WHAT IS LIFE ? — A HISTORY OF CONCEPTIONS FROM MYTHS OF CREATION TO ARTIFICIAL LIFE

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INTRODUCTION

This paper reviews major milestones in the evolution of conceptions about " living " as contrasted with " non-living ", a cardinal dichotomy which has intrigued mankind for millennia and received diverse expressions, interpretations and explanations in mythology, religion, philosophy and science. The evolution of life conceptions vividly exemplifies the principle of continued improvement, falsification and evolution of scientific theories (1963) as proposed by the Austrian-British philosopher Karl Popper (1902-1996) and the theory of paradigm shifts and scientific revolutions (1970) by the US philosopher and historian of science Thomas Kuhn (1922-1996). The following major paradigms are discussed :

- mythological
- philosophical
- biological
- physical and thermodynamical
- systems theoretical and
- computational.

The rich heritage of oral and spiritual tradition including myths of creation of various peoples bears witness to the fact that from unfathomable times man has wondered about his own existence and sought for an explanation of the purpose and origin of life and of the world. The myths were displaced by stories of creation of higher literary religions which in turn were contested by philosophical speculations only to be superseded by scientific explanations.

In the 19^{th} century, physical, energetic and thermodynamic preconditions of life became understood. Yet the classical sciences failed to offer more than descriptive explanations. In the 20^{th} century molecular biochemistry and theoretical biology were able to reveal and analyse subcellular biochemical processes, compounds and reactions and their controls in ever greater detail. But still, the first principles and the logic of the underlying machinery and its driving force remained mysteries until the missing links were filled in by system and information theory, cybernetics, non-equilibrium and complex dynamics and computer science. Today we understand the reasons why even modern natural sciences failed in explaining life adequately, namely : they followed the classical paradigm of analysis and reduction of phenomena into their basic elements. An atomistic approach based on isolated analyses does not work for complex systems such as living beings, cells or systems of chemical reactions where the whole is more than the sum of its parts. The fundamental principles of interdependence and integration and the consequent emergent qualities and functions resulting from appropriate complexity and architecture were simply lost and overshadowed by the quantity of detail.

A new paradigm for the study of complex phenomena emerged, however, in the mid-20th century with the invention of the computer and the subsequent development of systems theory, model thinking, information theory, cybernetics and computer science. Toward the end of the century a number of new fields arose — such as dynamical systems, irreversible and non-equilibrium dynamics, non-linear and complex systems, structural stability, synergetics, catastrophe theory, chaos and fractal theory, the theory of self-organisation etc. — which allowed to explain complex phenomena in both non-living and living nature.

Scientific knowledge and explanations are expected to be verifiable in terms of premises, experiments, observations, measurements or proofs which must be redemonstrable whenever suspected. In the case of complex phenomena, especially processes evolving over billions of years such as life on earth, this may be difficult or even impossible. Earlier steps of evolution are no longer available for inspection and analysis. The difficulties in obtaining proofs or explanation of certain questions leave room for unjustified speculations and beliefs to live on.

The computational paradigm does, however, offer new possibilities especially in the study of complex and evolving systems. By constructing computational models it is possible to make experiments with highly complex models and processes. By means of constructing precise mathematical and algorithmic models and by running simulations it is possible to observe their behaviour and evolution. These include models of biological, cognitive, linguistic, social and ecological systems. The computational paradigm is now bringing life, human and social sciences under the same conceptual and methodological framework as the exact and engineering sciences.

In a historical perspective, the complexity of living systems is so appalling that it is no wonder that their understanding has progressed so slowly. Over two thousand years of literary religions, philosophy and science have left the fundamental questions of life — its origin, the basic mechanism and its driving force behind it — unexplained. Scientific experiment, logical proof by valid methods of reasoning and realisation and demonstration by mathematical or computer models or engineering designs have proven more reliable methods of explanation, understanding and demonstration.

EVOLUTION OF PARADIGMS

Scientific conceptions change whenever better knowledge becomes available. Over time the conceptions about life and its origin have also changed and become more precise and reliable. However, because life is a highly complex phenomenon, it cannot be explained by any single principle or theory. Rather, an adequate explanation must necessarily involve a great many principles and theories across disciplines. In fact, the history exemplifies an evolution of ideas and theories akin to the evolution of life itself. The closer we come to the present time the more theories are seen as relevant to the explanation of various aspects of life. Moreover, life has no single root or beginning. Rather, it has not only a huge number of branches and leaves but also a huge root-stock, a tree of causes and effects which have led to and continue to direct its evolution. Moreover, the evolution of life is not only the result of variation and natural selection, but also the result of continuous emergence of new forms and functions and their falling together and interlocking into ever more complex systems and coevolving webs of systems.

Today it is, however, understood, as will be shown in the conclusions, that ultimately not more than a few fundamental preconditions and first principles are, after all, necessary and sufficient to explain how and why life at large is possible, where does it derive its driving force and what are the fundamental conditions for it to run, survive and evolve on the planet Earth or elsewhere.

In the history of ideas relevant to the explanation of various aspects of living systems it is possible to identify a number of stages and fields of science which involve very different conceptual frameworks, theories and paradigms.

The length of even a condensed list of subjects, fields and theories indicates that a great many ideas and principles have been proposed and formulated. In the course of history most of them have, however, been refuted while some have stood the time and offered basis for refinement and integration. Yet, many obsolete conceptions and beliefs continue to live unquestioned in religions, philosophy and even in science.

Because of the wide scope of the subject and lack of space many topics will have to be accounted for only briefly. Many points must also be left out, especially as we approach the front-line of science today. The presentation may also run the risk of becoming a chronology. Some interesting etymologies of life-related terms are also indicated.

RELIGIONS AND PHILOSOPHY

Many ancient conceptions about life and its origin are still extant in various traditions of folklore, religions, theologies and philosophical schools. They all share the characteristic of having survived nearly unchanged through ages in spite of developments in science and continue to dominate people's minds in many cultures irrespective of their mutual differences and evident internal and external contradictions.

About two and a half thousand years ago the Greek philosophers started to ponder questions of life, man and nature independent of myths and religions.

In the Middle Ages nature was understood as distinct domains or Kingdoms. The biblical myths and neo-Platonic conceptions about the creation of the world, life on Earth, man and soul were further refined by the scholastic philosophers and became part of the official church doctrine.

NATURAL PHILOSOPHY

The Renaissance and the New Time brought another departure from mythology and theology toward natural philosophy and empirical science. Specific phenomena of life, like motor functions, blood circulation, respiration, generation, spontaneous generation, embryo development and the study of tissue and micro-organisms by means of microscope, became subjects of investigation and experimentation.

CLASSICAL PHYSICS AND BIOLOGY

During the Enlightenment, comparative anatomy, classification of species, paleontology and theories of descent and evolution developed into major subjects of investigation. In the beginning of the 19th century the French naturalist Jean Baptiste Lamarck (1744-1829) coined the term *biology* (1802) identifying the field as an independent branch of natural science.

Toward the end of the century, discoveries in cytology, heredity, fertilisation and new methods in biochemistry and microscopy gave rise to cell theory and later to chromosome theory which subsequently allowed to observe and describe mitosis and meiosis. Earlier speculations were gradually superseded by descriptions of life processes in considerable detail on subcellular and later on biochemical and molecular levels. The fundamental questions concerning the physico-chemical and energetic basis and of the origin of life could not, however, be solved within biology. Their resolution required new results from classical physics, thermodynamics, chemical kinetics and molecular biochemistry in the 19th century.

ENTROPY AND FREE ENERGY

The study of the energetic efficiency of the steam engine, *i.e.* the transformation of heat into mechanical motion, led in the 19th century to the formulation of thermodynamics. The French engineer Sadi Carnot (1796-1832) investigated the cycling process of heat in the engine and noticed that some proportion of it was always lost. This observation was generalized by the Italian physicist Benito Clapeyron (1799-1864) who introduced the idea of an ideal or reversible process where all the heat spent on the engine would be transformed into useful mechanical work and the real or irreversible process which always involved some loss of heat. Comparing these it became possible to precisely define and calculate the efficiency of energy conversions.

Based on these results the German physicist Rudolf Clausius (1822-1888) introduced the concept of entropy, and formulated the second law of thermodynamics also called the *entropy law*. It became clear that all natural events involved energy conversion and that in any event wherever it was converted from one form into another, some proportion of it was inevitably lost in the form of dissipation and could not be recovered, while its total amount, according to the first law, was always conserved. The entropy law revealed that the laws of physics were not truly symmetric with respect to energy and time : physics was not totally reversible. The proportion of energy lost might vary from one case to another but was always inevitable. The entropy law turned out to be universally valid and was shown to concern living as well as non-living.

The entropy law also explained why heat never flows by itself from cooler to warmer but always in the opposite direction tending to spread and level out into the environment. All events in the nature and in the whole universe seemed to be on a " downhill " course. All processes were heading toward what came to be called the *thermal death* of the universe, a state where all energy potentials were eventually dispensed and any differences of form, order, structure or organisation evened out into a uniform thermodynamical equilibrium. According to this view, life on earth and possibly elsewhere in the universe was but a thin, local and temporary counterstream against the overall mainstream course of events toward decay and death. Moreover, tax had to be paid to entropy for making any use energy which was indispensable for the sustenance, survival and development of life.

This was a pessimistic prospect which raised sharply the question of how then was it possible at all that life could ever have come into existence, survived and even developed and flourished for billions of years ? Answers to these questions were to be found in the concepts of free energy, chemical thermodynamics, reaction kinetics and the logic of chain reactions and self-reproducing systems first in the 20th century.

The German physician, physiologist and physicist Herman von Helmholtz (1821-1894) formulated the law of conservation of energy precisely and, like

Mayer, understood that it was equally valid for electricity, chemistry and the living nature which received its energy from burning food like steam engines from burning coal. He was convinced that living beings possess no innate or vital force different from those driving the non-living nature. He tried also to prove this but was able to take only a first step.

In 1882 he defined the notion of *free energy* and derived an equation that relates the total energy of a system to the proportion of it that can be converted to forms of energy other than heat. By this result, Helmholtz anticipated chemical thermodynamics, *i.e.* extension of the concepts of free energy and entropy to chemistry and biochemistry. The thermodynamic criteria concerning the direction of chemical reactions were soon established and became crucial to understanding the reaction kinetics of the chemistry of life as formulated in the theories of autocatalytic and hypercyclic chemical reaction systems about a century later.

Chemical Thermodynamics

In the 20th century it was shown that free energy and entropy rather than heat are the prime determinants of the dynamics and thermodynamics of chemical reactions. In chemical reaction kinetics and the theory of dynamic chemical equilibrium the law of mass action was discovered. The mechanism and thermodynamics of catalysis were explained and extended to biochemical enzyme reactions.

In the mid 20th century chemical thermodynamics was further refined in the study of complex dynamical equilibrium and non-equilibrium systems which became known as *dissipative structures* and *non-equilibrium thermodynamics*. Toward the end of the century these theories were integrated into respective developments in non-linear physics, also known as *synergetics*, *complex dynamics* and the *theory of self-organizing systems*. In the 20th century the development of molecular biochemistry allowed to map the molecular structure of proteins, nucleic acids and other compounds and reactions but the logical machinery and mathematical theory of self-reproduction were to emerge only in the mid and late 20th century.

The Swiss-born Russian chemist Germain H. Hess (1802-1850) showed that the total energy of any reaction is independent of the *reaction path* (1831), *i.e.* of the intermediate states and partial products through which the reaction sequence proceeds. Moreover, he demonstrated that the change of amount of heat and the loss of energy for reasons of entropy are dependent only on the initial and *final* temperatures of the reaction and not on its pathway (1840). This result confirmed the validity of the entropy law in chemistry as anticipated by Mayer and von Helmholtz.

The US physical chemist Josiah W. Gibbs (1839-1903) perfected the results of Hess by deriving a general equation for chemical affinity which combined physical and chemical entropy in one formula. He also defined the thermodynamical condition which determines the reaction potential and the direction of flow of a given reaction (1873). This condition was a fundamental result in chemical kinetics and equilibrium and non-equilibrium dynamics, known today as the Gibbs' phase rule, the Gibbs' function or reaction pressure. The result turned out to be crucial also as the thermodynamic and energetic precondition of the basic machinery of life.

MOLECULAR BIOCHEMISTRY

The British physiologist and genetician John B. Haldane (1892-1964) showed that the laws of chemical thermodynamics (1924) were equally valid for biochemical enzyme reactions as for inorganic catalytic reactions. The Gibbs function was shown to be generally valid for inorganic, organic and biochemistry. Life processes did not contradict the entropy law although they were able to run apparently against the mainstream tendency of nature toward rest and decay. The result explained the energetic and entropy conditions of the chemistry of life but not the basic chemical and logical mechanisms underlying it. To solve these questions new advances were required in the analysis of the substance and topology of the pathways of the basic biochemical reactions related to energy and metabolism, the power houses of the chemistry of life.

Subsequently, the basic reaction cycles and pathways underlying the energy chemistry of life were explained on the molecular and reaction levels. The German-British biochemist Hans Krebs (1900-1981) resolved the pathway of animal cell metabolism known as the tricarboxylic cycle, the citric acid cycle or the Krebs cycle (1937). Details were filled in by the German-US biochemist Fritz Lipman (1899-1986). The US biochemist Melvin Calvin (b. 1911) described the biosynthetic pathway of photosynthesis, the reaction cycle by which green plants use photons of sun light to convert water and carbon dioxide into carbohydrates and oxygen (1949).

These results were significant steps toward understanding the physical and thermodynamical possibility and reaction kinetic conditions of the chemistry of life. They explained the basic energetics and thermodynamics on which life sustained but gave only little hint of how life on earth could have emerged and what were the basic mechanisms underlying self-reproduction. To put these questions into a historical perspective let us briefly review also he history of the ideas about the origins of life.

THE ORIGINS OF LIFE

We prefer to speak of the origins in plural rather than in singular since, as it will turn out, no single origin of life can be identified although various steps can be seen in some respects more significant than others. Before 1860 the question of the origin of life was primarily of religious and philosophical concern. The definite demonstration of non-generation of micro-organisms spontaneously by the French chemist Louis Pasteur (1822-1895) in 1860 and the formulation of the theory of evolution by the British naturalist Charles Darwin (1809-1882) at about the same time led to an impasse from which only two outcomes could be thought of : either a spontaneous generation of organisms simpler than microbes in a distant past and their subsequent evolution or an extraterrestrial origin of life on earth.

In the 20th century the hypothesis of the earthly origin of life was considered on a scientific basis. The Russian biochemist Alexandr I. Oparin (1894-1980) concluded that the theory of panspermia was no answer since it only pushed the question to some other heavenly body. Instead, he focused on metabolism and noted that in principle there was nothing that could not be explained in terms of physics and chemistry on earth and that biological evolution had been preceded by epochs of geological and chemical evolution (1922). By the time Oparin's book was translated into English (1934), the British physiologist and geneticist John Haldane (1892-1964) had independently considered the possibility of the earthly origin of life as a natural process (1929).

In the 1950s attempts were made to synthesise the basic biochemical compounds of life in vitro. The US physical chemist and nuclear physicist Harold C. Urey (1893-1981) put the question of the origin of life into the context of the origin of the Earth and of the Moon and their geological evolution (1952). He suggested that the early atmosphere contained hydrogen, ammonium, methane, water vapour, nitrogen and sulphides which were to be the prime constituents for the early chemistry of life. Their interaction under the severe geological conditions of volcanic activity, early ocean and atmospheric electricity could have preconditioned the emergence of life on earth.

In 1953, his student Stanley L. Miller (1930-) succeeded to synthesise several prebiotic compounds more complex than organic carbons, namely amino acids, the basic constituents of proteins and enzymes, in vitro from water, methane, ammonium and hydrogen under electric discharges. Meanwhile molecular chemistry had made advances and begun to reveal the chemical compositions and structures of proteins, nucleic acids and other basic biochemical compounds.

In 1957, the first international conference on the origin of life on the Earth was held in Moscow followed by a series of conferences elsewhere. Research projects were also started in many countries on the search for signs of extraterrestrial life or intelligence using radiotelescopes.

More recently, the Scottish chemist Graham Cairns-Smith (1982) suggested that life could have resulted from surface phenomena on early crystalline mineral clays (1982). Fine minerals and microcrystals rather than carbon compounds could possibly have catalysed the first metabolic reactions. Such mineral life could have started to replicate, begin to evolve and become integrated with energetic, protein, nucleic acid, etc., cycles until reaching a stage which he called the genetic take-over making genetic biological evolution possible.

Although intuitively plausible none of these hypotheses could be demonstrated. The genetic mechanisms of transcription and replication, protein synthesis, etc., pathways were known but no theory was available which could have explained the fundamental principles of how and why the basic machinery of the chemistry of life could have emerged and continued to keep running. Moreover, they were not able to explain the ability of living organisms or even complex non-living systems to maintain their dynamic equilibrium, coherence, continuity and identity under varying external conditions and disturbances from the hostile environment. Theories capable of answering these questions were, however, already becoming available in new fields other than natural or life sciences, namely systems theory, cybernetics and information theory and computer science.

SYSTEM AND INFORMATION SCIENCES

In the mid 20th century, despite notable advances in experimental, analytical and theoretical biology and other natural sciences, it had to be confessed that life was still a mystery. Classical and modern science had failed to provide the definitive answers to the fundamental questions of life. The deadlock had been realized by philosophers and scientists in the 1930s but it was the Austrian biologist Ludwig von Bertalanffy (1901-1972) who pronounced it clearly and showed the way out. He argued that the classical and modern sciences had failed and would continue to do so unless a new approach was adopted which would properly take into account the systemic nature and the dimension of complexity of living organisms. Convinced of this he formulated what is today known as the general systems theory (1940) anticipating the rise of a new paradigm in science and philosophy, the systems paradigm (Altmann and Koch 1998).

During the second World War the first electromechanical computers were built by the German electrical engineer Konrad Zuse (1910-1995) and the US electrical engineer Howard Aiken (1900-1973) and the first electronic computers by the Bulgarian-US physicist and mathematician John V. Atanasoff (b. 1903), the US electrical engineer John W. Mauchly (1907-1980) and others. The Hungarian-US physicist and mathematician John von Neumann (1903-1957) invented the principle of stored program-computer (1945), the idea on which modern computers are based. In the 1950s computers were used mostly in mathematics and physics but from the 1960s they were put to use in other fields of science and subsequently in all walks of life. The computer revolution also brought in a new conceptual framework and novel methodologies for all sciences.

The notion of information had been introduced in telecommunication technology by the Swedish-US telegraph and telephone engineer Harry Nyquist (1889-1976) in 1924. In the 1930s the German-US physicist and microbiologist Max Delbrück (1906-1981) introduced the notion of biological information. In the 1940s the Austrian physicist Erwin Schrödinger (1887-1961) wrote a small but influential book " What is Life ? " (1944) introducing the notion code of life.

In 1948 the US mathematician Claude Shannon (1916-) formulated the information theory which became the basis of the theory of representation and communication of information, also known as the statistical or combinatorial theory of information. The next year the US physicist and mathematician Norbert Wiener (1894-1964) formulated the theory of cybernetics, or communication and control in man, animal and the machine, as he phrased the idea in the title of his book (1949).

In 1953 the structure of the DNA molecule was analysed and described as a double helix by the British biochemist Francis Crick (b. 1916), his US colleague James Watson (1928-) and others. The next year the Russian-US physicist George Gamow (1904-1968) anticipated that it was the DNA that carried the code of life consisting of the four kinds of nucleic acid bases as its " code letters " whose order in sequences of three directed the selection of amino acids in the synthesis of proteins, an idea which was confirmed in 1960.

The development of systems theory, model thinking, information and communication theory, cybernetics and computer science offered the necessary conceptual tools and methods to study in precise terms complex systems and processes — not only in natural sciences and in engineering but also in life sciences. Various principles of systems and information theory became essential to understanding phenomena of control, self-regulation, integrity, coherence, equilibrium, growth, metamorphosis, self-organisation, development, etc., characteristic to living beings, species and ecologies.

The teleological problem could be explained in terms of the principle of feedback and learning mechanisms of cybernetics combined with results from non-equilibrium thermodynamics, complex dynamics and self-organisation. These allowed physical, chemical and biochemical reactions, reaction systems and life processes on the cellular and physiological levels and their evolution to be seen and explained in a unified initial-causal, system theoretical and mathematical conceptual framework.

Toward the end of the century classical systems theory and cybernetics were extended to non-linear and complex dynamics and the theory of self-organisation. From the 1970s onwards the catastrophe, chaos and fractal theory were developed which allowed mathematical explanation of non-linear phenomena like growth, metamorphosis and development, known today as the theory of self-organizing and evolving systems.

In living systems growth processes involve metabolism, catabolism, anabolism, cell division, etc., reaction pathways together with their complicated control loops. The theories of complex dynamical systems can explain how a system or individual may grow, undergo metamorphoses and structural changes and develop through self-organisation and how populations and species may evolve over time maintaining their relative dynamical equilibrium and identity. But even they are unable to explain the phenomenon of self-reproduction. Toward the end of the century logic, mathematics and computer science allowed to solve this most essential mechanism of life. Classical and modern systems theories were supplemented with the theories of automata, formal languages, algorithms and computations which again caused a paradigm shift first in logic, mathematics and computer science themselves and then in physics and chemistry followed by life, human and social sciences.

The computational paradigm of science was the result of the emergence of a number of new fields and theories the application of which to the classical and modern sciences gave birth to new multidisciplinary fields of research such as artificial intelligence, artificial life, computational cognition, computational linguistics, semiotics, memetics, virtual reality, etc., most of which fall beyond the focus of this paper although not of life as a systems phenomenon.

It is not possible nor necessary to review the history of system, information and computer sciences in this paper. The interested reader is referred to (Seppänen 1998). Instead, the rest of the paper will focus on the history of self-reproducing systems and the short history of the newly-conceived field of artificial life, and their roots which, too, derive from several disciplines.

SELF-REPRODUCING SYSTEMS

In classical and modern biology reproduction had been studied in the context of generation, regeneration and heredity. In the 20th century advances in analytical biochemistry, molecular biology and genetics reduced the study and explanation of cellular and subcellular processes to the molecular and reaction pathway levels.

But even modern biochemistry, molecular biology and theoretical biology were incapable of explaining the logic of reproduction, *i.e.* the abstract principles and mechanisms which underlie the biochemical reaction pathways and render self-reproduction possible at large.

The theory of self-reproducing systems was developed already in the 1940s, an early stage of computer science, but went for several decades almost unnoticed by theoretical biologists and molecular biochemists. Although highly complex in terms of compounds, reaction paths and kinetics, biochemical reactions and reaction systems can be classified into only a few basic types by their logic and topology, namely : transmuting, polymerizing, branching, cyclic and self-reproducing reaction systems. Moreover, the control mechanisms behind these types of reactions involve catalysis and inhibition, two fundamental principles of control — positive (exciting) and negative (inhibiting) feedback. But the most essential to explain and understand chemical self-reproducing are the notions of autocatalysis and autocatalytic cycles.

Historically, these ideas derive from different times and several disciplines. The idea of chain reaction arose in the 1910s from the study of fermentation, catalysis and chemical kinetics in the late 19th century and the analysis of explosion and polymerisation reactions in the beginning of the 20th century. In the 1930s the ideas of nuclear fission, chain reaction and the possibility of the atom bomb were conceived almost simultaneously with the discovery of the fusion chain reaction taking place in the Sun. In the 1960s the idea of a cyclic chain reaction and autocatalytic hypercycles were formulated in the study of biochemical reaction systems.

Catalysis and Autocatalysis

In 1887 the Swedish chemist Arrhenius had discovered inorganic catalysis and developed the theory of electrolytes. By the turn of the 20th century chemistry had matured enough to consider questions of kinetics and the structure of various types of chemical reactions. The German-US biochemist Leonor Michaelis (1875-1949) and his Canadian colleague Maud L. Menten (1879-1960) derived an equation known as the enzyme mechanism or Michaelis-Menten equation (1913). It described the rate of an enzyme-catalyzed reaction with respect to its substrate concentration. They also deduced that the catalyzed reaction was preceded by a reaction between the enzyme and its substrate to form the final complex whereby the enzyme was released again and remained intact, an idea which was confirmed 50 years later. In the general case, the catalyst may also occur as one of the products of the reaction or as an intermediate product which is subsequently consumed as a reagent. Thus, one chemical compound may assume one or more different roles — a reagent, a catalyst and/or a product — in a reaction or a reaction system.

The Polish chemist Jan Zawidski (1866-1928) discovered that in some reactions the product of the reaction was the same as its catalyst and called the situation autocatalysis, also self-catalysis. In a self-catalysing reaction, the concentration of the catalyst increases at each reaction by one molecule. These ideas led to the conception of more complex types of autocatalytic mechanisms such as linear polymerisation, branching chain reaction and cyclic chain reactions.

In analogy to self-catalysis, the Hungarian-British physical chemist Michael Polanyi (1891-1976) noticed that in some reactions the product acted against the reaction. The rate of reaction decreased and was finally caused to stop by the presence of increasing concentration of a product of the reaction itself which played the role of self-inhibition. In terms of cybernetics, autocatalytic and autoinhibiting reactions are examples of self-regulating reaction systems which involve positive and negative feedback control (Lat. *contra* + *rolare*), respectively, present in every reaction. In different types of more complex reaction systems these mechanisms can lead to unpredictable developments.

Reaction Chains and Chain Reactions

In 1913 the German chemist Max Bodenstein (1871-1942) investigated the effect of light on the formation of hydrogen chlorine (HCl) from its elements and observed that a single photon could trigger a sequence of millions of reactions. Each reaction excited by one photon occurred in separation but emitted a new photon which triggered the next reaction etc. To generalise the principle he introduced the notion of chain reaction and postulated a mechanism of repeated action of separate reactions.

Linear Polymerizing Chain Reactions

In 1921 the German organic chemist Hermann Staudinger (1881-1965) questioned the generally accepted view that rubber and other non-crystalline materials of high-molecular mass were merely disorderly aggregates of small molecules. Rather, he claimed them to be long chain-like molecules held together by ordinary chemical bonds (1947). The result was soon confirmed and laid foundation for macromolecular chemistry and the study of natural and synthetic polymers. Already in 1936 he had also anticipated that genes, too, are chain-like macromolecules with definite structure which determines their function in heredity, an idea which was confirmed two decades later.

In 1953 the German organic chemist Karl Ziegler (1898-1973) discovered by chance the catalytic mechanism of linear polythene synthesis from ethylene monomers in the presence of an organometallic catalyst at low pressure. The growth of the polymer chain occurred by appending ethylene monomers to the end of the chain under the influence of the catalyst. For this result he shared the 1963 Nobel Prize in chemistry with his Italian colleague Giulio Natta (1903-1978).

Branching Chain Reactions and Explosions

Linear chain reaction and polymerisation are simple mechanisms of catalytic reactions where the amount of catalyst remains unchanged whereas in autocatalytic reactions the catalyst itself is also reproduced. Thus, autocatalysis accelerates the chain reaction since the catalyst is reduplicated by one molecule at each reaction instance but is not consumed in the reactions they catalyse. Moreover, some reactions like nuclear reactions may produce more than one catalytic element giving rise to a tree-like process known as branching chain reaction which self-reproduces exponentially and results in an explosion. Indeed, historically, the idea of a branching chain reactions was conceived and pioneered in inorganic chemistry in the 1920s in the context of analysis of combustibles and explosives. In the 1930s analogous reactions were discovered in nuclear physics and in astrophysics.

The Russian physical chemist Nikolai N. Semenov (1896-1986) showed that combustion and violent explosions could be explained by assuming a chain reaction which proceeded in a tree-like fashion and called it branching chain reaction (1934). Each reaction initiated two or more new branches into the repetitively catalysed reaction pathway resulting in an exponential reaction rate which was manifested as an explosion.

In 1938 the Austrian-born Swedish physicist Ilse Meitner (1878-1968) and her nephew and colleague British-Austrian physicist Otto Frisch (1904-1979) realised the possibility of a nuclear bomb based on a chain reaction triggered by the fission of a uranium atom whereby neutrons are released to trigger further fission's. At that time both Meitner and Frisch were subject to persecution by the Nazi regime in Germany and were forced to leave the country. Keeping the idea secret they informed only their US colleagues and subsequently the US government, which was to lead into a flurry of research to develop the first atom bomb. Frisch also coined the term nuclear fission.

The same year (1938), the German physicist Carl Weizsäcker (1912-) independently suggested that energy in the Sun and stars is generated by a catalytic cycle of nuclear fusion reactions. The next year, the German-US physicist Hans Bethe (1906-) explained stellar energy production as a reaction cycle whereby four hydrogen nuclei are converted into one helium atom and radiation, a fusion chain reaction known as the Bethe-Weizsäcker cycle or carbon cycle and more popularly as the hydrogen bomb.

CYCLIC CHAIN REACTIONS

The Norwegian-born US theoretical chemist Lars Onsager (1903-1976) showed how a cyclic chain reaction consisting of three reactions, one feeding the next in a triangular cycle, can arise from three independent reversible reactions when appropriate energy is induced into one of the reactions in the form of a quantum of radiation (1931). Moreover, if the inflow of energy into the system is continuous the reaction wheel continues to rotate like a water-wheel as long as input reagents and free energy to run the system are available.

A wheel-like reaction system produces at each cycle one set of its output compounds and can be called a reproducing system. In the case of a catalysed cyclic chain reaction it may well occur that one or more of the output compounds of the system are equivalent to some of the catalysts of the reaction cycle itself, *i.e.* an autocatalytic reaction which is the key to understanding the logic of self-reproduction of entire reaction systems. Namely, it is logically possible that a reaction cycle or system of cycles reproduces not only one or a few of its own components and catalysts but all the necessary constituents to reproduce itself as a whole. In such a case we have a self-reproducing or autocatalytic cycle or system of cycles.

The simplest types of autocatalytic cycles are single-loop autocatalytic cycles and cross-catalytic or mutually catalysing cycles. A single-loop autocatalytic cycle is capable of producing all of its components by itself whereas in a cross-catalytic cycle two systems complement each other so that all components of both are reproduced. Clearly, it is logically possible that more than two systems mutually complement each other's reproduction. Moreover, it should be noted that such a system does not need be fully self-reproducing. It may well be only partially self-reproducing if the missing non-reproduced compounds are available from the environment as fuel or nutritive.

In the 1970s the Russian-born Belgian theoretical chemist Ilya Prigogine (1917-) analysed a model of an autocatalysing chemical reaction system which he called brussellator demonstrating and quantifying it experimentally. Later other autocatalytic cycles and pathways have been described. The mechanisms underlying the mutual catalysis and synthesis of proteins from amino acids under the control of nucleotides (DNA and RNA) and the syntheses and replication of nucleic acids catalysed by proteins offer examples of mutual autocatalyses.

HYPERCYCLES

In the 1970s the biocatalytic reaction cycles of reproduction in the real cell were analysed and formal models developed in order to explain their logic in terms of reaction system topology and catalytic mechanisms. These studies were made by molecular chemists independently and uninformed of the results achieved earlier in computer science.

The German physical chemist Manfred Eigen (1927-) proposed a model for a class of reaction systems which reproduce their own constituting compounds, *i.e.* a self-reproducing set of autocatalytic cycles calling them hypercycles (1971, 1979). The model was aimed at explaining the logical structure of the reaction cycles involving nucleic acids and proteins as a cycle of cycles. He was motivated by the question of what would be the simplest possible system which could occur, survive, self-reproduce and begin to develop in terms of reaction kinetics in the natural environment. He also tried to answer the key question of how the very " right kind " of molecules and reactions could have come together to form the first hypercyclic system, *i.e.* the emergence of chemical life.

The hypercycle model accounted for the chemical and thermodynamic constraints of reaction kinetics as well as the logical possibility of emergence of such a system by chance, its survival, self-reproduction and evolution as a population of chemical reaction systems. However, it did not answer where, when or under what conditions this event and the subsequent evolution could have occurred. Also the character and order of intermediate steps of chemical evolution remained open since much of the evidence of intermediate steps have disappeared. Chemical archaeology and palaeontology of the early molecular life is bound to confine to materials available as viral, bacterial and multicellular fossils and as extant molecular machineries of cell chemistry in the living species.

AUTOCATALYTIC POLYMER SETS

In the 1980s the US molecular biologist Stuart A. Kaufmann (1986) proposed an other model of chemical life which he called autocatalytic polymer sets. In this model two catalytic reactions, one cleaving and the other joining, were combined and together with a few other compounds and reactions constituted a mutual feedback system which again was able to self-reproduce.

In principle, autocatalytic cycles and explosions are instances of positive feedback in open branching process structures. In closed-loop control negative feedback leads to a dynamic equilibrium whereas positive feedback leads to non-equilibrium and collapse, explosion or, as in the case of living systems, to self-reproducing, growing, self-organising and developing systems. In this respect life, too, can be seen as a bomb, although a relatively slow one compared with simpler inorganic chemical or nuclear bombs, for reasons of their highly complex and open structure, slow transportation of chemical by circulation and diffusion and complex interlocking of the nearly dynamical equilibrium reaction pathways.

Under appropriate structural and functional conditions positive feedback in a robust closed-loop architecture's can lead to continuous growth and recursive development of the system rather than to a transient explosion and collapse.

THEORY OF SELF-REPRODUCING SYSTEMS

The discoveries made in chemistry and physics demonstrated that isolated, branching and cyclic chain reactions and reaction systems were found not only in the living but also in the non-living nature. A general theory was emerging to explain how nuclear, chemical, biochemical, cellular and multicellular systems are able to procreate by making copies of themselves by themselves.

Without the mechanism of self-reproduction life as we know it would never have emerged on earth since any non-self-reproducing life-like formation would have become extinct in one generation. Although life is characterisable by many attributes and functionalities other than self-reproduction such as metabolism, locomotion, various internal and external controls, senses, learning, etc., the mechanism of self-reproduction remains the most fundamental and indispensable precondition for the emergence and survival of life.

In the 1940s the idea of cellular automata and self-reproducing systems were conceived and considered in terms of logic and their relevance to biology was demonstrated. In the 1960s the ideas were developed and published. In the 1970s they were popularised along with the spreading of personal computers and the game called " Life " developed by US mathematician John Conway and publicized by the US mathematician and science writer Martin Gardner. The idea of self-reproduction was formulated into a general theory of autopoietic systems in which the principles was extended to analogous processes in social, economic and cultural systems.

Cellular Automata

The idea of a self-reproducing machine was first conceived in 1929 by the British crystallographer John D. Bernal (1901-1971). It took, however, two decades before it was considered theoretically and as an engineering challenge. The logical possibility of self-reproduction was solved mathematically in the theory of self-reproducing automata formulated by the Hungarian-US mathematician and computer scientist John von Neumann (1903-1957) in 1949. Later other kinds of models in terms of automata, algorithms, functional programs, computer viruses etc. were developed. These ideas and results allowed the logic of self-replication to be formalized and then applied to biochemistry, genetics and other fields.

In 1949 von Neumann held at the University of Illinois a series of lectures with the title Theory and Organization of Complicated Automata asking whether it would be possible to design and construct a machine that would assemble machines similar to itself, *i.e.* a self-assembling or self-reproducing machine. He first tried to configure a kinematics model of a machine assembling machines of its own kind from ready-made parts but failed because the design turned out to be exceedingly complex as a mechanical contrivance.

Then, his colleague Polish-US mathematician Stanislaw Ulam (1909-1984) suggested him to analyse the problem first in terms of logic, specifically as logic machines which he called cellular automata. Ulam's cellular automata were logical configurations in computer memory represented by analogous dot configurations on a square grid and their transitions whereby new dots were born, survived or died depending on the occupancy of their neighbouring squares. As a result deterministic but astonishing developments of dot patterns followed some of which turned out to be capable of self-reproduction.

The idea of an automaton had been proposed in 1936 by the US electrical engineer Stephen C. Kleene (b. 1909). The notion of a cellular automaton had also been anticipated by the German electrical engineer Konrad Zuse (1910-

1995) who designed and built the first programmable electric computer during the second World War (1941).

With cellular automata von Neumann succeeded to demonstrate that self-reproduction was indeed logically possible. His lecture notes General and Logical Theory of Automata (1951) were posthumously edited and published as Theory of Self-Reproducing Automata (1966). Von Neumann realized also that there was a lower bound to the complexity of machines capable of self-reproduction. His solution involved 29 logical states, which is not the simplest possible but still simple compared with the natural mechanism of self-reproduction of the living cell.

In operations research and economics von Neumann is known as the founder of the theory of games (1944) together with the US mathematical economist Oscar Morgenstern (1902-1977). Therefore, it is not far-fetched that he also speculated with a scenario of self-reproducing automata encountering each other whereby conflicts and collisions would arise and lead to struggle for survival in the memory of the computer, a computational metaphor of the real game of life and evolution (*cf.* Gr. *gamete*, wife, *gametes*, husband, *gamos*, marriage), the oldest game of life.

In computer engineering von Neumann invented the principle of stored-program memory (1946), the idea to store both program and data in the same memory which made the modern universal computer possible. This idea, too, is relevant to living systems since it allows us to see the real world as a memory made out of elementary particles, atoms, molecules, quantum states, events, and interactions, *i.e.* as a quantum computer, and the nature and anything that happens in it, including the processes of life and evolution, as computations of programs written in the same language as the data they process, *i.e.* atoms and molecules.

Von Neumann is known also for his works in mathematics and mathematical physics as well as for his role in the Manhattan project under which the first atom bomb was developed. It is paradoxical that both life and the most serious threat to it involve the same principles and theories of self-reproduction, games and computations.

AUTOPOIETIC SYSTEMS

In the 1970s the Chilean biologist and computer scientist Fransisco Varela (b. 1946) together with his colleagues neuroscientist Humberto Maturana and computer scientist Ricardo Uribe developed a general theory of self-reproduction which they called autopoiesis (1974) (Gr. *auto*, self + *poiein*, create, compose, lat. *poema*, poem, *cf.* Finn. *poikia*, give birth, *poika*, son). They defined an autopoietic system as any system capable of maintaining its functions and of self-reproduction irrespective of its other characteristics. Thus, hypercyclic and autocatalytic reaction systems, self-reproducing cellular automata, recursive functions, computer viruses, etc. were examples of different kinds of autopoietic systems. Analogous processes could be seen to occur on other levels of systems such as neural systems, thinking, natural language and communication, social and economic systems as well as political, religious, philosophical and scientific ideas and ideologies. Today, we are witnessing the emergence of a new sphere of autopoietic systems, the world wide web and artificial virtual realities, worlds and cultures.

Artificial Life

In 1987 the US anthropologist and computer scientist Christopher G. Langton (1989) coined the term artificial life (AL), more popularly also A-life, and organised the first workshop on the subject in Los Alamos, where the first atom bomb had been developed. The term was derived in analogy to another field of applied computer science, artificial intelligence (AI), which had been defined and founded about 30 years before (1956) by the US mathematician and computer scientist John McCarthy (1927-) together with Claude Shannon.

The task of AL was to study natural and artificial lifelike systems and behaviour by means of theoretical analyses, simulations and realisations of man-made engineering designs and constructions such as computer programs, agents, robots, etc. The aim of AL was to complement the traditional biosciences which were concerned with the analysis of life-as-we-know-it and to put it into a new and wider perspective of life-as-it-could-be.

Since then AL has established itself as a multidisciplinary field with regular international conferences and has shown its potential not only as a branch of science and engineering but also of art and a flourishing business in the entertainment industry. In science AL has became an umbrella for many earlier isolated multidisciplinary developments intersecting life sciences, mathematics, computer science and engineering such as robotics, biomechanics, prosthetics, biotronics, biocybernetics, genetic engineering, genetic algorithms, evolutionary computing, metabolism, neural computing and extending to sociology, ecology, ethology, semiotics, cognitive science, philosophy life and mind, virtual realities, etc.

These developments are blurring old distinctions between mathematical, natural, life, human and social sciences and cultural studies as well as between the classical, modern and post-modern science — a characteristic of the emerging new paradigm of postdisciplinary science. Moreover, they are upsetting our conceptions about life, mind and consciousness by placing the fundamental questions of philosophy — the differences between living and non-living, mind and matter, natural and artificial, etc. — into a new perspective.

Philosophically and conceptually, artificial lifelike systems are based on the principles of systems theory, analogy, model theory, functionalism and the theory of metaphor which allow to identify the essential, common and dissimilar features between different kinds of systems — living and non-living, natural and artificial, physical and logical, real and symbolic, bodily and mental, material and spiritual etc. The new paradigm of science promises to answer many fundamental questions of philosophy, many long-standing open questions of science and to bridge many of the prevailing gaps of understanding and initial-causal explanation created by the compartmentalisation and inability of the classical and modern sciences to deal with the dimension of complexity.

Conclusions

Life and mind are the most complex natural phenomena known to man, so complex that no single principle or theory is able to explain more than perhaps one or a few aspects of many. This is the reason for the multitude of various isms in the traditions of religions, philosophy and science. During the past two thousand years the conceptions of life have evolved from myths of creation and philosophical speculation to scientific explanations ranging from descriptive, empirical and analytical to the theoretical, systems theoretical and computational paradigms. Classical physics was able to explain the energetic and entropy conditions of life but not its systemic, control, self-organizing, growth or developmental aspects which required the results of systems theory, cybernetics and complex dynamics. These, in their turn, failed to explain the logical and computational principles underlying the prime mover of life — the architecture and energetics of self-reproduction.

The logical and computational mechanisms of self-reproduction are a striking example of the principle of emergence — the becoming into being of a new quality, function or ability as if out of nothing and by itself as the result of accumulation of an appropriate level and kind of complexity and architecture in a system — a phenomenon known as the system effect, synergy or emergence — the becoming into being of a new whole capable of accomplishing something that was only potentially possible before.

Life and the entire biological and cultural evolution can be seen as processes of potentially unending emergence of ever new forms, structures, functions, behaviours, abilities and faculties which continue to accumulate around the self-reproducing engine run by the minimum principle, the phase rule and free energy. In the geological and biological time scales autocatalytic cycles and their associated reaction pathways have become interlocked into progressively complex and varied configurations depending on the different and continuously changing and coevolving environmental conditions and effects. The availability and flow of energy into and through the fundamental engine of life and its accumulation into its various forms of chemical, biochemical, subcellular and cellular mechanisms and pathways have given rise to the emergence of ever higher levels and more complex forms, structures and functions and systems on the neural, mental, social and cultural including technological levels.

At certain stages of chemical and biological evolution other important mechanisms — such as the genetic code, sex, various catabolic, metabolic, endocrine and immunological mechanisms, pathways and organs — have similarly emerged as results of blind mutation, variation and recombination as results of replication errors and other external and internal effects and become incorporated into the living systems to be passed on in their genetic code and the self-replication mechanism. The fundamental chemical engine of life has proven — during the past four billion years — powerful enough to support the entire chemical, biological and cultural evolution's and to cause further levels and evolving and coevolving systems to emerge. At the turn of our millennium we can already observe the emergence of the next stage of evolution — the digital space anticipating computational culture and machine evolution and coevolution with the human civilisation.

To conclude, the fundamental physical and thermodynamical conditions under which life became possible, runs, survives and evolves and coevolves are the same as those of any phenomenon in nature, living or non-living, namely :

1. the minimum principle (the principle of least resistance, anything that happens the way of least effort in terms of relaxation of energy potentials in the nature and the entire universe) ;

2. the energy law (the law of conservation of energy, according to which it can become converted from one form into other but not created or destroyed) ;

3. the entropy law (the law of dissipation, according to which at any event whatever happens in the nature and the entire universe free energy is slightly dissipated into lower forms).

Although the overall trend in nature and the entire universe tends toward decay and death it is still possible that locally and temporally processes opposite to the mainstream occur provided that certain conditions as to the architecture and energetics of the machinery are met. As peculiar to and determining of the most essential qualities of living systems — natural or artificial — as contrasted with the non-living, suffice one first principle and two conditions, namely :

4. the logical possibility of a chemical mechanism of self-reproduction (an autocatalytic self-reproducing hypercyclic chemical reaction system, the wheel or engine of life) ;

5. the phase rule (Gibbs' function) of chemical thermodynamics (which guarantees that the wheel is energetically and thermodynamically able turn and the engine to run) ;

6. availability of free energy and matter, *i.e.* fuel and raw materials for the wheel to continue to turn and the engine to run, self-reproduce and evolve.

The logic of the basic mechanism underlying and supporting all life is the chemical wheel which complying with the minimum principle and the energy and entropy laws is able *rotate* (Lat. *rota*, wheel, chariot, *rotare*, turn round, whirl, revolve, *cf.* Skr. *rta*, wheel, Finn. *rata*, orbit, Germ. *rad*), as conditioned by the Gibb's function of chemical thermodynamics and the energy condition of availability of free energy which constitute the necessary and sufficient conditions for life to run and to explain its running and the driving force behind it. For plants and lower organisms free energy and nutritive are available in the form of photons and inorganic compounds in the soil, water and air and for animals including man in the form of chemical potential energy accumulated in other species.

The logical possibility and conception by " chance ", or rather, by necessity, of the first chemical self-reproducing reaction system nearly four billion years ago was sufficient for life to emerge, start to run and survive, proliferate, evolve and coevolve on earth and to continue to do so as long as its conditions prevail on the planet. Moreover, they allow, at least in principle, the possibility of realisation by design other forms of life — chemical or non-chemical — by man. Clearly, the fundamental conditions and mechanisms do not explain the innumerable features, functions, abilities and faculties found in various living species which have emerged during the course of evolution, but still remain the main preconditions and first principles for their emergence. Other systemic principles are available to explain the emergence and functioning of mechanisms such as sexual reproduction, metabolism, the immunological system, the sensory and the nervous system, various control systems, learning, symbioses, ethology, etc., as well as brain and mind, mental functions, awareness, consciousness, art and culture, etc., characteristic to various species. These phenomena are, however, explainable by secondary, tertiary or higher order of principles and add-on features to the basic machinery.

From the philosophy of computing point of view, ultimately, life can be seen as a quantum chemical computation being executed in and by the nature as a special class of Turing machines, the self-reproducing automata. In terms of the computational view life is an initial-causal, parallel, recursive, self-reproducing, constructive, evolving, coevolving, learning and communicating computation which has led to the emergence of physical, chemical, biological, cognitive and cultural levels of computations. Thus, the missing link in the scientific explanation of life has been filled in by the theory of computation.

The computational paradigm of science has revolutionised our conception of life and is at the threshold of revolutionising our conceptions of mind, intelligence and consciousness. The computational view allows us to see the phenomena of nature, life, mind and culture in a unified conceptual and theoretical framework incorporating all levels of organisational and functional complexity, behaviour, action, interaction and play of energy with matter from the level of quantum events to cosmology and from atoms, molecules, reaction systems, self-reproducing cycles and living beings to mind, languages and culture. The latter include our creative thought, conceptions, discoveries and inventions as well as their realisations as cultural artefacts including spiritual culture as folklore, mythology, religions, philosophy, arts and science and culture including technology — tools, machines, computers, artificial life, machine intelligence, machine consciousness, etc. — as quantum computations of the nature rather than merely as man-made models and theories about nature, life and man himself.

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LITERATURE

1. G. Altmann, W.A. Koch (eds), *Systems — New Paradigms for the Human Sciences*, Berlin, 1998.

2. F. Capra, *The Web of Life. A New Scientific Understanding of Living Systems*, New York, 1996.

3. S.J. Dick, *The Biological Universe. The Twentieth-Century Extraterrestrial Life Debate and the Limits of Science*, Cambridge, 1996.

4. E. Hyvönen, J. Seppänen (eds), *Keinoelämä — Artificial Life. Tekniikkaa, luonnontiedettä, filosofiaa ja taidetta*, Espoo, 1995.

5. S. Linnaluoto, J. Seppänen (eds), " SETI — Search for Extraterrestrial Intelligence ", *International Interdisciplinary Seminar* (Star Days, 6-7 March 1993, Heureka, Vantaa, Finland, Espoo, 1993).

6. T. Kuhn, *The Structure of Scientific Revolutions*, Chicago, 1970.

7. L. Margulis , D. Sagan , *What is Life ?*, New York, 1995.

8. A.L. McAlester, *The History of Life*, NJ, 1977.

9. M.P. Murphy, L.A.J. O'Neill (eds), *What is Life ? The Next Fifty Years*, Cambridge, 1995.

10. J. von Neumann, *Theory of Self-Reproducing Automata*, Urbana, 1966.

11. K.R. Popper, *Conjectures and Refutations : The Growth of Scientific Knowledge*, New York, 1963.

12. E. Schrödinger, *What is Life ?*, Cambridge, 1944.

13. J. Seppänen, " Systems Ideology in Human and Social Sciences ", in Altmann and Koch (eds), *History and Philosophy of System and Model Thinking, Information Theory and Cybernetics* (1998).