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

Dmitry A. Kukuruznyak*

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

Nonequilibrium “active agents” establish bonds with each other and create a quickly evolving condensed state known as active matter. Recently, active matter composed of motile self-organizing biopolymers demonstrated a biotic-like motion similar to cytoplasmic streaming. It was suggested that the active matter could produce cells. However, active matter physics cannot yet define an “organism” and thus make a satisfactory connection to biology. This paper describes an organism made of active agents and explains how the active condensed matter could produce animate beings. It argues that life is a specific condensed matter phenomenon and 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 speculates on how these macromolecules produce the basic cell. Then it discusses the role of water in biological cells. Taking a physicist’s perspective, this paper describes ordered reconstructions of the active condensed matter, driven by the ongoing condensation of this matter.

Keywords: active matter, basic cell, molecular machines, prebiotic evolution, abiogenesis, morphogenesis.

1 Mechanical counterparts of a living organism

Some examples of active matter include 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 in equilibrium systems [3,4]. This paper shows how 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. Such constraints will frustrate the agents and inhibit their activity. As a result, condensing active matter could jam and eventually come to a complete halt.

From this point of view, the simplest macroscopic example of active condensed matter is 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. However, the grains cannot actualize this motion because they are constrained by the walls of the container and by each other. Therefore, the jammed arrest is the trivial particular case of the active condensed matter’s motion.

The simplest nontrivial motion is the flow of 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 see that the voids that enter the matter from the open hole represent a new kind of active agent. 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.

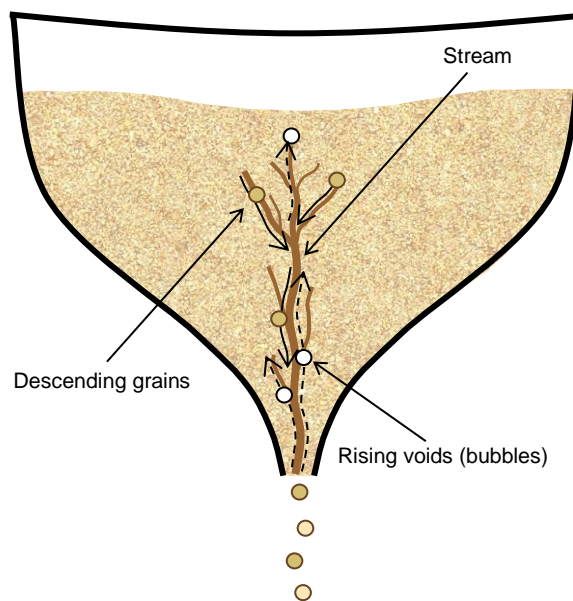


Fig. 1. Active reconstruction of the granular matter in the hourglass.

I intend to use this particular example as a model system and propose building general active condensed matter dynamics on it. The model would contain the active agents with two different abilities: the first ability will be to form the condensed state by creating bonds among the agents, while the second will be to destroy the condensed state by breaking these bonds. The first ability will promote jams and inhibit the agents’ activities, whereas the second will eliminate the jams and excite their activities. The joint and cooperative work of these two kinds of agents will sustain the uninterrupted activity of the active matter without 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 makes 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 into almost the same position as the original plugging grain. Instead of evolving beyond recognition, this jammed matter periodically returns to the "almost original" formation. Nonetheless, the recurring situations are not identical: through the stop-and-go motions, the whole pile will eventually pass through the orifice and disappear.

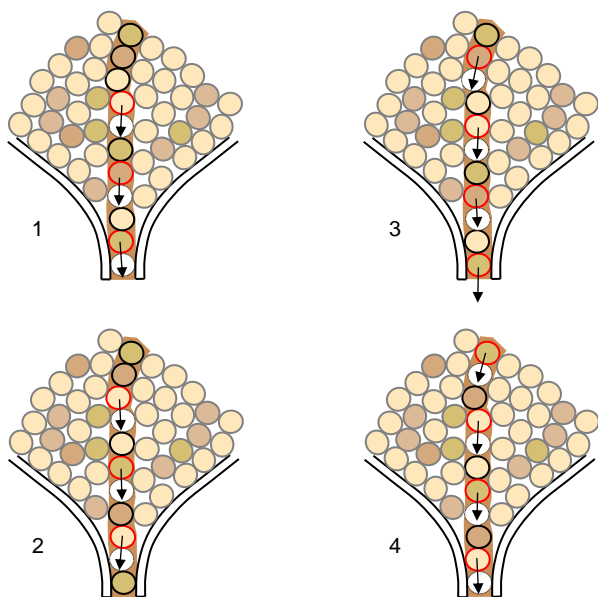


Fig. 2. Recurring stop-and-go motion in the stream at different moments in time.

The flow of the granular matter through the hole causes its structural makeover. Specifically, it produces a more ordered and more active substructure, which 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 unjammed substructure emerges because the active agents change their properties under the influence of the moving agents. The descending grains dig and arrange the stream channel in the granular matter. A single descending grain leaves a trail of modified structure behind. Similar

events then reoccur, and the granular matter accumulates the 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 subsystem should be considered as a collective active agent that arranges itself and un-jams the inactive disordered remainder. **I 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 unjammed and ordered organism and its jammed habitat exemplifies the emergence of complex life.**

2 Emergence of the organism

The flow of the granular matter into an external reservoir creates the organized material substructure. The grains travel down along this substructure. The substructure 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 facilitates the motion of the grains [7,8].

While the matter flows into the external reservoir, the exchange of the elements is bilateral. The matter gives the reservoir the grains; in return, it takes voids, which resemble little bubbles that rise upward during the relaxations 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 a pattern. This pattern is the ordered substructure.

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 substructure 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, activating them and keeping the whole process running.

The new substructure is not just voids. It is also modified bonds between the grains. The moving grains rupture the granular matter, leaving a trail of 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 "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. Because the grains 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” [9]. This is the submission of all the processes in reconstruction of the 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 of grains into voids is the source of the enslaving commands. It periodically generates new portions of permissions and “ejects” them farther into the matter, as signals (voids), which 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, which assists the further flow of information.

The enslaving cannot work without feedback. The feedback is the responsive reconstruction of the condensed matter that brings the next grain into the funnel. It returns the condensed matter to an “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 comprises the arranged active agents could be the prototype and the mechanical analogue of a living organism.

I contend that a living organism is a condensed matter body that implements an orderly autonomous reconstruction. The organism is immersed in a larger condensed matter body—its habitat—and exchanges elements with this habitat.

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

The habitat is full of energy but includes obstructed and inactive agents. The organism manipulates and rearranges its habitat. It removes the obstructions, activates the habitat’s agents, and incorporates them into 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, though “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 that emerges from the enslaving agent is a special active agent that unjams the constrained condensed matter. The energy for the self-arranging and growth is drawn from the agents, that is, from their ability to produce orderly motions.

5 Jammed active condensed matter of protein macromolecules

An analogous collective motion could occur in active subcellular protein bodies and molecular machines [10]. Those organic macromolecules move because of 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 [11].

During the chemical condensation, the biotic organic macromolecules contain active agents that set them in motion. Fig. 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 breaking bond repels two atoms. In the condensed body, such motions propel the neighboring atoms, causing mechanical relaxations of the condensed matter.

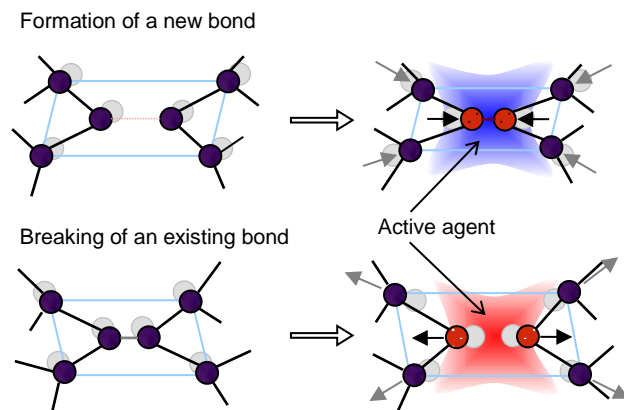


Fig. 3. Constructing and breaking chemical bonds in the condensed molecular matter. The elementary active agents.

I contend 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 an obstacle. The reconstruction corresponds to the removal of that obstacle. This is an extremely complex, multistage process, which proceeds gradually, through 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 others 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 to other locations. This could break a new constraint and start a new active motion at a new location. 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. This corresponds to the open hole of the hourglass. It creates a complex reconstruction around itself that could be treated as the “collective organism.” Within 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 an 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 their neighbors’ motions or compete by impeding one another. I argue that, through multiple interactions, all of these reconstructions will 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 2 of this paper, “The Neural network as an active condensed matter body.”

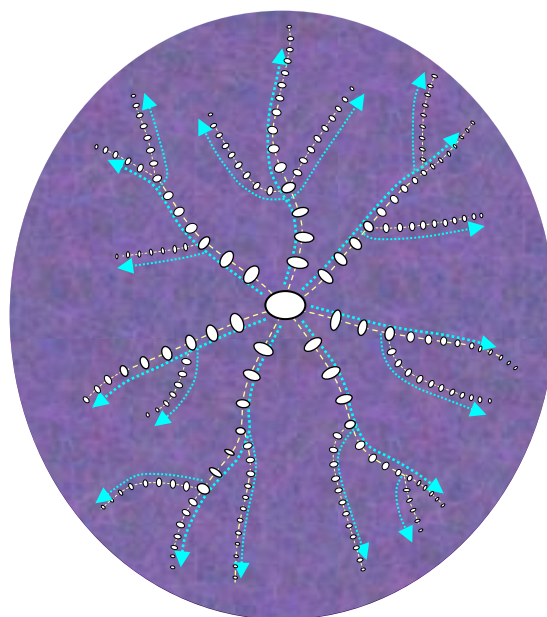


Fig. 4. The condensed matter reconstruction caused by the elementary active agent. The active agent generates or consumes space. This produces a cascade of ruptures and voids.

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

Active protein bodies, such as folding proteins and molecular machines, could be termed 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 in 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, performing their accurate and precise modifications. By doing that, they can change their behaviors. In particular, they can facilitate or inhibit their activity.

If the internal structure of the biomolecule 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 organisms 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. These will be activated by other active bodies. At this time, however, the agents are inhibited not by the external constraints imposed by their neighbors (as happens in the granular matter) but by 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 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.

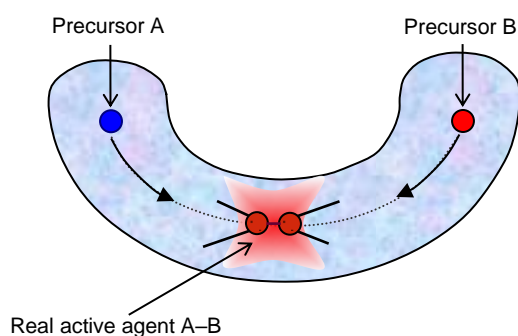


Fig. 5. Prospective active agent separated into two chemical precursors. The active agent arises when the chemical precursors meet.

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

Fig. 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, which moves along this habitat in a circulatory fashion and performs chemical transfer.

The simplest protein agents that can move in the reciprocating regime are the so-called molecular machines, or molecular motors [12,13]. 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, which then 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.

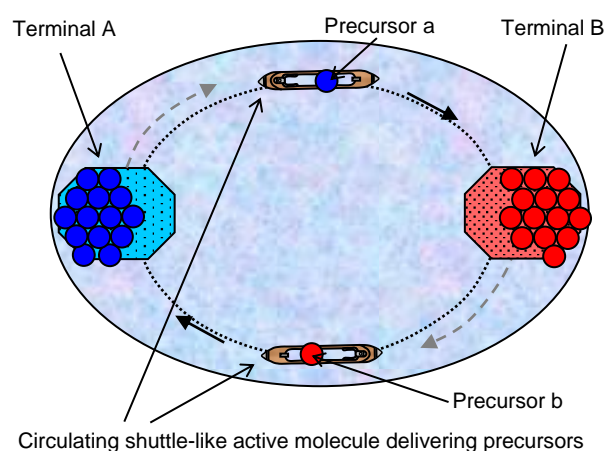


Fig. 6. Schematic representation of the basic cell.

This symbiotic configuration of the two active condensed bodies could be called a basic cell. It is the simplest complex biotic organism, and a complex agent that comprises 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 resenders 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 has been suggested that the first condensed matter bodies that acquired this ability were ribozymes, the

predecessors of ribosomes [14]. They are special active macromolecules consisting of proteins and RNA. The ribozymes catalyze production of other proteins. Additionally, they can make their own copies [15].

Fig. 7 depicts an 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 locations. The water is assumed to be a partially ordered polymer that could serve as a support for the moving macromolecules.

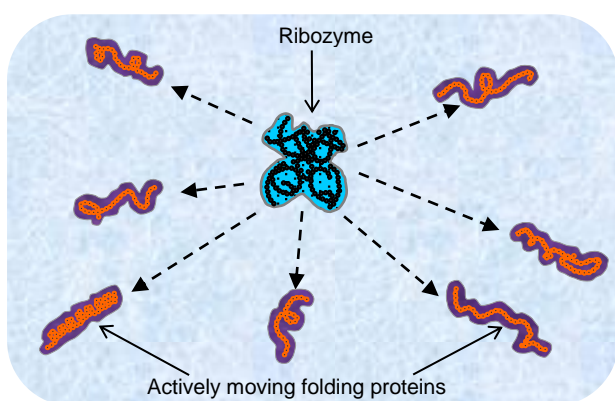


Fig. 7. Active ribozyme produces new active macromolecules (folding proteins) that move in the water.

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 also could 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 moving macromolecules.

Fig. 8 depicts a basic cell composed of two active ribozymes and an active, reciprocating molecular machine. The molecular machine circulates among 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.

Fig. 7 illustrates the concept that is usually referred to as the "RNA world hypothesis" [16]. It implies that complex life evolved from the producing macromolecules, such as ribozymes. Fig. 8 illustrates the basic cell that 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.

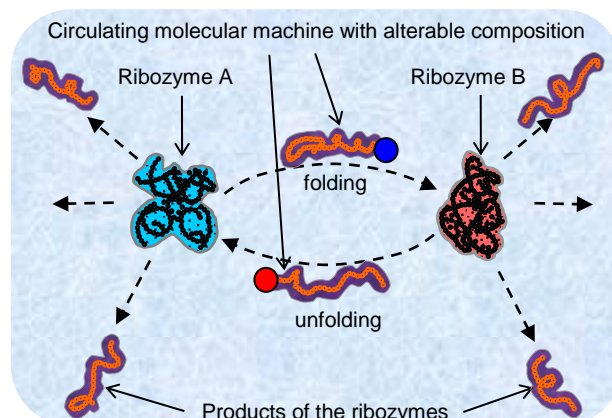


Fig. 8. The basic cell made of the circulating molecular machine and two ribozymes. The circulating molecular machine should be able to fold and unfold depending on its chemical composition.

The first ribozymes could emerge from disordered blobs of organic molecules during their self-disentanglement. This would correspond to the process that occurs in the granular matter of the hourglass. However, it remains unclear how the first basic cell might have emerged. Its spontaneous formation during random processes seems utterly implausible [17].

10 Water as an active condensed matter body

Clarifying this matter requires modification of the RNA world concept to take water into consideration. In my opinion, water should not be regarded as a passive environment for the actively operating macromolecules. Instead, it may be regarded as one big, active "reconstructing macromolecule." In this scenario, water corresponds to the granular matter of the hourglass. It performs orderly reconstructions and gives birth to ordered substructures, such as the active macromolecules.

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

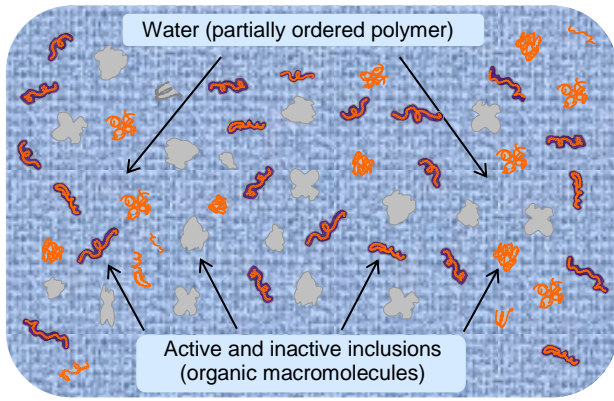


Fig. 9. The active ordered inclusions of the chemical condensate in the less ordered water medium.

Fig. 9 shows that the water-based active condensed matter is strongly inhomogeneous. It consists of ordered (and for this reason more active) organic macromolecules separated by 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 one another, and imposing ordered manipulations becomes more difficult for these macromolecules. At the same time, these softer regions bring a significant advantage: the active macromolecules that perform incompatible motions stop hampering one another. It is a very effective means to remove the jams. The compatible (cooperating) motions will enhance one another; 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 resulting 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 submolecular to the almost macroscopic. On this length scale, it can be easily observed in living cells. This motion is usually referred to as cytoplasmic streaming or cyclosis [18,19].

11 The biological cell

As 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 embedded “organelles.”

Experimental observations show that the cytoplasmic stream consists of multiple open circulations. Many real cells have one large, dominant 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.

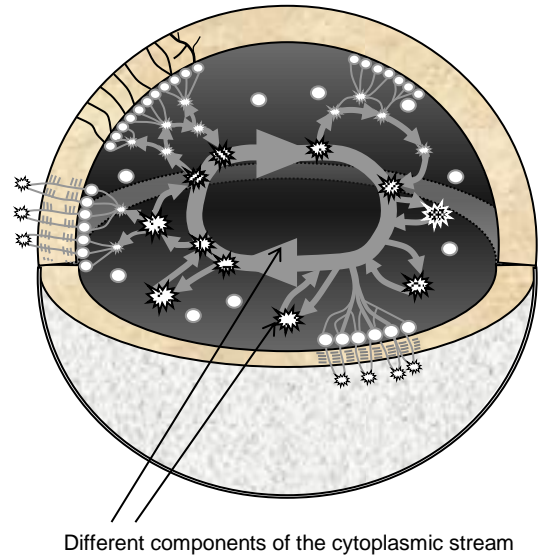


Fig. 10. Schematic representation of the cytoplasmic streaming in a cell.

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, which 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 to deliver small molecules needed for the synthesis of larger molecules. (The diffusion of large macromolecules remains prohibited because they remain stuck in the cytosol. Those can move only through the active processes.)

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

12 Prebiotic evolution and the origin of life

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

Using this description, one can form a conjecture as to how an organism emerged. In my opinion, it arose during spontaneous disentanglement of entangled, water-based, condensed matter.

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

Fig. 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 location. 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.

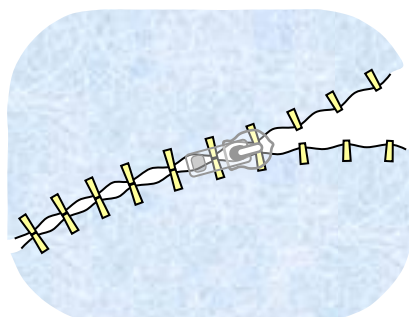


Fig. 11. Schematic representation of the cascading condensation in homogeneous water polymer loaded with suspended chemical precursors.

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 chemical condensates. The evolution of this prebiotic active matter might accelerate exponentially.

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 prebiotic condensed matter heterogeneous. Perhaps the cell simultaneously emerges on several different length scales. On the molecular scale, the active organic macromolecules become ordered, 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 scale, the active water separates into the mobile “cytoplasmic stream” and the stationary “body” of the cell.

13 The cell with rational behavior

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

The cell is surrounded with a semipermeable membrane. This barrier constricts and attenuates the streams that circulate between the cell and its environment. In order to move, the streams must breach this barrier. This process has a lot in common with the breaking of a dam by a flow of water. The stronger the flow, the faster it destroys the dam. The breach could proceed in an avalanche-like fashion. The cellular barrier resists the rupture and can quickly heal.

This semipermeable, 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 get screened off without producing any feedback.

From time to time, the cell responds to a particular external signal; it excites the external source, building a feedback loop with 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 is saturated with the needed precursors, the feedback loop withers. The restoration of the barrier becomes dominant and the extended action of the cell gets inhibited.

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

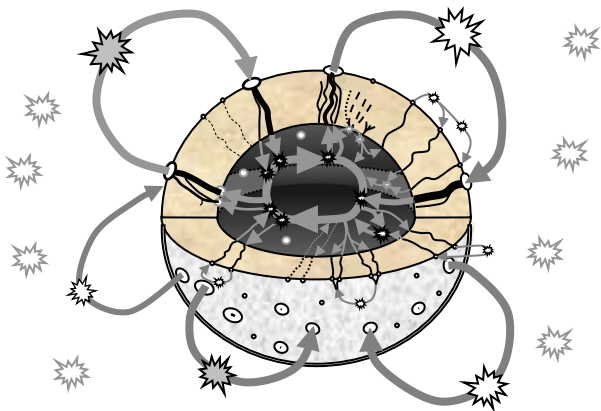


Fig. 12. The cell travels through the surrounding habitat in small prominences. The semipermeable membrane substantially reduces the flows between the cell and its environment. The flows could expand the capillaries and transform into large streams.

Remarkably, the cell behaves quite prudently. For instance, it does not react to a 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 path of 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 actions performed. The poorly healed ruptures might break more easily. The cell can thus reproduce previously executed actions, or even extend them, producing more complex actions.

14 Multicellular organism with variable behavior

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

The master cell considers other (less active) cells as 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, which are constricted by the barriers. From time to time, the master cell 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.

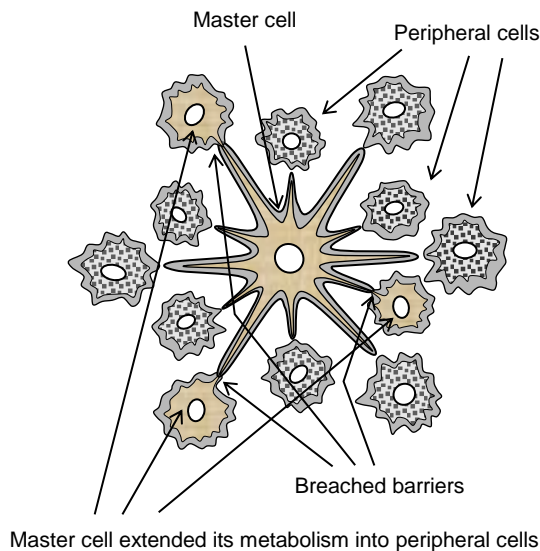


Fig. 13. The master cell and its enslaved peripheral cells. The master cell breaches barriers and connects to the peripheral cells, extending its metabolism.

The described master cell plays the role of a “brain” that consists of a single cell. Perhaps the real brain is the analogous master organ, but it contains great numbers of these master cells. The master cells—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 2 of this paper.

Conclusions

The 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 an already existing condensed body. Reproduction and growth of biological organisms correspond to fabrication and accumulation of ordered chemical condensates. I have argued that this chemical condensation might cause the emergence of biological organisms and prompt their evolution.

Using the example of the granular matter of the hourglass, I have attempted to demonstrate that the emergence and growth of the organisms could be driven by the complementary process of decondensation, which involves elimination of excessive bonds from the condensed body. In 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, these could be fabricated from scratch, using existing industrial and scientific tools. I intend to construct these and use them as “generators of

autonomous behavior” that will make decisions and solve problems like biological organisms. These topics are discussed in Part 2 of this paper, “The neural network as an active condensed matter body.”

* Email: kukuruznyak@googlemail.com

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