

# On the applicability of the principle of the quantity-to-quality transition to chemical evolution that led to life

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**Abstract:** We review and re-examine the arguments for the proposal that life emerged by a quantity-to-quality transition of abiotic matter. This idea was originally proposed by the dialectical materialists, who are the proponents of the materialistic approach to Hegel's laws of dialectics. We find that one of the universal features of the quantity-to-quality transitions is the change in the organization of the system, which brings about novelty. We suggest that the principle of the quantity-to-quality transition may be a part of the algorithm of life, which is not Earth-centric.

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## Introduction and objectives

One of the key objectives of astrobiology is to discover the algorithm for life. The definition of life that everybody accepts, and especially one that is not Earth-centric, which would be suitable to search for life on Mars or elsewhere, has not been achieved yet (Pályi *et al.* 2002; Popa 2004). Astrobiologists are examining various philosophical views on life, as possible guides towards these objectives. Most astrobiology books thus start with a philosophical account of the topics of life and its emergence (Oparin 1924, 1953, 1968; Lahav 1999; Fry 2000; Chela-Flores 2001; Bennet *et al.* 2003; Lurquin 2003).

Our previous work has led us towards this ambitious goal of working on the algorithm of life. We have pursued the algorithm for the biotic evolution of the secondary metabolites (Kolb 1998). We have examined the Darwinian paradigm for this evolution, the algorithms for the 'inventive' evolution and the combinatorial chemistry, and have pointed to the applications for drug design. We have also studied the applicability of the Darwinian principles to chemical evolution (Kolb 1999; Perry & Kolb 2004).

We have offered a new definition of life, which utilizes a generalized principle that is not Earth-centric: 'life is a new quality brought upon an organic chemical system by a dialectic change resulting from an increase in the quantity of complexity of the system. This new quality is characterized by the ability of temporal self-maintenance and self-preservation' (Kolb 2002). This definition was inspired by the principles of dialectic change. Recently, we have offered a preliminary account of the ideas on the emergence of life by a quantity-to-quality transition of abiotic matter (Kolb 2005).

The principle of the quantity-to-quality transition is one of the three principles of dialectic change.

In this paper we repeat the previous basic arguments (Kolb 2005), but we update and expand the discussion, provide a more comprehensive examination of the subject and reach a firmer conclusion.

## Proposal that life emerges by a quantity-to-quality transition of abiotic matter

In this section, first we review the quantity-to-quality transformation and then see how it was applied to the origins of life by different authors.

### *From Hegel's laws of logic to Engels' dialectical materialism*

The law of transformation of quantity into quality and *vice versa*, is the first of three laws of dialectics, which were formulated by Hegel (1970, 1975). Engels states that while all of these laws 'were developed by Hegel in his idealist fashion as mere laws of thought', they are actually real laws for the development of nature (Engels 1960). According to Engels, '... in nature, in a manner exactly fixed for each individual case, qualitative changes can occur by the quantitative addition or quantitative subtraction of matter or motion (so-called energy)' ... 'All qualitative differences in nature rest on differences of chemical composition or on different quantities or forms of motion (energy), or, as is always the case, on both. Hence it is impossible to alter the quality of a body without addition or subtraction of matter or motion, i.e. without quantitative alteration of the body concerned.'

Engels examines the quantity-to-quality transition in three different areas of natural science: those of mechanics, physics and chemistry.

Engels first considers mechanics, as the science of heavenly and terrestrial masses, and states: 'in mechanics, no qualities occur: at most, states such as equilibrium, motion, potential energy, which all depend on measurable transference of motion and are themselves capable of quantitative expression. Hence, in so far as qualitative change takes place here, it is determined by a corresponding quantitative change'.

Engels then considers physics, which he defines as the mechanics of molecules, in which the molecules are chemically unalterable or indifferent. He considers interactions of the molecules caused by change in motion/energy, and gives examples of the sudden emergence of new qualities. These are the boiling and freezing of a liquid, and the liquefaction of a gas, among others. He writes: '... the so-called physical constants are for the most part nothing but designations of the nodal points at which quantitative addition or subtraction of motion produces qualitative change in the state of the body concerned, at which, therefore, quantity is transformed into quality'.

A visible new quality is indeed generated at these nodal points: ice melts, water boils, gas liquefies at characteristic temperatures/pressures. However, at every step of the process required for these changes, such as cooling, heating or increasing pressure, respectively, the molecules change their quality. 'Here every change is a transformation of quantity into quality, a consequence of quantitative change of the amount of motion of one form or another that is inherent in the body or communicated to it.'

What causes the emergence of a new quality if molecules themselves do not change? We suggest that it is a different spatial organization of the molecules. In the solid state, for example, molecules are the most orderly, in the liquid state they are less orderly and in the gas state they are even less so. The remarkable sudden changes between these states upon the addition/subtraction of heat are due to the changes in the organization of the collection of the molecules. The energy that is supplied/removed from the collection includes the changes of entropy, which is a measure of order. In the language of contemporary science we would further link the molecular spatial organization to the amount of the intermolecular interactions, which ultimately would be reflected as the solid, liquid or gas phases. This process of quantity-to-quality transition is completely reversible.

Both Hegel and Engels examined chemistry (Engels 1939, 1960; Hegel 1970, 1975). They were both very knowledgeable of the chemistry achievements of their times. Hegel had not received much credit for his knowledge of chemistry until relatively recently (Von Engelhardt 1984). Moreover, the role that Hegel's chemical knowledge had in helping him formulate his logic is now recognized and studied (Burbridge 1996). Engels writes: 'The sphere, however, in which the law of nature discovered by Hegel celebrates its most important triumph is that of chemistry .... That was already known by

Hegel himself .... As in the case of oxygen: if three atoms unite into a molecule, instead of the usual two, we get ozone, a body which is very considerably different from ordinary oxygen in its odour and reactions. And indeed the various proportions in which oxygen combines with nitrogen or sulphur, each of which produces a substance qualitatively different from any others! How different laughing gas (nitrogen monoxide  $N_2O$ ) is from nitric anhydride (nitrogen pentoxide,  $N_2O_5$ )!' (Engels 1960).

We update the chemical picture with the knowledge that was not available to either Hegel or Engels. In chemical changes the atomic nuclei come close together and exchange and reorganize the electrons that are associated with them. The oxygen atom (O) is composed of its nucleus and electrons. The new chemical species that are produced from O, namely molecular oxygen ( $O_2$ ) and ozone ( $O_3$ ), contain oxygen nuclei (two or three, respectively), which are qualitatively the same as in O, and the electrons, whose total number is the sum of the electrons from each individual O, and whose quality is unchanged (electrons are 'indistinguishable'). In the process of making  $O_2$  and  $O_3$ , the oxygen nuclei from the participating O atoms come close together. The electrons that were associated with the O nuclei now assume a different spatial arrangement, also called the electronic configuration. The latter is described by orbitals, which are regions in space in which the probability of finding electrons is high (more than 95%). These orbitals are distinctly different in O,  $O_2$  and  $O_3$ , and they are the most direct cause of the different chemical properties and reactivity of these three species (Solomons & Fryle 2004).

The individual atomic nuclei and electrons of the participating oxygen atoms did not change their quality in the process of making  $O_2$  and  $O_3$ . The new qualities that emerged, those of  $O_2$  and  $O_3$ , are due to the new spatial arrangements of nuclei and the new configurations of electrons. The quality that was destroyed was the old organization of the nuclei and the electrons of O atoms. These chemical processes are accompanied by energy changes and are, in principle, reversible.

Engels provided more examples from chemistry (Engels 1960). He considered a homologous series of normal paraffins, primary alcohols and normal fatty acids, in which the compounds in the series differ only by one  $CH_2$  unit. He observed that upon each addition of the  $CH_2$  quantity, the quality of the resulting species was different, in terms of the physical properties, such as melting and boiling points. He also examined the phenomenon of allotropy, in which the arrangements of the same atoms, such as carbon, give different forms, such as graphite or diamond, which exhibit different qualities. He explained that these new qualities are achieved 'by means of a change of position and of connection with neighbouring molecules', which lead to 'allotrope or a different state of aggregation' (Engels 1960). Cameron picked this up and has referred to such changes as the transition of the 'quantity-arrangement to quality' (Cameron 1995). Cameron pointed out the importance of the positional factors on the example of the double helix of DNA.

Engels also discussed Mendeleev's periodic chart, which demonstrates that 'the chemical properties of the elements are a periodic function of their atomic weights' (Engels 1960). (Today we know that it is the atomic number instead of the atomic weight.) Engels further described how this principle was tested by predicting the existence of an unknown element, temporarily named 'eka-aluminium', which was later discovered, and named gallium. This is a powerful example of the quantity-to-quality transition, as it can be tested, and it has a predictive power. Jordan (1967) examined the variety of examples of the quantity-to-quality transitions described by Engels, and suggested that Engels was not merely looking for a law-like correlation, but for a doctrine of evolutionary advance. Since the evolutionary advance is marked by the emergence of primary novelties, and the transformation of quantity to quality provides novelties, Engels may have wished to formulate a law of evolutionary cosmology (Jordan 1967).

*Is the quantity-to-quality transition gradual or sudden?*

This subject was addressed by Spirkin & Yakhot (1971). They write: 'The essence of the law of the transformation of quantitative changes into qualitative changes consists in the fact that small, at first imperceptible, qualitative changes, by gradual accumulation, lead at some stage to radical qualitative changes, involving the disappearance of old qualities and the emergence of new ones – which bring about, in their turn, further quantitative changes. This moment of transformation to a new quality is called a leap ... in nature ... it is always a leap that brings new qualities. This was how inanimate nature produced animate nature .... So the answer to the question of how a quantitative change is transformed into a qualitative change is: by means of a leap; and the transformation cannot occur in any other way'.

There are three parts to their presentation. The first part describes the details of the quantity-to-quality transition. The second part depicts the transformation to a new quality as a sudden event. The third part claims that life originated by such a sudden transition. Let us examine these parts separately. We need to start from the definitions of quality and quantity that Spirkin and Yakhot used: 'The quality of a thing is the sum total of all those essential features which make it possible to define its inner nature' and 'Quantity characterizes things and phenomena by their number, size, volume, etc.'. We note that other definitions of quality and quantity exist (Rogers 2001), but the discussion of those is not helpful in the examination of Spirkin and Yakhot's argument, which rests on their own definition. We assume, however, that the Spirkin–Yakhot definition of quality allows quality to be amenable to direct measurement, as it is the case with the Rogers' definition.

We present one of the examples Spirkin and Yakhot give to illustrate the quantity-to-quality transition. They describe building a dam by a gradual addition of rocks in the riverbed: 'first a batch of rock was thrown into the riverbed. There was no dam as yet. And there was still no dam after the second and third batches. However, a moment came when the

number of rocks that had been thrown into the river was such that they began to have a radical effect on the flow of water. A few more rocks and the river was dammed .... While the quantitative changes were taking place within certain limits they did not seem to result in the formation of a new quality (in this case a dam). However, as soon as they reached a certain, definite *quantitative* limit, or measure, the changes began to produce visible *qualitative* effects.'

We examine this example to see how it supports the statement in their hypothesis that the transformation of quantitative changes consists of small, at first imperceptible, qualitative changes, by gradual accumulation. We immediately encounter problems. How can the quantitative changes of adding rocks lead to any gradual qualitative changes, if the new quality, the dam, does not exist until the very last rock is added?

Another statement from the hypothesis, that radical qualitative changes involve the disappearance of old qualities, is not obvious in the dam example. The dam does not change the quality of the individual rocks, and thus there are no disappearances of the qualities of the individual rocks, as they become a dam.

One may attempt to define a rock to include its 'latent quality' to make a dam, by being the last rock that is added, or, broader, to be a part of the dam, since the dam cannot exist without the foundation rocks. However, such a 'latent quality' of rocks is not their essential quality and does not reflect their inner nature, as required by Spirkin and Yakhot's definition of quality. It would be most unusual to describe the quality of a rock as a potential dam. As there are many other possible uses of rocks, it would be difficult to include them all in the definition of the quality of a rock. Such a definition would be open-ended, as we would keep adding new definitions for the rocks, as the new uses for them are discovered. Such definitions would be a fusion of Aristotle's material cause (the rocks), formal cause (the form of the dam) and the final cause (the purpose of the dam) (Bothamley 1993; Kolak & Thomson 2006).

We see more problems as we continue our examination. When the individual rocks become part of the dam, their location and their spatial relationship to the other rocks change: from a selection of rocks found by the riverside, they are moved to an organized rock wall in the riverbed, a dam. Thus the new quality realized by the rocks as they make a dam is due to the new spatial organization of the rocks. It would be unusual to claim that a rock changes its quality as it is moved from a bunch of rocks to the rock wall. Since rocks can be moved in space in many different ways, it would be difficult to account for this in the definition of the quality of the rocks. We would generate an endless generation of 'new qualities' just by rearranging the rocks.

In conclusion to this step of our analysis, it appears that there is no new quality generated or old quality destroyed in the individual rocks in the process of building a dam. We could expand the common definition of quality to include usefulness and the position in space, but these are not 'essential features' that define the 'inner nature' of the rocks.

However, there is no doubt that a new quality, a dam, was indeed generated by moving the rocks and organizing them into a wall. If the quality of the individual rocks did not change, how is this possible? We propose that the new quality that emerged is due to the new spatial organization of the rocks. The quality that was destroyed in the process would be the old spatial organization of the rocks. The old organization of the rocks, consisting of a pile of spread out, disorganized rocks at the riverside, is destroyed as the new organization is achieved by moving the rocks to an organized wall in the riverbed. The change from a collection of rocks to a dam is gradual, until the 'last rock' causes a sudden visible change of blocking the river flow. The individual rocks are not changed. The process of building a dam is, in principle reversible, as the rocks can be recovered from the dam and placed in their original positions.

We now examine the second part of Spirkin and Yakhot's hypothesis: 'So the answer to the question of how a quantitative change is transformed into a qualitative change is: by means of a leap; and the transformation cannot occur in any other way'.

Spirkin and Yakhot do not define a leap. A common definition of leap from the dictionary, which seems most appropriate, is: 'a sudden passage or transition'. The definition of 'sudden' that seems most appropriate is: 'made or brought about in a short time' (Merriam-Webster 1996). We need to define 'time' and 'short time'. We use the relative or common time, 'some sensible or external measure of duration by means of motion' which is approximated by clocks and calendars, as opposed to the absolute or mathematical time, which it is a duration that has no relation to anything external and would exist even without any material objects in the physical Universe (Weinert 2005). Starting from this adopted definition of time, what is considered to be a short time compared to a long time? We examine several examples of duration of the quantity-to-quality transitions in nature.

We start with the time necessary for the transition of an electron within the atom (from the higher orbital of hydrogen,  $2s$ , to its lower orbital,  $1s$ ). This example gives us a feel for the time needed for the transitions of electrons, which are common in chemistry, and which would be relevant to the previously discussed examples of chemical reactions. The time necessary is approximately  $10^{-8}$  s (Eisberg & Resnick 1985). This is an unimaginably short period of time on our human timescale. We consider electronic transitions to be sudden, but we really do not have any means of examining the details of such transitions, due to the limitations imposed by quantum chemistry.

Next we examine the timescale involved in the emergence of the Earth by the accretion process. We learn that scientists are divided in their opinion whether Earth accreted 'slowly', within 100 million to 1 billion years, or 'rapidly', within 100 000 to 10 million years (Anderson 1999). Both processes would be unimaginably long, based on our human time scale. Thus, we cannot use the human scale. Instead, we must use a much longer, geological timescale. The sudden process here would have to be defined by using the latter timescale.

Let us examine the solidification of a liquid by cooling, which happens on the human timescale. It may happen quickly, for example in case of water, and we can nicely see the sudden formation of ice within seconds to minutes. Some other pure liquids, especially organic, may take quite long time to solidify upon cooling, one hour or much longer. Sometimes the solid will not form at once. It may start as a partial solidification, or as a patch of the solid in a liquid region, and then it may slowly spread out to the remaining regions of the liquid. The reason may be the difficulty the liquid has in organizing itself into the crystalline lattice. An observer, for example an impatient chemist who is waiting for the solid to form, may not call this solidification sudden, but would instead say that the solidification was achieved gradually. Thus, depending on the case of the liquid, would we consider all solidifications sudden, or just some? We also see here a subjective component in this decision-making: an impatient person may not consider the transition that happens within one hour to be sudden, whereas a patient person may.

We conclude that different quantity-to-quality transitions may occur on different timescales. 'Sudden' translates to different times for the transitions of electrons, for the accretion of Earth and for the solidification of different liquids. Because of this, the dictionary definition of sudden, in which the human timescale is implied, is not helpful. The problem with the timescale for the quantity-to-quality transition was addressed by Meljuxin, as cited by Planty-Bonjour (1967). 'The concepts of "rapid" and "slow" leaps are relative because they have no intrinsic value, only a value relative to the previous state of existence. Thus, if the period of transition from the old quality to the new one is relatively short compared with the duration of the preceding state, the leap is called rapid; in the contrary case, it is called slow.' However, the idea of a slow leap is counterintuitive to the concept of a leap, which is usually considered to be fast. Because of the relativistic and potentially subjective or even arbitrary character of the definitions of 'sudden' and the 'slow leap', the hypothesis that quantity-to-quality transitions in nature are sudden leaps cannot be objectively tested and falsified (Losee 2001) on some 'representative example'. The latter would be hard to find. Known examples require the use of the specific timescales, which may not be applicable to other examples.

In the third part of their presentation, Spirkin and Yakhot hypothesized that life originated by a quantity-to-quality leap from inanimate to animate nature. We proposed in this paper that the universal feature of quantity-to-quality transitions is a change in the organization of the system. Our proposal is relevant to the hypothesis that life began when various chemical and energy cycles became coupled (organized) together, which was recently reviewed (Perry & Kolb 2004).

*Jean-Paul Sartre on the quantity-to-quality transition as it applies to the origins of life and our comments on his views*

In this section we examine the views of Jean-Paul Sartre on this subject. In his work 'Critique of Dialectic Reason'

Jean-Paul Sartre states: 'It may be said that the metaphysical hypothesis of a dialectic of Nature becomes more interesting when it is used to explain the passage from inorganic matter to organic bodies, and the evolution of life on earth .... Nothing is gained by proclaiming that the evolution of the species or the appearance of life are moments of the 'dialectic of Nature' as long as we are ignorant of *how* life appeared and *how* species are transformed' (Sartre 1982). Sartre gave a strong warning about the application of the quantity-to-quality transition law in nature, by indicating the dogmatic way in which it was applied to nature by the dialectic materialists. He criticized the claim of the dialectic materialists that the laws of dialectic materialism are the most general laws of nature, and pointed out that their claim is not rigorously supported by scientific examples. Sartre states that the dialectics is dogmatic and unproven. 'As for the dialectic of Nature, it cannot be anything more than the object of a metaphysical hypothesis.' Although he considers the existence of the dialectic in nature to be a possibility, he gives the following strong critique: '... the only dialectic one will find in Nature is a dialectic that one has put there oneself'.

Despite this strong criticism, we believe that the idea where the appearance of life is the result of the dialectic process should be further studied. Life is indeed a new quality as compared to abiotic matter, and is characterized by higher complexity and a higher level of organization than the abiotic components from which it presumably evolved. The law of the quantity-to-quality transition points to the organization of life as one of its essential qualities, and may provide the mechanism for how life emerges from simple abiotic material by a series of quantity-to-quality transitions. For example, Kauffman, in his theory of emergence of order out of chaos, considers how an increase in the quantity of participating chemical species (such as polypeptides) leads to the spontaneous emergence of a new quality, that of autocatalysis (Kauffman 1993, 1995). Woods and Grant (2002) consider the general phenomenon of the emergence of order out of chaos as one of the examples of the quantity-to-quality transitions in nature. They consider various edge-of-chaos models, in which the small quantitative changes lead to self-organization, such as in the example of a pile of sand to which more sand is added, leading first to an avalanche and then to the self-organized stability. They also describe various transitions that involve critical quantities, such as nuclear reactions. Coacervates, micelles and vesicles, all of great importance in prebiotic chemistry, spontaneously self-assemble when the critical concentrations of their constituents are reached by the gradual increase in their quantities. The coacervates, micelles and vesicles will grow, and upon reaching a critical size, will split into the daughter cells. The key examples on coacervates are from Oparin (1924, 1953, 1968). Other examples, including the follow-up of Oparin's work, have been reviewed (Perry & Kolb 2004).

Dialectics can indeed be applied in a dogmatic manner, but do not have to be. The dialectics in nature is indeed not proven to be a general law. However, various examples for the

quantity-to-quality transitions in nature have been described, and there may be more, which have not yet been discovered. These could potentially be useful for the understanding of the algorithm for life.

## Conclusions

We have reviewed and re-examined the idea that life emerged by a quantity-to-quality transition of the abiotic matter. This idea was originally proposed by the dialectical materialists, who are the proponents of the materialistic approach to Hegel's laws of dialectics. We proposed that the universal feature of the quantity-to-quality transitions is a change in the organization of the system. We have provided various examples from the literature of the quantity-to-quality transitions in nature, and suggest that this principle needs to be investigated further, and that further examples of it should be sought. This principle may be potentially valuable for our understanding of the algorithm for life on Earth and elsewhere.

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## Dedication

This paper is dedicated to the memory of A.I. Oparin, the father of the field of the chemical origins of life. While I have never met this great man, who passed away before I became a mature scientist, it was his 1924 pamphlet on the chemical origins of life (Oparin 1924) that sparked my interest in science when I was only 13 years old, and has shaped my life since. I was touched by Oparin's greatness and have felt inspired ever since I came across his precious book, a small tattered paperback, now lost somewhere, or perhaps found by another interested 13 year old.

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