. When a system is in such a *static* stable state it is said to be in equilibrium, like a ball at rest at the bottom of a well. And even though quantum mechanics accounts for some non-zero probability of deviating from equilibrium (spontaneous formation of the ink droplet) the chances are so small that in any real situation such chances can be ignored. In a biological context the parts that eventually make up a stable system are the underlying chemical reactions responsible for maintenance and organization of cells. These reactions can produce stable states as well but are *dynamic* states instead of *static* ones.

This difference is subtle but important. Ink and water molecules bump into each other but don't react but various molecules present in even the smallest biological systems do. Upon collision plenty of molecules are able to react if enzymes are present to catalyze the reactions. However, even in a diverse molecular environment it is highly unlikely that the right reactants as well as the catalysts (enzyme) for that particular reaction would meet. Some products, however, are able to function as catalysts in their own formation and are formally known as *autocatalysts*.[2] The unlikeliness of the right reactants and catalysts is no issue in case of an autocatalytic reaction since it is a self-sustaining system [6]. One such system in particular is of great importance in living systems: self-replicating autocatalytic molecules.

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[2] A big difference between catalysis and autocatalysis, besides the use of products, is the reaction rate between them. In the autocatalytic reaction, the rate of product formation proceeds exponentially whilst the catalytic reaction only happens linearly. Autocatalysis will therefore out-compete normal catalytic reactions almost instantly.

A self-replicating molecule needs materials for its replication and because its products have the ability to self-replicate, so too do they. If such a self-replicating molecule were to replicate every minute then, within 3 hours, the entire Earth's mass would be consumed to sustain the replication processes. Obviously this will not happen because the rate of production is balanced by a corresponding rate of decay. This balance stabilizes the autocatalytic self-replicating system but in a specific way. The stable state reached is not an equilibrium state for that would be a thermodynamic equilibrium and corresponds to death in a biological system [52]. The stable state is *dynamic* indicating the products are formed and broken down in a continuous fashion and *kinetic* in the sense that a high rate of production and low rate of decay adds to the stability. Therefore no *static* stability occurs in living things but a *dynamic kinetic stability* originates [56]. This special kind of stability by entropy of an autocatalytic self-replicating system is able to establish order from disorder without breaking The Second Law of Thermodynamics and is a key element in the structural basis for complex organization.

3.5 Recapitulation

Many systems can be aptly characterized as merely the sum of its parts, but some systems show higher-order properties at the level of the whole system that are not present in its parts. Although emergent properties cannot be predicted beforehand a lack of knowledge of a system's parts and/or interactions does not entail a lack of understanding of the whole.

In statistic mechanics it is possible to make sense of a system without detailed knowledge about its many parts. Instead, a system's macrostate(s) can be calculated by determining the highest probability frequency of its number of microstates. The probabilistic nature of a system's macrostate tends to correspond to the system's most energetically favorable and stable configuration.

In any thermodynamic system a stable configuration increases (or increased) entropy except in living systems. A statistical notion of entropy can be used to explain this exception. Erwin Schrödinger used a statistical notion of entropy to generate an idea he called negentropy to explain living systems as out-of-equilibrium systems that locally decrease entropy. The entropy of the whole system (the universe's) still increases preventing a violation of the Second Law of Thermodynamics.

A dynamically stable state on a molecular basis is a self-replicating autocatalytic system and functions as a first level of organization. A self-replicating autocatalytic system forms a chemical basis from which a system can transition towards a biological one. At this level of organization a response to selection can occur, because it can out compete other catalytic systems. The system can therefore increase its complexity and express a dynamic and kinetic stability.

The next chapter will look at the autocatalytic system as a mechanism that is able to locally decrease entropy and, over time, can develop further levels of (complex) organization.

Chapter 4

Bounded Complex Organization in Biological and Artificial Systems

To create a concept of life as an emergent property which originates from the interplay between biological individuality and entropy two more ideas need to be put forward. These are notions of contained organization by compartmentalization and increased complexity by autocatalysis crossing a percolation threshold and correspond to biological individuality and entropy, respectively.

The first thing explained in this chapter is that dynamic stability is possible when things that make up the stability are bounded. A compartment (or vesicle) allows for a local increase in stability and doesn't undermine the notion of entropy described above.

Section 4.2 contains a dense and slightly simplified idea about the emergence of proto-metabolism inside a vesicle. The most important concepts in this section are the rise of autocatalysis and especially the idea of an autocatalytic web snapping into existence when a percolation threshold is crossed. It ends with fusing the idea of emergent properties with the concept of a compartmentalized entity embodying a minimum degree of complexity. At the lowest level of organization, where there exist a minimum degree of complexity, biological individuality and entropy give rise to first signs of life.

The last sections of this chapter discuss interpretations of artificial life. The prefix "biological" is briefly mentioned and the notion of substrate neutrality is given attention.

4.1 Compartmentalization

Static stability is like water in a lake. If one were to shoot multiple pictures of the lake with small delays between the photographs each picture would still show the same lake built from the same water molecules. *Dynamic kinetic stability* is like water in a mountain river and if one were to shoot multiple pictures of the river each photograph would show the same stream of water but consisting of different water molecules. Besides a form of stability the lake and the river share another feature: they are both bounded. An autocatalytic self-replicating entity is unable to function if it cannot acquire enough material for the rate of formation to equal the rate of decay. There is a need for sufficient building blocks and they have to be in close vicinity to each other for the entire system to persist in time. The best way to ensure the autocatalytic self-replicating entity is able to gather enough building blocks and sustain its reaction is to lock everything up in a small space[1] [58].

It is no coincidence that all life on Earth is cellular. Cells compartmentalize their content with a semi-permeable membrane which allows for diffusion. The cell membrane of selectively lets through building blocks and waste products allowing for a dynamic and kinetic stable inner environment [59]. Still, compartmentalizing an autocatalytic self-replicating entity with a large amount of building blocks may look like a cell but isn't yet a living thing. Compartmentalization is one step closer to something we consider to be living but before such a thing is reached both autocatalysis and self-replication need to be described from a different, more realistic, perspective.

4.2 Birth of Life: a Hypothesis

Even in a pre-biotic world molecular diversity may be constrained by selection [19]. Luckily, selection between compartments arises favouring crowded inner environments over emptier ones [60]. Inside a crowded compartment different molecules may function as catalysts in other molecules' reaction(s) producing yet other chemicals [61]. What happens next might be the most important step in the transition from a non-living system to a living one. Instead of the production of one single autocatalyst a variety of molecules and their reactions produce several autocatalysts creating a giant autocatalytic web. One large interconnected system forming a closed complex autocatalytic set appears at a critical value when moving from order to chaos. This will be illustrated with

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[1] "To be an entity, distinguished from the environment, requires a barrier to free diffusion. The necessity of thermodynamically isolating a subsystem is an irreducible condition of life. [...] It is the closure of an amphiphilic bilayer membrane into a vesicle that represents discrete transition from nonlife to life" [57, p.8].

the example below. Complexity starts to increase as a (large) compartment becomes more crowded.[2] As the number of (diverse) chemicals within the compartment rises more reactions become possible and eventually a point is reached at which an autocatalytic system snaps into existence [63]. This process is easily visualized by the following thought experiment.

Consider a thousand light bulbs all randomly distributed on a floor. Initially all light bulbs are isolated and switched off but if a light bulb is connected to at least one other light bulb it is switched on. Light bulbs are connected by randomly choosing two and putting a simple wire between them. The goal of the experiment is to find the number of wires to get all light bulbs connected and burning. In the first stage of the experiment it's most likely two non-burning light bulbs will get connected. After a while chances become relatively large non-burning light bulbs get connected to burning ones leading to the rise of large clusters. As the ratio of wires to light bulbs continues to increase and passes 0.5 a sudden transition occurs where almost all large clusters get connected to each other and the entire floor is almost entire lid up by burning light bulbs. After this transition only a few more non-burning light bulbs need to get connected.[3] It might take a long time to get all light bulbs in the on-state because many light bulbs will get connected which are already on.

The actual result of the experiment is not of importance but what happens halfway through the experiment is. As the ratio of wires to light bulbs passes (roughly) 0.5 a phase transition occurs where the size of the largest cluster of burning light bulbs suddenly jumps from just under 150 to well over 800 -[4], see figure 4.1. The threshold for the critical ratio of wires to light bulbs giving rise to the phase transition is called the *percolation threshold* and is used in various mathematical models describing complicated systems and networks [64].

Lightbulbs and wires don't interact but molecules do. The diversity of molecules increases not only by different substances of building blocks but by difference in length as well. Through ligation and cleavage the molecular diversity increases slowly as does the number of reactions between them. As soon as the ratio of reactions to molecules reaches a critical point and crosses the percolation

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[2] A way to increase molecular complexity is for one to bring together more enzymes and nucleic acids, or more enzyme species in order to induce, in principle, a metabolic cycle [62, p.232].

[3] The chance to select non-burning light bulbs with the first wire is 1 (since all are off at the start of the experiment). Connecting the last light bulb only has a $\frac{1}{1000} = 0.1\%$ chance of getting lit.

[4] As the number of light bulbs reaches infinity the transition becomes discontinuous. In the example the jump from 150 to 800 will follow an S-shaped curve but will approximate a step-function with an increasing number of light bulbs.

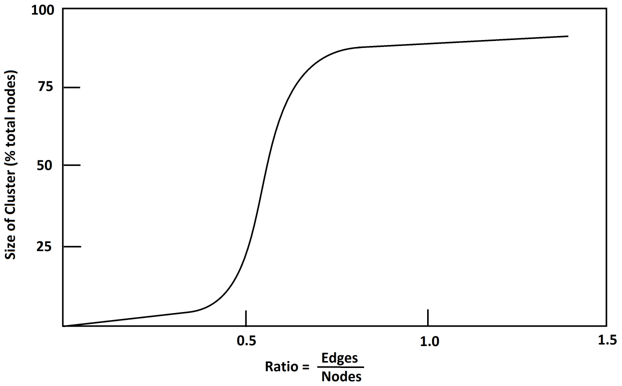

Figure 4.1: Schematic drawing of a phase transition were the number of total light bulbs (nodes) shows a steep increase as the ratio of (Wires/Bulbs), or (Edges/Nodes), exceeds 0.5. Image (modulated) from [63, p.57].

threshold an autocatalytic system suddenly jumps into existence. Every "new" molecule adds to "crowdedness" and leads to (new) possible reactions within the compartment. This makes it more complex but not yet functional. However, after the percolation threshold is crossed a self-sustaining entity arises giving rise to higher-order properties [6][64]. The addition of complexity is quantized in terms of molecules and the reactions between them. First in terms of an ever more crowded compartment, second in terms of a higher diversity of molecules and possible reactions, and third in terms of functionality after the autocatalytic system occurred.

A closed autocatalytic set with simple molecules can display stunning order without violating any law of physics. Although the order inside a compartment shows a local *decrease* of entropy the entire system, consisting of the inside and outside environment of the the "cell", shows an *increase* in entropy [52]. It's like someone gluing a broken piece of china back together, partly restoring order but using so much physical energy for the local decrease of entropy that the total amount of disorder still increases. The order inside the compartment gives rise to complex phenomena eventually leading to emergent properties [65].

Complexity increases until a functional autocatalytic system occurs, which happens due to a local decrease in entropy. This will be the base level of complexity necessary to allow for the rise of emergent properties. Examples of such properties are increased functionality (diversified replicate system), complex structure (stable double layered cell membrane), catalytic efficiency (effective energy consumption and waste segregation), evolvability, etc. Once a compartmentalized proto-metabolic unit emerges, evolution by natural selection is able to drive its increased complexity further due to the existence of a ground level organization at which a response to selection can occur. I argue that the meaning of "evolving increased complexity" is about creating new levels of organization at which (pre-)biotic entities can be active. By establishing their place in the (internal) organization composed by other pre-biotic entities the first signs of nested individuality can appear. These nested individuals show signs or display properties which may be attributed to living things [57].

From a scientific point of view the scenario described in the paragraph above is speculative. The reason for this is that there has not (yet) been scientific success regarding the transition from proto-cell to biological living individual, in other words making a proto-cell viable. It's currently not experimentally feasible to create enough molecular diversity inside a small vesicle (such as a (one-layered) lipid) or to establish a phase transition into an autocatalytic web *in vivo*. At this moment the focus lies on self-replication and building stable vesicles. It seems hard to move from a vesicle containing a pre-biotic look-a-like replicate system (genes) and increase its complexity in a stable fashion. This is not yet scientifically understood. Philosophically, however, there might be an idea why this transition is hard to establish and that idea has to do with genes as information bearers.

4.3 Artificial Life

How do we move from a vesicle containing what is believed to be the bear minimum number of materials needed for self-replication and maintenance to an entity that can be claimed to be viable? A possible answer to this question follows below. Furthermore, life *in silico* is discussed in the remainder of this chapter. Here life within a digital domain and robotic life are shortly mentioned. And a link is made between substrate-neutrality and living biological individuals.

4.3.1 Genetic "Genes"

Self-replication needs a template and enough material to operate successfully. This is known from present-day examples such as RNA and DNA. However, the most valuable feature of successful, e.g. errorless, replication is conservation of genetic information. Contrary to previous beliefs the genetic code is a product of the living world and may have come later as it functioned for more efficient reproduction of already living things [66]. A self-replicating molecule is not, in and of itself, genetic, even if it has the potential to become an information bearer in a later stage of its existence. It will become genetic 'only if it is placed in a network of relations associating it with various intracellular functions' [66, p.19].

A variety of functions is produced by molecular diversity which originates from copying errors and/or other chemical reactions. In fact, the rise of molecular diversity is key in creating a network suitable for a self-replicating entity to become an informational element, or “genetic”. In and of itself, self-replication is not able to make a molecule a genetic entity because it doesn’t necessarily have the capacity to produce the (emergent) properties of a cell that contains it. Before a particular molecule becomes an information bearer it needs to allow for a high number of interactions. The better a molecule is at “holding” information the more resilient it must be to change, for changing the molecule causes loss of information. The higher the resilience the lower its interactions. So either information is kept and interactions stunned or interactions are abundant but information is lost.

On top of this problem an information bearer needs machinery to transcribe and translate the information it contains. On the other hand, the biological machinery to execute transcription and translation needs to be produced. The production, however, relies on reading the information of the information bearer. So both information bearer and biological machinery to read the information need to exist simultaneously.

4.3.2 Non-Biological Life

Chapter 3 briefly mentioned the inability to experimentally create a phase transition where a large number of molecules snap into an autocatalytic functioning web *in vivo*. The term *in vivo* is of importance. Testing the conditions under which the percolation threshold is crossed is with today’s computing power easily done *in silico*. Computer technology is often used to gain understanding of the interactions within (or between) living things by translating that behaviour into a digital world. Synthesizing life in artificial media makes it possible to ‘develop practical applications involving new technologies that exploit intuitions and methods it takes from living systems’ [67, p.395]. The synthesis of life can be done by either creating a living world within digital boundaries or by introducing robots (or “robotic life”) into the real biological world.

Robots function mainly by regulation of a control center. Sometimes several control units work in parallel but there always remain cores or centres of control. This is characteristically non-biological, where the accumulated interactions of many things work together. No one specific location is solely responsible for all activity. Living worlds inside digital domains are at least as far from the real deal as robotic life is. Artificial life does not represent biological systems but is, nonetheless, exceptionally suitable to generate simple instances of lifelike phenomena [67, p.396].

4.4 Substrate Neutrality

The strongest claim of artificial life researchers is the expectation that many of the most fundamental features of the evolution of life on Earth will be shown to be independent of the physical media that happen to embody the process [67, p.397]. I argue that this is wrong. The embodied process is the very thing realized by internal organization of and relations between the parts that make up living biological individuals. Putting the focus on the "process" is valid but the claim that this is independent of the physical media is not.

In chapter 1 it was shown that not every interaction between physical matter is possible. For example, atoms have a predefined number of electrons they can carry in each shell. The number of electrons per shell is bounded by physical laws causing quantized energy levels between them. Atoms are therefore bounded in their interactions based on the favorability of the energy exchange between them. Some atoms bind better or more likely to some than to others. Some are more likely to share electrons than others are. This is a consequence of the fabric of nature.

The possibilities to create biological life are limited (or bounded) in the same respect. Interaction of entities depends on the very nature of those entities. Biological building blocks, even in their inanimate form, are able to interact in a wide variety of ways but due to their nature this variety is not limitless. Some building blocks are more likely to interact than others shaping further levels of organization and complexity later on. Organization and relations between entities rely on the nature of those entities. Due to the "nature of nature" life is inherently bounded. Those entities that are able to interact in such a way as to eventually produce and later on influence life will come to carry the prefix "biological". Biological individuals and life are intertwined by the vast but limited possibilities of interacting matter. The interactions underlying this entanglement, e.g. an autocatalytic web inside a compartment or an autopoietic system consisting of aggregates of cells, can be described by the concepts of biological individuality and statistical thermodynamic entropy put forward in the previous chapters.

Although some biological individuals are argued not to be living, such as genes, they do carry the prefix biological. I argue, however, that this is applicable only after they become part of an entity which has sufficient levels of organization to bring about emergent properties. Because only then their role in the total organization will be established by means of the relations with other (biological) entities. Only after a base level of complexity within a vesicle is crossed do we speak of viable vesicles, or cells [68]. When taken out of existence a unique cell has ceased to exist, when recreated another unique cell (different from the first one) will have arisen. Any stage before that a "protocell" remains non-biological.

4.5 Recapitulation

Compartmentalization contains but does not isolate an autocatalytic system and allows for it to maintain and develop itself. A self-replicating autocatalytic web snaps into existence when the ratio between molecular species and reactions between them reaches a percolation threshold. Once the threshold is crossed a phase transition occurs that produces a dynamic and kinetically stable system that is able to locally decrease entropy.

Increasing complexity of the system creates new levels of organization at which a response to selection can occur. What starts as a non-living crowded vesicle transitions into a protocell that leads the way to the first biological individual. A further increase in complexity produces emergent properties such as improved functionality, structure, and catalytic efficiency. Besides single cells containing a self-replicating autocatalytic web that drives a local decrease in entropy a collective of cells embodies a autopoietic system that can do the same.

Complex levels of organization eventually depend on a molecule (or several) that can function as information bearers for the entire system. However, this relies on the (molecular) organization as a whole.

Life-like phenomenon can be digitally expressed but are different from biological life due to a center of control and a lack of interaction or dependence on its environment. Also, biological life was shown to be limited by the number of interactions possible by nature. This restriction is unlikely, if not impossible, to overcome for artificial life and will therefore always be different from biological life.

Conclusion

From chapter 1 we know it is hard to define individuality. We used Pradeu's definition of individuality to understand were problems of defining individuality originate from. The chapter showed that there exist individual things that do not satisfy all criteria very well. The criteria listed by Pradeu's definition fitted well with natural kinds, such as atoms, but sometimes poorly with living things. Living things are not always clearly separated, they change through time and were argued to have boundaries that are dependent upon the observer's satisfaction.

Chapter 2 showed that a definition of biological individuality as individuals that are living things displayed similar problems. There exist examples of biological individuals that are living things but do not satisfy all criteria of individuality and examples of biological individuals that are not alive. These problems were solved by constructing a descriptive definition of biological individuality that is the union of the sets of Darwinian individuals and organisms. This categorization embraces pluralism and contains all levels of organization at which a response to selection can occur. Both Darwinian individuals and organisms contain clear and more marginal cases due to reproduction and evolution. This construction matches a hierarchy of nested individuals, both vertically and horizontally, spanning the full biological world. Nested biological individuals are argued to rely on their place inside a larger organization and the relations they have with other individuals. No level of organization is favored over another and each level displays a specific form of activity leading to different levels of complexity within any nested biological individual.

Chapter 3 explained that emergent properties arise due to the parts of a system producing novel functions at higher levels of organization that could not have been predicted beforehand. A lack of predictability does not mean a system is poorly understood and a macrostate of a system can still be known without knowledge about the details of each and every microstate. Such a macrostate is often a stable state in a thermodynamic system and refers to its energetically most favorable state where entropy has increased the most. Living systems, however, show a decrease in entropy but Erwin Schrödinger showed that by using of a statistical notion of entropy it is possible for a system to locally decrease entropy whilst increasing the entropy of the total system. This explanation shows that living systems do not violate the Second Law of Thermodynamics.

Chapter 4 explained, besides the complexity, the stability of living things. A dynamic kinetic stable system is represented by a self-replicating autocatalytic system that is contained within a compartment but not isolated from its environment. A compartmentalized entity harboring a high degree of various interacting molecules is able to cross a percolation threshold in order to snap an autocatalytic web into existence that further drives a local decrease in entropy. Crossing a minimal degree of complexity will allow for emergent properties to arise which, at the same time, instantiate the first biological individual. Biological individuality and entropy meet for the first time at the lowest level of organization and relate to a minimal level of complexity while maintaining its internal order. The first living biological individual then is a cell and the chapter argued that from that point on the prefix biological may also be used for whatever system fulfills a distinctive role inside that organization of the whole (such as genes as information bearers). Our efforts in trying to represent life in different media will not work but are capable of broadening our understanding of it. The reason it will not work in different media is that life *in silico* is constructed in such a way that it favours a level of organization which localizes a center of control and lacks interaction with the environment. In addition, the nature of the physical media restricts the interactions of and relations between matter.

The idea of biological individuality put forward in this thesis embraces pluralism and is therefore in disagreement with other notions of biological individuality that endorse monism. De Sousa would disagree with the notion of biological individuality of this thesis and argues that 'In the light of bizarre cases, we have a choice between insisting on a weak criterion of individuality that will fit the entire gamut of biological diversity, and a strong one which will exclude most living things. The second view, I [De Sousa] will argue, casts the clearer light on the living world as a whole and on ourselves in particular' [69, p.196]. It seems contradictory to me to exclude most living things in order to shed a clearer light on the living world. The problem of a monoistic interpretation of individuality is, I believe, besides excluding current borderline cases, there may be many undiscovered or evolving biological individuals that we will want to interpret as biological individuals in the near future. A second objection I have against De Sousa's view is making human beings a central focus of attention. In the biological world human beings are just another form of life and are not more a biological individual than other things in the biological world.

Another categorization of biological individuality has been put forward by R.

Wilson in his book *Genes and the Agents of Life. The Individual in the Fragile Sciences.* Wilson's idea was not analysed in this thesis, because it cannot be squared with the rise of emergent properties. Wilson rethinks the place the individual has in biology and takes agents to be individuals [70, p.7]. He includes species, organisms, and genes as being agents of life. This is still in alignment with the main direction of chapter 2 but Wilson's characterization of agency is where it becomes problematic. He states: "I intend to characterize an agent in quite a general way: an agent is an individual entity that is a locus of causation or action." [70, p.6]. This characterization does not fit with emergent properties which may constitute organization without a pre-defined locus of causation.

The idea of life as an emergent property does not fit well in scientific branches that approach life from a merely reductionist point of view. In this thesis I already made a case for involving emergentism but I like to stress that this is not necessarily a common strategy in research about cellular dynamics, origin of life, or constructing minimal cells. However, systems biology becomes more apparent in these branches and does embrace a holistic interpretation of biological systems.

Besides arguing for emergentism I stated that the nature of interactions of organic material is not the same as the nature of the interactions of inorganic material and that therefore emergent properties would be different. One might object to this and say it could be possible that different interactions may create similar emergent properties we might come to conceptualize as life. My critique on this, however, is that no evidence exist (in systems biology) that would support that hypothesis.

The idea of life as an emergent property is, for the most part, in agreement with Bruce Weber's interpretation of life. Weber argues for the importance of understanding the origin of life to better understand what life is [71]. In doing so he focuses his attention on the part Schrödinger was claimed to have left out, giving attention to a chemical basis as a step prior to biological systems. Weber also states that understanding information signalling and interpretation will help explain the emergence of life [72][73]. What I do not agree on with Weber is his need for additional laws in order to define emergent complexity [73][74]. Weber opts for additional laws after he recognizes three different strengths or forms of emergence. In my opinion, this complicates an already complex subject even further without any evidence suggesting there should be new laws. Just as in Schrödinger's case Weber's wonder if additional laws might be necessary to explain life do not seem to find reasonable ground for further support.

Bibliography

[1] J. Gayon. Defining Life: Synthesis and Conclusions. *Origins of Life and Evolution of Biospheres*, 40:231–244, 2010.

[2] J.S. Fruton. *Molecules and Life.* Wiley, 1972.

[3] F.G. Hopkins. The Dynamic Side of Biochemistry. *Nature*, 92:213–223, 1949.

[4] J.B.S. Haldane. *What is Life?* Boni and Gaer, 1947.

[5] Lynn Margulis and Dorian Sagan. *What is Life?* University of California Press, 1995.

[6] John Maynard Smith and Eörs Szathmáry. *The Origins of Life.* Oxford University Press, 1999.

[7] Frédéric Bouchard and Philippe Huneman. *From Groups to Individuals: Evolution and Emerging Individuality.* MIT Press, 2013.

[8] Ricard Solé and Brian Goodwin. *Signs of Life: How Complexity Pervades Biology.* Basic Books, 2000.

[9] Andreas Wagner. *Robustness and Evolvability in Living Systems.* Princeton University Press, 2005.

[10] Edda Klipp, Wolfram Liebermeister, Christoph Wierling, Axel Kowald, Hans Lehrach, and Ralf Herwig. *Systems Biology.* Wiley-Blackwell, 2009.

[11] Kim Sterelny and Paul E. Griffiths. *Sex and Death.* University of Chicago Press, 1999.

[12] Friedrich Wöhler. Ueber künstliche Bildung des Harnstoffs. *Annalen der Physik und Chemie*, 88(2):252–256, 1828.

[13] Anson Rabinbach. *The Human Motor: Energy, Fatigue, and the Origins of Modernity.* University of California Press, 1992.

[14] Thomas Pradeu. Immunity and the Emergence of Individuality. In Frédéric Bouchard and Philippe Huneman, editors, *From Groups to Individuals: Evolution and Emerging Individuality*, pages 77–96. MIT Press, 2013.

[15] Ellen Clarke. The Problem of Biological Individuality. *Biological Theory*, 5(4):312–325, 2010.

[16] Ellen Clarke. The Multiple Realizability of Biological Individuals. *Journal of Philosophy*, 110(8):413–435, 2013.

[17] A.F. Chalmers. *What is this Thing Called Science?* Open University Press, 1980.

[18] B. Ellis. *Scientific Essentialism.* Cambridge University Press, 2001.

[19] J.W. Schopf. Disparate Rates, Differing Fates: Tempo and Mode of Evolution Changed from the Precambrian to the Phanerozoic. *Proceedings of the National Academy of Sciences*, 91(15):6735–6742, 1994.

[20] A.R. Liddle. *An Introduction to Modern Cosmology.* John Wiley & Sons, 2003.

[21] Brian K. Hall and Benedikt Hallgrímsson. *Strickberger's Evolution.* Jones and Bartlett, 2008.

[22] D. Hull. A Matter of Individuality. *Philosophy of Science*, 45:335–360, 1978.

[23] M. Ghiselin. A Radical Solution to the Species Problem. *Systematic Zoology*, 23:536–544, 1974.

[24] R. Boyd. Homeostasis, Species, and Higher Taxa. In R. Wilson, editor, *Species: New Interdisciplinary Essays*, pages 141–185. MIT Press, 1999.

[25] Philip Kitcher. Species. *Philosophy of Science*, 51:308–333, 1984.

[26] Ellen Clarke and Samir Okasha. Species and Organisms: What are the Problems? In Frédéric Bouchard and Philippe Huneman, editors, *From Groups to Individuals: Evolution and Emerging Individuality*, pages 55–76. MIT Press, 2013.

[27] Peter Godfrey-Smith. Darwinian Individuals. In Frédéric Bouchard and Philippe Huneman, editors, *From Groups to Individuals: Evolution and Emerging Individuality*, pages 17–36. MIT Press, 2013.

[28] James Elwick. Containing Multitudes: Herbert Spencer, Organisms Social, and Orders of Individuality. In Mark Francin and W. Taylor, editors, *Herbert Spencer: Legacies*, pages 89–110. Routledge, 2014.

[29] Charles J. Goodnight. Defining the Individual. In Frédéric Bouchard and Philippe Huneman, editors, *From Groups to Individuals: Evolution and Emerging Individuality*, pages 37–54. MIT Press, 2013.

[30] Leo W. Buss. *The Evolution of Individuality.* Princeton University Press, 1987.

[31] Peter Godfrey-Smith. Individuality and Life Cycles. In Thomas Pradeu and Alexandre Guay, editors, *Individuals Across the Sciences*, pages 85–102. Oxford University Press, 2014.

[32] R.C. Lewontin. The Units of Selection. *Annual Review of Ecology and Systematics*, 1:1–18, 2009.

[33] R.C. Lewontin. Adaptation. In R. Levins and R.C. Lewontin, editors, *The Dialectical Biologist*, pages 65–84. Harvard University Press, 1985.

[34] Jack Wilson. *Biological Individuality.* Cambridge University Press, 1999.

[35] Ohad Nachtomy, Ayelet Shavit, and Justin Smith. Leibnizian Organisms, Nested Individuals, and Units of Selection. *Theory in Biosciences*, 121(2):205–230, 2002.

[36] Ellen Clarke. Plant Individuality and Multilevel Selection Theory. In K. Sterelny and B. Calcott, editors, *The Major Transitions in Evolution Revisited*, pages 227–250. MIT Press, 2011.

[37] Richard Dawkins. *The Selfish Gene.* Oxford University Press, 1976.

[38] I.R. Cohen, R. Atlan, and S. Efroni. Genetics as Explanation: Limits to the Human Genome Project. In *Encyclopedia of Life Sciences.* John Wiley & Sons, 2009.

[39] Hans Primas. Emergence in Exact Natural Sciences. *Acta Polytechnica Scandinavica*, 91:83–98, 1998.

[40] Jurgen Schroder. Emergence: Non-Deducibility or Downwards Causation? *Philosophical Quarterly*, 193(48):433–452, 1998.

[41] Editors of the American Heritage Dictionaries. American Heritage Dictionary of the English Language, 2016.

[42] Russ Abbott. Emergence Explained: Getting Epiphenomena to Do Real Work. *Complexity*, 12(1):13–26, 2006.

[43] David J. Griffiths. *Introduction to Quantum Mechanics.* Pearson Prentice Hall, 1995.

[44] Daniel W. Schroeder. *An Introduction to Thermal Physics*. Weber State University, 2000.

[45] Jos Uffink. Bluff your way in the Second Law of Thermodynamics. *Studies in History and Philosophy of Modern Physics*, 32(3):305–394, 2001.

[46] Daniel F. Styer. Insight into Entropy. *American Journal of Physics*, 68(12):1090–1096, 2000.

[47] Harold Grad. The Many Faces of Entropy. *Communications on Pure and Applied Mathematics*, 14:323–354, 1961.

[48] Jos Uffink. Can the Maximum Entropy Principle be Explained as a Consistency Requirement? *Studies in History and Philosophy of Modern Physics*, 26(3):223–261, 1995.

[49] Jos Uffink. The Constraint Rule of the Maximum Entropy Principle. *Studies in History and Philosophy of Modern Physics*, 27(1):47–79, 1996.

[50] Leo Szilard. On the Decrease of Entropy in a Thermodynamic System by the Intervention of Intelligent Beings. *Zeitschrift für Physik*, 53:840–856, 1927.

[51] J.D. Norton. Eaters of the Lotus: Landauer's Principle and the Return of Maxwell's Demon. *Studies in History and Philosophy of Modern Physics*, 36:375–411, 2005.

[52] Erwin Schrödinger. *What is Life?* Cambridge University Press, 1944.

[53] Hans U. Gumbrecht, Robert P. Harrison, Robert B. Laughlin, and Michael R. Hendrickson. *What is Life? The Intellectual Pertinence of Erwin Schrödinger*. Stanford University Press, 2011.

[54] L. Pauling. Schrödinger's Contribution to Chemistry and Biology. In C.W. Kilmister, editor, *Schrödinger: Centenary Celebration of a Polymath*, pages 225–233. Cambridge University Press, 1987.

[55] M. Perutz. Erwin Schrödinger's What is Life? and Molecular Biology. In C.W. Kilmister, editor, *Schrödinger: Centenary Celebration of a Polymath*, pages 234–251. Cambridge University Press, 1987.

[56] Addy Pross. *What is Life? How Chemistry Becomes Biology*. Oxford University Press, 2012.

[57] H.J. Morowitz. *Beginnings of Cellular Life*. Yale University Press, 1992.

[58] Roy A. Black, Matthew C. Blosser, and Benjamin L. Stottrup. Nucleobases Bind to and Stabilize Aggregates of a Prebiotic Amphiphile, Providing a Viable Mechanism for the Emergence of Protocells. *PNAS*, 110(33):13272–13276, 2013.

[59] Philip Nelson. *Biological Physics.* W.H. Freeman and Company, 2008.

[60] Pasquale Stano, Erica D'Aguanno, and Jurgen Bolz. A Remarkable Self-Organization Process as the Origin of Primitive Functional Cells. *Angewandte Chemie*, 52(10):13397–13400, 2013.

[61] Matthew W. Powner, Béatrice Gerland, and John D. Sutherland. Synthesis of Activated Pyrimidine Ribonucleotides in Prebiotically Plausible Conditions. *Nature*, 459:239–242, 2009.

[62] Pier Luigi Luisi. *The Emergence of Life. From Chemical Origins to Synthetic Biology.* Cambridge University Press, 2006.

[63] Stuart Kauffman. *At Home in the Universe.* Oxford University Press, 1995.

[64] Muhammad Sahimi. *Applications of Percolation Theory.* Taylor & Francis, 1994.

[65] Bruce H. Weber. Irreducible Complexity and The Problem of Biochemical Emergence. *Biology and Philosophy*, 14:593–605, 1999.

[66] Michel Morange. *Life Explained.* Yale University Press, 2008.

[67] Mark Bedau. The Scientific and Philosophical Scope of Artificial Life. *Leonardo*, 35(4):395–400, 2002.

[68] Irene Chen and Peter Walde. From Self-Assembled Vesicles to Protocells. *Cold Spring Harbor Perspectives in Biology*, 2(7):1–13, 2010.

[69] Ronald de Sousa. Biological Individuality. *Croation Journal of Philosophy*, 5(15):195–218, 2005.

[70] Robert A. Wilson. *Genes and the Agents of Life: The Individual in the Fragile Sciences.* Cambridge University Press, 2005.

[71] Bruce H. Weber. Emergence of Life. *Zygon*, 42(4):837–856, 2007.

[72] Bruce H. Weber. On the Emergence of Living Systems. *Biosemiotics*, 2(3):343–359, 2009.

[73] Bruce H. Weber. Towards a General Biology: Emergence of Life and Information fromo the Perspective of Complex Systems Dynamics. *Biological Information: New Perspectives*, pages 533–559, 2013.

[74] Bruce H. Weber. What is Life? Defining Life in the Context of Emergent Complexity. *Origins of Life and Evolution of Biospheres*, 40:221–229, 2010.