



HAL
open science

The Physics of Life. Part 3: The Artificial Animate Materials

Dmitry A Kukuruznyak

► **To cite this version:**

Dmitry A Kukuruznyak. The Physics of Life. Part 3: The Artificial Animate Materials. 2020. hal-02541236

HAL Id: hal-02541236

<https://hal.science/hal-02541236>

Preprint submitted on 13 Apr 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial - NoDerivatives 4.0 International License

The Physics of Life. Part 3: The Artificial Animate Materials

Dmitry A. Kukuruznyak*

*Moscow Animate Materials Center, The Animate Condensed Matter Company
Prosp. Vernadskogo 11/19 – 11, Moscow 119311, Russia*

This paper introduces artificial animate-like materials suitable for fabrication of synthetic quasi organisms with independent autonomous behaviors. The artificial animate matter undergoes chemical condensation accompanied by ordering structural transformations. Its atoms build new, or improve existing, chemical bonds. While doing so, they arrange their local atomic neighborhoods. These small reconstructions interact, coordinate their efforts, and combine into large collective reconstructions. The combined collective reconstruction of the orderly condensing body may form a closed loop and create a self-sustaining process, in which case it makes an independent organism. The organism sustains its function by reconstructing its environment, exchanging energy and matter with the environment, and producing new active atoms. In general, the quasi organism maintains its structure during operation. At the same time, thanks to the exchange of matter with the environment, it varies its structure and adapts its behavior. The notion of artificial animate matter may produce new conceptual, mathematical, and physical models of living subjects. In practical applications, the animate materials can be used for the mass production of simple artificial brains.

Keywords: animate state of matter, autonomous motion, definition of life, living matter, collective condensation.

1 Introduction

1.1 The working physical definition of life

In Part 1 of this manuscript, entitled “The Animate Organism as an Active Condensed Matter Body”, I have suggested that the animate state should be regarded as a special aggregate state of matter, characterized by autonomous non-random reconstructions [1]. While passive inanimate matter is mixed by chaotic thermal fluctuations, the active animate matter generates its own ordering reconstructions. I have argued that these reconstructions start at the atomic scale, being caused by the collective chemical condensation: The body of the organism builds lacking — or improves existing — chemical bonds between its own atoms. The chemically active atoms replace energetically unfavorable chemical bonds with stronger and more energetically favorable chemical bonds. While doing so, the active atoms arrange their local atomic neighborhoods. In living bodies, these reconstructions combine into large collective reconstructions. Those are perceived as voluntary actions of the animate bodies [2].

The collectively condensing matter manipulates its own constituents in orderly ways. It controls the ongoing chemical processes, and builds products that cannot appear in inanimate matter accidentally. By joining precursors, it produces new active atoms, thus causing its own further activity. I suppose that this process outlines the principle of operation of any living organism.

A living cell cannot be a group of detached molecules. To generate non-random reconstructions, it must be a “giant connected macromolecule”; all its components must be orderly arranged and held together by means of (no matter

how weak) chemical and physical bonds. This macromolecule reconstructs by making internal tears and permutations. This intrinsic reconstruction impedes accidental chemical reactions, and promotes controlled reactions: Large molecules and radicals are embedded in the reconstructing body. The body holds these molecules, and manipulates them in an orderly manner. It breaks the precursors into certain pieces; it joins these pieces in particular ways, and obtains definite products. At larger length scales, the body of the cell assembles these products into precise subcellular arrangements. (The cellular macromolecule still undergoes random reconstructions, caused by thermal fluctuations. Small molecules diffuse within the body of the cell without changing its general ordered structure.)

The cellular body is a multiscale structure [3]. It consists of smaller and simpler pieces. Those pieces are composed of even simpler parts. And so on. Most of these parts are actively reconstructing. The smaller is the part, the quicker is the reconstruction. The fastest processes occur at the atomic scale. The total reconstruction of the living biological cell is composed of a colossal number of smaller reconstructions.

The reconstruction observed at the cellular scale is called cyclosis or cytoplasmic streaming [4,5]. It assists the motion and reproduction of metabolites. The motion of metabolites is looped into a self-sustaining circulation: The cytoplasmic streaming moves the metabolites across the cell. The cell produces new metabolites, thus causing new reconstructions. The same reconstruction carries out directional exchange of products and precursors between the cell and its habitat. Therefore, the independent organism sustains its own activity using the habitat’s resources.

I give the following definition of a living organism. *The cellular organism is a specifically arranged condensed matter body that carries out collective reconstructions, driven by the irreversible chemical condensation. It orderly manipulates its own parts, and some parts of its habitat. Using these manipulations, it generates new active atoms and ensures its own further activity. The orderly mechanical reconstructions originate from the aimed actions of the atoms that reconstruct their chemical bonds.*

The inanimate habitat of the cell is a weaker-linked condensed matter body. It has the capacity to condense. However, it cannot do that on its own because it executes only random reconstructions, which do not produce any specially arranged products. The habitat remains “entangled” meaning that its structure cannot generate orderly collective reconstructions. By the ordering manipulations, the cell disentangles the habitat, and produces highly ordered condensates. It may also incorporate the disentangled products into its own body. As a result, the volume of the organism can grow. Under favorable conditions, this may lead to reproduction. The operation of the cell is illustrated in Fig. 1.

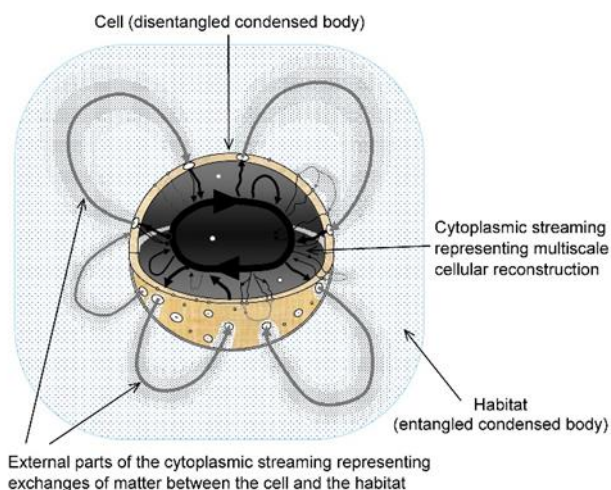


Fig. 1. A living cell in an inanimate habitat. The water-based habitat is an entangled condensed matter body. It has enough source materials for the production of well-packed condensates (large organic molecules). However, it cannot condense because it executes only random reconstructions. The cell is a disintegrated body executing non-random reconstructions. It manipulates its constituents in orderly ways, disentangles the habitat, fabricates specially arranged products, and grows.

1.2 My contention

I notice that some non-biological materials have the capacity — and a physical inclination — to condense. However, they remain entangled. They cannot produce any ordered reconstructions, and for this reason cannot orderly condense on their own. An external agent may disentangle them, and produce pieces of active condensate. These active bodies will independently reconstruct, driven by the ongoing

condensation. Some of these “condensing condensates” can obtain recognizable characteristics of living subjects. They can resemble biological organisms, yet be simpler than real biological organisms. In particular, they can execute ordering autonomous reconstructions at a lesser number of spatial and temporal scales. Nonetheless, they may still generate complex autonomous acts, and show complex autonomous behaviors. I call the orderly condensing compounds “the animate materials”, and suggest making simple forms of artificial life from such materials.

2 Defining autonomous behavior

Before proceeding to fabrication, I will define the term “autonomous behavior” in relation to condensed matter. I will state that a condensed matter body acquires its own willful behavior when it starts generating a specific kind of unprovoked autonomous reconstructions. The biological motive power was explained in Section 1.1. Here I will briefly describe some characteristic traits of these reconstructions. I intend to demonstrate that condensing macromolecules can generate reasonable adaptive behavior.

2.1 A team of elementary active agents

I assume that the simplest subject that performs aimed actions is a pair of active atoms establishing a chemical bond. During approximately 10 nanoseconds (that is the time required to build a new molecular orbital), this “elementary active agent” reorders its local atomic environment (because chemical bonds must obtain very specific parameters) [6]. It converts some of atomic matter into energy, and performs mechanical work.

In biological organisms, numerous elementary agents act simultaneously. Here I explain how these individual agents interact, and create coordinated collective actions. To be exact, I describe how the individual active agents create a collective agent.

2.2 Emergence of the collective agent

The collective agent is the condensed matter body that hosts the individual agents. The individual agents move and reconstruct their common condensed body. The collective reconstructions of this body are the collective acts. In order to produce coordinated collective reconstructions, the condensed body must be arranged in particular ways, i.e. it must be “disintegrated”. A good collective agent must satisfy one additional requirement: The common condensed body must fully control the acts of individual agents. How is this done?

The condensed body must obstruct the acting agents. It must block any movement and inhibit the individual agents’ activities. An individual agent may perform an action only with the permission of the condensed body. The condensed body issues these permissions by executing reconstructions, which remove some constraints from the individual agents.

The evolving condensed matter body that fully controls the individual agents becomes the true collective active agent. It has the “collective will” that subjugates the wills of the individual active agents. The individual active agents never do what they want. Instead, they execute the collective will of the group.

2.3 The collective reconstruction

The collective action is an incredibly complex process. It involves a colossal number of communications between the individual agents (active atoms) and the collective agent (active condensed body). The process of forming an act is explained in Part 2 of this manuscript, “The Neural Network as an Active Condensed Matter Body” [7]. Here, I simply describe the general form of the action.

The collective reconstruction of the evolving condensed body proceeds as follows: First, the body breaks some existing chemical bonds. This removes some internal obstacles, and excites some of the inhibited agents. They break more bonds and remove more constraints, and so on. It appears as though the condensed body spontaneously makes a tear in itself. Then the body discharges a weaker-connected, more active, and more mobile part from itself, and moves this part to a different location. The action stops when this part exhausts its energy, stops, merges with the rest of the body, and gets re-stitched using new chemical bonds. (Fig. 2a)

The same collective reconstruction could be described in a slightly different way: After the spontaneous tear, the body widens the gap in itself, and partially turns itself out through this gap. The gap gets filled with a new material, and closes. The action stops when the tear is healed. (Fig. 2b)

Note that this collective reconstruction resembles local atomic reconstructions that occur at the molecular scale. They involve the stimulated removal of some (dissatisfying) chemical bonds, an atomic permutation, followed by making of some new (more satisfying) chemical bonds. Here, the characteristic atomic permutations reappear at a larger scale.

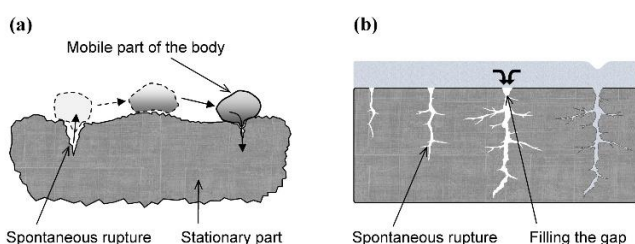


Fig. 2. Autonomous reconstruction (action) of an active condensed matter body. (a) Discharging of a moving material piece. (b) Spontaneous generation of an internal tear followed by filling the gap with new material.

2.4 Sequences of conflicting actions

After completing one action, the transforming condensed matter body can make a new rupture, and execute another action. This happens because completion of a particular

collective action may liberate some previously inhibited conflicting agents. In general, in the evolving condensed body — instead of acting simultaneously — the individual agents operate in succession. The evolving body as a whole executes sequences of different complex actions one after another. There are also stimulated actions: the reconstructions transport metabolites to new locations. They produce new active agents, which cause new actions. The collective organism proper appears when the motion and reproduction of metabolites gets looped into a self-stimulating circulation.

2.5 General principles of decision making

The collective agent will undertake its next action according to the following rules [7]. Above all, it will choose the least obstructed action. Simultaneously, it will choose the most desired action. Therefore, the collective agent will elaborate a compromise between the path of least resistance and the greatest satisfaction.

During the generation of sequences of actions, the collective agent will first pick the actions that require the smallest investment of energy to produce the fastest excitation. After the easiest options are expended, it will switch to progressively more difficult actions.

The collective agent has a strong desire to heal the internal tears, and terminate any action during its execution. When the action starts to bring back a lesser satisfaction, the desire to stop will win. The collective agent may abandon the action, and progress to another, more satisfying action, though it may return to the abandoned action at a later time.

The behavior of the collective agent is rather sound and reasonable. It is also very adaptive: the executed actions respond to external influences, which affect the internal obstructions and the agents’ desires.

2.6 Predictable and unpredictable actions

Generally, the structure of the action depends on the shape of the tear that appears in the reconstructing body. This shape determines which particular agents are getting excited.

If the condensed body is homogeneous, and is uniformly interlinked using similar bonds, the tears will be unpredictable. However, if the condensed body is segmented into well-defined pieces by means of “easy tear lines”, the body will rupture in a predictable manner [7].

A biological cell is segmented and heterogeneous; it realizes the second scenario. While ripping, its body separates into certain well-defined metabolites. They move predictably, reaching certain destinations and causing foreseeable chemical transformations.

In other reconstructing condensed matter bodies, such as neural nets, the first scenario is common. A neural network can make an unpredictable tear, and make a completely new act. However, the condensed body memorizes its ruptures as

new “easy tear lines”. When the body is exposed to the same stimuli, it repeats the memorized actions. This is learning.

After repeating similar actions for several times, the tear lines may get elongated and become more complex. Consequently, an “experienced” condensed matter body may produce increasingly complex actions [7].

For the artificial animate beings, I intend to use materials that combine both of these capacities. On the one hand, they should be pre-segmented to perform basic predictable actions. On the other hand, they must be able to make new rips, and invent new actions. They will be taught by forming new advantageous tear lines in their bodies.

3 Material embodiments

3.1 Artificial organism in artificial habitat

Figure 3a schematically shows a living organism in an inanimate habitat. The complex multiscale reconstruction of the organism is represented by the cytoplasmic streaming.

One can construct an artificial condensed matter body, and instigate its self-sustaining condensation process. For this goal, one should re-arrange a body prone to polymerization, so that to make one bond forming event cause new bond forming events. For an independent organism, these events should loop into a self-stimulating process.

This body should be immersed into a specially entangled insufficiently condensed habitat. The artificial organism must disentangle this habitat using certain ordered manipulations, produce well-packed condensates, and incorporate them into its own body.

I have not been able to devise such a completely artificial non-biological system.

3.2 Quasi-life based on decondensation

There is an alternative way to obtain an artificial organism in an artificial habitat. For the habitat, I propose to use an entangled condensed matter body with an excess of chemical bonds. For the organism, I will employ a piece of “disentangled decondensate”, i.e. a less dense, lesser constrained, and more agile piece of the condensed body. The organism should promote the chemical decondensation process, which involves the removal or replacement of the excess chemical bonds. This situation is illustrated in Fig. 3b.

The reconstructing materials driven by the orderly decondensation have numerous practical advantages. Firstly, the habitat resembles a regular solid. It is much easier to handle. Secondly, this evolving system generates minimal amounts of motion. Its reconstructions are much simpler than those occurring in real biological matter. They are much easier to observe and describe. Finally, the quasi-organisms based on decondensation may retain very simple metabolisms. Thanks to this simplicity, the quasi-life can be effortlessly invented from scratch.

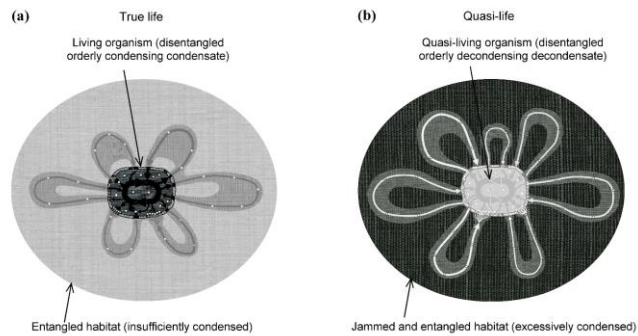


Fig. 3. (a) True life. The insufficiently condensed habitat cannot condense on its own. The living organism disentangles the habitat, promoting its condensation. The disentanglement is illustrated by the branches of cytoplasmic streaming that exit the cell, and transport material between the cell and the habitat. (b) Quasi-life. The excessively condensed habitat is jammed and entangled, and cannot decondense on its own. The quasi-organism disentangles the habitat, promoting its decondensation.

3.3 The simplest quasi-organism

The simplest quasi-organism in the simplest inanimate habitat is described in Part 1 of this paper, “The Animate Organism as an Active Condensed Matter Body” [1]. It is shown in Fig. 4. It is more common than anyone could have imagined. It is the moving stream in the hourglass.

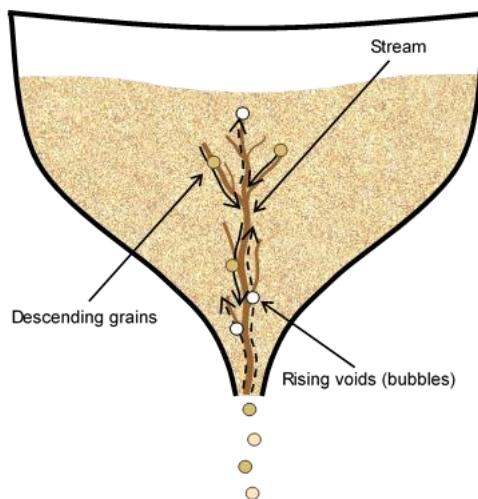


Fig. 4. The non-random reconstruction of granular matter in the hourglass. The active stream implements the sustained motion and reproduction of quasi metabolites. It can be regarded as the simplest prototype and the mechanical analogue of a living organism.

In the hourglass, a pile of sand flows out of the bulb through a single open hole at the bottom. This granular matter consists of two noticeably different parts: the predominantly motionless main body, and the moving part, which resembles a stream. The descending grains travel down along this stream.

The whole reconstruction is driven by the gravity, and is assisted by the pseudo chemical transformation that occurs at the bottom of the glass, where the grains are replaced by the voids. The voids resemble little bubbles that rise upward

during the reconstruction of the matter. Not all of these new voids reach the surface of the pile. Some of them remain in the medium as spaces between the grains. They make the matter less dense and less connected. Little by little, those voids accumulate and form the ordered evolving stream.

The ordered stream is the “disentangled decondensate”: it is the loosest, and the least jammed part of the condensed body. I contend that this stream is a macroscopic counterpart of a living organism. Its predominately motionless surroundings correspond to the inanimate habitat.

The operation of the stream is described in Part 1 of this paper, “The Animate Organism as an Active Condensed Matter Body” [1]. Here I simply state that the quasi-organism reconstructs the habitat, rearranges the grains, and engages them in its own active motion. Inside of the stream, the grains go through a series of slight metabolic-like transformations. They lose their potential energy or initial “desire” to fall down. The voids go through similar metabolic transformations, losing their ability to rise up, and breaking into smaller voids.

This macroscopic counterpart of a living organism is ultimately simple. Both the organism and the habitat consist of only two types of elements: the grains and the voids. The organism has only two types of metabolites: the moving grains and the moving voids. Their metabolic transformations are trivial. The granular matter is more jammed than entangled. Its disentanglement is rudimentary. In addition, all the irreversible events comprising the reconstruction take place at a single length scale.

3.4 Emergent phenomena and disentanglement

Regardless of this simplicity, the evolving condensed matter of the hourglass shows many phenomena pertaining to real biological matter. Specifically, its reconstructions do not destroy the condensed state. Moreover, the reconstructions periodically bring the granular matter into the “almost original” formation. This particular quality is crucial for realizing repeatable reconstructions. The quasi-organism in the hourglass has a sustainable circulation of the moving grains and voids and a metabolic-like chain of transformations.

Thanks to the recurring reconstructions, the granular matter of the hourglass memorizes events, accumulates changes, and undergoes a metamorphosis. In particular, the accumulation of voids causes the growth of the organism’s body: the volume of the stream expands from the orifice. Also, the stream becomes better organized and more ordered. The energy for the self-arranging and growth is drawn from the grains, that is, from their ability to produce orderly movements under gravity.

The structural disentanglement of the evolving matter caused by the recurring ordering reconstructions is associated with so-called emergent phenomena [8]. Their regular manifestations are self-organization, cellular differentiation, etc. [9,10,11] The evolving granular matter of the hourglass exhibits the emergent phenomenon explicating the origin of

life: Every time the hourglass is turned over, its primordial matter separates into the structured and disentangled animate organism and the entangled inanimate habitat. The seed of the organism is the recurring reconstruction that occurs at the bottom of the glass.

3.5 The envisioned living-like system

The stream of the hourglass is actually only one half of the living system. The complete system exists at the interface between two condensed matter bodies as illustrated in Fig. 5. One medium should contain an excess of chemical bonds, and be prone to decondensation. Another medium should suffer a lack of chemical bonds, and have a strong desire to condense. The first medium corresponds to “the condensed matter predominantly composed of grains” and the second one corresponds to “the matter predominantly composed of voids”. Only the voids are now material entities. These two media must be separated by an isolating barrier. Just like in the hourglass, the barrier must have an open pinhole. When a small portion of the first material (i.e. “the grain”) crosses the interface, it chemically reacts with the second material producing a new active piece (i.e. “the void”), which travels in the opposite direction. When this new piece reaches the first material, it undergoes the reverse metabolic transformation (i.e. “the void” becomes “the grain”). Then this cycle is repeated. As in the hourglass case, the metabolic conversion of “grains” into “voids” could be gradual and consist of a metabolic chain of multiple segments.

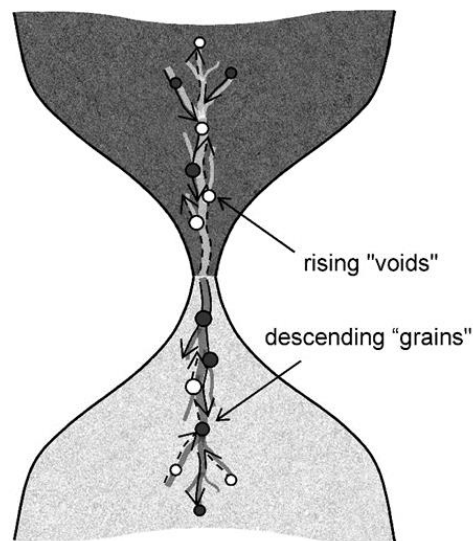


Fig. 5. The quasi-living organism at the interface between the decondensing and condensing materials. The two streams create a self-sustaining reconstruction that disentangles both materials.

The interface might contain multiple pinholes. Several quasi-organisms would work there in parallel. Since all of them are immersed into the common condensed matter body, their (initially independent) reconstructions may create a

collective reconstruction, and form a collective quasi-organism (Fig. 6). For this quality, the common condensed matter body must effectively inhibit the individual reconstructions. Basically, the common body must be very stiff, and resemble a solid.

I intend to employ this particular design for fabrication of simple forms of autonomous adaptive behavior. Roughly speaking, every individual stream will correspond to a living neuron. The collective organism composed of many streams will correspond to a neural network. The collective reconstructions will be more complex compared to the single-stream reconstructions. They should produce more complex actions.



Fig. 6. Several quasi-organisms working in parallel. Initially, the organisms work independently. Then they grow, connect to one another, and create a collective reconstruction.

3.6 The embodied living-like system

The experimental system described in the previous section can be simplified. Take the hourglass as an inspiration. Let “the grains” part of the system be real, and “the voids” part be virtual. It can be simulated using software, and supplemented with actuators and sensors. This experimental system is explained in Part 2 of this manuscript, “The Neural Network as an Active Condensed Matter Body” (Fig. 11 of Part 2) [7].

Figure 7 shows the interface between the simulated, and the real evolving condensed matter bodies. The real body is a material bar prone to decondensation. It gets stamped with an array of punch stamps. The punch stamps induce plastic deformations and thus emulate the actions of the second medium. Pressing on the punch stamp creates a pattern of internal tears and voids in the material bar. After removing the load, the material bar recuperates by filling the voids and healing the rips. Although, this recuperation is incomplete: the material “memorizes its tear lines”. The structure of the real material, and its current responses, are monitored using specially designed sensors. The stamping is periodically repeated to emulate back-and-forth exchanges between the real and the simulated bodies.

Thanks to the memory effects, the repetitive stamping un-jams and disentangles the material bar, and causes the system of healing ruptures to grow in size and complexity. Eventually, they should create a complex collective reconstruction.

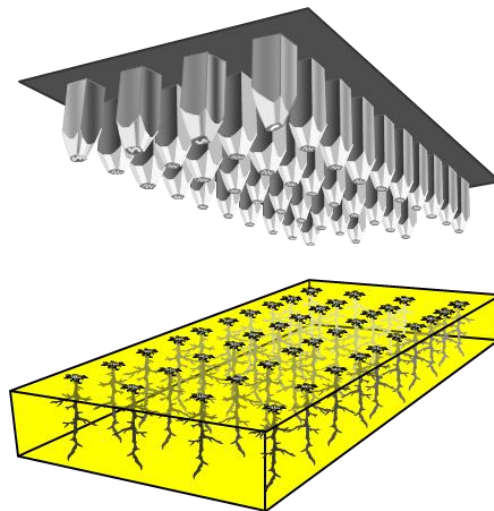


Fig. 7. Schematic representation of active matter driven by punch stamps. A condensed matter bar gets stamped with an array of punch stamps. The punch stamps emulate the actions of the virtual part of the organism.

I have embodied this system experimentally. It is described in Part 2 of this manuscript, “The Neural Network as an Active Condensed Matter Body”. The real material bodies were CD-RW (rewritable) discs; the virtual half of the reconstructing matter was stored in a computer as a digital image, and the sensors and actuators were realized using a standard CD-ROM drive. By repetitive recordings of a particular digital file, I produced arrays of “burn pits” on the surface of the disc. The recording inflicts strong heating and localized plastic deformations in the body of the polycarbonate disc. Basically, every burn pit may be used in the same way as a punch stamp. After a few hundred recording cycles, the discs start producing writing errors. They were interpreted as the disc’s responses to stimulations.

The results of this experiment are described in detail in Part 2 of this manuscript [7]. They indicate that the local reconstructions around every individual burn pit interact, communicate with each other, and eventually produce one big integrated reconstruction. The whole disc acts as a single entity and produces a coordinated complex action composed of many smaller reconstructions.

3.7 Further possible experiments

Possible indications of the collective reconstructions in the evolving CD-RW discs is my main experimental result so far. I did not attempt to give these collective reconstructions any particular structure, or obtain any useful functionality. This would be a reasonable next step. After that, it would be logical to proceed to fabrication of copious amounts of different quasi-organisms with different behaviors, followed by a tedious process of artificial selection. Currently I gather funds, people, and physical resources for this enterprise.

Conclusions

In this paper, I attempted to define life as a physical phenomenon, and presented conceptual and physical models of living organisms. In my view, animate matter generates non-random reconstructions caused by the collective chemical condensation. A living organism is a specially arranged condensed matter body that sustains these reconstructions. They disentangle the organism's body; this enables its further condensation. The inanimate habitat is an entangled condensed matter body. Its structure cannot produce any ordered reconstructions. The organism disentangles the habitat promoting its controlled condensation. In short, life is a combination of the collective condensation and the collective disentanglement of condensed matter.

Additionally, I have introduced entangled materials with excessive degrees of condensation. They can be disentangled, and produce ordered reconstructions driven by decondensation. They can produce quasi-living forms with complex behaviors analogous to those of real biological organisms. The artificial quasi-organisms have one important advantage. They can be mass produced industrially. I intend to use these quasi-living forms for fabricating simple artificial brains. I anticipate that they may complement or replace artificial neural networks in practical applications.

References

* E-mail: kukuruznyak@animatematerials.com

- [1] D. A. Kukuruznyak, The Physics of Life. Part I: The Animate Organism as an Active Condensed Matter Body. 2017. [〈 hal-01575989v2 〉](https://hal.archives-ouvertes.fr/hal-01575989v2) <https://hal.archives-ouvertes.fr/hal-01575989/document>
- [2] R. D. Allen, *The Journal of Cell Biology*, 1981, **91**(3 pt.2), 148s.
- [3] G. West, *Scale*, Penguin Press, New York, 2017.
- [4] F. G. Woodhouse and R. E. Goldstein, *Proc. Natl. Acad. Sci. USA*, 2013, **110**, 14132.
- [5] R. E. Goldstein and J-W. van de Meent, *Interface Focus*, **5**, 2015, 20150030.
- [6] G. E. Zaikov, V. G. Zaikov and A. K. Mikitaev, *Chemical Reaction in Condensed Phase: The Quantitative Level*, Nova Science Publishers, New York, 2006.
- [7] D. A. Kukuruznyak, The Physics of Life. Part II: The Neural Network as an Active Condensed Matter Body. 2017. [〈 hal-01575993v2 〉](https://hal.archives-ouvertes.fr/hal-01575993v2) <https://hal.archives-ouvertes.fr/hal-01575993/document>
- [8] J. Goldstein, *Emergence*, 1999, **1** (1), 49.
- [9] P. Glansdorff and I. Prigogine, *Thermodynamic Theory of Structure, Stability and Fluctuations*, Wiley-Interscience, London, 1971.

[10] S. Camazine, *Self-organization in Biological Systems. Princeton studies in complexity (reprint ed.)*, Princeton University Press, 2003.

[11] L. Wolpert, *The triumph of the embryo*, Dover Publications, Mineola, NY, 2008.