Life and its Close Relatives

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Abstract. When driven by an external thermodynamic gradient, non-biological physical systems can exhibit a wide range of behaviours usually associated with living systems. Consequently, Artificial Life researchers should be open to the possibility that there is no hard-and-fast distinction between the biological and the physical. This suggests a novel field of research: the application of biologists' methods for studying organisms to simple "near-life" phenomena in non-equilibrium physical systems. We illustrate this with some examples, including natural dynamic phenomena such as hurricanes and human artefacts such as photocopiers. This has implications for the notion of agency, which we discuss.

Key words: Near-life, Thermodynamics, Dissipative Structures, Autopoiesis, Developmental Systems Theory

1 Introduction

1.1 A-Life and Near-Life

The premise of Artificial Life is that there is more to being alive than the details of terrestrial biology; that there are abstract principles which underlie those particular instantiations of life we happen to share a planet with. In this paper we will argue that, besides "life as it could be" [6], we should also be considering "near-life as it is": life-like properties in the familiar inanimate world. Indeed, we will see that hurricanes and even photocopiers have thought-provoking features in common with living organisms.

When we use the word "life" in this paper, we do not refer to a definition but to a class of examples, namely those things existing on this planet which biologists consider alive: the eukaryotes, prokaryotes and occasionally viruses. Similarly, we use "life-like" informally to refer to various properties shared by all or most of these examples.

Central to our approach is the study of life-like phenomena that arise naturally within a wider system, either simulated or physical. We propose to study "near-living" systems in the same kind of way that a biologist studies living organisms: by observing them in their natural habitat; by studying their behaviour; and by trying to see how their anatomy functions. The processes behind life-like behaviour in non-living systems are likely to be much easier to understand than in living systems. Our purpose in this paper is not merely to point out similarities between some non-living systems and living systems, but to suggest that principled further studies of such similarities could be a gold-mine of new results.

1.2 Non-Equilibrium Thermodynamics

Physical systems in thermal equilibrium are not life-like: the second law of thermodynamics means that isolated macroscopic systems tend towards more or less homogeneous equilibrium states. However, this does not apply to open systems in which an externally imposed "thermodynamic gradient" causes a continual flow of matter or energy through the system. In such *non-equilibrium* systems complex patterns can arise and persist. Authors such as Prigogine, Schneider & Kay and Kauffman [12, 14, 5] have observed that life is an example of such a "dissipative structure." Life exists within the Earth system, which is an open system with a gradient imposed primarily by the sun[1].

Living organisms exist within this system and are constrained by the second law of thermodynamics. Therefore many of their properties have to be realised in non-trivial ways. No organism can maintain its structure by isolating itself from the world: the need to "feed on negative entropy" (Schrödinger [15]) guarantees that interaction with the world is required in order to find food or other sources of energy. Ruiz-Mirazo and Moreno connect this to the theory of autopoiesis [13].

Simulation work in artificial life has often ignored thermodynamics; it is common to see research using physically unrealistic cellular automata, abstract artificial chemistries in which there is no quantity corresponding to entropy, or simulated agents which eat abstract "food" (if indeed they need to eat at all).

In contrast, our approach builds upon and extends previous authors' observations about the relationship between life and thermodynamics. An abiotic non-equilibrium system has many parallels with an ecosystem; our focus is on the equivalents to organisms that exist in such systems, and the specific properties that they do or do not share with biological organisms. These properties vary depending on the system under consideration, so our methodology is to investigate many different types of non-equilibrium system, looking for the general circumstances under which various life-like properties arise.

2 Some Examples of Near-Life

2.1 Hurricanes

A hurricane is a classic exemplar of a dissipative structure. It is instructive to focus on this example because hurricanes exhibit a phenomenon we call individuation. Emanuel [3] gives the following characterisation of a hurricane's operation:

"[Air] flows inward at constant temperature within a thin boundary layer [above the sea surface], where it loses angular momentum and gains moist entropy from the sea surface. It then ascends and flows outward to large radii,

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[1] More precisely, the gradient is formed by the difference in temperatures between the incoming solar radiation and deep space.

preserving its angular momentum and moist entropy. Eventually, at large radii, the air loses moist entropy by radiative cooling to space…" These processes occur simultaneously. Their rates balance so that the hurricane as a whole is stable.

The net result of the interactions between these processes is that the hurricane is formed and remains stable to perturbations. Moreover it is formed as a spatially distinct individual, separate from other hurricanes (this can be compared to the definition of autopoiesis by Maturana & Varela [8, 9] as a "network of processes" that "constitute" a "unity.").

A hurricane has functionally differentiated parts: near the sea surface the water is drawn towards the eye, picking up moisture from the sea and rotational speed from the Coriolis force; in the eyewall itself the air is moving rapidly upward. Each part, together with its associated processes, is necessary for the whole to persist. This is analogous to an organism's anatomy.

A hurricane remains an individual entity because of its vortex structure, whereas a cell is surrounded by a membrane. We see this as the same phenomenon, individuation, occurring by different mechanisms. In both cases the result is that the system is localised in space and distinct from other individuals.

Although the research is so far preliminary, hurricanes may also be able to exhibit behaviour that could be called adaptive. Shimokawa et al. [16] claim that when the prevailing wind is subtracted from the data, tropical cyclones tend to move towards regions which are better able to sustain them, namely those with a greater temperature gradient between the sea and the upper atmosphere[2].

The hurricane has been given as an example of a "self-organising" system before but its similarities to living cells have not been studied in depth. We feel that such a study would provide many novel scientific insights.

2.2 Reaction-Diffusion Spots

Hurricanes are large, comparatively complex and difficult to study. A much simpler and easier-to-study example of an individuated dissipative system can be found in the patterns that form in reaction-diffusion systems [11]. Reaction-diffusion systems are very simple and easily simulated non-equilibrium chemical systems in which reactions take place among chemical species that are able to diffuse along a plane. The non-equilibrium conditions are maintained by continually adding reactants and removing products from the system. Under some parameter regimes the system can form a pattern in which there are spatially distinct "spots" of an autocatalytic substance, separated by regions in which no autocatalyst is present (see fig. 1, left).

We can observe interesting life-like properties in the form and behaviour of reaction-diffusion spots: like all dissipative systems they export entropy and are dependent on specific thermodynamic gradients; they are patterns in matter and energy; like organisms, they exist mostly as identifiable individuals; under certain parameter regimes they reproduce [11].

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[2] More strictly, higher Maximum Potential Intensity, a measure that takes into account both the temperature and pressure gradients that power hurricanes.

Studying reaction-diffusion spots according to our methodology involves treating a single spot as a model agent and studying it from a "spot-centric" point of view. The following simulation-based results have been demonstrated in [17], and a paper giving details of the experiments is in preparation. Briefly, we found that reaction-diffusion spots, perhaps like hurricanes, tend to move towards areas where more food is available, a behaviour that could be called "adaptive." We also found that individuated spots are very likely to arise when there is a negative feedback added between the whole system's activity and overall supply of food (this situation is common in natural systems and we think the result is suggestive of a possible general phenomenon). Using this as a method for producing individuated entities we were able to produce agents with a more complex 'anatomy' than just a single spot (fig. 1, right). Some of these more complex agents exhibited a very limited form of heredity in their reproduction.

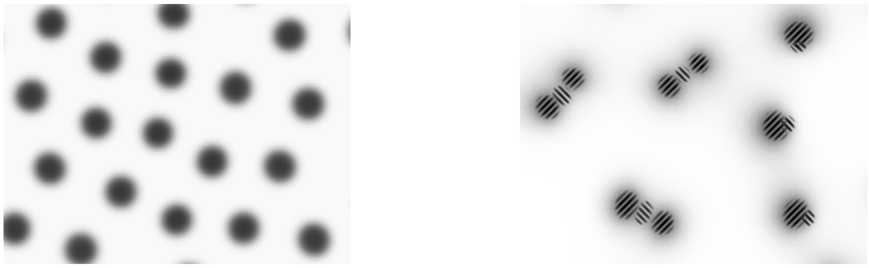

Fig. 1. *left*: "individuated" spots of autocatalyst in a reaction-diffusion system; *right*: structurally complex individuated entities in a reaction diffusion system. Each consists of spots of two different autocatalysts (represented with diagonal stripes in this image) coexisting symbiotically, mediated by an exchange of nutrients, one of which is shown in grey. Details will be published in a forthcoming paper.

2.3 Photocopiers

In this section we will examine a photocopier — a stereotypical inanimate object — from a point of view that might be called "enactive." That is, it is a point of view in which the photocopier itself is the central player, maintaining its identity and behaving adaptively as a result of dynamical interactions with its environment. This is a difficult viewpoint to take at first, since our intuition tells us that a photocopier is not the sort of thing that can "act." Rather, we normally think of it as acted upon by human beings. However, this intuition can be stretched, and we hope the reader will agree that it is worthwhile to do so.

We chose a photocopier for this example because it is usually repaired when it breaks down; any such machine would have done. In particular, the fact that the photocopier performs a copying task has no special significance.

We focus on this example because it shows how far our intuitions can be stretched without reaching a *reductio ad absurdum*: a photocopier is an archetypal example of an inanimate object, but when considered as an agent engaged in complex interactions with its environment it becomes in many ways the most life-like of our three examples.

When trying to support our natural intuition of a qualitative difference between photocopiers and bacteria, we may cite a variety of apparently relevant facts. Bacteria have DNA, and we can observe the complex process of bacterial reproduction under the microscope, whereas the same is not true of photocopiers. A photocopier, unlike a bacterium, consists of mostly static and chemically inert parts; if a part of the photocopier becomes damaged, it does not reconstitute itself internally. Bacteria display complex adaptive behaviour including chemotaxis and habituation; photocopiers don't appear to.

This may seem like a conclusive list of differences between a cell and a photocopier. And some of these differences are genuine, if perhaps arbitrary: photocopiers do indeed lack DNA. However, on closer scrutiny some of the other issues will turn out to be less clear-cut. We think that many if not all of the most significant differences between cells and photocopiers can be seen as differences of degree rather than kind.

Dynamic Identity One prototypical property of bacteria and other living organisms is their identity as patterns of matter and energy. Individual atoms flow through the organism, and the overall organism is maintained even if all the material parts change. We can consider a photocopier that has this property, although the rate of material turnover is much slower than in a cell: when the parts of this photocopier break they are replaced by an engineer. Like the hammer which retains its identity despite having a new handle and a new head, matter flows through the photocopier leaving its photocopier-ness unchanged.

In ordinary discourse, we would not describe the process as *self*-repair, since we prefer to locate causal primacy in the engineer rather than the photocopier. But seen from a logical point of view, both photocopier and engineer are necessary parts of the physical process; the repair is caused by the interaction between the two. It is no different for bacteria: ongoing cell repair is caused by the interaction between the cell and its environment, since the organism must be able to absorb relevant nutrients and excrete waste.

Note that some important physical principles can be observed in action here. In order for this process to continue, the photocopier's environment has to be in a very specific state of thermodynamic disequilibrium: it has to contain appropriately competent and motivated engineers.

From a more photocopier-centric point of view one could say that the photocopier causes the repair to be carried out: simply by performing a useful office task, the photocopier is able to co-opt the complex behaviour of humans in its environment in just such a way that the raw materials needed to maintain its structure are extracted from the ground, fashioned into the appropriate spare parts and correctly installed. Seen from this perspective the photocopier is a master of manipulating its environment. It needs no deliberative intelligence to perform these feats, however: one is reminded of species of orchid that cause their pollen to be spread by mimicking the form of a female bee.

Many of these processes take place outside the physical (spatial) bounds of the photocopier itself, with most of them involving human activity in some way. This is in contrast to the usual conception of an organism, since these systems rely heavily on a network of metabolic or dynamical processes that occur within the system's physical boundary. We argue however that this difference between artefacts and organisms is one of degree rather than a difference in kind, since all organisms must rely on some processes that are external to their spatial boundary, some of which will often involve the action of other organisms.

Individuation The phenomenon of individuation is evident in this example: photocopiers are maintained as individual photocopiers. Half a photocopier will not function as one and will not be maintained as one. We can imagine an environment in which half a photocopier might be maintained: we might find one inhabiting a display case in a museum, for example. But in this case it is being maintained as a museum exhibit rather than as a photocopier: it would be a different species of artefact.

Reproduction and Evolution Although there are obvious differences between the process of "evolution" in photocopiers and in living organisms, we can still observe some similarities. The photocopier phenotype has become better adapted to its ecological niche over time, as successful photocopiers are re-produced in factories and successful designs retained and modified. A photocopier's external casing does not contain its blueprints, whereas we often regard the "design" for a cell as being in its DNA (with developmental influences from the internal and external environment). But this notion is perspectival rather than factual: as Oyama [10] points out, the interaction of environment and genome forms the cell, with both being required. Reproduction and development in *any* organism relies heavily on environmental machinery external to the organism itself. The photocopier phenotype interacts with its blueprint indirectly through the phenotype's effects on photocopier sales, which fund the production of more photocopiers from the blueprint. In turn the sales depend on the successful operation of the photocopiers, among other factors.

3 Discussion

When we picture something which symbolises the fundamental properties of a living being, the chances are good that we imagine a biological object: a living organism such as a cell, plant or animal, or perhaps the DNA helix. Alternatively, we may think of our favourite simulation model in Artificial Life. It is unlikely in the extreme that we picture an inanimate object such as a rock, a hurricane or a photocopier. Due in part to our evolutionary heritage, humans have a definite sense of what is alive and what is not.

We assert that scientists should treat this intuition with suspicion. In the past, it has given rise to erroneous theories of an *animal spirit* or *elan vital* as an explanation for the remarkable behaviours of living organisms. Although these ideas have long been discarded by formal science, the underlying psychological stance is more enduring, and it has led science astray in the past.

In this sense, we echo Oyama's insights in *Developmental Systems Theory* (e.g. [10]): human beings like to postulate chains of effect which attribute causal primacy to a particular part of a holistically integrated system. In the scientific imagination, part of the system becomes the *agent* and the rest is the *environment*. Oyama argues that attributing causal primacy to genes is a conceptual error within developmental biology; we contend that similar problems arise when we think about living and non-living systems.

Thermodynamic gradients can be found nearly everywhere in the physical universe, and consequently we should not be surprised if near-life is abundant in interesting forms. By "near-life", we simply mean non-biological systems which share important characteristics with living organisms, including any of the following: reproduction, particularly with heritable variation; maintenance of a dynamic pattern of matter and energy; production of spatially separated individuals; "goal-directed" behaviour. All of these properties can be observed in comparatively simple non-equilibrium systems; there is every reason to suppose we will find more such properties. It is quite possible, for example, that one could find life-like structures that exhibit a developmental trajectory over their existence; or show a permanent memory-like change in behaviour in response to a stimulus; or have a more complex form of heredity.

It is not a new idea to look for life-like processes in non-biological systems. Lovelock [7] describes the entire Earth system as a "single living system", using terms such as "physiology" and "anatomy." Our ambitions concern simple and physically numerous systems which can be studied experimentally.

While many of the similarities between life and dissipative structures are well-known, most previous commentators (e.g. Prigogine, Schneider & Kay [12, 14]) have considered only natural (as opposed to artificial) phenomena. However, artificial structures are part of the same physical world as natural structures. Our perspective allows us to observe physical characteristics associated with biology even in apparently prototypical inanimate objects such as photocopiers. Of course, it is not a new idea to attribute biological properties to cultural artefacts (this occurs in "meme theory," which concentrates on "selfish replicator" properties, e.g. Blackmore [1]) or to consider physical artefacts as an integral part of a biological system (Clark & Chalmers [2]). We add the observation that ordinary physical artefacts can also be a type of life-like dissipative structure, providing they exist in a human environment which maintains them against decay. This is particularly instructive because it illustrates the extent to which our intuitions can be stretched without breaking.

3.1 Proposed Future Research

Searching for life-like properties of phenomena that arise in physical rather than computational systems is an under-researched area of A-Life that has potential for some very important results. Current "wet" A-Life research (i.e. *in vitro* chemical experiments), tends to focus on the deliberate design of life-like structures (e.g. synthetic bacteria [4] or formation of lipid vesicles), rather than on open-ended observation of structures that form naturally. However, interesting behaviour can also be observed spontaneously in non-equilibrium systems, including ones which are simple enough for physically realistic computer simulation (e.g. [17] and forthcoming work). More research along these lines would help to bridge the gap between biology and physics.

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