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THE INTERNAL AND EXTERNAL LIMITATIONS OF INTRODUCING NOVELTY IN BIOLOGY

Judging from the contents of *Wielka Encyklopedia Powszechna* (The Great Universal Encyclopedia) published by PWN, in the Polish language terms such as *twórczość* (creativity), *wynalazek* (invention) or *inwencja* (inventiveness) carry a very limited, operational meaning. The entry for *twórczość* refers only to a periodical bearing the title; *wynalazek* is only characterised as a legal concept; while *inwencja* is treated solely as a musical term. The old *Encyklopedia Powszechna* (Universal Encyclopedia) issued by Samuel Orgelbrand in 1884 proves a more comprehensive source of information in this respect. It defines *twórczość* (creativity) as the "ability to find new combinations out of materials common to everyone (notions, ideas, natural phenomena, facts or social and political relations), in order to either create new ideas and opinions or implement ideas of one's own or of others." The entry also introduces a distinction between inventive and practical creativity. Hopefully, however, despite the conciseness of the entries in modern encyclopaedic sources, the notions of creativity, inventiveness and invention do have some equivalents in the features of human beings and the society of Poland. Creativity – understood as the ability to create new ideas – may be defined in a manner similar to the one presented in the century-old encyclopaedia, with only one emendation: new combinations may arise not only out of known "materials," but also by means of adding new elements to the mixture.

The ability to create lies within the scope of interest of psychologists, sociologists and specialists in other human sciences. This human competence

is, however, rooted in biology. This branch of science has been included in the fields of study concerned with the understanding of the origins, mechanics and development of the mentioned human properties, as evidenced by the emergence of the recent advancements in ethological research on the behaviour of animals and their ability to learn, to create and employ symbols, to be inventive (Bonner 1980; Kurth, Eibl-Eibesfeldt 1975; Köhler 1925; Premack, Premack 1983; Schrier, Stollnitz 1971); the developing field of evolutionary epistemology (Vollmer 1980; Riedl 1969) searching for the eldest sources and patterns of human cognitive behaviour, which have been amassed, altered and enriched in the process of the evolution of the behavioural models of our animal relatives. This being said, the mentioned issues, fascinating though they may be, shall not be discussed in the present article, as it aims at searching for origins and sources of creativity at a deeper level, in basic biological mechanisms.

In fact, our analysis must go even deeper. New views on cosmology, postulating the constant expansion of the universe that was birthed in the "Big Bang," describe the creation of order out of chaos, the emergence of elementary particles, atoms, their combinations, galaxies, suns and planets. Prigogine's non-equilibrium thermodynamics (Glansdorf, Prigogine 1979; Nicolis, Prigogine 1977; Prigogine 1978 and 1980) breaks off with the symmetry of time. The directionality of time, stemming from the Second Law of Thermodynamics, is treated not as an indication of our imperfect cognition, or as an anomaly that may be disregarded, but as a basic principle of non-reversible processes, that are far from being at equilibrium and constitute the foundation of our universe. The course of events that occurred in the first split seconds of time starting from the Big Bang, or the question of whether the world that emerged was the only option or just one of the many possibilities, may prove irrelevant to the topic under our consideration. Equally insignificant in this context is the question of whether the Second Law of Thermodynamics applies only to the known universe or extends beyond it. We live in a world that is available to us, and even if it developed as a result of some great fluctuation and other possible worlds may exist, the emergence of life and our species was only possible as a result of those fluctuations and bifurcations in which – as demonstrated by Prigogine – the appearance of order out of chaos and the creation of organised systems and dissipative structures out of a pre-existing disorder are really achievable. Thus, in his recent book for the general reader Prigogine (Prigogine, Stengers 1984) discusses the "creative course of time," while Elasser (1982), Popper (1977) and Medawar (1974) mention the creative element in biology.

Life itself consists of creating novelty and is constantly searching for new structures and functions. The details of the history of life are still, and perhaps shall forever remain, outside the scope of our knowledge. Given the fact that history is based on accidental, unpredictable courses of events resulting from fluctuations of systems in imprecisely defined underlying conditions, its reconstruction may only be conjectural. However, as proved by Eigen (Eigen, Schustr 1979), Prigogine's theory and the knowledge of the structure and functions of living organisms may serve as the basis for a probable model of the process of biogenesis congruent with the current state of research in biology, physics and chemistry. The emergence of life may be counted among the most astonishing "inventions" of the universe. The process resulted in self-replicating structures capable of extracting matter, energy and information from their environment and transforming them into new self-replicating structures. Significantly, they also had the ability, or even a necessity (defined by the rules of probability) to make mistakes in the process of replication. As is often the case, the error became the source of innovation. The production of identical copies of structures out of pre-existing elements would be tantamount to stagnation, a consolidation of a single, already defined system. The error in replication of some of the components introduced a new element, the error in the reconstruction of a combination of elements within a system gave rise to a new structure. Naturally, the majority of errors led nowhere – the new structures proved ineffective and were consequently eliminated. In some cases, however, the mistakes were advantageous, leading to a better use of the environmental resources or enabling the system to explore a previously unavailable environment, or perhaps having little or no deteriorating effect on the efficiency of the system, but allowing it to explore the changes at some later point in the future.

The creation of novelty and inventiveness – though not appearing consciously – have been the basis for the transformation of the hypothetical proto-cells called protobionts into structures known to science (such as prokaryotes – e.g. bacteria) and as yet undiscovered (such as the proposed proto-eukaryotes). The term eukaryotes, i.e. organisms with a nucleus in their cells, applies to all known living organisms apart from bacteria.

One astonishing phenomenon that must be brought to mind is the fact that although bacteria have existed for more than three billion years (see e.g. Kunicki-Goldfinger 1976), the earliest known fossils seem to differ very little from currently observable types. In other words, prokaryotes appear to be an extremely conservative group. Conversely, eukaryotes – the earliest traces of which are found in rocks around a billion years younger than the

age of bacteria, have developed an incredible abundance of forms – from single-cell amoebas and algae to humans.

Do prokaryotes lack the ability to innovate, then? The answer is yes and no. When the development of protobionts led to a state far from equilibrium, a bifurcation occurred, opening new possibilities for evolution. The realisation of one of the possible paths led to the emergence of a prokaryote cell – at the same time closing all other possibilities.

Prokaryotes are very small structures; their size oscillates around 1/1000 of a millimetre. The small volume of their bodies causes many limitations. They do not possess a definite cell nucleus or complex chromosome structures; they cannot develop cellular skeletal structures; the mobility of cytoplasm proves redundant; contractile proteins, tubulin and calcium-related proteins do not form. In a way, their structure has become petrified – it cannot become larger or more complex. It is not possible for their pool of genetic material to expand. In the case of bacteria, the DNA helix has reached its critical length. Extending it any further would disturb the fidelity of replication and destabilise the organism. Increasing the number of helices would be impossible without an apparatus ensuring their distribution among offspring cells – and such organisms possess neither the space nor the materials to develop such an apparatus. As a result, prokaryotes are not capable of introducing structural innovation and create new forms that would differ morphologically and boast a more complex structure.

At the same time, however, prokaryotes are equipped with a large arsenal of possibilities for biochemical and physiological innovation; they are capable of creating new functional systems.

Their susceptibility to mutation is, most probably, similar to that of eukaryotes. Be that as it may, they have much potential for rebuilding their genome. The main reason for this is the sheer number of prokaryotes – each gram of earth contains hundreds of millions of them. Secondly, they multiply rapidly – many bacteria cells may divide every ten minutes or so. Thirdly, prokaryotes have developed numerous methods of transferring their genetic material: conjugation, transduction, transformation and special mechanisms of relocating a fragment of genetic material to a different part of the genome or between different genomes. These mechanisms have created favourable conditions for the emergence of a great diversity in the physiology of prokaryotes.

The first prokaryotes were almost certainly anaerobic heterotrophs feeding on the organic substances that had gathered on the Earth's surface in the process of abiogenetic synthesis of inorganic matter. It was prokaryotes

that "invented" the methods of consuming carbon dioxide and salts. One of the first attempts of this kind was most probably the mechanism "discovered" by methanogenic bacteria binding CO_2 in a specialised process using the energy produced in the anaerobic oxidisation of hydrogen combined with the reduction of carbon dioxide to methane. Another, more advanced "invention" was carbon fixation through the Calvin cycle. Initially the process was anaerobic in nature and employed the energy of the Sun – today this method is still observable in purple sulphur and non-sulphur bacteria as well as in green sulphur bacteria. Later on, a new revolutionary "invention" appeared – aerobic photosynthesis resulting in the release of oxygen. This feat was also achieved by bacteria, such as cyanobacteria (still found in today's waters) and related organisms. The "innovation" brought significant changes to the Earth's surface and the biosphere – photosynthesis is the main source of oxygen in the air. Before the development of this process, oxygen only appeared as a product of the photodissasociation of water and was scarce in the atmosphere. Cyanobacteria were the first organisms to produce it in ever increasing quantities. As the amount of oxygen in the air grew, the ozone layer began to form, shielding Earth from harmful UV light, which, in turn, enabled life to enter shallow waters and the surface of the land. It became possible to substitute the existing anaerobic models with oxygen breathing. The "invention" of aerobic respiration, which provided more than ten times as much energy per one unit of oxidised substrates, is another "contribution" made by bacteria. Finally, bacteria have "invented" methods of feeding on various organic substances – not only on ones produced by other living organisms, but also on products of their transformations and man-made chemical compounds, such as hydrocarbons, formaldehyde, phenols, detergents etc.

Internal limitations resulting from the peculiarities in prokaryotes' physical frame have prevented their structures from evolving. This set-back was compensated for by extremely varied and abundant physiological evolution.

The current available information seems to suggest that proto-eukaryotes were anaerobic organisms that were mostly predatory in nature, i.e. fed on particular matter, mainly bacteria. The energetically inefficient anaerobic respiration made further evolution difficult, if not downright impossible. Astonishingly, however, proto-eukaryotes made a new "invention" – their existence based on close cooperation with prokaryotes (Kunicki-Goldfinger 1980 and 1983). It appears that rather than search for a method of developing aerobic respiration on their own, eukaryotes adopted an existing "invention"

made by bacteria. They simply absorbed oxygen-breathing bacteria, creating a symbiotic system. The efficiently breathing bacteria provided an energy source; the eukaryotic host sheltered the bacteria within its cell and provided a steady flow of organic matter. In time, the bacteria simplified their structure and transformed into mitochondria, playing the role of the energy source in each cell. Later on, some cells also absorbed photosynthesising cyanobacteria or similar organisms – this "invention" is responsible for the emergence of green plants. Plants assimilate carbon dioxide with the help of sunlight – the process occurs in chloroplasts, intracellular structures derived from cyanobacteria or their relatives (Kunicki-Goldfinger 1980, 1983). From a structural point of view, the composition of their cells gave eukaryotes the potential for further structural evolution. The limiting factor was the lack of an efficient mechanism that would provide energy. Entering a symbiosis with prokaryotes allowed these organisms to bypass their limitations.

The entire course of further evolution consists of a series of "inventions", some of which were very small and simply perfected an existing structure. They are responsible for the abundance of forms within a single type, e.g. in insects, birds or mammals. Others were groundbreaking changes, altering entire models of organisms – these led to the emergence of new types of living creatures, such as the aforementioned insects, birds, etc. There is much evidence to support the claim that, although the former category of evolutionary "inventions" (based on small alterations within an existing structure) resulted from the mechanisms described in the synthetic theory of evolution, the latter kind (changing the entire structural plan) was brought on by bifurcations after the evolving systems had reached a state far from equilibrium, as specified by Prigogine. The bifurcations may always occur if a system strays far from equilibrium – which may, in turn, happen if for some reason it increases in size and becomes more complex as a result of significant changes in the environment etc. Prigogine analysed such processes, using simpler models such as hydrodynamic phenomena and combinations of chemical reactions. Interestingly, more than a hundred years before a similar notion was mentioned (but not characterised in detail) by the pioneer of electromagnetism, J. C. Maxwell. He writes that (1892: 443):

> In all such cases [e.g. a gunpowder explosion, which he describes
> in an earlier passage] there is one common circumstance – the
> system has a quantity of potential energy, which is capable of
> being transformed into motion, but which cannot begin to be so
> transformed till the system has reached a certain configuration,
> to attain which requires an expenditure of work, which in certain

cases may be infinitesimally small, and in general bears no definite proportion to the energy developed in consequence thereof. For example, the rock loosed by frost and balanced on a singular point of the mountain-side, the little spark which kindles the great forest, the little word that sets the world a fighting, the little scruple which prevents a man from doing his will, the little spore which blights all the potatoes, the little gemmule which makes us philosophers or idiots. Every existence above a certain rank has its singular points: the higher the rank, the more of them. At these points, influences whose physical magnitude is too small to be taken account of by a finite being, may produce results of the greatest importance. All great results produced by human endeavour depend on taking advantage of these singular states when they occur.

When a system is far from equilibrium and – to use Maxwell's terms – it has numerous singular points, minuscule stimuli may cause tremendous effects. Meteorologists use the term "butterfly effect" to describe a situation in which a small change in the initial conditions triggers a chain of events resulting in a natural disaster. Similarly, in the world of living organisms – which are, in their nature, far from equilibrium at least occasionally and locally – trivial causes may have great effects.

A system far from equilibrium reaching the stage of bifurcation may develop in several different directions. The path to be implemented is chosen at random; it is a coincidence – the infinitesimally small, incalculable stimulus described by Maxwell. Thus, the choice of bifurcation is coincidental in nature, yet after it has been made, further development of the system, if it proves possible, proceeds in a strictly deterministic manner, until the system strays from equilibrium again, provided that such an occurrence takes place.

Such choices of new biological "inventions" may pertain to global phenomena, e.g. the emergence of prokaryotic and eukaryotic cells, the development of basic mechanisms for acquiring and processing energy, etc. Yet they might also pertain to very small phenomena. For example, in the history of living organisms light-sensitive receptors have been "invented" several times. Even the particular types of photoreceptors that may be found in the human eye have been "designed" by a number of organisms. *Halobacteria* living in salty environments produce bacteriorhodopsin, which is almost identical to the light-sensitive proteins in our eyes. This genus of bacteria makes two similar types of bacteriorhodopsin and uses it in a very

different manner than mammals do. One type is involved in the mechanism of transforming sunlight into chemical energy needed to fuel the metabolism; the other is coupled with the locomotive system of the bacteria enabling it to choose the direction of its motion depending on the source and colour of the light that reaches it. Rhodopsin has also been discovered in single-cell algae called *Chlamydomas*. It is found in the so-called eye spot and is used to direct the organism towards the source of light. Finally, rhodopsin may also be found in certain brain structures of some species of birds. It reacts to the few photons that penetrate through the skull and is used to regulate the repetitive periods of the birds' life. As illustrated, the "invention" has been made several times and used to different ends. At the present state of research science can offer many examples of similar phenomena.

As stated above, the choice of bifurcation – the use of Maxwell's singular point – is random. This does not mean that these random choices are not influenced by various limitations – both internal and external. The external ones result from the laws of physics and chemistry. Consequently, all choices that would violate these laws are automatically rejected. As regards the issue under consideration, however, internal limitations seem more interesting.

Internal limitations stem from the "memory" available to living organisms. Apart from the intellectual and emotional memory, characteristic of humans and presumably also of certain species of birds and mammals, organisms possess many types of memory. First of all, they have their genetic memory, embedded in their DNA structure. This type of memory directly regulates mainly the time, intensity and location of protein synthesis. Such memory comprises genetic information, and is therefore transferred from one generation to another. As with most processes of this kind, transmission errors can and do occur – the memory becomes distorted. These types of changes are dubbed mutations. The memory is also modified to some degree when the memories of parent organisms are combined and mixed in the offspring. The distortions that occur during the transferring of genetic information are the source of genetic variability. They are also the source of novelty, as the changes resulting from distortions may be creative in character, leading to the emergence of new structures or a change in their function.

Genetic memory is extremely long-lasting; certain elements are as old as life on Earth, i.e. more than three billion years old. All living organisms share the same DNA structure, utilise the same genetic code (the differences in the code of certain mitochondria may be disregarded). The representation

of genetic information regarding the structure of certain proteins found in many organisms is nearly the same in all of them. For example, the structure of cytochrome c, a protein involved in the electron transport chain used in cellular respiration, varies very little regardless of whether it is found in bacteria or in a human being. This indicates that the genetic information on the structure of the protein must also be similar. Histones, which are proteins found in eukaryote chromosomes, are identical in nearly all eukaryotic organisms. Thus, genetic memory may be considered durable, but modifiable. Moreover, it is constantly expanded in the process of evolution. In the case of bacteria the amount of genetic information is relatively small compared to eukaryotes, especially eumetazoa.

Organisms also possess topological memory, which pertains mainly to the general model of their structure. Unfortunately, little is known about the manner of preservation and transfer of this memory or its relation to genetic memory. It certainly has some kind of connection to the skeletal structures of cells and its gradients and oscillations.

Biochemical memory, in contrast, is short-lasting. For example *Escherichia coli* bacteria are not capable of fermenting lactose until they have come in contact with this type of sugar. Only after the smallest amount of lactose particles has entered the cell of *E. coli*, does the bacterium treat it as a signal to commence the synthesis of enzymatic proteins needed for fermentation. The preliminary stage of the synthesis involves transcribing the genetic information regarding the structure of these proteins from DNA to messenger RNA, which initiates the synthesis of the proteins. The messenger RNA is produced for as long as the cell emits an appropriate signal, i.e. as long as any particles of lactose are present. When lactose disappears, synthesis of proteins ceases. The mRNA itself is not durable – its half-life lasts only for several minutes. Thus, a bacterium only "remembers" how to synthesise specific enzymes for a period of a few minutes, and is not able to initiate the process without receiving a new signal. In eukaryotic cells messenger RNA is much more durable, and therefore the biochemical memory of such organisms may be longer-lasting. The workings of such memory may be illustrated with many more examples, the one provided here merely served as a means to offer a general characterisation.

Vertebrate animals, warm-blooded ones in particular, have developed a new and intriguing model of immunological memory. In a very simplified manner, it can be described as a process of "remembering" even an isolated case of contact with any alien protein, and – consequently – also with bacteria which contain its own proteins differing from that of the organism

that identifies them. After the alien protein or bacteria has entered the organism, white blood cells start to produce a specific type of protein called antibodies, which react only to the kind of protein that triggered their synthesis. This type of memory is the basis for developing immunity to an infectious disease after contracting it once, or by means of a vaccine. Immunological memory is also the reason behind the fact that specific types of sera work against various kinds of toxins (e.g. snake venom, botulinum toxin, c. tetani endospores, etc.). Finally, it is responsible for intolerance reactions, e.g. after a transfusion of a different blood type or an organ transplant, or in various types of allergies.

Each of the possible novelties emerging after a bifurcation may only be implemented if it conforms to the limitations delineated by the different types of "memory" embedded in the changing organism. Naturally, the novelty on which the bifurcation is based may destabilise the system, pushing it further from the state of equilibrium; but it cannot destroy its structure and hamper functioning – otherwise it will perish along with the system.

Thus, all types of memory impose certain limitations on evolutionary invention and the new elements that are introduced to the system. In fact, such limitations emerge with every attempt at inventing something new. Each choice in every successive bifurcation excludes all other possibilities, which stem only from the possibility that is rejected. It also clears the path for implementing all potential possibilities incorporated in the chosen course of bifurcation. Each new invention represents the loss of certain possibilities and the gain of some other chances for change. In a manner of speaking, biological inventions are channelled, directed in a certain way by these mentioned limitations. Naturally, it is not possible to predict the choice a system will make at the point of bifurcation. Yet once the choice has been made, the possibilities of taking a given direction may be studied and determined.

Complex systems straying from equilibrium and undergoing successive bifurcations are characterised by mechanisms of communication (transfer of information) between the elements of the system and between the system and its environment. These mechanisms ensure internal coherence of the system and regulate the relations between the surroundings and the system, which must by definition be open and susceptible to the flow or energy, matter and information from the outside. Naturally, living systems also possess this property.

To illustrate this point, let us use the simplest example taken from the life cycle of the most primitive living organisms, namely bacteria. Each

bacterial cell encounters numerous stimuli in the form of a physical and chemical influence on the environment. Most of these stimuli are not received by the organism; the bacterium does not react to them unless their intensity causes a non-singular, destructive effect. Bacterial cells are equipped with many receptors, mostly chemical in nature, which allow it to identify the stimulus and determine its intensity, and in many cases also the direction from which the signal is emitted. Such receptors in the cell membrane are usually specific to a given bacterium and enable the cell to identify the nature of the stimulus and to react appropriately (e.g. by changing the direction or speed of its movement). Other receptors are used to determined the chemical structure of the objects encountered by the bacterium on its path. Certain chemical structures on the cellular membranes of an animal, a plant or another bacterium may act as a signal to stick to this surface. This is the method used by the bacteria that live inside other organisms (human or animal) to identify the structures which they can enter and live within. Rhizobia bacteria, which fix atmospheric nitrogen, employ a similar mechanism to identify the root hairs on the surface of legume plants. As a result, they infect only those plants which are capable of entering a symbiosis with them. Certain bacteria are also able to receive physical signals from the environment, e.g. detect light – as mentioned in a previous section of the present article.

The entire metabolism of a cell is dependent on the interplay of a large number of intracellular signals, chemical stimuli, which take the form of proteins or small-particle regulatory substances.

Finally, even bacteria engage in communication between specimens. One example of such processes may be observed in myxobacteria. These small organisms (measuring several thousandths of a millimetre) have an elongated shape and can move by gliding on surfaces. At a certain stage of growth, when the amount of food and the concentration of bacterial cells reaches a specific critical level, the bacteria begin to huddle together. This is because in such circumstances their cells start to synthesise and secrete a relatively simple organic substance called cyclic adenosine monophosphate (cAMP), which plays various regulatory roles in nearly all living organisms. The surface of the cell membrane of a myxobactorium contains special receptors for identifying cAMP. The presence of this substance in its environment acts as a stimulus prompting the bacteria to start their march towards the point of maximum cAMP concentration. It also stimulates them to start synthesising this substance. Thus, if at a certain stage of the population's growth a cell begins to secrete cAMP, it draws the closest cells to itself,

prompting them to synthesise greater amounts of cAMP. The signal to "come together" will therefore be transmitted by an ever-growing group of cells, becoming stronger and stronger and reaching further and further from the cell which initiated it. As a result, cells from an area as large as several square centimetres will gather in a single spot. They will then proceed to create aggregations known as fruiting bodies, which are massive enough to be easily seen by the naked eye and contain vegetative forms of the bacteria.

Thus, all living organisms seem to have the ability to send and receive signals. A signal may be characterised as a type of influence of a specific chemical or physical nature. However, the physical or chemical nature of a given influence is not enough to classify it as a signal. The decisive factor is the relation between the influence and the system that comes in contact with it. A given influence becomes a signal if the system exposed to it possesses a mechanism to identify it (usually in the form of certain types of receptors) and methods of transforming the stimulus into changes within the system. The use of influences as signals was also "invented" by living organisms. The creative ingenuity of bacteria is rather meagre in this respect – their mechanisms of receiving and transmitting signals are simple and to a large degree may be explained on the molecular level.

Bacteria are far removed from structures as complex as a human being, yet ultimately our bodies are the result of a series of successive "inventions" selected and reinforced in the process of evolution. It should therefore be remembered that the human organism has roots that hide mechanisms which developed in the course of evolution, even if they are obscured by cultural phenomena. Our actions continue to be realised within the framework of limitations imposed by all types of "memory" cumulating in our biological development. These limitations may be bypassed, yet this would require a deeper knowledge of them, which does not seem attainable without biological research.

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