On Experimenting on the Emergence of Life

—Appraisal of Demonstrative Pronoun—

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Abstract

Experimental endeavor addressing the emergence of life faces two different frameworks of space and time. While the space-time framework applicable to the experimentalist who is designing the setup is classical in accepting both space and time being homogeneous with infinite extension, the framework intrinsic to atoms and molecules moving around inside the setup is quantum-mechanical and accordingly nonlocal though limited in its extension. A descriptive access to those atoms and molecules carrying quantum non-locality with limited extension can be made with use of the corresponding demonstrative pronouns. One advantage of referring to demonstrative pronouns instead of ordinary nouns rests upon the ease with which one can avoid an unnecessary theoretical burden of sticking to the classical space-time framework with infinite extension all the time. Once the empirical fact of quantum non-locality with limited extension is duly focused upon, atoms and molecules as quanta can become cohesive between themselves if they happen to interact with each other. Quantum non-locality makes material interactions cohesive in precipitating synchronization between the mutually interacting bodies. Assimilation as a material capacity grounded upon the cohesiveness latent in the act of coming into synchronization, which is totally absent in the classical framework, can underlie the synthetic chemical reactions which may have been relevant to the emergence of life.

Key words: assimilation, catabolism, coherence, decoherence, demonstrative pronoun, heat engine, internal measurement

Introduction

Experimenting on the emergence of life in the laboratory is both highly technical and theoretical, or even philosophical. One candidate for coping with the present convoluted situation surrounding the issue may be to focus upon the descriptive scheme one has to employ in any case. When one decides to be involved in a theoretical speculation on the emergence of life as many theoreticians and philosophers have practiced so far, a common descriptive vehicle to be adopted for the objective is third-person description in the present tense. Although it seems quite powerful in exercising its

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overwhelming influence in an almost ubiquitous manner, third person description in the present tense, when applied to describing whatever material bodies in motion, succumbs to a methodological stipulation such that the descriptive author is forced to accept the framework of space and time, both homogeneous and infinite in their extension, prior to figuring out the descriptive object (Matsuno, 2003). In turn, the descriptive object comes to share the same temporality of the present tense of the descriptive origin as assuming the same nowness applied to everywhere throughout the discourse. Needless to say, the present descriptive stipulation of methodological origin comes to terms with the framework of classical science in accepting both space and time with infinite extension in the present tense. Despite that, the empirical reality revealed in the form of quantum non-locality manifests that the space-time framework available to each atom and molecule appearing in the empirical domain remains finite in its extension. Quantum non-locality incorporates into itself some aspect that third-person description in the present tense cannot accommodate, though quantum mechanics practiced in third person description in the present tense proceeds under the stipulation of synchronization completed all over the descriptive object as classical mechanics does. That is an issue of measurement approachable exclusively in second-person description (Matsuno, 1989).

Quantum non-locality grounds itself upon the empirical observation that each quantum as a nonlocal material organization maintains a coherent synchronicity only internally, that is to say, exclusively inside the organization called a quantum of finite extension. Coherent synchronicity is found in the aspect that the parameter called time specifying the time coordinate of the underlying unitary dynamics is shared everywhere inside the organization. Insofar as one appreciates the appropriateness of the unitary dynamics in quantum mechanics, each quantum comes to assume the space-time framework of its own that is necessarily limited in its extension.

Moreover, if no interaction were available to the participating quanta, there would be no likelihood of extending the space-time framework beyond the one confined within each quantum. In contrast, if interaction is available to each participating quantum as it should be, there should certainly be a possibility of extending the space-time framework beyond the one limited to within each quantum. A physical means for the objective is simply interaction between any pair of interacting quanta as an agent of making the pair come into synchronization with each other, since interaction takes for granted the synchronous coincidence of the two parties to act upon each other.

Once the material capacity of coming into synchronization by the name of interaction is legitimately focused upon, it may invoke an almost impossible task of distinguishing between synchronization in the product and the similar one in the making. Descriptive effort toward distinguishing between the two would not seem likely in the respect that once an ordinary noun to name some object is coined in third-person de-

scription in the present tense, it would claim its presence at any present moment and would defy its own metamorphosis through a possible synchronization with others of the similar nature. For instance, energy conservation with regard to a quantum as perceived from the unitary dynamics is implemented in the process of fulfilling the conservation when viewed from the perspective of the act of synchronization, since the quantum in the empirical world, that is approachable only through measurement or equivalently in second-person description, is constantly in the process of coming into interaction with its outside. What is occurring is conservation in the making, instead of the one in the product.

This observation suggests to us to pay more legitimate attention to the demonstrative pronoun referring to the activity of coming into synchronization itself, since our empirical endeavor toward addressing the emergence and evolution of life comes to face the constant takeover of older names by newer ones of the incumbent players appearing on the evolutionary stage. One advantage of focusing upon such a demonstrative pronoun in the empirical study on the emergence of life resides within the ease with which one can address the underlying material dynamics without naming all of the molecular participants appearing in the act of coming into synchronization at least for the time being. A necessary price to pay for the adoption of demonstrative pronouns for describing material dynamics of whatever sort is appraisal of second person description, which should be vindicated on material grounds. As a matter of fact, quantum mechanics provides us with a reliable framework of securing the material act of coming into synchronization even without naming each material participant appearing on the scene in an explicit manner.

We shall in the following refer to the act of coming into synchronization or its analogues as a substitute for the demonstrative pronoun pointing to the molecular participants appearing in the act of synchronization.

Overview

The emergence of life that happened to occur on our Earth could have been physical. However, there still has been a considerable gap between the empirical fact of the emergence of life and a sound understanding of the very emergence in physical terms. This observation alone may provide us with a further opportunity of scrutinizing the role of physics that has proved quite successful in the non-living material world. One decisive clue for the present issue must be the nature of cohesive properties unique to the living material world. Even a unicellular organism can maintain an extremely complex organization inside the cell. The cohesive interaction specific to the maintenance of the cellular organization is certainly more than those ascribed to mere electrostatic interactions, the latter of which in fact have been a major factor for substantiating various organizations met in the non-living material world. The

question at this point will be whether there could have been a cohesive factor being affirmative to the emergence and organization of life while it could certainly be grounded upon material and physical basis.

Our attempt in this direction will be to focus upon a certain physical scheme that may come up with such a cohesive character, though which has been overlooked for a long time. That is the issue of synchronizing clocks of material origin among themselves. The issue of clock synchronization has totally been dismissed in classical physics, irrespective of whether in non-relativistic or in relativistic regime. Classical physics is unique in declaring the presence of immaterial scheme of synchronization to the global extent like in the case of Newtonian absolute time. However, quantum physics has gradually come up with the notion of non-locality, implying the synchronous presence of nonlocal events, though only to certain limited extent spatially, thanks to the time-honored double-slit experiment and its analogues in the updated styles.

Quantum non-locality is about the empirical fact of non-local simultaneity of those events confined within a quantum or within its entangled form with others of the similar nature. Each quantum is characterized by a clock it carries in the sense that synchronization is constantly operative internally as represented in the form of the unitary dynamics parameterized in the time coordinate applicable to a nonlocal extent, though limited in its spatial scope. Then, interaction of one quantum with another one comes to suggest occurrence of an event of synchronous coincidence of the two parties at least during the ongoing interaction, since the interaction between the two has to be synchronous to both parties in each act of interaction. Otherwise, the notion of interaction would be jeopardized. Interaction between two quanta assumes synchronization of the two clocks, each of which is carried by the participating quantum. One thus observes that interaction between the two parties can be cohesive in precipitating synchronous coincidence of the acts by the two participants at least occasionally like in a collision or in yielding synchronous presence of the two as in synthesizing one quantum out of the two in the end.

In the classical world that is hypothetical at best, there is only one master-clock to which every material participant is destined to refer through the definite scheme of synchronization. Descriptive analysis of the classical object proceeds in third person description in the present tense as letting the same temporality prevail throughout the object. There is no likelihood of the physical act of cohesion upon synchronization in the classical scheme since everything has been declared to be synchronized and organized with everything else from the start. In the quantum world that is factual, on the other hand, there are only local clocks each of which is potential in establishing a form of synchronization with others in the neighborhood. Unless the stipulation of sticking to third person description in the present tense is forcibly put in place, the act of coming into synchronization could survive. Monopoly of third

person description in the present tense does not apply to quantum phenomena as revealed in the occurrence of measurement on material grounds, which is accessible only in second person description. Synchronization of local clocks serving as a cohesive factor is exclusively quantum mechanical in its origin while there is no likelihood of such cohesion in the classical scheme.

At the same time, synchronization of local clocks is semiotic in exercising the activity of relating each clock to others of the similar nature in the neighborhood. One thus recognizes a triadic relationship among the activity of synchronization, one clock to be read out, and another clock to be adjusted (Matsuno, 1999b). Among the three, the one that is approachable externally is the clock to be adjusted, or the material imprint of the underlying triadic relationship.

In fact, atoms are relics or material imprints of the Big Bang and the subsequent supernovae explosions, according to the currently accepted cosmology. From this perspective, any atoms present on any planetary systems including our Earth are atomic imprints of the earlier events of the Big-Bag cosmology. At the same time, DNA molecules retrievable from dinosaurs frozen in stones found on the surface of the Earth are also molecular imprints of the organisms going into extinction by now, while living creatures inhabiting there constantly feed upon material resources made out of atoms or atomic imprints. Moreover, if a DNA molecule retrieved from a recent fossil is put in an appropriate ribosome, it can restart the protein synthesis already programmed on the DNA sequence. This observation then raises a serious question of how one could distinguish molecular imprints between living and non-living.

Molecular imprints are quite relative in their implications and context-dependent with regard to how they are related to living things. The present vague aspect surrounding molecular imprints is, however, not necessarily disadvantageous in clarifying the issue of how living things could emerge in the cosmological context. Rather, molecular imprints will turn out advantageous as an analytical tool in introducing those material units that may have the capacity of searching for the material contexts to be fitted in on their own (de Duve, 2005). This will be a theme to be explored in the present article. One question unique to molecular imprints is whether they are a record of something to be read out by the human external observer or a memory of something to be deciphered by a material body internal to whatever material organization. For this objective, we shall first examine the material basis upholding the occurrence of molecular imprints. That is quantum mechanics.

Quantum Mechanical Underpinning

Formation and transformation of molecular imprints or molecules in short are in the process of chemical reactions to be deciphered in quantum mechanical terms. Consider, for instance, a formation of two water molecules from two hydrogen molecules

and one oxygen molecule. The reactions get started when the three molecules come to conjoin altogether in a coherently orchestrated fashion or in a synchronized manner as carrying a certain amount of energy, not too much and at the same time not too less. Coherent orchestration of the reacting molecules, which occurs in the assimilation of each reactant into the coherent body, is prerequisite to the succeeding reactions. Then, the reaction products come out of the coherently orchestrated body as precipitating two water molecules, each of which can move around almost freely with the other in a decoherent fashion. The chemical reactions then follow the sequence from coherent assimilation of each reactant into the orchestrated reacting body, to decoherent dissociation of the reaction products.

Needless to say, both coherent assimilation and decoherent dissociation are quantum mechanical in their origin. Nonetheless, both of them are not specified in the quantum mechanical laws of motion as demonstrated in the Schrödinger equation of the wavefunction or its equivalent in the Hamilton dynamics in the Hilbert space. The standard unitary dynamics for quantum mechanics takes the occurrence of global coherence for granted from the start. The process of coming into coherence cannot suitably be addressed in the scheme that assumes total coherence from the very beginning. Likewise, the process of decoherence remains outside of the unitary dynamics that preserves the coherence once specified. This observation urges us to look for the quantum mechanical basis of both coherent assimilation and decoherent dissociation in other than the quantum mechanical laws of motion themselves. That is an issue of measurement.

One unique aspect of measurement in quantum mechanics is seen in the appraisal of decoherence (Everett, 1957). The measurement apparatus of whatever sort can single out and detect a certain property of the measured body while the preservation of the pre-established coherent orchestration of the body turns out vulnerable in the process of measurement. Anthropocentric measurement exclusively emphasizes the decoherence aspect of the measured object. Despite that, measurement is more than what decoherence is all about. If the process of measurement internal to material bodies of whatever sort is duly focused upon (Matsuno, 1985), it can also appreciate the occurrence of coherent assimilation as squarely facing the physical process of coming into coherence in real time. Measurement known as internal measurement can address both coherent assimilation and decoherent dissociation, which are necessary for deciphering the occurrence of molecular imprints.

Molecular Imprints; Record or Memory?

Molecular imprints as a remnant of an organism of remote past age preserved in the Earth's crust is a record to be read out by the paleontologist. Such a record is anthropocentric in that only the paleontologist is competent enough and responsible

for providing the reading frame required for the deciphering. In contrast, molecular imprints as part of a living organism carry the memory to be read out by the very organism, as being part of the whole from within. Memory takes participation of the reading frame of material origin for granted. It assumes intervention of a certain material processor for deciphering what is stored in the form of memory. The processor is by no means a monopoly of the human external observer. In short, the memory stored in the computer hard disk is specific only to the central processing unit, that is, CPU, and not to the computer scientist.

A carbon atom in the molecule of carbon dioxide in the air can be identified and recorded as such by the physicist. There is nothing inconvenient in the present physical recording of atoms and molecules. However, molecule registered as a record differs from molecule functioning as a memory. Molecule as a memory is a material token passed over from past events and processed at the present moment by the material body that can read it as such. Carbon dioxide in the air is a material token to be taken in by a photosynthetic plant having the capacity of assimilating it to the own body. Anabolism on the part of photosynthetic plant assumes the memory such that carbon dioxide in the ambient can be the material resource to feed upon. In parallel, carbon dioxide in the air is a molecular imprint having the memory, or equivalently the capacity, that it can be assimilated into photosynthetic plants.

Assimilation of small molecules into the larger material organization such as an organism is unquestionably a material process upon the synchronization among the participants, which is unfailingly quantum mechanical in its functional origin. Assimilation or anabolism met in biology is intrinsically cohesive as grounding itself upon the physical notion of interaction in inducing the coming into synchronization between any pair of interacting material bodies. However, it has not been well worked out in the traditional scheme of physics. A main difficulty with it resides within the methodological stipulation unique to the latter. To be sure, physics is competent in coping with a wide variety of material processes in terms of the notions that are memory-free. The wavefunction is a typical example of demonstrating how effective the memory-free state attributes could be in the endeavor of describing what the molecule is all about. The state attributes such as the phase-space coordinates of the wavefunction can easily be frozen and registered in the record by the physicist. Memory attributes, if any, are thus necessarily marginalized by the stipulation that the state attributes should underlie the deciphering of them. On the other hand, once such a strict stipulation dismissing the memory attributes is lifted, a new perspective may be in sight. One clue toward this directive comes from the practicing of biochemistry.

Biochemical processes demonstrate how versatile and ubiquitous the process of material assimilation or anabolism could be as a marker of synchronization in the material realm. Underlying the process of assimilation are molecular enzymes that are

quite substrate-specific and unidirectional in regulating the involved chemical reactions. In fact, the origin of molecular assimilation met in the practice of biochemistry could be taken almost equivalent to the origin of living things. This association of the origin of molecular enzymes with the origin of living things however does not help us to perceive how molecular enzymes could have come into being. Replacing molecular enzymes simply by living things does not clarify the issue. A more pressing agenda is whether memory-specific molecular assimilation could get started even in the absence of molecular enzymes that biochemistry is at home with. Only when the process of molecular assimilation can be demonstrated to take place without the help of molecular enzymes of biological origin, one may be able to conceive of how molecular enzymes or living things could emerge on the material basis. One suggestive clue in this regard is the occurrence of internal measurement taking care of coherent assimilation legitimately founded on the physical basis without importing the biochemical heritage already established elsewhere. This should be an issue to be settled empirically or experimentally, rather than either deductively or hypothetically. Empirical reality of the act of coming into synchronization, if legitimate, would have to be justified exclusively upon empirical observations, rather than through theoretical articulations or deductions. From now on, we shall be concerned mainly with empirical facts. Earlier review of the facts will appear in Matsuno (2008), some of which is reproduced in the following.

Molecular Assimilation without Enzymes

A most simple and straightforward example of molecular assimilation is an indefinite growth of the population of the molecules of like kind as feeding upon whatever molecular resources, though necessarily limited in both spatial and temporal extensions. What is proceeding there is to assimilate the available molecular resources into the molecules of like kind. An exponential growth of the population of the molecules of like kind is a typical example. In fact, if an autocatalytic molecule is available, an exponential growth of the population of such molecules could be likely if the conditions are of a right kind. Rather, what should be sought here is a sort of conditions enabling an exponential growth of the population of a certain chemical species without importing an autocatalytic molecule already synthesized in an explicitly completed form elsewhere (Wächtershäuser, 2006). One candidate for fulfilling this requirement must be the conditions similar to the ones supporting the likelihood of hydrothermal circulation of seawater on the floor of the ocean of the Earth.

Chemical reactions occurring in the reaction solution while visiting both hot and cold regions repeatedly in a cyclic manner are peculiar in that the reaction products are constantly converted into the reactants with the aid of the physical means of making the circulation of the reaction solution between the hot and the cold possi-

ble. The products synthesized in the preceding cycle can be made the reactants in the succeeding cycle. In particular, the reactants can gain thermal energy driving various synthetic reactions while visiting hot regions. In this setting, once a reaction product in the current cycle happens to be similar to the reactant in a previous cycle, the over-all reaction will turn out network-catalytic in assisting the synthesis of the product of like kind through the reaction cycle. Hydrothermal circulation of the reaction solution serves as a physical means for the realization of such a reaction cycle. An exponential growth of the population of the reaction product, at least initially, will be a straightforward consequence. This consequence can be established even in the absence of a self-sufficient autocatalytic molecule to start with if the conditions of a right kind are available. For instance, elongation of oligomers in a hot region and hydrolysis of those oligomeric products in the cold environment, when combined together through repeated circulations, can induce an exponential growth of the population of the oligomers if their residence time in the hot region is so limited as to prevent their thermal decompositions. Network-catalytic reactions conditioned by the repeated cycles of heating and quenching come to sustain an exponential growth of the reaction product as a form of molecular assimilation.

Significant to the occurrence of an exponential growth of the reaction product is the material capacity of sensing, searching for and cultivating the necessary resources available in the environments in an exhaustive manner. In fact, the exponential growth of the reaction product is a demonstration of molecular assimilation to an extremely enhanced extent in the sense that the rate of assimilation per unit time is in proportion to the amount of those molecules already assimilated. Since the available resources are not unlimited, exponential assimilation is context-dependent in that the resources available in the accessible environments are exhaustively explored in due course of time. Molecules participating in the exponential assimilation can thus carry with themselves the memory of the accessible environments.

What remains to be seen here is how to ascertain on an experimental basis the present likelihood of molecular assimilation whose growth is exponential in time at least over a limited time interval, even in the absence of molecular enzymes. We then constructed a flow reactor simulating hydrothermal circulation of seawater through hot vents in the ocean (Matsuno, 1997).

Molecular Imprint of Hydrothermal Circulation

When the aqueous solution including only glycine, the simplest amino acid molecule of all, was run in the flow reactor circulating the fluid across the temperature gradients between 230°C and 0°C repeatedly with the cycle time of roughly 1 minute, we observed an exponential growth of diglycine and triglycine over a limited time interval at least initially (Imai et al., 1999). The exponential assimilation

or synthesis of both oligomers can unquestionably serve as the molecular imprints of the flow reactor we attempted. The upper limit of the exponential assimilation that could eventually be reached in due course of time is unique exclusively to the experimental setup we prepared, that is to say, the environment accessible to the chemical reactions proceeding there. The exponential assimilation would eventually turn the growing molecules into the molecular imprints of the environments to be exploited for the sake of their exponential growth.

What is more, the shakeup of the molecular imprints of exponential assimilation would also become inevitable, that is definitely history-dependent. In the case of the reaction solution starting with only glycine monomers, for instance, we observed the takeover of the exponential assimilation by tetraglycine after the preceding synthesis of diglycine and triglycine had been saturated. The emergence of tetraglycine is history-dependent in the sense that it emerged only after the synthesis of diglycine and triglycine had been saturated and by no means vice versa. The process of exponential assimilation is intrinsically evolutionary and irreversible in its operation. When a certain chemical species gets involved in an exponential explosion of its population, the species that actually grows exponentially is the one having the largest growth rate among the contenders. All of the other alternatives are wiped out in the process. However, the exponential growth of that species cannot survive indefinitely. Once the growth reaches a saturation level for whatever reasons, this level can now prepare a refreshed stage for a new species to start up an alternative exponential growth. The exponential growth of tetraglycine actually started after the growth of both diglycine and triglycine had been saturated.

In a similar vein, when we attempted the reaction solution comprising both glycine and alanine initially, the dimer that first appeared was glycylalanine, and then followed by the emergence of alanylglycine (Ogata et al., 2000). Once alanylglycine appeared in the reaction solution, the exponential assimilation into alanylglycine got started as dissecting the pre-existing glycylalanine in which alanylglycine effectively functioned as a molecular enzyme decomposing glycylalanine once synthesized. The sequence of the takeover of exponential assimilation was from glycylalanine to alanylglycine, but not vice versa, with no exceptions. When the synthesis of glycylalanine reaches its saturation level, the succeeding fate of glycylalanine could be at least two-fold. One is to utilize the dimer of glycylalanine as a unit for further exponential synthesis with other monomers and oligomers, and one more alternative is to dissect the dimer into monomeric units as the resources for an alternative exponential synthesis of de novo oligomers. Our experimental observation of the synthesis of alanylglycine actually revealed the case that the appearance of a molecular enzyme carrying a protease-like capacity sets a refreshed condition for starting up the takeover by a de novo exponential assimilation. As a matter of fact, a set of emerging molecular enzymes like alanylglycine can be stabilized in the reaction system once

they become an indispensable member of the currently prevailing exponential assimilation. Alanylglycine as a molecular enzyme can certainly function as a molecular imprint memorizing how the vicissitudes of exponential assimilation could have been in place so far.

The demonstration of how exponential assimilation gets started and alternated in the flow reactor simulating hydrothermal circulation of seawater through hot vents rests upon the interplay between endergonic and exergonic reactions. Peptide synthesis is endergonic, while the cooling of the reactants transferred from the hot vents is exergonic. The endergonic products, once quenched rapidly in the cold environments, can be stabilized there without suffering further exergonic decompositions. Rapid quenching tends to accomplish the exergonic decomposition of the endergonic products only incompletely as leaving behind those endergonic derivatives that may still maintain the endergonic remnants of chemical synthesis internally.

What is peculiar to the synthesis of endergonic derivatives in the hydrothermal circulation is the incremental increase of the amount of energy supplied to the ongoing endergonic reactions every time the reactants visit the hot regions or their neighborhood. The energy accumulated in the endergonic derivatives can increase as the frequency of visiting the hot regions increases. For instance, endergonic synthesis of tetraglycine from glycine monomers can be made possible only after the reaction solution including glycine visits the hot regions repeatedly. Synthesis of tetraglycine from monomeric glycine cannot be accomplished instantaneously during a very short visit to the hot region only once. To the contrary, tetraglycine can be formed only after following the intervening prior stages of synthesizing diglycine and triglycine as endergonic derivatives that could remain meta-stable at least temporarily during the repeated cycles of heating and cooling.

Hydrothermal circulation round the hot and the cold provides a physical means for exploring the energy required for completing endergonic reactions step by step incrementally as repeating the cycle. In this regard, one more serious test for examining the plausibility of step-by-step accumulation of the energy required for endergonic reactions may come from the experimental likelihood of implementing the prebiotic citric acid cycle in the absence of molecular enzymes.

Endergonic Derivatives and the Citric Acid Cycle

The citric acid cycle constitutes the inner-most core of the whole network of metabolic pathways found in any biological organisms. The prebiotic significance of the likely occurrence of the citric acid cycle may be found in the evolutionary emergence of the cycle in the absence of molecular enzymes of biological origin (Morowitz et al., 2000).

Every step of chemical reactions round the citric acid cycle is either endergonic

or exergonic (Smith and Morowitz, 2004). The highest energy barrier for running the oxidative citric acid cycle resides in the endergonic reaction pathway from L-malate to oxaloacetate requiring the energy as much as 29.7 kJ/mol. Although the second steepest energy barrier is found in the endergonic pathway from citrate to isocitrate, the energy required for crossing over the barrier is about 13.3 kJ/mol that is less than half of the energy required for the pathway from L-malate to oxaloacetate. The contemporary citric acid cycle drives both the endergonic and exergonic reactions along the cycle with the aid of biological enzymes and coenzymes in the normal thermal ambient. However, such enzymes and coenzymes could not have been available in the prebiotic setting. If the evolutionary emergence of the citric acid cycle is a matter of concern, an evolutionary scheme implementing the cycle in the absence of biological enzymes would have to be worked out. At this point enters the evolutionary opportunity such that hydrothermal circulation of the reaction solution going through the hot and the cold repeatedly in a cyclic manner may play a positive role, especially in preparing endergonic derivatives as a means of accumulating the energy required for the endergonic reactions step by step incrementally.

We then attempted to run the flow reactor for the reaction solution comprising all of the eight major kinds of carboxylic acid molecules constituting the citric acid cycle, that is, oxaloacetate, citrate, isocitrate, alpha-ketoglutarate, succinate, fumarate, L-malate, and pyruvate serving as both the energy and carbon sources to the cycle (Matsuno and Nemoto, 2005). The temperature gradient traversing the hot and the cold in the flow reactor was implemented over the crossover region between 120°C and 0°C, in which the reaction products made at 120°C were rapidly transferred and quenched at 0°C in a cyclic manner. The observation we made revealed an increase, though slight, of the concentration of oxaloacetate in time going along with the flow-reactor operation, indicating that the endergonic reaction transforming L-malate into oxaloacetate was certainly operative (Matsuno, 2006).

Rapid quenching of the reaction products from 120°C to 0°C in a repeatedly circulating manner can provide the energy as much as 29.7 kJ/mol required for the endergonic reactions. This observation is consistent with the synthesis of phosphodiester bonds for making the 3'-5' linked oligonucleotides out of monomeric nucleotide molecule of AMP requiring the energy about 22 kJ/mol, through hydrothermal circulation between 110°C and 0°C (Ogasawara et al., 2000). Likewise, we also observed the synthesis of pyrophosphate bonds requiring about 29 kJ/mol in the reaction of making ADP and ATP from AMP and trimetaphosphate serving as the phosphate source, in the flow reactor circulating the reaction solution between 100°C and 0°C (Ozawa et al., 2004). Needless to say, the peptide synthesis requiring about 11 kJ/mol per bond was made possible in the flow reactor simulating hydrothermal circulation of seawater through the hot vents (Imai et al., 1999).

When these observations are integrated together, we come to recognize that it

may be possible to have the products from endergonic reactions requiring the energy of order of 30 kJ/mol even by means of hydrothermal circulation alone. However, the resulting reaction products as the molecular imprints of the underlying hydrothermal environments are not robust enough evolutionarily. Once those molecular imprints happen to be removed to the other places far away from their birthplace near the hydrothermal vents on the ocean floor, they would soon lose most of the capacity of energy transductions imputed to the presence of hydrothermal environments. No energy input for supporting the molecular imprints could be conceivable once they are detached from the birthplace. In this regard, the oxidative citric acid cycle might have played a significant role.

The reaction from isocitrate to alpha-ketoglutarate along the circular reaction pathway of the cycle is exergonic as releasing the energy as much as 20.9 kJ/mol, though the reaction pathway from L-malate to oxaloacetate is endergonic. In addition, the succeeding reaction from alpha-ketoglutarate to succinate is also exergonic as releasing 36.4 kJ/mol. More specifically, on conditions that the supply of pyruvate serving as both the energy and carbon sources is guaranteed by whatever means, one turn of the reaction pathways round the oxidative citric acid cycle is effectively exergonic as releasing the net energy of 49 kJ/mol. This energy transduction may suggest a likely evolutionary scenario such that once the citric acid cycle is put in place, the cycle could serve as the primary candidate for the energy supplier if pyruvate is already available. The role of hydrothermal circulation toward the operation of the citric acid cycle would have to be at most catalytic and not energetic, as making the energy input to the cycle from the hydrothermal system superfluous. Then, an issue may arise with regard to whether there could have been available any further evolutionary opportunity to the possible takeover of catalytic capability by other than the operation of hydrothermal circulation.

Carbon Flow, Anabolic and Catabolic

Evolutionary likelihood of starting up the citric acid cycle in the absence of molecular enzymes of biological origin could have been substantiated if pyruvate may become available by whatever means. The prebiotic synthesis of pyruvate could in fact be likely in the vicinity of hydrothermal vents (Cody et al., 2000; McCollom et al., 1999). The prebiotic citric acid cycle conceivable in the hydrothermal environments can be characterized by two kinds of carbon flow. One is the intake of carbon into the cycle that is anabolic, and another is the takeout of carbon from the cycle that is catabolic. Between these two flows, catabolic carbon atoms in the form of carbon dioxide are statistically independent with each other if the originating carbon dioxide molecules are different. The outgoing catabolic carbon flow measures the extent to which carbon atoms already assimilated into the anabolism may remain and survive

in the inside. One figure of merit in this regard is the catabolic rate of carbon per carbon atom, residing in the reaction cycle of circulating carbon flows as in the case of the citric acid cycle. The catabolic rate of carbon gives a quantitative estimate of how many times one carbon atom in the assimilated body can be alternated per unit time by new ones entering in the form of anabolic flow from the outside. Equivalently, the catabolic rate of carbon also measures the turnover rate of carbon as counting how many times one carbon atom in the assimilated body can be replaced by new ones entering from the outside.

One significant aspect of the turnover rate of carbon as focusing upon the catabolic carbon flows, in which each carbon dioxide molecule behaves almost independently with others statistically, is found in the observation that the anabolism proceeds toward minimizing the turnover rate (Matsuno, 1978). The underlying reasons are quite simple and straightforward in that the most prevailing material elements residing in the anabolic assimilation are the ones that can minimize the turnover rate, because of the statistical independence of the outgoing carbon atoms among themselves. Those material elements with the greater turnover rate cannot compete with the ones with the smaller turnover rate in the material assimilation and in the resulting accumulation.

Once anabolism gets started, a new evolutionary directive may be in sight in the form of minimizing the turnover rate of carbon exclusively on the material ground. At the same time, there might also happen to raise a new impasse if the turnover rate actually vanishes in the limit of its minimization. No turnover would come to imply no anabolism and accordingly no chances for biological organizations. One alternative for preventing the turnover rate from actually vanishing is the presence of temperature gradients supporting the occurrence of both anabolic and catabolic activities, since it is the very occurrence of temperature gradients which could make possible the process of material assimilation in the first place, as met in the hydrothermal environments. Unless the physical approach to the heat reservoir at the lower temperatures is blocked off, material assimilation could be likely. The pressing issue in this regard must be what sort of low-temperature heat reservoirs could be available and accessible to the process of material assimilation proceeding within the thin crust of the surface of the Earth. This perspective begs the question on the nature and classification of the low-temperature heat reservoirs accessible to the surface of the Earth.

Insofar as only the thin atmosphere surrounding the surface of the Earth is focused upon, gas molecules in the air are almost in thermal equilibrium with each other at the normal ambient temperature. If the organization of material assimilation is in thermal equilibrium with the surrounding atmosphere, the photons going back and forth through the interface between the two would eventually come to be balanced in the form of radiation field in thermal equilibrium. There is no net emission or

absorption of photons by the organization. This absence of net photon flow through the interface, however, meets severe counterfactual evidence.

ATP hydrolysis as a basic material means of biological energy transduction driving respiration and motor activity among many others is under the condition that the energy, once released, has to be dissipated with no chances of being struck back and counteraction, as differing from the case of radiations in thermal equilibrium. Both ATP synthesis and hydrolysis are constantly running down the energy landscape in an irreversibly unidirectional manner. Although the atomic substrates of ATP molecules including hydrogen, carbon, oxygen and phosphor are usable repeatedly countless times, the flow of energy is totally different. That is strictly unidirectional from the source to the sink with no exception. The real question with ATP hydrolysis is where it could find and make an access to the sink at low temperatures that can absorb the used and dissipated energy. If the dissipation were to take place in the form of infrared photons being in thermal equilibrium with the radiation field of the ambient atmosphere, there would be no chances of being totally absorbed by the ambient, since the counteraction from the ambient would also have to be counted equally. The energy of the photons carrying the dissipated energy must be much less than that of infrared photons.

One clue for figuring out where the sink for ATP hydrolysis could be located is to estimate the energy of photons being emitted from the hydrolysis. ATP hydrolysis proceeding in actomyosin complexes as a functional unit of muscle contraction releases energy as much as 29 kJ (7 kcal)/mol over the time interval of order of 10 milli-seconds. If the energy release takes place continuously over the interval, the average photon energy can be of order of 10^{-19} erg, that is equivalent to the radiation energy at temperature roughly 1 milli-Kelvin. In other words, ATP hydrolysis would come to search for the sink that can absorb the microwave photons whose frequency is of order of 10^8 Hz, otherwise proper functioning of ATP hydrolysis would be jeopardized because of the difficulty in finding the appropriate sink (Matsuno, 1999a). At this point enters the cosmological constraint. In fact, thanks to the ever-lasting cosmic expansion, outer deep space looks transparent to the microwave photons of frequency around 10^8 Hz though it remains opaque to far infrared photons constituting the cosmic microwave background specified by temperature at 2.725 K or frequency around 10^{11} Hz (Matsuno, 2006).

Carbon assimilation or anabolism characterized by the minimization of its turnover rate is constantly under the cosmological constraint guaranteeing the presence of the sinks for dissipated photons. The empirical peculiarity of cosmic expansion leaves outer space transparent even to a tiny amount of photons if the emitted photons are the microwave photons in a limited frequency range, say, around 10^8 Hz. This microwave transparency originating in the cosmic expansion does not, however, apply to the photons constituting the cosmic microwave background in the frequency

range centered around 10^{11} Hz. The microwave receiver, wherever located in the cosmological context, can certainly detect noise signals imputed to the cosmic microwave background. Receiving such noise signals is equivalent to being susceptible to radiations from the heat reservoir maintained at 2.725 K. Henceforth, there should be no likelihood for dissipating energy exclusively in an irreversible and unidirectional manner in the form of the photons whose frequencies happen to coincide with those constituting the cosmic microwave background.

The cosmic microwave transparency open to the frequencies far below 10^{11} Hz, on the other hand, provides one decisive condition on how the process of carbon assimilation into the supporting reaction cycles could have emerged and evolved since then on the planet Earth. If only those molecules present in the thin crust of the atmosphere surrounding the surface of the Earth are focused upon, they can participate in the thermal motion specified by the ambient temperature. It would then be inconceivable to expect the occurrence of biological organizations only from the motion of the molecules in thermal equilibrium with their immediate environments. Inorganic materials such as stones and rocks on the surface of the Earth can be in thermal equilibrium with the ambient locally either spatially or temporarily, or both unless the ambient conditions are disturbed significantly. To the contrary, however, biological organisms and their precursors constantly defy the asymptotic approach to thermal equilibrium with their immediate ambient in contact because of its intrinsic capacity of exploring the sinks for the dissipated energy on the cosmological scale. One decisive practical means for exploring the sinks on the cosmological scale here on the planet Earth could have been to utilize ATP hydrolysis as a source of energy driving a wide variety of biological functions and to dispose of the consequential waste with the use of the cosmic microwave transparency.

In short, participation of ATP molecules in biological organizations requires at least two different classes of low-temperature heat reservoir. One is the normal thermal environment on the surface of the Earth serving as a low-temperature heat reservoir toward the sun light or the geothermal heat driving the ATP synthesis. One more class of low-temperature reservoir is for absorbing the necessarily dissipated energy precipitated from ATP hydrolysis delivering the energy for driving various biological functions. The thermal environment toward ATP synthesis in general or the temperature gradient applied to it in particular must be different from that toward ATP hydrolysis; otherwise the operation of both ATP synthesis and hydrolysis may be disturbed on the basis of thermodynamics in the presence of temperature gradients. An ATP molecule as an end product of synthesis cannot be the end product of its decomposition through hydrolysis at the same time as sharing and experiencing the same temperature gradient. Nonetheless, ATP hydrolysis takes the normal thermal environment on the surface of the Earth to be one end of the source for generating

and maintaining the necessary temperature gradient. The cosmic microwave transparency serves as a physical means for substantiating the necessary low-temperature reservoir required for the proper operation of ATP hydrolysis without interfering with ATP synthesis on the planet Earth.

Concluding Remarks

As much as atoms are the material imprints of both the startup of the current Big-Bang cosmology and the succeeding supernovae explosions, bio-molecules can be the molecular imprints of the ever-lasting cosmic expansion. This perspective invites us to figure out the role of quantum mechanics, which furnishes whatever material organization, either non-biological or biological, with its stability, under a new light (Davies, 2004). The stability of an atom can be fathomed quantum mechanically even without referring directly to the details of its emergence through the historical development on the cosmological scale. In a similar vein, the stability of bio-molecules in general and molecular enzymes in particular should also be sought in quantum mechanics, though in a bit different manner compared to the case of atoms and non-biological molecules. The difference resides in the fact that bio-molecules could be substantiated only through constantly disposing of the dissipated energy with use of the cosmic microwave transparency. The underlying functional unit is a heat engine processing both energy intake and takeout in a continuous fashion, in which the cosmic microwave transparency takes care of the takeout of the used energy.

The likelihood of the occurrence of a heat engine in quantum mechanics now suggests at least two possibilities. One possibility is that the heat engine is merely a secondary derivative, fabricated from the quantum already established in the non-biological realm, and one more alternative is that the heat engine belongs to a new class of quantum that has not yet been worked out in the realm of traditional physics. Between these two alternatives, the one which could be likely is the instance of quantum as a heat engine. A principal reason behind is that the occasion of taking advantage of the cosmic microwave transparency is fundamentally irreducible on the cosmological scale and there should be no chance of expecting to derive it from something else that may remain more fundamental in the current cosmology.

Quantum as a heat engine just happens to be irreducible as much as the cosmic microwave transparency is. This shared and common irreducibility makes bio-molecules taken as the molecular imprints of the ever-lasting cosmic expansion also to be the molecular imprints of the supporting heat engine. In addition, the molecular imprints carry with themselves the memory to be read out by the built-in operating system, that is nothing other than the processor identified with a quantum as a heat engine.

The material unit or imprint employed for referring to a quantum can be either

a record or a memory of the vast historical events experienced by it. At this point, physics has been quite competent in deciphering the quantum as the material record of past events. In contrast, biology is striving toward focusing upon the functional processor for letting the molecular imprints be read out as a memory of the past events. Quantum as a heat engine thus provides one pathway through which one may naturally reach biology while being anchored at the stronghold of physics at the same time. Biology is astronomical even from its very start in taking advantage of the cosmic microwave transparency. Bio-molecules are the molecular imprints of the quantum as a heat engine whose heat reservoir positioned at the lower temperature side happens to be the ever-expanding universe itself.

In short, the genetic code can be the molecular imprints of the functional organization for synchronizing local clocks of quantum mechanical origin. Interaction conceived within the framework of quantum mechanics practiced exclusively in second person description as shedding legitimate light on demonstrative pronouns is cohesive enough in helping form synchronization between interacting physical bodies of whatever sort. At the least, focusing upon the act of coming into synchronization as a demonstrative pronoun could be effective in designing further experiments on the emergence of life in the laboratory.

References

- [1] Cody, G.D., Boctor, N.Z., Filley, T.R., Hazen, R.M., Scott, J.H. and Yonder, S.H., Jr. (2000) Primordial carbonylated iron-sulfur compounds and the synthesis of pyruvate, *Science* **289**, 1337–1340.
- [2] Davies, P.C.W. (2004) Does quantum mechanics play a non-trivial role in life? *BioSystems* **78**, 69–79.
- [3] de Duve, C. (2005) *Singularities: Landmarks on the Pathways of Life*. Cambridge University Press, New York.
- [4] Everett, H. (1957) Relative state interpretation of quantum mechanics. *Rev. Mod. Phys.* **29**, 454–462.
- [5] Imai, E., Honda, H., Hatori, K., Brack, A., Matsuno, K. (1999) Elongation of oligopeptides in a simulated submarine hydrothermal system. *Science* **283**, 831–833.
- [6] Matsuno, K. (1978) Evolution of dissipative system: a theoretical basis of Margalef's principle on ecosystem. *J. Theor. Biol.* **70**, 23–31.
- [7] Matsuno, K. (1985) How can quantum mechanics of material evolution be possible?: symmetry and symmetry-breaking in protobiological evolution. *BioSystems* **17**, 179–192.
- [8] Matsuno, K. (1989) *Protobiology: Physical Basis of Biology*. CRC Press, Boca Raton, FL.
- [9] Matsuno, K. (1997) A design principle of a flow reactor simulating prebiotic evolution.

Viva Origino **25**, 191–204.

- [10] Matsuno, K. (1999a) Cell motility as an entangled quantum coherence. *BioSystems* **51**, 15–19.
- [11] Matsuno, K. (1999b) The clock and its triadic relationship. *Semiotica* **127**, 433–452.
- [12] Matsuno, K., (2003) Quantum mechanics in first, second and third person descriptions. *BioSystems* **68**, 107–118.
- [13] Matsuno, K. (2006) Forming and maintaining a heat engine for quantum biology. *BioSystems* **85**, 23–29.
- [14] Matsuno, K. (2008) Molecular semiotics toward the emergence of life. *Biosemitotics* **1**, in press.
- [15] Matsuno, K., Nemoto, A. (2005) Quantum as a heat engine: the physics of intensities unique to the origin of life. *Phys. Rev. Life* **2**, 227–250.
- [16] McCollom, T.M., Ritter, G. and B.R. Simoneit, B.R. (1999) Lipid synthesis under hydrothermal conditions by Fischer-Tropsch-type reactions. *Origins Life Evol. Biospheres* **29**, 153–66.
- [17] Morowitz, H.J., Kostelnik, J.D., Yang, J. and Cody, G.D. (2000) The origin of intermediary metabolism. *Proc. Nat'l Acad. Sci. USA* **97**, 7704–7708.
- [18] Ogasawara, H., Yoshida, A., Imai, E., Honda, H., Hatori, K., Matsuno, K. (2000) Synthesizing oligomers from monomeric nucleotides in simulated hydrothermal environments. *Origins Life Evol. Biospheres* **30**, 519–526.
- [19] Ogata, Y., Imai, E., Honda, H., Hatori, K., Matsuno, K. (2000) Hydrothermal circulation of seawater through hot vents and contribution of interface chemistry to prebiotic synthesis. *Origins Life Evol. Biospheres* **30**, 527–537.
- [20] Ozawa, K., Nemoto, Imai, E., Honda, H., Hatori, K., Matsuno, K. (2004) Phosphorylation of nucleotide molecules in hydrothermal environments. *Origins Life Evol. Biospheres* **34**, 465–471.
- [21] Smith, E., Morowitz, H.J. (2004) Universality in intermediary metabolism. *Proc. Nat'l Acad. Sci. USA* **101**, 13168–13173.
- [22] Wächtershäuser, G. (2006) From volcanic origins of chemoautotrophic life to bacteria, archaea and eukarya. *Phil. Trans. Roy. Soc. London* **B361**, 1787–1806.