



HAL
open science

Physics of Life. Part I: Animate Organism as an Active Condensed Matter Body

Dmitry A Kukuruznyak

► **To cite this version:**

Dmitry A Kukuruznyak. Physics of Life. Part I: Animate Organism as an Active Condensed Matter Body. 2017. hal-01575989v1

HAL Id: hal-01575989

<https://hal.science/hal-01575989v1>

Preprint submitted on 22 Aug 2017 (v1), last revised 13 Sep 2017 (v2)

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

Physics of Life. Part I: Animate Organism as an Active Condensed Matter Body

Dmitry A. Kukuruznyak*

Max Planck Institute for Solid State Research, Heisenbergstrasse 1, 70569 Stuttgart, Germany

The non-equilibrium “active agents” establish bonds with each other and create a quickly evolving condensed state known as the active matter. Recently, the active matter composed of the motile self-organizing biopolymers demonstrated a biotic-like motion similar to cytoplasmic streaming. It was suggested that the active matter could produce cells. However, the active matter physics cannot yet define “an organism” and thus make a satisfactory connection to biology. This paper describes the organism made of the active agents, and explains how the active condensed matter could produce animate beings. It argues that life is a specific condensed matter phenomenon. It describes this phenomenon. From this perspective, it formulates a hypothesis regarding the origin of biological life. The discussion starts from the model active agents and the conceptual description of an animate form. Then it explains how chemical transformations actuate protein-based macromolecules. It conjectures how these macromolecules produce the basic cell. Then it discusses the role of water in biological cells. From a physicist's perspective, the manuscript describes ordered reconstructions of the active condensed matter driven by the ongoing condensation of this matter.

Keywords: active matter, basic cell, molecular machines, pre-biotic evolution, abiogenesis, morphogenesis.

1 Mechanical counterpart of a living organism

Examples of the active matter are flocks of birds, swarms of insects, and large moving groups of self-organizing biopolymers [1,2]. When the active agents interact with each other, collective behaviors emerge that are unlike anything possible with equilibrium systems [3,4]. This paper shows how the active agents can organize into one big agent and form a collective animate organism [5,6].

The most important property of the active agents is their ability to build bonds with each other and produce a condensed state. The bonds constrain the individual agents' motions. The constraints will frustrate the agents and inhibit their activity. The condensing active matter could jam and eventually come to a complete halt.

From this point of view, the simplest macroscopic example of the active condensed matter is the granular matter under gravity, such as a pile of sand in a container. There, the weighty grains could become active agents because they want to execute a destined motion, specifically, to fall down. The grains could not actualize this motion because they are constrained by the walls of the container and each other. Therefore, the jammed arrest is the trivial particular case of the active condensed matter's motion.

The simplest non-trivial motion is the flow of the granular matter in an hourglass. (FIG. 1.) There, the pile of sand is connected to an external reservoir of space and moves into this reservoir through a single open hole. It is easy to notice that the voids that enter the matter from the open hole represent a new kind of the active agents. The voids eliminate obstacles for the grains' motions. In this regard, they exhibit functionality directly opposite to that of the grains: instead of creating constraints, they eliminate them.

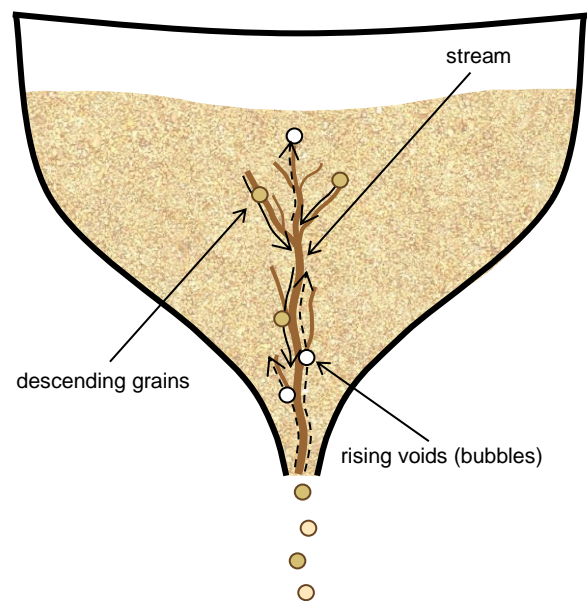


FIG. 1. Active reconstruction of the granular matter in the hourglass.

The author intends to use this particular example as a model system, and proposes building the general active condensed matter dynamics on it. The model would contain the active agents with two different abilities: the first kind will form the condensed state by creating the bonds between the agents, while the second kind will destroy the condensed state by breaking these bonds. The first kind will promote jams and inhibit the agents' activities, whereas the second kind will eliminate the jams and excite their activities. The joint and cooperative work of these two kinds of agents will sustain the activity of the active matter without halts or disintegration of the condensed state.

The reconstruction of the jammed active matter in the hourglass involves stop-and-go motions: An unobstructed agent moves a short distance before it meets a new obstacle and stops. Simultaneously, this short motion removes an obstruction and gives way for another agent's motion. (FIG. 2.) Very often, the whole reconstruction proceeds through periodic reproduction of "recurring" configurations. For example, in the hourglass, the disappearance of the grain that plugs the funnel triggers the process that brings another grain in almost the same position as the original plugging grain. Instead of evolving beyond recognition, this jammed matter periodically returns to the "almost original" formation. Yet, the recurring situations are not identical: by the stop-and-go motions, the whole pile will eventually pass through the orifice and disappear.

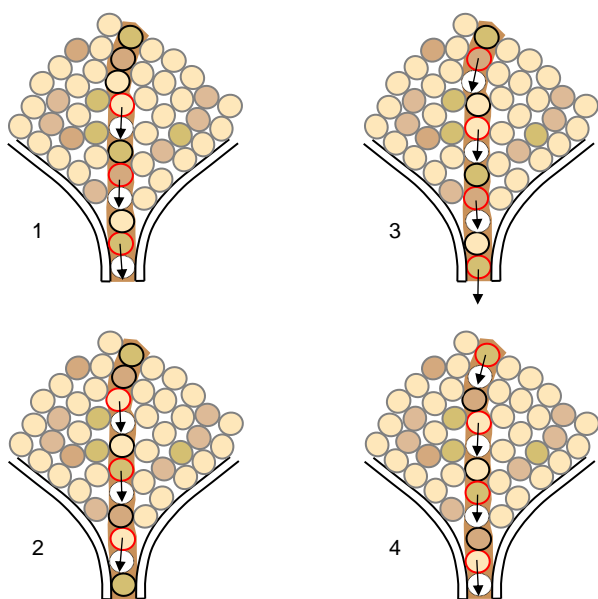


FIG. 2. Recurring stop-and-go motion in the stream at different moments in time.

The flow of the granular matter through the hole causes its structural makeover. Specifically, it produces a more ordered and more active sub-structure that resembles a stream. The descending grains prefer to move along the stream. The stream starts growing from the orifice and slowly progresses farther up into the matter. This substructure is better arranged: The grains "stand in an ordered queue", one after another, waiting for their turn to execute a tumble. The recurrent situations are reproduced all the way along the length of this stream. The rest of the granular matter remains disordered. For this reason, it stays jammed and motionless.

The un-jammed substructure emerges because the active agents change their properties under the influences of the moving agents: The descending grains dig and arrange the stream's channel in the granular matter. A single descending grain leaves a trail of the modified structure behind. The

similar events then reoccur, and the granular matter accumulates the inflicted structural modifications.

The actively moving agents move and rearrange the condensed matter. The same is true for the active stream as a whole. This active sub-system should be considered as a collective active agent that arranges itself and un-jams the inactive disordered remainder. **The author will argue that the active stream that emerges and grows in the hourglass is the prototype and the mechanical analogue of a collective living organism. The separation of the active condensed matter into the un-jammed and ordered organism and its jammed habitat will exemplify the emergence of complex life.**

2 Emergence of the organism

The flow of the granular matter into an external reservoir creates the organized material sub-structure. The grains travel down along this sub-structure. The sub-structure is most ordered at the bottom, near the orifice. At the surface of the pile, it separates into diffused capillaries, and dissolves. The ordered stream grows progressively: first, only the grains nearest to the orifice are involved in motion, then more distant grains begin to move. The ordered stream makes the motion of the grains easier.

During the flow of the matter into the external reservoir, the exchange of the elements is bilateral. The matter gives the reservoir the grains; in return, it takes voids. Those resemble little bubbles that rise upward during the relaxations of the pile. Not all 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 arrange into a pattern. This pattern is the ordered sub-structure.

The internal voids serve as new small "internal reservoirs of space"; the granular matter settles down by filling these voids. The voids that are not currently filled are the inactive agents. The stream's sub-structure is the arrangement of the active and inactive agents. At the orifice, the pseudo-chemical transformation takes place: the grains become the voids. The stream then populates the condensed matter with these new active and inactive voids, and activates them, keeping the whole process running.

The new sub-structure is not just voids. It is also modified bonds between the grains. The moving grains rupture the granular matter, leaving a trail of the broken bonds behind.

3 Information. Enslaving effect

In the granular matter, the grains have a significant volume and are placed tightly back to back. Every grain is an obstacle for the other grains' motions. Disappearance of the grain at the bottom of the funnel implies elimination of an obstacle. This event generates a new signal in the condensed matter; it produces a "permission to move". The tumbling grains relay this permission along the stream farther into the condensed matter. Therefore, the operation of the stream could be described in terms of production, transfer, and

acquisition of signals. Since the grain all look alike, the stream transports new material but almost identical information.

The stream of the hourglass demonstrates the phenomenon that will be termed the enslaving effect [7]. It is submission of all the processes in the reconstructing condensed matter to one chief process. Enslaving emerges when a single source of information in the active matter controls operation of all the other recipients and sources of information. In the hourglass, the information that controls all motions is generated at the open end of the funnel.

The pseudo-chemical transformation “grains-into-voids” is the source of the enslaving commands. It periodically generates new portions of permissions and “ejects” them as signals (voids) farther into the matter. They are assimilated by the recipients. The new sources of information (agents) appear farther and farther from the primary source. These new sources are arranged in a particular pattern. This pattern assists further flow of information.

The enslaving cannot work without a feedback. The feedback is the response reconstruction of the condensed matter that brings the next grain into the funnel. It returns the condensed matter to the “almost original” state. The active matter can generate another order only after receiving this confirmation. The return to the original operating position should occur in every segment of the command chain along the full length of the ordered stream. If the execution is unconfirmed, the whole process could stop. Fortunately, every order may be executed in many possible ways (by different grains filling the same void).

4 The mechanical counterpart of a living organism

The active ordered stream that consists of the arranged active agents could be the prototype and the mechanical analogue of a living organism.

According to the author, a living organism is a condensed matter body that implements an orderly autonomous reconstruction. The organism is immersed into a larger condensed matter body, i.e. the habitat. It exchanges elements with this habitat.

The organism is a collective active agent that consists of smaller and simpler agents arranged in a particular pattern. They exchange signals (that are also active agents) and form a coordinated group with the characteristic chain of command and feedback.

The habitat is full of energy but consists of the obstructed and inactive agents. The organism manipulates and rearranges its habitat. It removes the obstructions, activates the habitat’s agents, and incorporates them in its own coordinated group. The active agents transit into the organism, and temporarily become its elemental parts. In the organism, the agents travel along stable routes undergoing controlled and predictable transformations. After they expend all their energy, they are disposed of as waste. At different times, the

body of the organism is composed of different although “equivalent” active and inactive elements.

The material body of the organism is the “recurrent pattern”. It is a piece of the reconstructing condensed matter that periodically returns its elements into a recognizable “original formation”. The body of the organism also grows: the volume of the recurrent pattern expands as a greater fraction of the active condensed matter becomes involved in the recurring motion. The body emerges from the enslaving agent that is a special active agent that un-jams the constrained condensed matter. The order and the energy for the self-arranging and growth is drawn from the agents, i.e. from their ability to produce orderly motions.

5 Jammed active condensed matter of protein macromolecules

The analogous collective motion could occur in the active subcellular protein bodies and molecular machines [8]. Those organic macromolecules move because of the intrinsic chemical transformations. In those macromolecules, all the atoms are tied to each other by several constraining chemical bonds. For this reason, their condensed bodies remain strongly jammed. However, they still reconstruct. In particular, they may continue the process of chemical condensation. That involves creation of additional chemical bonds in already existing condensed matter. This process is commonly observed during protein folding [9].

During the chemical condensation, the biotic organic macromolecules contain active agents that set them in motion. Figure 3 shows how the macromolecule becomes animated when a new additional chemical bond is formed in its body. During construction, the chemical bond pulls two atoms closer together. Likewise, a bond breaking repels two atoms. In the condensed body, such motions propel the neighboring atoms causing mechanical relaxations of the condensed matter.

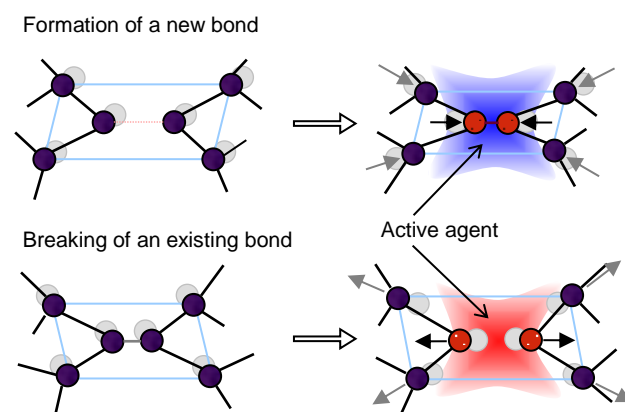


FIG. 3. Constructing and breaking chemical bonds in the molecular condensed matter. The elementary active agents.

The author enunciates that the most elementary active agents, and the basic sources of the mechanical motion in

the biotic condensed matter, are the chemical bonds during forming, rupture, or reconstruction.

The active agent pushes or pulls the surrounding atoms “making space for itself”. Generally, it requires reconstructions of the condensed matter, such as transmutations of the elements. (Essentially, the condensed matter cannot deform without restructuring.) The active agent considers the condensed matter as an obstacle. The reconstruction corresponds to the removal of that obstacle. It is an extremely complex, multistage process. It proceeds gradually, by multiple acts of communication and feedback between the agent and the condensed matter:

The reconstruction starts when the active agent alters the bonds in the condensed body: some bonds become stronger, whereas other ones become weaker or get broken. The removal of the internal constraint corresponds to the emergence of a void in the granular matter of the hourglass. It activates some previously inhibited agents and instigates an additional reconstruction. This reconstruction closes the void, restores the constraint, and stops the motion. However, it also transfers some parts of this void into other places. This could break a new constraint and start a new active motion at a new place. Therefore, the realized reconstruction is registered as the cascading “propagation of voids”. (FIG. 4.)

The elementary active agent produces or consumes space, generates ruptures and voids, and pushes them away in different directions. It corresponds to the open hole of the hourglass. It creates a complex reconstruction around itself that could be treated as the “collective organism”. In this organism, the enslaved agents communicate with the enslaving active agent.

The motions in the active macromolecules differ from that of the hourglass in one important regard: many different “enslaving agents” exist and operate in the molecular body simultaneously. Every one of them generates its own set of commands, and builds its own reconstruction around itself. This situation would compare to the hourglass with multiple open holes. Every open hole would build its own active stream. The streams would affect each other: they would either cooperate by helping the neighbors’ motions, or compete by impeding each other. The author will argue that, by multiple interactions, all these reconstructions would reorganize to eliminate the competition and retain the cooperation. As a result, they will create a coordinated collective reconstruction.

If every separate reconstruction subjugated to an isolated “enslaving agent” could be associated with an independent organism, then their coordinated ensemble should be regarded as a large collective organism. Formation of the collective organism and its behavior is described in Part II of this manuscript entitled “Neural network as an active condensed matter body”.

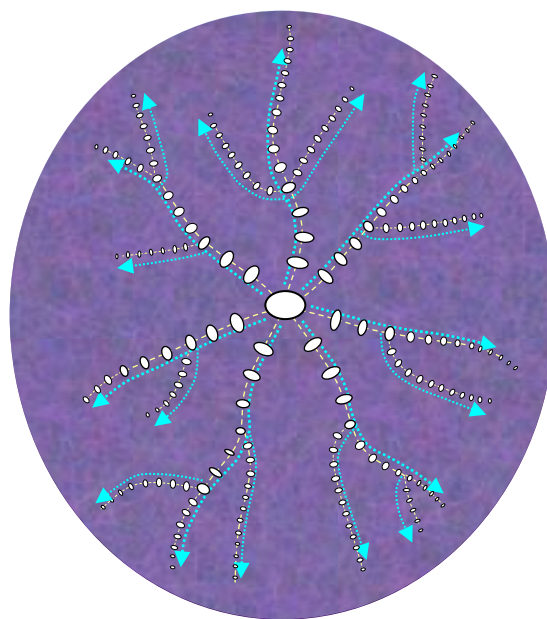


FIG. 4. The condensed matter reconstruction caused by the elementary active agent. The active agent generates or consumes space. This produces a cascade of ruptures and voids in the matter.

6 Active protein bodies as the archetypes of the forms of life

The active protein bodies such as folding proteins and molecular machines could be the first “animate pieces of condensed matter”. They can voluntarily move, perform mechanical work, and transform their surroundings.

The biotic macromolecules have one absolutely special characteristic: their atoms are arranged in precise orders. Therefore, their actions and motions are also ordered and organized. If a biotic macromolecule is placed into an ordered habitat, it will move directionally along that environment using it as a support. The active macromolecules can manipulate other macromolecules in an orderly fashion inflicting their accurate and precise modifications. By doing that, they can change their behaviors. In particular, they can activate or inhibit them.

If the internal structure of the bio-molecule is somehow disturbed, it would remain jammed being unable to perform an ordered action. This internal jam could be called an internal entanglement. The entangled protein could store large amounts of chemical energy but still be inactive because of the internal obstructions. Its activation requires deliberate structural modifications performed by other active macromolecules. It should be emphasized that those alterations could not be achieved by any random interventions, accidental processes, or thermal fluctuations.

7 Collective organism made of the active protein bodies

The biotic macromolecules could unite, make up a larger condensed matter body, and create a larger collective organism. For the most part, this condensed body would contain the entangled and inhibited macromolecules. They will be activated by other active bodies. Only at this time, the agents are inhibited not because of the external constraints imposed by the neighbors (as it happens in the granular matter), but because of the internal obstructions. The entanglement is removed exclusively by the ordered manipulations performed by the disentangled active agents.

8 The basic cell

The complex protein bodies may exhibit a special type of entanglement when the elementary active agents are divided into the disconnected precursors. (FIG. 5.) This entanglement becomes absolutely hopeless when the protein body completely lacks a certain precursor for a needed chemical reaction. This body could still be activated by an external intervention if this intervention brings a needed reagent from somewhere else.

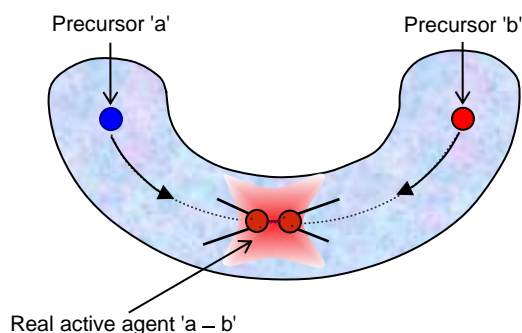


FIG. 5. Prospective active agent separated into two chemical precursors. The active agent arises when the chemical precursors meet.

Correspondingly, there is a special type of disentanglement: one active and un-jammed condensed matter agent moves along another (entangled) agent and performs directional transfer of the chemical reactants.

Figure 6 illustrates this directional transfer assisted by an active protein that moves in the back-and-forth reciprocating regime along another protein body. The two participating bodies differ in size. The larger one contains separated chemical precursors and needs a disentanglement. It provides a "habitat" for the smaller disentangled active protein that moves along this habitat in a circulatory fashion and performs transfer of the chemicals.

The simplest protein agents that can move in the reciprocating regime are the so-called molecular machines, or molecular motors [10,11]. Any live cell has an abundance of them in a wide variety. The circulation of the carrier proceeds roughly as follows. When the molecular machine has a certain

chemical composition, it moves in one direction. When it has a different composition, it moves in the opposite direction. During its motion, it carries certain chemicals. When the active molecular machine reaches its destination, it engages in a chemical reaction with the terminal. The new elementary active agents are formed at the terminal. They change the composition of the carrier. It starts moving in the opposite direction carrying a new chemical. When it reaches the second terminal, it triggers a new chemical reaction, and prepares for the new cycle of travel. Thus, the active carrier joins the separated chemical precursors.

The circulation exemplifies mutual cooperation and symbiosis of two active condensed bodies. The motile active body sustains the activity of the host by achieving its disentanglement. In return, the host provides the motile agent with energy and material.

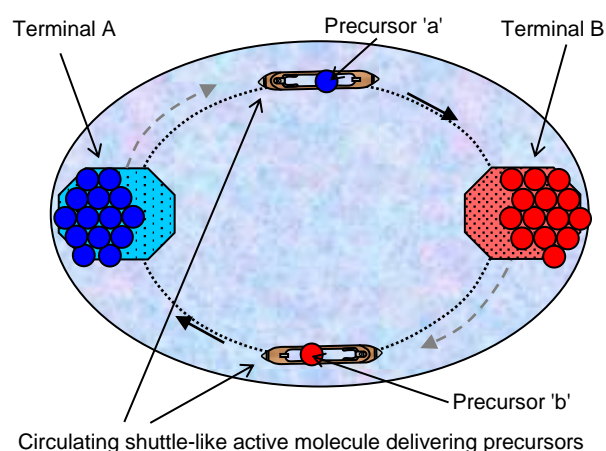


FIG. 6. Schematic representation of the basic cell.

This symbiotic configuration of the two active condensed bodies could be called the basic cell. It is the simplest complex biotic organism and a complex agent that consists of the two simpler ones. The motile part of the organism transfers the controlling signal. The stationary parts of the organism (including terminals) are the recipients, the processors and the enslaved re-senders of the signal. The symbiotic cooperation ensures periodic regeneration of the controlling signal.

9 The basic cell and the RNA world hypothesis

All biological organisms share one fundamental property: they can grow and reproduce themselves. This property originates from the ability of some active biotic molecules to synthesize complex high molecular weight products from simple low molecular weight precursors.

It was suggested that the first condensed matter bodies that acquired this ability were ribozymes, the predecessors of ribosomes [12]. They are special active macromolecules

consisting of proteins and RNA. The ribozymes catalyze production of other proteins. Additionally, they can make their own copies [13].

Figure 7 depicts the active ribozyme suspended in water. The ribozyme periodically synthesizes active macromolecules and ejects them into its environment. The active macromolecules are the folding proteins. During the ordered folding, they actively move to new places. The water is assumed to be a partially ordered polymer that could serve as a support for the moving macromolecules.

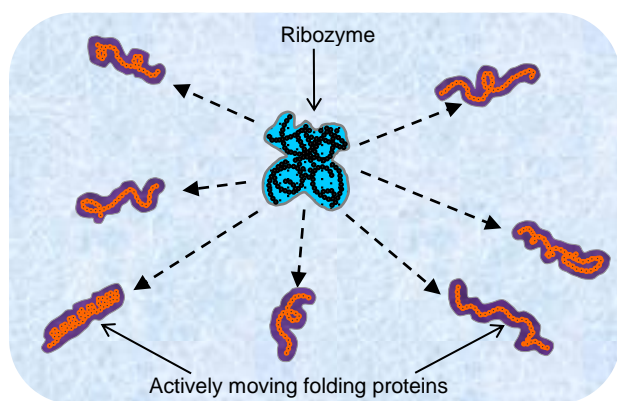


FIG. 7. Active ribozyme produces new active macromolecules (folding proteins) that move in the water.

The moving macromolecule could fold into a new ribozyme situated at some distance from its parent, or it could fold into a different macromolecule. For instance, it could fold into a different ribozyme that would start manufacturing new types of proteins. It could also become an inactive inert macromolecule stuck in the water polymer. It will then reinforce the soft water structure making it less susceptible to disordering thermal fluctuations. The water will become a stronger and more reliable support for the next generations of the moving macromolecules.

Figure 8 depicts the basic cell composed of two active ribozymes and an active reciprocating molecular machine. The molecular machine circulates between the ribozymes instigating their activity by delivering chemical precursors.

The reciprocating molecular machine is the least constrained and the most active part of the basic cell. It carries out the fastest chemical reactions. Therefore, it is the fastest generator of information. For this reason, the reciprocating molecular machine enslaves the behavior of the ribozymes. The circulating molecular machine quickly depletes its own chemical resources, but it regains them at the terminals (i.e. the ribozymes). The completely restorable molecular machine can perform an unlimited number of runs.

Figure 7 illustrates the concept that is usually referred to as the “RNA world hypothesis” [14]. It implies that the complex life had evolved from the producing macromolecules such as the ribozymes. Figure 8 that describes the basic cell could be regarded as a logical

extension of this concept. One might suppose that all the subsequent cells had evolved from this combination of the active producing macromolecules.

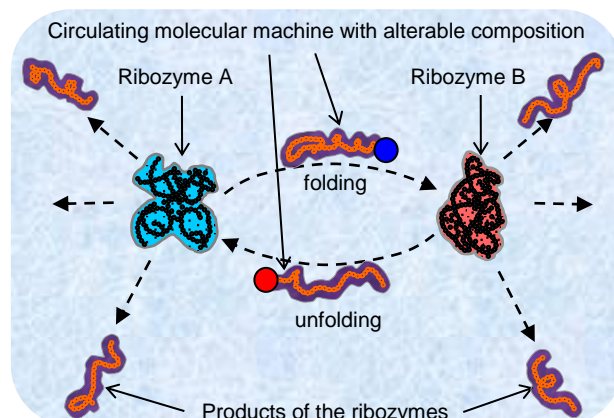


FIG. 8. The basic cell made of the circulating molecular machine and two ribozymes. The circulating molecular machine should be able to fold and unfold depending on its chemical composition.

The first ribozymes could emerge from the disordered blobs of the organic molecules during their self-disentanglement. This would correspond to the process that occurs in the granular matter of the hourglass. However, it would still remain unclear how the first basic cell had emerged. Its spontaneous formation during random processes seems utterly implausible [15].

10 Water as an active condensed matter body

To clarify this matter, the author will have to modify the RNA world concept and take water into consideration. In the author's opinion, water should not be regarded as a passive environment of the actively operating macromolecules. Instead, it may be regarded as one big active “reconstructing macromolecule”. Now, water corresponds to the granular matter of the hourglass. It performs orderly reconstructions and gives birth to the ordered sub-structures such as the active macromolecules.

Water as a condensed matter can be actuated by the same chemical condensation that actuates the active organic macromolecules. This is illustrated in FIG. 9. The figure depicts water populated with the active ribozymes and folding proteins. These organic macromolecules are driven by the chemical condensation (and decondensation) processes. There are no borders between the macromolecules and the water polymer. It is the unified active condensed matter. Moreover, the chemical condensation may occur directly in the water polymer: **Water loaded with chemical precursors condensates and produces the organic condensate molecules.**

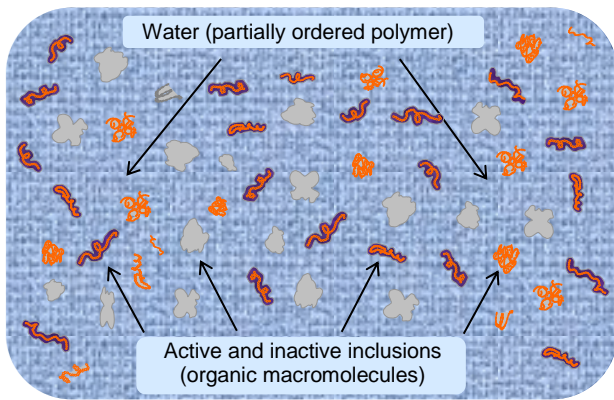


FIG. 9. The active ordered inclusions of the chemical condensate in the less ordered water medium.

The figure shows that the water-based active condensed matter is strongly inhomogeneous. It consists of the ordered (and for this reason more active) organic macromolecules separated by the less ordered water regions. The “pure” water is softer and is more susceptible to random reconstructions caused by thermal fluctuations.

The softer regions “isolate” the active organic macromolecules from each other. For the active macromolecules, imposing ordered manipulations becomes more difficult. At the same time, these softer regions bring a significant advantage: the active macromolecules that perform incompatible motions stop hampering each other. It is a very effective means to remove the jams. The compatible (cooperating) motions will enhance each other. They will actuate the whole condensed matter. (The compatible motions will be significantly attenuated by the softer water regions as well. However, those will not be completely eliminated.)

The resultant reconstruction of the water-based condensed matter will be very complex. Presumably, it will consist of the vast number of motions and proceed simultaneously on many different length scales, from the sub-molecular to the almost macroscopic one. On this length scale, it can be easily observed in living cells. This motion is usually referred to as the cytoplasmic streaming or cyclosis [16,17].

11 The biological cell

Like in the hourglass, the total reconstruction of the water-based active condensed matter will separate into more active and less active parts. The largest active part will be mobile; it will be associated with the cytoplasmic stream. The less active parts will remain virtually motionless; they will play the role of the static “body of the cell” with the embedded “organelles”.

Experimental observations show that the cytoplasmic stream consists of multiple open circulations. Many real cells have one big dominating circulation as shown in FIG. 10. This cytoplasmic circulation plays the role of the reciprocating molecular machine. It delivers chemical

precursors and connects different parts of the cell. It is also the collective enslaving agent that controls the behavior of the cell. The static parts of the cell recuperate the stream and sustain its activity.

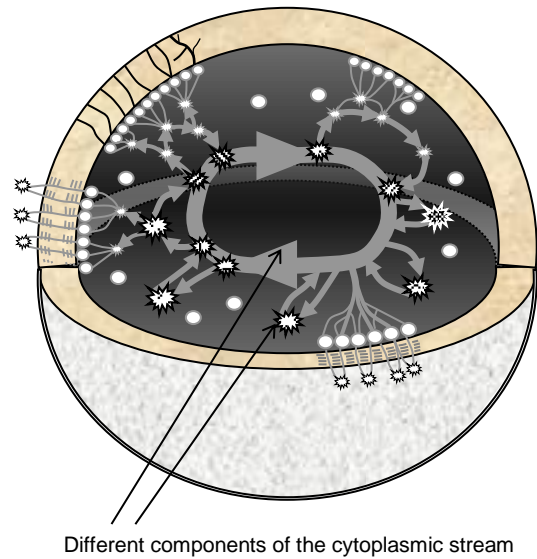


FIG. 10. Schematic representation of the cytoplasmic streaming in a cell.

The biological cell retains the characteristic features of the basic cell. But only roughly: both the cytoplasmic streams and the static organelles of the cell have many different components that realize various functions.

The biological organism as an ordered reconstruction of the active condensed matter constantly fights against random reconstructions caused by thermal fluctuations and external influences. Suppressing disorder is important because the organism implies strictly directional transfer of signals and active agents. However, neither ordering nor disordering should ever win the battle: in addition to the orderly motions, the cytosol must support diffusion and transport of the chemicals along the drops of the chemical potential. The organism uses this transport mechanism for delivering small molecules needed for the synthesis of larger molecules. (The diffusion of large macromolecules remains prohibited because they stuck in the cytosol. Those can only move by the active processes.)

Unfortunately, the fact that the cytosol remains liquid-like and “soft” confuses researchers. They tend to consider the actively reconstructing cytosol as a simple liquid; they completely disregard its directional motion. In other words, the scientists completely overlook the processes that define life as a physical phenomenon. Instead, they concentrate on self-replication.

12 Pre-biotic evolution and the origin of life

A live biological cell is a condensed matter body that consists of active and inactive organic molecules and water. It carries out a complex ordered reconstruction. The reconstruction is driven by the irreversible chemical condensation. The condensation implies adding of lacking chemical bonds to the existing condensed matter and creating chemical condensates.

After providing this description, one can conjecture how the organism emerged. In the author's opinion, it arises during spontaneous disentanglement of the entangled water-based condensed matter.

The initial condensation-driven reconstructions resemble crack propagation in homogeneous solid matter. There is one important difference: fracturing corresponds to decondensation of the matter; it involves elimination of excessive bonds. Forming the missing bonds is the inverse effect. It compares to “fastening an open zipper” in the body of the condensed matter. This process “eliminates the existing voids”.

Figure 11 illustrates this process. The initial condensed matter has holes. Closing one hole causes relaxation of the matter and transfer of the material; it may widen or compress another hole at a new place. This triggers condensation and closing of the second hole. The condensed matter produces the chain of condensation events. The cascading condensation leaves a permanent trace in the condensed matter. The trace consists of a denser chemical condensate.

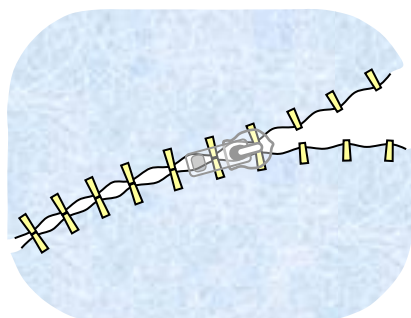


FIG. 11. Schematic representation of the cascading condensation in homogeneous water polymer loaded with suspended chemical precursors.

The cascading condensation in water accomplishes production of the first chain-like organic molecules. These condensates may serve as seeds for further reconstructions. Those will produce larger organic condensates. During the continued condensation, the active water will accumulate the chemical condensates. The evolution of this pre-biotic active matter might go crescendo.

At some stage, the organic condensates acquire their own activity. In other words, they launch their own intrinsic condensation and decondensation processes. Then they start actuating water and actively participating in the production of

new condensate macromolecules. The outside observer might regard this as “production” or even “self-replication” of macromolecules. In fact, the self-replication of the chemical condensates may involve at least two active bodies: the replicator (such as the ribozyme) and its active water ambience. Moreover, it is unclear which contribution would play a more important role.

The active reconstructions make the pre-biotic condensed matter heterogeneous. Perhaps, the cell simultaneously emerges on several different length scales. On the molecular scale, the active organic macromolecules order, grow in size, diversify, and acquire distinct functions. Some of them become stationary proto-ribozymes, and others become the motile “signaling molecules”. On the cellular length scale, the active water separates into the mobile “cytoplasmic stream” and the stationary “body of the cell”.

13 The cell with a rational behavior

The cell may disentangle and re-arrange its habitat as described in Sections 1, 4, and 8. Let us consider the following situation: the cytoplasmic stream detaches small parts from itself and sends them into its external ambient. There, they chemically react with the external terminals (food) and return back to the cell in the transformed conditions. Thanks to this interaction, the cell feeds and rejuvenates. (FIG. 12.)

The cell is surrounded with a semi-permeable membrane. This barrier constricts and attenuates the streams that circulate between the cell and its environment. In order to go, the streams must breach this barrier. This process has a lot in common with a break of a dam by a flow of water. Stronger the flow is, faster it destroys the dam. The breach could proceed in an avalanche-like regime. The cellular barrier resists the rupture, and can quickly heal. This semi-permeable restorable barrier brings about the variable behavior:

The external environment of the cell may have ample amounts of the active processes that produce motile signals. The barricaded cell imitates an observer that registers many external calls from different sources. However, it does not necessarily react to all of these calls. Thanks to the barrier, the majority of the signals gets screened off without producing any feedback.

From time to time, the cells responds to a particular external signal; it excites the external source, building a feedback loop with a reinforcement. The barrier breaks. It boosts the communications. One could say that at this moment, the metabolism of the cell expands by “attaching a temporary external organ” to the cell. The metabolic network of the cell enlarges.) After the cell satiates with the needed precursors, the feedback loop withers. The restoration of the barrier overtakes. The extended action of the cell gets inhibited.

On the long time scale, the cell generates a sequence of different extended actions. Between these actions, it could be in a state of rest, when only the internal metabolism is active.

At this state, it continues to register a vast amount of external calls. However, these calls do not yield any automatic responses. One might conclude that the cell has its own free will and a freedom of choice.

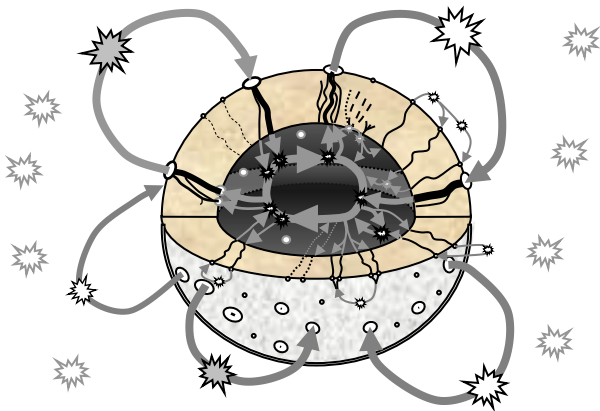


FIG. 12. The cell travels through the surrounding habitat in small prominences. The semi-permeable membrane substantially reduces the flows between the cell and its environment. The flows could expand the capillaries and transform into big streams.

Remarkably, the cell behaves quite prudently. For instance, it does not react to the signal that it does not need. When the cell chooses an extended action, it is guided by rather sound principles: it breaks the barriers that are the easiest to break, and chooses streams that provide the fastest positive feedback. In other words, it elaborates a compromise between the paths of the least resistance and the needed satisfaction. This simple mind never searches for the most effective solution and it rarely finds the maximal reward. Advantageously, it never stalls.

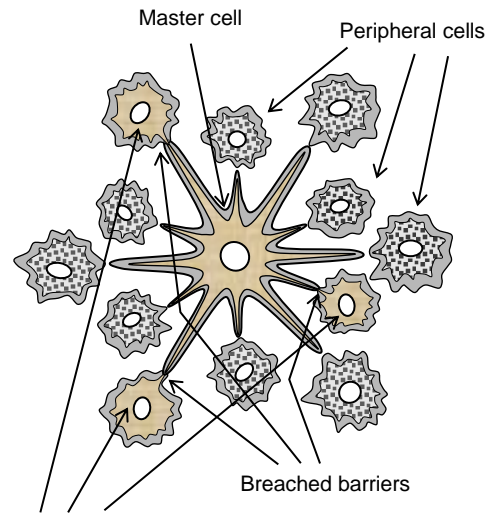
It should be added that as long as the ruptures of the barrier are not completely healed the cell would retain memory about the performed actions. The poorly healed ruptures could break easier. The cell can reproduce the previously executed actions, or even extend them, producing more complex actions.

14 Multicellular organism with a variable behavior

The active cell may generate an adaptive variable behavior of a multicellular organism. Figure 13 shows a simple multicellular organism that contains the most active “master cell” that enslaves all the other cells.

The master cell considers other (less active) cells as its peripheral organs that it can excite or inhibit. In the state of rest, the master cell is preoccupied with its own business using only its own internal metabolic networks. At the same time, the master cell monitors its neighbors by registering their signals constricted by the barriers. From time to time, it

performs extended actions by breaking the barriers and exciting its peripheral organs. The barriers break when the master cell intensifies communications with these peripheral cells. When the extended action stops, these additional communications break off and the master cell separates itself from its periphery.



Master cell extended its metabolism into peripheral cells

FIG. 13. The master cell and its enslaved peripheral cells. The master cell breaches barriers and connects to the peripheral cells extending its metabolism.

The described master cell plays the role of the brain that consists of a single cell. Perhaps, the real brain is the analogous master organ. Only it contains great numbers of the “master cells”. The master cells, i.e. the neurons, are the active agents that form an active condensed matter body and a single unified collective active agent. The variable behavior of this active condensed body and the emergence of the collective mind will be discussed in Part II of this manuscript.

Conclusions

Life of a biological organism may be associated with the autonomous reconstruction of its condensed matter body. The reconstruction is driven by the chemical condensation of this body. An organism with a stable body implies a stable, ordered, and coordinated reconstruction. The process of chemical condensation involves establishing additional chemical bonds in already existing condensed body. Reproduction and growth of biological organisms correspond to fabrication and accumulation of ordered chemical condensates. The author argued that the chemical condensation might cause the emergence of biological organisms and prompt their evolution.

Using the example of the granular matter of the hourglass, the author demonstrated that the emergence and growth of the organisms could be driven by the complementary process of

decondensation. It involves elimination of the excessive bonds from the condensed body. In the condensed matter prone to structural decay, the orderly decondensation may produce active coordinated reconstructions analogous to those of the organic forms of life. Unlike their organic counterparts, those could be fabricated from scratch using existing industrial and scientific tools. The author intends to

* Email: kukuruznyak@googlemail.com

[1] S. Ramaswamy, *Annu. Rev. Condens. Matter Phys.* **1**, 323–345 (2010).

[2] M. C. Marcetti, J. F. Joanny, S. Ramaswamy, T. B. [Liverpool, J. Prost, M. Rao, R. Adita Simha, *Rev. Mod. Phys.* **85**, 1143–1189 (2012).

[3] G. Popkin, *Nature* **529**, 16–18 (2016).

[4] T. Sanchez, D. T. N. Chen, S. J. DeCamp, M. Heymann, Z. Dogic, *Nature* **491**, 431–434 (2012).

[5] J. W. Pepper, M. D. Herron, *Biol. Rev.* **83**, 621–627 (2008).

[6] D. C. Queller, J. E. Strassmann, *Phil. Trans. R. Soc. B* **364**, 3143–3155 (2009).

[7] H. Haken, *Synergetics: Introduction and Advanced Topics* (Springer-Verlag Berlin Heidelberg, 2004).

[8] Z. Bu, D. J. Callaway, *Adv. Protein Chem. Struct. Biol.* **83**, 163–221 (2011).

make them and use them as “generators of autonomous behavior” that would make decisions and solve problems like biological organisms. These topics are discussed in Part II of this manuscript entitled “Neural network as an active condensed matter body”.

[9] B. Alberts, A. Johnson, J. Lewis, M. Raff, K. Roberts, P. Walters, *The Shape and Structure of Proteins. Molecular Biology of the Cell* (Garland Science, 2002).

[10] P. Satir, S. T. Christensen, *Histochem. Cell Biol.* **129**, 687–693 (2008).

[11] R. Ballardini, V. Balzani, A. Credi, M. T. Gandolfi, M. Venturi, *Acc. Chem. Res.* **34**, 445–455 (2001).

[12] M. J. Fedor, J. R. Williamson, *Nat. Rev. Mol. Cell Biol.* **6**, 399–412 (2005).

[13] W. K. Johnston, P. J. Unrau, M. S. Lawrence, M. E. Glasner, D. P. Bartel, *Science* **292**, 1319–1325 (2001).

[14] M. Neveu, H. J. Kim, S. A. Benner, *Astrobiology* **13**, 391–403 (2013).

[15] H. S. Bernhardt, *Biol. Direct* **7**:23 (2012).

[16] F. G. Woodhouse, R. E. Goldstein, *Proc. Natl. Acad. Sci. USA* **110**, 14132–14137 (2013).

[17] R. E. Goldstein, J-W. van de Meent, *Interface Focus* **5**, 20150030 (2015).