

Fundamental principles of cognitive biology

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Abstract

Cognitive biology aims at a synthesis of data of various scientific disciplines within a single frame of conceiving life as epistemic unfolding of the universe (the epistemic principle). In accord with evolutionary epistemology, it considers biological evolution as a progressing process of accumulation of knowledge. The knowledge is embodied in constructions of organisms, and the structural complexity of those constructions which carry embodied knowledge corresponds to their epistemic complexity. In contrast to evolutionary epistemology, cognitive biology is based on the assumption that the molecular level is fundamental for cognition and adheres to a principle of minimal complexity, which stipulates that the most efficient way to study any trait of life is by studying it at the simplest level at which it occurs. Several principles of cognitive biology are similar to extremum principles of physics and may represent tight junctions between ontic and epistemic realms. A principle of minimisation of suffering is derived from the evidence of human conscious emotional experience. It has a bearing upon such notions as onticity, fitness, altruism, science, future of mankind. This principle, just as all the other principles of cognitive biology, is descriptive, not normative.

Key words

Algorithmic complexity, cognitive biology, complementarity, Gödel, epistemic complexity, epistemic principle, extremum principles, Jaynes, logical parity, minimisation of suffering, molecular recognition, ratchet.

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"A modern molecular biologist might paraphrase the poet Pope by saying, The proper study of mankind is the bacterium."

(Koshland 1977)

Introduction

The expansion of molecular biology, which has begun in the early 1960s, is both exciting and appalling. It is providing ever deeper insight into the mechanisms of functioning of the living cell. This enables, in turn, ever more powerful interventions into those mechanisms, with consequences which may be already transcending human capacity to foresee, evaluate and control. The results of manipulations with the nucleus of the cell may turn out to be more far-reaching than have been the results of manipulations with the nucleus of the atom.

Disquieting is the progressing instrumentalisation of molecular biology. More and more science is turning into technoscience, or even a sheer engineering. Priorities of research are being reoriented toward technology. In a highly competitive field of research, with complicated methods, instrumental knowledge has a priority. The situation in molecular biology has its parallels in other areas of contemporary scientific endeavour. Our instrumental knowledge, our ability to manipulate things and events, singled out and treated out of their context, is great, our understanding the underlying complexity, which results from their interconnections and of which they are parts, is poor and lagging behind. In addition, by assembling the disentangled things and events into new combinations we are creating new systems of unprecedented complexity.

The discrepancy in how little we know relative to how much we can do may be unique in the history of terrestrial life (but not, as it will be reasoned later, in the history of life in the universe). Doing and knowing have been so far a unit, two sides of the same evolutionary coin. Applying to non-human organisms they may be considered as two names for the same target of evolutionary selection. The precarious disparity in human knowing and doing, in cognition and behaviour, need be urgently diminished or abolished and this calls for setting priorities of scientific research

toward profound comprehension of human cognition and behaviour. Konrad Lorenz, who had been incessantly stressing this need (Lorenz 1983a), would be pleased to witness the recent upsurge of cognitive sciences.

In general, however, cognitive sciences aim at revealing *mechanisms* of cognitive processes. A danger of instrumentalisation and also of misuse of knowledge is considerable (Changeux, J. P., cited in Butler 1998). In a somewhat vague contradistinction of cognitive sciences is epistemology, which aims at understanding the very *nature* of knowledge: what is it, how is it possible, how it evolved, what is its role in the universe. Epistemology has been traditionally a major discipline of philosophy. However, recent attempts at its „naturalisation“, mainly under the name of genetic epistemology (Piaget 1967) or evolutionary epistemology (Radnitzky/Bartley 1987, Riedl/Delpo 1996, as well as the references therein), may be conceived of as a part of a process of detachment from philosophy of its hitherto genuine disciplines.

Philosophy does not produce knowledge, although it has been intended to do so; it has been and continues to be a source of emotionally and socially effective beliefs. Only some of them may, by chance, prove to map some features of the world into human-made reality. This statement does not underrate the importance of philosophy. As human longing for meaning and universal understanding springs up deep from the emotional ground, philosophy will continue to thrive (the backlash of postmodernism and the fashion of pseudoscience notwithstanding) and epistemology will continue to be part of philosophy. It is conceivable that epistemology as part of science may evolve not to become a natural science, but rather a formal science like mathematics, cybernetics, statistical physics, game theory.

Can molecular biology constitute a part, or even foundation, of „naturalised“ epistemology? Instead of serving just as a powerful instrumentarium in revealing the mechanisms of brain functioning, may it open a novel path toward understanding *the essence* of cognitive phenomena, including emotion and even consciousness? However subtle, or even futile, the distinction may appear at first sight, it may, in fact, have a profound meaning. It would promote some views and concepts of molecular biology, successful so far mainly in instrumental science, into the realm of conceptual science. A „bottom-up“ approach to epistemological problems, that encompasses molecular biology, has been called cognitive biology (Kováč 1986a). Owing to its ample use of concepts and reasoning of thermodynamics, it may be considered as an

outgrowth of bioenergetics (Kováč 1986b, 1987). Some pioneering ideas have been formulated by Goodwin (1976). The main credit should be given to Hans Kuhn. For him, life from its very beginning, starting from self-copying nucleic acids, was an unceasing process of accumulation of knowledge (Kuhn 1972,1988).

This paper is a short outline of essential principles which, altogether, provide a rationale for cognitive biology. Their list is not exhaustive. Although some of them may appear to have a normative character, it will be argued that they all are descriptive. Their more formal and detailed description will be subject of subsequent publications.

Elaboration of conceptions

1. The principle of logical parity

Regarding the interest of biologists in the most various aspects of human cognition it is rather surprising that little attention has been given to the biology of logic. Even in studies of evolutionary epistemologists such considerations are rare. Popper insisted in his early writings upon a strict separation of logic and psychology in the analysis of scientific discovery (Popper 1957). According to Vollmer (1987, p180), the foundation of logic is one of the most difficult problems and is hitherto unresolved. It can be inferred that for Lorenz human logic was a species-specific outcome of the human evolutionary trajectory, yet correctly reflecting relevant features of the world (Lorenz 1973). On the other hand, for Piaget, logic is not innate to any human individual in the sense that it exists at any age. Logico-mathematical structures are extracted in the course of ontogenesis from operations on the surroundings; accordingly, there are a sort of abstract manipulations of the adult human subject with the objects in his/her environment (Piaget 1967). Probably the most extensive analysis of the evolutionary nature of logic has been provided by Riedl (1979,1992). According to him the evolution of logic is closely linked to the evolution of language and logic is also determined by a language. European logic with its subject/predicate structure is conditioned by the structure of European languages and may differ from that of Chinese.

Against the view that logic is „human-specific“ or even „culture-specific“ and that a number of internally consistent but mutually excluding logics may be feasible in the world, it may be argued that computers, non-living machines, do obey the rules of formal logic. A rather naive rejoinder may point out that it need be so because the computers are the invention of a single culture, the same that has „invented“ formal logic. Less naive may appear another rejoinder stating that the operation of computers must be isomorphous with the operation of the human mind, not culture-specific but necessarily species-specific just as the mind itself is, since the computers are just „*exomental instruments*“ (in analogy with mechanical tools and machines that have been called „exosomatic instruments“ by Lotka and the term popularised by Georgescu-Roegen (1971, p307)) of the human species.

It will be shown later by evolutionary reasoning that the computer metaphor of the human mind is misplaced and misleading, and accordingly the two arguments with the computers lose substance. It seems feasible that, in the course of evolution, motor behaviour of living organisms, mechanical work on the surroundings, moving and rearranging objects in space and time, has been continuously becoming less overt, has been internalised, more and more reduced to pretended actions, transformed into internal virtual manipulation with the objects. The final achievement of this ever-growing abstraction may be human thinking - an abstract motor behaviour. Vollmer (1987, p104), referring to Lorenz (1943), considered „das Hantieren im Vorstellungsraum“ (handling in the imagination space) as the initial form of thinking.

An object cannot simultaneously be and not be at the same place; two different objects cannot at the same time occupy an identical region of space, etc. But this is precisely what is being said, in abstract terms, by logic. All rules of formal logic are nothing but an abstract translation of the physical necessity. By implication, logical operations of our mind or of our computers are mere tautological *translations*, applied in order to make the facts of the world more comprehensible to us. Due to these operations we are able to organise our sensations and conceptions to *construct* reality. Reality is, indeed, species-specific and also culture-specific, and to a considerable extent even individual-specific, but there is no species-specific or culture-specific logic: Logic and the world are the same thing, split into two by the construction and limitations of our mind. This separation, illusory duality and, at the same time, complementarity of the world and the mind, is being named the principle of logical parity.

The logic as a phenomenon resulting from the world/mind splitting is a ground on which the logic as a formal science, with all its branches (such as relational, modal, temporal, deontic logic), has been built up. Only the latter is, as science in its entirety, our construction, part of human-specific reality. It should be properly called *the science of logic*. It helps us to create and categorise concepts in such a way that they facilitate our understanding of the world (the conceptual aspect) and our manipulation with the world (the instrumental aspect). Cognitive biology insists upon a clear definition of concepts, chosen according to a criterion of their maximal conceptual and instrumental usefulness, stipulating that all concepts belong to the reality and none of them to the world.

It would be too pretentious to label the principle of logical parity by another name: the principle of general complementarity. Considering other limitations of the human mind, Bohr introduced a principle of complementarity to account for particle-wave duality of quantum physics. We live in a world of „medium“ dimensions, a macroworld. (This is the term standardly used in physics. It corresponds to the term „mesocosm“ proposed by Vollmer (1987).) Our mind can perceive phenomena of this macroworld and to conceptualise them appropriately, but has not been constructed to conceive of the microworld, the world described by the mathematical formalism of quantum physics. To give this formalism a „human-tailored“ explication we have to take recourse to our percepts and concepts fitting the macroworld. This is why we conceive of an electron as a particle in explaining the results of one experimental arrangement and as a wave in interpreting the data from another experimental arrangement.

According to Bohr (1964) we have to apply the same principle of complementarity in explaining brain-mind dualism. Following his reasoning we may call the pertinent world the „psychoworld“. It seems that a similar principle may be needed for explaining phenomena of the „megaworld“, the world of galaxies, the subject of cosmological inquiry. Our world is not of „medium dimensions“ in space only, but also in complexity. Complementarity of the „psychoworld“ may be mainly conditioned by its „high-dimensional“ complexity. This is why we may need the principle of complementarity in our analysis of still another world, the „socioworld“: a world created by cultural evolution, which, by its complexity, may escape straightforward human understanding and need several complementary explications, each of

them internally consistent and all of them mutually incompatible. The duality world/logic may underlie all these other complementarities.

The principle of logical parity has a bearing upon the concept of rationality. It will be shown later that it may be useful to distinguish conceptual rationality and instrumental rationality. Each of the two represents not a state, but a process. In both of them the aim is to connect two distinct points by a trajectory. Ideal rationality corresponds to the shortest trajectory which, in a simple case, would be a straight line. The complete absence of rationality is represented by random walk. The „real“ rationality, including the „bounded“ rationality of humans (Simon 1983), is situated between the two extremes, and is conditioned by the amount of available knowledge. It is immediately apparent that the concept of rationality is on a par with the concept of extremum principles in physics, which seem to be the basis of all fundamental laws of nature (Feynman et al. 1966b). There must be a profound meaning in this parity that has not been sufficiently appreciated yet.

If physical necessity can always be translated into logical necessity, the inverse translation is also a possibility (except that logic deals with all feasible worlds, not just the one created by the contingencies of evolution of our universe). What is logical, is always possible, either virtually, in principle, or as a fact of nature. Darwinian interpretation of evolution has been generally considered to be a theory, a useful explanation of our observations of living nature. It is not a theory. It is a logical necessity and, by translation, a fact of any universe containing self-replicating entities. In any environment, containing restricted amount of resources, exponential growth, competition and selection of self-replicating entities are ensuing automatically. Biological evolution is but a particular case of the fact of evolution (Eigen/Winkler, 1975). The replicator equation (Schuster/Sigmund 1983) is one of the most fundamental equations of the universe.

But how to prove that our universe, with its logic of self-replicating entities, is not virtual? This will be a matter of the last principle of those enumerated here.

2. The principle of double epistemic closure

There is a universal characteristic of any living system to sense relevant features of its surroundings and to react appropriately upon them in order to preserve its own

permanence, its *onticity*. Indeed, the relevance of the features is determined by their value, positive or negative, for the maintenance of onticity of the particular living system; those which are neutral have no relevance and are not being sensed. The human species may have not differed for a long time in this characteristic from all other species, until the exuberant redundancy of the human brain has enabled cultural evolution. As cultural evolution has been progressing, myths, a species-specific adaptive arrangement assuring onticity by suppression of cognitive chaos and cementing group cohesion, have been transmuting into philosophy and later into experimental science. Once established, philosophy and science, by their autonomous dynamics largely independent of human intention, have made neutral features, of no biological relevance, subjects of human sensing and appreciation, and inciters of new forms of behaviour. Self-consciousness, itself possibly a product of brain redundancy, has been allotted with an additional new function: reflection of (and on) the world.

It appears, in a simplifying course-grained view, that for the majority of early philosophers of the birth-place of philosophy, the ancient Greece, human reflection had no limits, however restricted and superficial may have been immediate perception and cognition. The *logos* of Nature was considered to be isomorphous with the *logos* of human mind and thus fully accessible to human comprehension. Gradually, hesitations and doubts were accumulating and they found their culmination in Kant's transcendental philosophy. Kant's views on limits imposed on human cognition have been biologically reinterpreted by Lorenz (1983b). This reinterpretation, anticipated by a number of Lorenz's predecessors (listed in Campbell 1974) may be designated as *a foundation stone* of evolutionary epistemology. Pre-Kantian epistemological scepticism, for instance four kinds of „idols“ of Francis Bacon, may be easily reinterpreted and „naturalised“ in a similar way. Deficiencies of the human mind have been extensively analysed by all evolutionary epistemologists. Riedl did in several books and succinctly presented in a paper (Riedl 1995).

The limits of the human mind, its possibilities and constraints, imposed by contingencies of evolution of the species, seem to be insurmountable. Due to them, our reality, a model of the world, is species-specific. (Implying that other species construct their own species-specific reality.) They confined us to the world of medium dimensions and low complexity. The worlds outside are separated by barriers which may be called *Kant's barriers*. When we attempt to cross the barriers,

complementarity may be the only means of how to interpret the phenomena encountered there.

The species-specific delimitation of the cognitive capacities may be called the first epistemic closure.

There is another closure, more general and more fundamental. It was anticipated by a number of philosophers, starting from a minority of philosophical „dissidents“ in the antiquity (Protagoras, Timon, Zeno), through Hume up to Kant. It has first received a rigorous formulation in 1931 by Gödel in his incompleteness theorem. Gödel's theorem concerns formal systems of mathematics and restrictions imposed upon them (for a simple exposition see Nagel/Newman 1958, Hofstadter 1980, Penrose 1994). Whatever set of consistent rules one adopts for manipulating mathematical symbols in a system of axioms, there must always be some statement, framed in the language of these symbols, whose truth or falsity cannot be decided using those axioms and rules. In addition, in a closed system of finite axioms and rules, there is also no way of telling whether or not the starting assumptions are logically consistent or not. If one tries to solve the problem by adding a new rule or a new axiom, one just creates new undecidable statements. To understand the system of mathematics fully one must go outside mathematics.

As Hofstadter pointed out, it can have a suggestive value to translate Gödel's theorem into other domains, provided one specifies in advance that the translations are metaphorical and not intended to be taken literally (Hofstadter 1980, p696). Mathematicians have often shown irritation or scorn upon witnessing mathematical outsiders backing their scepticism in various non-mathematical domains by referring to Gödel. However, as shown by Chaitin (1990), Gödel's theorem can be seen not as an isolated paradox but a natural consequence of constraints imposed on cognition capacity by information theory. In the theory of algorithmic complexity (Kolmogorov 1965, Chaitin 1975), complexity of a series of digits is equal to the size in bits of the minimal program of the series. A system may be represented by a very long series of digits, but its complexity is low if the minimal program that will yield the given series consists just of a small number of digits. The information of the series is present in a „compressed“ form in the minimal program. If the minimal program is approximately of the same length as is the series, the complexity of the series is maximal, and its information cannot be compressed, because the series of digits is random. Since the minimal program cannot be compressed, it is always random. Within a system of

axioms and rules of inference, it can be proved that a series is non-random - by finding a program which is shorter in digits - but there is no way how to prove that it is random and cannot be compressed any more. A computer program running in order to find out this proof will never halt. In a formal system of certain complexity no series of digits can be proved to be random (that is, of maximal algorithmic complexity), unless the complexity of the series is less than that of the system itself.

This shows immediately that Gödel's theorem is related to Turing's halting problem (see Hofstadter 1980, p425), Tarski's theory of truth (Tarski 1949) and also Popper's falsification principle (Popper 1957). Indeed, all these formulations imply the same statement about a system of a specific complexity (which should be valid not only for algorithmic complexity but also for other conceptions of complexity): It is impossible - and the impossibility is grounded on logic, and hence, by translation, on the properties of the material world - to achieve a complete knowledge of a system of a specific complexity with the means available exclusively within the system; to achieve it one needs also means from another, larger system of greater complexity, a *metasystem*. The size of complexity of a formal system determines the size and the limits of its *epistemic capacity*.

Penrose's attempts to show that the conscious activity of the human brain transcends beyond computation (Penrose 1989, 1994) can be understood along this line. Human mind may be more complex than is complexity of formal systems of mathematics. If these systems, and logic underlying them, are translatable into properties of the physical world, the transcendence of the formal systems would imply that some novel, hitherto unknown, physical principles may govern the non-computational faculty of the conscious brain. A deep relationship between Gödel's incompleteness theorem and what he called a paradox of the human brain was already taken up by Kuhlenbeck (1982). He pointed out that our world of consciousness is a phenomenon of the brain, but our brain is also a phenomenon of the brain. Hence, a closure. To solve the paradox one would need another hypothetical brain that would be placed not in a domain of consciousness but in an extramental public space-time system. Gerlach (1988), who brought out this close relationship between Gödel and Kuhlenbeck, has proposed to acknowledge the merit of Kuhlenbeck by renaming the brain paradox and call it „Kuhlenbeck's paradox“.

Hofstadter has also analysed this problem. He maintained that there may be no fundamental, i. e. Gödelian, reason that would bar the understanding of the human

mind. It „may be completely clear to more intelligent beings“. (Hofstadter 1980, p707). - Unfortunately, biological evolution on earth has not supplied such beings yet.

Despite this evolutionary hint, the principle of the second epistemic closure is fundamentally different from that of the first closure: The statement that a system cannot be fully understood with the means of the system itself applies to any formal system, whatever is its complexity. It holds for any living systems, independently of the evolutionary contingencies which had shaped its cognitive abilities and, eventually, its species-specific reality. It is a principle of logic, not of evolution. In Kant's epistemology, both the first epistemic closure and the second epistemic closure are implicit.

Instead of evoking some divine „metabrain“ to achieve a most comprehensive understanding of the essence of human cognition, one can undertake an opposite approach: to reach first a full comprehension of cognition of living beings simpler than human. Since the complexity of simpler organisms is surely lower than is the complexity of human - and this may apply also to epistemic „formal systems“ of these simpler organisms - the human cognitive system may be conceived of as a „metasystem“ with respect to the cognitive systems of simpler species. An extrapolation of this knowledge towards human cognition may then be a way of how to circumvent the „Kuhlenbeck's barrier“. There is out of these considerations that stems the next principle.

3. The principle of minimum complexity

There are fundamental and unresolved issues associated with the definition of complexity. Indeed, this single word is commonly used to describe quite different characteristics of quite different systems. To avoid confusion, it will be attempted in this paper to use the word „complexity“ with an adjective in all cases in which unambiguous, and possibly mathematical, definitions are available, e.g. algorithmic complexity, sequence complexity, thermodynamic complexity, epistemic complexity. When used without adjective, it will mean an intuitive, even if rather vague, notion of something that is not simple, but complicated, compounded, organised.

Only a tiny part of what we know today of human heredity has been obtained in studies on human subjects. The major part has been a result of extrapolations from

studies on simpler organisms. From pea of the Founding Farther of genetics Mendel, *downwards* to the fruit fly of Morgan, still lower to yeast of Ephrussi and Lindegren and bacteria of Lederberg and Monod, down to the ground of the phage of Benzer, Delbrück and Lwoff, such has been a victorious *upward* path of genetics and molecular biology.

Max Delbrück, who had been a successful physicist, before he turned to biology, has particularly marked this trajectory. His ambition was to describe biological systems with a similar precision as had been applied to physical systems. It was obvious to him that, to achieve this goal, most simple biological systems should be chosen. This is why he studied phototaxis of simple fungi (*Phycomyces*) as a model of organisms' reacting at the external stimuli. Historical was his decision in 1937 to take up the study of bacteriophage: it may be seen as a start of molecular biology (Stent 1963). Bacteriophage can be considered to be the simplest living „thing“. The study of bacteriophage enabled the elaboration of the concept of the gene as a unit of heredity, an insight into the internal structure of the gene by intragenic mutations, the elucidation of the nature of genetic recombination. All this had been accomplished before nucleic acids were discovered as material carriers of genes and before biochemistry assumed the dominating position in molecular biology.

Delbrück's success in genetics, made possible by employing the simplest system exhibiting heredity, has inspired his pupils and collaborators to use a similar approach in another discipline of science, in neurobiology. *Aplysia*, an animal with just a few hundreds of neurones was studied and later another simple organism, *Caenorhabditis elegans*. The sequence of all genes of *C. elegans* has now been reported (*C. elegans* sequencing consortium 1998) and already the first comparative analysis of genes coding for neuronal functions has revealed a striking homology with many of highly conserved neuronal genes of mammals and of human disease genes (Bargmann 1998).

This experience, well-proven also in other branches of science, substantiates the formulation of a principle of both heuristic and conceptual significance: The most efficient way to study a concrete biological phenomenon is by studying it on the simplest organism in which this phenomenon can be found - here it is experimentally best accessible and, because of its evolutionary simplicity, theoretically the most comprehensible.

This is the principle of minimal complexity. To acknowledge Delbrück's merit, it may just well be called Delbrück's principle.

The principle would be easy to apply, almost automatically, if it were easy to detect the lowest evolutionary level at which the concrete phenomenon occurs. To find the lowest level is, however, the most difficult problem. The problem is linked to the question of homology and analogy. Two phenomena may be similar in appearance and nevertheless of entirely different evolutionary origin. Even if identical in form and function, their conceptual unification will only be a metaphor. A metaphor may be most misleading and may incite to naive interpretations. This is often the case when phenomena of a lower level are being explained by phenomena of a higher level, as is the standard case of antropomorphisms.

The question of homologies is connected with another difficulty. What should be the minimal resemblance and the maximal evolutionary distance to make it meaningful to speak of a homology? (Wray/Abouheif 1998). Comparative morphology has often faced this ambiguity. It is encountered in an elementary form in molecular biology when comparing sequence homology of nucleic acids or proteins. In a sense, all our genes originate from a single, evolutionary oldest, gene and relative to it all our genes are homologous. This, however, is a trivial statement of no explanatory value. A recent conference has amply shown how elusive the concept of homology is (Tautz 1998).

The essence of the problem becomes clear when we search for homology at levels higher than the molecular one. To what extent is social behaviour of mammals homologous to that of insects or even bacteria? Is human consciousness homologous to consciousness of other animals? If we assign to human 100% of consciousness, has the chimpanzee 80%, the mouse 2%, the fruit fly 0.01 and yeast 0.000001% of consciousness? The question concerns the very essence of cognitive sciences: is cognition a characteristic of all living forms, does life equal to cognition, or, in an opposite view, is cognition exclusively a human faculty? It is amazing that both extreme views coexist within contemporary cognitive sciences and have their respective supporters and militants. Even in evolutionary epistemology the views diverge (Heschl 1998, Vollmer 1985, p294). All aspects of this crucial question are too extensive to be dealt with here and will be a subject of a separate publication.

The core of the problem is obviously the phenomenon known under various names: emergence, fulguration, discontinuity, qualitative transition. To take up the

example of consciousness, mentioned above, if one did not admit that there must be a threshold for the evolutionary origin of consciousness, under which there is no consciousness at all, one would obviously end in panpsychism granting consciousness even to elementary particles. Some qualitative transitions, such as phase transitions in thermodynamics or percolation in statistical physics, have their rigorous mathematical underpinning. On the other hand, some qualitative changes have been described by science as only apparent, such as visual perception, with qualitative discontinuities in colour corresponding to continuous changes in wavelengths of the electromagnetic radiation. It is in this area that the major challenge for epistemology exists: some „phase transitions“ do occur in the world and are being translated into „phase transitions“ in species-specific reality; some others concern phenomena of the world with no repercussion in reality; still others - the vast majority of them may be of this kind - concern exclusively the reality endowing it with qualitatively distinct phenomena which have no parallels in the world (and this is made often still more complicated due to the nature of our concepts: all concepts are mutually demarcated, enforce discontinuities and parcel out, sometimes quite arbitrarily, the reality). To discern between these three different categories of qualitative transitions is a matter of empirical research and, hence, will always be provisional. This is why a choice of a subject of research, which would exhibit minimal complexity of the phenomenon of interest, must be mainly tentative and its adequacy remains to be proved subsequently by results of the very research.

At any case, the principle presupposes that there are levels of complexity in the living world and that, in the course of biological evolution, there has been a continuous growth of complexity.

4. The epistemic principle

Ever since Darwin there have been incessant discussions in biology as to whether biological evolution is progressive and has a direction. If there is progress in biological evolution, one can speak of simpler and more complicated, lower and higher organisms, one can attempt to find and define evolutionary tendencies or even formulate some laws of evolution. If there is no progress, such terms have no sense and may be refuted as antropomorphisms.

The substance of the argumentation of those who do not admit any progress in evolution is the statement that in a specific environment individual organisms - or, adopting a „gene eyes’ view“, their genes - compete with other organisms for a single utility: Darwinian fitness. Fitness is being achieved by various means. In the same environment different organisms optimise their fitness by adopting different strategies and many strategies may be equally successful. The environment for a single organism are not only physical conditions but also all the other organisms. Fitness of a single organism is therefore a highly dynamic function in which are variables the fitness of all other organisms. Man may appear to be an organism with a high fitness, with the present population number of 6 billions. However imposing the figure may be, it is negligible when compared with the number, or even with a cell mass, of bacteria. Some bacterial species have existed on earth since several billion of years, not much changing, and it seems probable that they will continue to exist after the species *Homo sapiens* will no longer be here. If they have survived for such a long time and also face a bright future, there is no ground for seeing a progress in evolution and no reason to label humans as higher, and bacteria as lower organisms.

The controversy about the progress in evolution may stem from a misunderstanding which is due to the ambiguous connotation of the word „progress“. In European culture, at least from the time of the Enlightenment, progress has been seen as something to be wished, something valuable, „good“. It has been considered as inevitable in cultural evolution: anything more progressive has had a better chance to push through, it has have, we may say, higher Darwinian fitness when compared with something conservative and retarding.

Omitting the normative connotation, the word „progress“ is left as a neutral, valueless expression of an evolutionary tendency. The tendency is undeniable: the tendency toward appearance of ever more complex organisms. The very fact that bacteria, with simple cell organisation and simple behaviour, are evolutionary old and man, a being with the brain as an organ with the highest structural complexity as has ever appeared in evolution, is a proof. The fact is not changed by the possibility that the fitness of bacteria may be higher than is the fitness of man. It is also possible that some bacteria are evolutionary younger than man and, at the same time, of low complexity. Such a possibility does again not argue against the universal evolutionary tendency, which may be pictured by a metaphor of a complicated *maze*: life incessantly, at all levels, by millions of species, is „testing“ all the possibilities of how

to advance ahead. The vast majority of the species perish or end in deadlocks where they survive with no possibility to advance. To advance - where, toward what goal?

Progress in evolution has its thermodynamic reason. Dynamics of the world is irreversible, directed by the second law of thermodynamics. Without that law, the world would have a Newtonian character: as an ideal pendulum in an ideal void it would persist in a monotonous, eternal movement, symmetric in time. In such a case, neither the evolution of life would have an arrow of time: Darwinian variations would resemble endless musical variations on a single theme. Natural selection would play reversibly with such variations.

As pointed out recently by Fontana et al. (1997, p210), resounding the recurrent focal question of contemporary biology, „selection has no generative power; it merely dispenses with the „unfit“, thus identifying the *kinetic* aspect of an evolutionary process. The principle problem in evolution is one of *construction*: to understand how the organisations upon which the process of natural selection is based arise, and to understand how mutation can give rise to organisational, that is, phenotypic novelty.“ In principle, the answer was provided already more than three decades ago by non-equilibrium thermodynamics: systems far from thermodynamic equilibrium spontaneously evolve to ordered states, called dissipative structures, as a result of fluctuations (Prigogine 1967). This, of course, is not a full answer: *constructions*, present in living systems, are mainly conservative structures, not dissipative, and the task remains to elucidate how the constructions, more and more complex, arise and how they are maintained. It is here that the value of the principle of minimal complexity comes to the fore.

It has been often argued that the origin of life must have been a highly improbable event, having taken place perhaps once in the history of the universe. A support for such a claim has been found, quite erroneously, in the second law of thermodynamics. It has been overlooked that the second law operates in the world governed by fundamental forces. In the field of forces elementary particles, atoms, molecules associate, forming larger units and the dissipation of potential energy has thus a creative role in generating structures. It seems now to be virtually sure that in any part of the universe, where the thermodynamic conditions of temperature and pressure are similar to those that had been those some four billion years on our Earth, life must arise as a physical necessity.

With the advent of self-copying nucleic acids another new quality has appeared in the universe: *molecular recognition*. There is no recognition between two atoms of hydrogen and oxygen which, under specific conditions, associate to form a molecule of water. The association is a physical necessity, it is a *nomie* process. The association of nucleotidetriphosphates with the macromolecular single-stranded template of self-replicating nucleic acid and the resulting Watson-Crick pairing of the corresponding bases is another kind of process. It is an *ex post* necessity, a pseudo-nomic process, behind which is hidden historical contingency: a selection of a macromolecule with a certain specific sequence of units (which, incidentally, may have been degenerate) from an ensemble of similar macromolecules: a molecule endowed with a specific function, and, hence, exhibiting teleonomy. In contradistinction to simple atomic or molecular associations, molecular recognition is a *teleonomic* process, a result of evolutionary contingency and selection.

A molecule with self-copying ability must have a certain minimal complexity; in this case, the sequence complexity. It is this complexity that enables the molecule to fulfil a function, to do a specific work on its environment, the result of which is the dynamic maintenance of the molecule's *onticity*, the molecule's survival. To be so, the molecule must have a certain minimal knowledge of the relevant features of the environment, there must be a correspondence, however coarse-grained and abstract, between these features of the environment and the structure of the molecule. In general, at all levels of life, not just at the level of nucleic acid molecules, a complexity, which serves a specific function, and only that, corresponds to an *embodied knowledge*, translated into the constructions of a system. The environment is a rich set of potential niches: each niche is a problem to be solved, to survive in theniche means to solve the problem, and the solution is the embodied knowledge, an algorithm of how to act in order to survive.

Hence, life from its very beginning is a cognitive system: the self-copying molecule, pursuing its onticity in the world, accordingly, the simplest teleonomic system, is already a *subject* facing the world as an object. At all levels, from the simplest to the most complex, the overall construction of the subject, the embodiment of the achieved knowledge, represents its *epistemic complexity*. It is the epistemic complexity which continually increases in biological evolution, and also in cultural evolution, and gives the evolution its direction.

What forced the original self-replicating molecules to increase in complexity in the course of evolution, to associate with one another and with other molecular species, to produce higher levels of complexity, and, hence, other levels of embodied knowledge?

In Spiegelman's experiments with self-copying of nucleic acid of the phage Q_B in an artificial system, evolution did not progress toward increasing complexity of nucleic acids, but toward its diminishing - the highest Darwinian fitness had the molecules which replicates at the highest rate and these molecules became shorter than the original one, with a lower algorithmic complexity (Spiegelman 1971). This should occur in a simple and closed environment. Evolutionary reactors operates under steady state, with constant influx of substrates and ouflux of products, but also under simple and constant conditions. Under such conditions there is a selection for simple, rapidly replicating molecules (Küppers 1979).

Different is the situation in the „evolutionary reactor“ of the world. Replicating systems are present in a „vessel“ of unlimited size, in an environment which is complex and steadily changing. A tiny change is enough to bring a rapidly replicating simple system into the environment which will its replication slow down or which will it destroy. Systems which are *accidentally* more complex and which would be, in an unchanging environment, eliminated, may gain advantage just because in their complexity a potential for „survival“ under the changed conditions may have resided. It may be said that their greater complexity represents a more complex formal system and thus a larger epistemic capacity of the replicating molecule as a *subject*..

The higher is the rate of replication of a complex system, the higher is the consumption of resources, the higher energy dissipation in the evolutionary reactor, the larger a distance from thermodynamic equilibrium. Increasing the distance from thermodynamic equilibrium continues also when conservative structures, constructions, begin to be built up, embodying ever greater evolutionary knowledge. For maintaining them, energy dissipation is no longer required: there are kinetic barriers which keep their thermodynamic distance and retard their transition into equilibrium.

This enables biological evolution to be a continual growth of knowledge: creation of subjects with ever greater embodied knowledge, ever less probable, placed ever farther from thermodynamic equilibrium. Biological evolution is *inventive*, and this is *the* reason why it is *progressing*.

It should be made clear that algorithmic complexity of the sequence of units in unidimensional space may have approximately corresponded to complexity of the first replicating nucleic acids. When nucleic acids have subsequently produced a more complicated auxiliary devices, membranes, tissues, individuals, societies in order to make their onticity much more robust, complexity of the systems has assumed a form which cannot be expressed in such a simple manner. Complexity of nucleic acids themselves of the genome exceeds their sequential complexity: it is a complexity consisting in appropriate timing of gene transcription, implicating not only three dimensions of the space, but also the fourth dimension of time (Jacob 1981, p89). It will be shown in another publication that this complexity is related to thermodynamic depth (Lloyd/Pagels 1988). And that, in order to express it, object and subject should be considered as a unit, in inseparable interaction, as pointed out in a different context by Grassberger (1989) and Gell-Mann (1994).

There is an intriguing relationship between epistemic complexity, fitness and truth. This will be analysed in another paper. An individual subject with high epistemic complexity exhibits robustness with respect to fluctuations in the environment. But also a large set of simple agents, such as a species existing in many identical copies, widely dispersed or closely collaborating, can be robust and survive under various attacks from the side of the environment, and even compete out complex subjects with much greater embodied knowledge, if the latter are sparse comparing to the former. It is this intricacy which serves as an argument to those which oppose the idea of progress in evolution. The intricate relationship is also obvious in cultural evolution. The saying that "a majority is always right" is far less trivial than it may seem. The relationship makes the epistemic "maze" more complicated but does not violate the universal evolutionary tendency.

Embodied knowledge enables teleonomic systems to proceed toward goals (underlain by the ultimate goal of onticity) by minimising the length of the trajectory. A virtually random walk at the beginning is being more and more biased in the course of evolution. In this sense, any teleonomic system is always rational, with the degree of rationality being determined by the difference between ideal trajectory, a straight-line (corresponding to the ideal rationality) and the biased zigzag trajectory allowed by the limited amount of the embodied knowledge.

The biological rationality has an essential shortcoming: it is always the rationality of Russell's hen (a recurrent theme of Riedl's epistemological analysis,

e.g. Riedl 1994). A hen, fed by a farmer, anticipates the future as a continuation of this beneficence with no idea that this is just preparing her for a pan. Even though anticipating, she does not see the future, the anticipation is essentially an extrapolation from the past experience. The only exception has appeared at the level of rationality of the individual human person: even though with great difficulties, man can have a restricted foresight and make prognoses. But this may well turn to be just a tiny flash in the history of life on earth. Cultural evolution, with autonomous dynamics of memes, may have a rationality superior to that of an individual human person, but it appears to be again no more than the rationality of Russell's hen.

It is so even in the case of science, a triumph of human rationality. As stated by Popper, a scientific theory „can only prove its „fitness“ to survive those tests which it *did* survive; just as in the case of an organism, „fitness“, unfortunately, only means actual survival, and past performance in no way assure future success“ (Popper, 1976, p103).

There is no reason of why self-copying molecules should not arise anywhere in the universe. On the basis of some reasonable assumptions from contemporary science, it can be easily calculated from Drake's equation (Drake 1990) that life must be a general phenomenon of the universe. The origin of life seems to be a nomic process, and only then teleonomic processes set in. As implied by the Copernican principle (Gott 1993), our earth, and our species, do not occupy any unusual, or exceptional, position in space and time. The universe as a whole is *epistemically unfolding* by creating localised foci at which processes of knowledge accumulation are running ahead. The maze metaphor, used to explain progression of life on earth but also the failure of the vast majority of actors to succeed and their inevitable extinction, should apply to the entire universe.

The tendency toward the epistemic unfolding of the universe is named the epistemic principle.

Our earth, our species, we are actors in the unfolding. We shall keep in mind: we occupy no privileged position in the universe. We have no reason to suppose that we have been elected. We have many reasons to assume that this has not been the case.

5. The principle of ratchetting

As has been pointed out, dissipation of energy in evolution enables not just the maintenance of dissipative structures but also the formation of conservative structures, constructions. Constructions are systems far from thermodynamic equilibrium, separated from it mainly by kinetic barriers. Thermodynamics of constructions has not been worked out. Growth of knowledge in evolution means the accumulation of ever more complicated constructions.

Dynamics of the living systems, at all levels of hierarchy, consists in uni-directional ratchetting. The idea of a ratchet has been introduced into science by Feynman, who used it to illustrate some implications of the second law of thermodynamics, in particular, that useful work cannot be extracted from equilibrium fluctuations (Feynman et al. 1966a). A simple mechanical ratchet consists of *a wheel with asymmetrically skewed teeth and a spring-loaded pawl*, which allows it to spin in one direction only and prevents backward motion. Molecular, evolutionary, developmental, cognitive, social ratchets are all based on this simple principle. At the molecular level, constructions allow life to use molecular ratchets: arrangements allowing to bias the Brownian motion of particles in an anisotropic medium without thermal gradients, a net force, or a macroscopic electric field (Magnasco 1993, Peskin et al. 1993, Astumian 1997). Random thermal motion of particles is rectified to serve a function, to do a useful work on the environment. A relation to the concept of rationality, as has been outlined above, is immediately apparent: random walk means „no rationality“, a straight line means an „ideal rationality“ (but also causal connection, *nomicity*) and anything in between means a „bounded rationality“. Molecular ratchets are devices exhibiting *molecular rationality* and may be considered as the prototype of systems with „bounded rationality“.

Molecular ratchets have been proposed mainly to account for working of molecular motors, such as muscle proteins or ATP synthase. In essence, however, even simpler proteins may function as ratchets. This may apply to the basic cognitive devices, molecular receptors. Brownian motion of a molecule of ligand is biased by the electric field of a receptor, ligand is being bound to receptor and a part of binding energy, instead of being dissipated straight away, is used to accomplish a molecular work by receptor: transfer of signal across the protein molecule. Ligand binding is coupled, *conjugated*, with signal transduction. This is an elementary form, at a molecular level, of a universal phenomenon of conjugation. Forms, numbers, and

levels of conjugations have been increasing in evolution. Described in these terms, life in its entirety is but a huge system of countless conjugations through which the flow of energy, starting from the radiation energy of the sun, is canalised, forced to jump by steps, through a few selected degrees of freedom, down to the inevitable sink of thermal energy, instead of being dissipated downright. In this optics, even the most complex human activities, including science and art, are just evolutionary inserts into the flow and the eventual dissipation of the solar energy.

The incessant inventing of constructions is itself a process of ratchetting. Evolution as a whole is a ratchet. Muller's ratchet has well been known in the evolutionary biology: accumulation of deleterious mutations, resulting in an increase of the mutational load and an inexorable, ratchet-like, loss of the least mutated class (Maynard Smith 1989, p241). Muller's ratchet is a virtual one, it may never operate, or perhaps, just exceptionally (Andersson/Hughes 1996): sex may have been an invention of how to prevent its operation. The preventive effect of sex may be amplified by outbreeding ratchets, which encompass various mechanisms to prevent inbreeding, including for instance *incest tabu* in humans.

An insight into the most elementary evolutionary ratchets has been provided by computer modelling of RNA evolution (Fontana/Schuster 1998). The probability of transition between two different RNA molecules, which differ from one another by a single mutation, is not symmetric: the destruction of a structural element through a single point mutation is easier than its creation.

The most effective evolutionary ratchet is made possible by Weismann's barrier, separating genotype from phenotype. Thanks to Weismann's ratchet, the entire battlefield of an individual organism's „Dasein“, with all its failures, disappointments, degeneration, senile resignation, is separated from the playground of the *evolutionary dicing*, which takes place at the genome level and, the case of parasitism disregarding, pushes the genome unidirectionally toward greater complexity. It is at this elementary, molecular level that is rooted the universal Campbell's „variation and selective retention“ phenomenon (Campbell, 1974).

It has been pointed out that evolution pulls organisms ever farther from thermodynamic equilibrium. It has been aptly put by Prigogine and his collaborators at a number of occasions (*e. g.* Nicolis/Prigogine 1987) that matter far from equilibrium is creative. The larger dissipation of energy, the more powerful is self-organisation and the more order is being created in an irreversible manner. To

appreciate the pioneering studies of Prigogine and his insight, we may call this working of evolution Prigogine's ratchet.

Ratchetting plays a major role in development. By a simple analogy, the excellent discovery of George Beadle from the early days of biochemical genetics, indicating that there is, generally, one gene coding for one enzyme - the „one gene-one enzyme“ hypothesis - might be transferred to morphogenesis by inferring „one gene-one morphological trait“. Notwithstanding the probability, that no scientist has ever attempted to make such a sweeping analogy, the assumption has long been a scapegoat of all brands of anti-neodarwinists and biological structuralists. In order to specify the activity of each gene, in each cell of a multicellular organism, at each state of development, the program controlling this process should be enormous and, instead of being characterised by a great, but manageable, complexity the organism would need be endowed with some miraculous „supercomplexity“. Perhaps even the ingenious metaphor of a cake recipe (Dawkins 1987, p294), less demanding of program space, may still be too pretentious. Instead, a kind of somatic Darwinian mechanisms may operate (Edelman 1987, Kupiec 1997, Britten 1998), constrained to such an extent that it must end in a quasi-determined final state, but without requiring a too excessive program and with no need of a central controlling authority, a „genome brain“ (or, for that matter, a „genome central committee“). At each step of morphogenesis, starting from two cells of the earliest embryo, various combinations of merely local associations, essentially stochastic or only slightly biased, may be occurring, but only the appropriate ones are developmentally retained by stage-specific developmental ratchets, which, by clicking round one notch, open a stage for new, higher-level associations. A complex global order is spontaneously emerging from exclusively local interactions of simple units.

This seems to be the universal principle of ordering in evolution, development, cognition and megasocieties's structuring. Again, the principle of minimal complexity suggests that molecular biology can make a major contribution towards its full elucidation. Nowadays, it may be receiving the strongest support from studies in artificial intelligence (Maes 1997): A complex behaviour emerges from the interactions of autonomous simple agents, situated in the environment, each of them assigned to fulfil a set of simple goals. There is no general planner, no internal structure corresponding to "the plan" of the system, no central representation shared by the agents.

Another principle is implicit in the principle of ratchetting. It may be called the principle of *hierarchical continuity of design* and loosely linked to Jacob's principle of tinkering (Jacob 1977). Evolutionary dicing combined with evolutionary ratchetting makes of evolution a process in which any new move must necessarily build upon the previous ones. Devices and constructions invented in the past are being remodelled into new ones and also serve to support the latter. Even if no longer functional, they are rarely thrown away but rather kept in store or disassembled and their parts used as in other combinations as modules for other purposes. This is also one of the reasons of increasing redundancy in evolution at all levels of biological organisation, from the redundancy of genes up to the majestic redundancy of human neurones, and, for that matter, of human culture. Increasing redundancy in evolution has been changing life *from game to play*. Adaptive behaviour has been complemented with *expressive behaviour*. Upon the onset of cultural evolution, the two forms of behaviour have been extended by an additional, *meme-enforced behaviour*.

Shaping and constraining evolution, the continuity of design is of fundamental importance in development. Much more strictly than in evolution, in development is any new move conditioned by all the previous moves. Because of continuous branching of developmental moves, previous moves recede deeper and deeper into the hierarchy. Since development is genetically controlled, the results of very early moves remain almost immutable. Any modification of the early genes of the embryonic stage, no matter how advantageous in itself, would presuppose a simultaneous accommodation of all the genes involved in later stages of ontogenesis - the probability of such a co-ordinated modification is virtually zero. There is a progressive and irreversible *encapsulation* of all previous achievements. This process has been named *generative entrenchment* by Wimsatt (1986). He has illustrated its virtual irreversibility at a model of a developmental lock: a digital cylindrical lock consisting of wheels, each with a number of possible positions, in which the correct position of a wheel is dependent on the actual position of a preceding wheel. The resetting of a wheel placed early in the process would incur the necessity to readjust simultaneously the correct positions of all subsequent wheels, but not in the other way round. Indeed, the digital developmental lock may be interpreted as representing a sort of developmental ratchet. A case in point demonstrating ratchetting, with both continuity of design and tinkering, is the gene *Pax6* (Desplan 1997). A gene, the

initial function of which was to regulate photoreceptor differentiation in a primitive "eye" formed only of photoreceptors, has been promoted to the contemporary position of a master regulator in eye formation in flies, mice, and humans. It controls the genes that were added later in evolution as the eye was becoming more complicated.

The same general principle underlies human cognitive ontogenesis. With *imprinting* at the bottom, through the very first filling in of the genetically determined abstract, but nevertheless specific, mind's „letterboxes“ with concrete concepts, ideas and habits (*incipation*), through contingencies of reinforcement up to the conscious reflection. And, at all levels, variations, local interactions, selective retention by the imposed cognitive ratchets, new levels built up upon the unmoveable deeper levels, resulting in a unified, coherent and dynamic structure. Generally, the earlier in individual life has a cognitive module been assembled, the more resistant is it to any subsequent modification. It has been argued that Husserl's notion of *Lebenswelt*, taken over by existentialists, unique to every human being and apparently inaccessible to others, corresponds to the reality constructed in this idiosyncratic way in ontogeny of every individual (Kováč 1992). By extension, specific human cultures arise and evolve on the basis of the same principle (Kováč 1999).

Ratchetting in evolution, in development, and in cognition fulfils the same essential function: it allows step-wise accumulation and meaningful application of knowledge and prevents its futile diminution or degradation by running the process backwards. Ratchets operate at many hierarchical levels, from molecules up to megasocieties. The concept of *granulation*, analogous to the concept of graining of statistical physics, is instrumental in analysing these hierarchies. It will be dealt with in a separate paper.

6. The principle of minimal prejudice

„Von Anfang an muß das Leben ausgestattet gewesen sein mit allgemeinem Wissen, dem Wissen, das wir gewöhnlich Wissen von Naturgesetzen nennen. Selbstverständlich nicht Wissen in dem Sinne vom bewussten Wissen.“ (Popper 1987, p32.) This is an unfortunate formulation. It may have been one of the reasons why Popper supposed that the origin of life must have been an „unbelievably improbable“ event. Life is *constrained* by *all* laws of nature, but this does not imply that, from its

very beginning, it should know them. Popper himself, like all evolutionary epistemologists, asserted that knowledge of an environment means *adaptation* to it („...die Anpassung des Lebens an seine Umgebung ist eine Art von Erkenntnis“). This clearly implies that adaptation to a simple environment is equal to a simple knowledge and that, in the course of evolution, the continuous increase in complexity of niches which life can occupy means a continuous growth of knowledge - hence, the continuous increase in epistemic complexity.

Limited knowledge was a major cause of the extinction of species. The laws of nature have enforced themselves mercilessly when life did not know them. Ambiguous with regard to extinction has been another characteristic of living beings: inflexibility of beliefs, fanaticism. Organisms are *fanatics*. Simple organisms with no capacity to learn, and even self-copying nucleic acid molecules, are absolute fanatics. Organisms do not invent and maintain hypotheses, they abound in *beliefs*, and only some of these beliefs represent, in a specific environment, pieces of knowledge. Which implies that only some of the constructions of organisms are embodied knowledge, the others are but *embodied beliefs*. Once adapted to its environment, a simple organism remains totally inflexible. If we take a mutation in a bacterium as a new belief about the environment, we can say that the mutant would sacrifice its life to prove its fidelity to that belief. In organisms with learning capacity the situation is not as different as we may assume: as already mentioned, the principle of continuity of design takes care for maintaining and preserving in the course of individual life those beliefs and that behaviour that had been acquired early in ontogeny. From the point of view of the common gene pool, this has been nevertheless largely an adaptive arrangement: it is one of the main source for generating and maintaining polymorphism, for survival of a species in fluctuating environment and, by increasing variance, for enlarging its evolutionary potential. Under a specific fluctuation, some fanatics would perish while others gain in fitness; upon a swing of the environmental pendulum into the opposite direction, the chances would turn round; but species, consisting of pure liberals, of pure sceptics, or of pure opportunists would not be robust enough to survive the fluctuations and would get extinct.

The human species has been no exception. Man, like all other animals, is not a Popperian rationalist eager to expose his/her explanations of the world to testing and ready to replace them by new ones. Human beings are *mythophils*: they firmly stick to their beliefs, often ready to die for them just as sturdily as are ready the bacteria.

The environment, in which our main mental dispositions have been shaped by selection, did not favour fitness of individuals who were irresolute, hesitating, tolerant, amazed at the complexity of the world and susceptible to cognitive chaos and existential anxiety. There must have been also a strong selection pressure for group conformity. Myths, unmoveable, indisputable, all-encompassing and omniscient explications of the world, have been most efficient group „glues“, making of a group a powerful unit and exacerbating intergroup competition. They continue to fulfil this function in their contemporary form of ideologies. The „deficiencies of human reason“ (Riedl 1995), generating cognitive illusions and extremely biased prejudices, function as an excellent nutrient medium for exuberant growth and spreading of the memes constituting collective myths and ideologies. A particularly important cognitive illusion for reinforcing group cohesion is individual's *self-deception*: Socrates' maxim „Know yourself“ must be much more difficult to achieve than anybody of us in our self-deception would admit.

It has been said repeatedly that many features of the physical and mental outfit of humans, selected for life in small nonanonymous groups of hunters and gatherers in the savannah, may no longer be adaptive in the socioworld created by cultural evolution. Experimental science, a unique invention of European culture, may provide a partial corrective. Not so much by conscious activities of scientists - an individual scientist may be no less a mythophil than is a layperson, he/she firmly sticks to his/her beliefs - but by its manner of how the world is being transformed into reality: experimental results allow no biases in rationality, they must conform to the laws of nature, underlain by the extremum principles. They impose upon the work of scientists a principle, which itself is an extremum principle, and which runs counter human „natural“ mental disposition: the principle of minimal prejudice. It may be called Jaynes' principle, according to a physicist who first gave it a precise formulation. It has been anticipated by many philosophers and scientists by such ideas as Occam's razor (Russell 1961, p462), economy of thought (Mach 1923), parsimony (Sober 1992).

Jaynes has given the principle a mathematical formulation. According to him, if one has an incomplete knowledge of the subject, the minimally prejudiced assignment of probabilities is that which maximises Shannon's entropy, subject to the given information (Jaynes 1957). The corollary of his argument has been the demonstration that the laws of thermodynamics can be derived as consequences of the principle. The

thermodynamic entropy of Clausius becomes a special case of Shannon's entropy if one asks the right question. It may not be too exaggerated to expect that foundations of some other disciplines of science may also be derived from Jaynes' principle.

There is an obvious link between the principle of minimal prejudice and the notion of rationality sketched above. And yet, there have often been reflections on rationality in which the principle of minimal prejudice has been violated. Rationality has been almost exclusively considered to be a matter of reasoning, of mental calculation, of conscious appreciation of profits and losses. A „*wisdom of the body*“, achieved by evolutionary selection, has been ignored, a possibility of rational action has been denied other animals, rationality has been ascribed to the individual human person and nothing has been known of the superior rationality of adaptive dynamic systems. And, above all, rationality of emotions and their decisive role in meaningful behaviour has not been recognised. The belief in the power of the individual human reason has been a strongly biased prejudice, particularly in European culture. A prejudice that has no evolutionary justification.

The very principle of the minimal prejudice substantiates the next principle of cognitive biology.

7. The principle of minimisation of suffering

If bacteria had consciousness and were capable of self-reflection, their world view would be definitely „bacteriocentric“. The same would hold for rats, except that the latter would construct reality that would be „rattocentric“. The former and the latter would be proud of their evolutionary prosperity and would scoff at man who has been led, by redundancy of the human brain and associated cultural evolution, towards such absurd evolutionary oddities as the atomic bomb or the mass television entertainment. We, human beings, can ask such theoretical questions as to what it is like to be a bat (Nagel 1974), but will never penetrate into the bat-specific reality. We are confined to our human-specific reality and, by all our evolutionary and developmental ratchets, forced to be anthropocentric.

A bacterial philosopher, sentenced to life imprisonment in his/her species-specific formal system, would ask precisely the same most general questions as has been asking for two and a half thousand years the human philosopher: (1) Does the

world exist at all; is it not but my illusion? (2) If something exists, why it does exist, why there is something rather than nothing? Just as his/her human colleague, the bacterial philosopher will find no answer. In order to find them he/she should jump out of his/her formal system - and it is impossible.

Evidence, the conclusive one, that the world exists, do we, humans, get in a different way. We get it through our *conscious experience of emotion*. By consciously feeling joy and pain.

Emotions have evolved as an efficient adaptive arrangement to secure onticity of living beings. Many attempts have recently been made to trace their evolutionary origin (Plutchik 1991, Damasio 1994, Wimmer 1995), but, just as in the case of cognition, opinions diverge, with two extremes: one, considering emotions as a privilege of humans, and another, ascribing emotions even to non-living thermostats. The principle of minimal complexity should be useful in this analysis. It is tempting to search for emotions in any teleonomic system with built-in devices for evaluation of external stimuli (Kováč 1982).

A peculiarity, and possibly the uniqueness, of the species *Homo sapiens* is the coincidence of emotions and self-consciousness. It is this parallelism, or rather inseparability, of these two evolutionary achievements that renders possible double human transcendence - jumping out of the formal system of our reasoning, and surmounting the fundamental imperative of life: struggle for individual onticity, and nothing but individual onticity, at any price! As will be argued later, both self-consciousness and the capacity for deep emotions, indeed, hyperemotionality, may be end products of *a singular run-away process* in human evolution, so that they widely exceed adaptive qualification. Emotions are a most powerful motor of expressive behaviour.

In spite of successful attempts at explaining human altruism by the elegant proofs that account for altruism in all biological species, including plants and micro-organisms, we know from introspection that human altruism has a specific, most efficient source: *empathy*. Empathy does not only conduct our behaviour toward another human being; it also provides the most pervasive evidence of his/her existence (Buber 1923). It is much stronger than would be Bayesian reasoning which is also used to justify the Copernican principle: none of us occupies any special position in the universe. If we combine the former and the latter arguments, a

conclusion, voiced already almost three decades ago by Linus Pauling (1970), is inevitable:

„The evidence of my senses tells me that I am a man, like other men. When I cut myself I am hurt, I suffer, I cry out. I see that when some other person cuts himself he cries out. I conclude from his behaviour that he is suffering in the same way that I was. None of my observations leads me to believe that there is something special about me that sets me apart from other human beings, in any fundamental way; instead, I am led to believe that I am a man, like other men. I want to be free of suffering to the greatest extent possible. I want to live a happy and useful life, a satisfying life. I want other people to help me to be happy, to help to keep my suffering to a minimum. It is accordingly my duty to help them to be happy, to strive to prevent suffering to other people. By this argument I am led to a fundamental ethical principle: the decisions among alternative courses of action should be made in such ways as to minimise the predicted amounts of human suffering. (...)

I have contended that the principle of the minimisation of human suffering is a scientific principle, with a logical, scientific basis. I do not disagree with Professor Jacques Monod, who said that ethics must be based on axioms, just as geometry is based on axioms. Professor Waddington then pointed out that, although different geometries may be developed on the basis of different axioms, all people agree that in the practical world we can accept Euclidean geometry and its axioms. I feel that, although we have theoretical freedom allowing various ethical systems to be formulated, the choice of a reasonable and practical ethical system is highly restricted by our knowledge about the nature of the physical and biological world, and that the only acceptable ethical systems are those that are essentially equivalent to that based upon the principle of the minimisation of human suffering.“

Any ethical norm can be maintained in a population by two different manners. First, it may be increasing fitness of the individuals who observe the norm. In the simplest case this would be due to reciprocal altruism - a sort of calculation, which, indeed, may be implicit in such universal moral commandments, as is „do not do to your neighbour what you don't wish he/she would do to you“. Or it may be a strongly virulent meme, which spreads in the population even though it may reduce individual fitness of the infected human carriers. The principle of the minimisation of suffering, based on empathy, combines both biological and cultural contributions. Empathy as a biological feature would be one of those abstract and specific mind's „letterboxes“,

mentioned above, that can be filled in either by compassion, charity and self-sacrifice, or by envy, vengeance or malicious cruelty. Neither of the two opposite kinds of behaviour has ever been observed in non-human animals, which proves that they are made possible by a faculty exclusive to humans. It depends mainly on the composition of the meme pool of the specific cultural environments which of the two kinds of behaviour will predominate.

Nature is indifferent to suffering. A part of human suffering is a consequence of deliberate human action, but a larger one is unintended, caused by ignorance and by human incapacity in the face of blind forces of nature and society. Ignorance, impotency, inferiority, fear have constituted the nutrient medium for memes of envy and cruelty, their opposites have favoured countenance, compassion, devotion, social playfulness. For centuries, science has been explained and justified as an activity aiming at reducing the ignorance and the incapacity. All the principles of cognitive biology substantiate the concept of science as an organised reduction of ignorance. At the same time, the string of the presented arguments associates science more directly with the reduction of suffering. The „search for truth“ has been often presented as an internal norm of science. It is not: science with lies is simply no science. In the same vein, the principle of minimisation of suffering gives science an additional dimension. Not as a norm: the more "genuine" science is, the closer it is to this extremum principle. While Pauling's reasoning ended with a normative proposal of a basis for an ethical system, this statement is purely descriptive. The origin of science, and its subsequent evolution as an institution, have been inherently linked with the reduction of human worries: pain, distress, labour, misery, anxiety. Science has become the main instrument in human efforts to minimise pain and to maximise pleasure. Cognitive biology just explains why it is so.

This is not to say that a research in which suffering, unintended or intended, is incurred, is no science. It is a science with a large proportion of ignorance. As life on earth, as life in the universe, science itself progresses forward in a maze: there is a major evolutionary tendency, but there are also many false paths and deadlocks. The success is not prescribed.

Discussion

Is there any need for the new term of cognitive biology? Is cognitive biology part of evolutionary epistemology or evolutionary epistemology itself under a new guise? The opposite may hold: cognitive biology is a larger set, with evolutionary epistemology as a subset. Cognitive biology has grown out of molecular biology, with an assumption that the elucidation of molecular recognition, of processing of molecular signals, of the organisation of gene networks, of protein computation may provide a clue for understanding higher cognitive processes. At the same time, its close association with physics and chemistry may help to end the perennial controversies and confusions concerning the relations between information and physical entropy and to enable a more precise and formalised description of knowledge, epistemic complexity and rationality.

Some of the most prominent physicists have anticipated the fundamental importance of extremum principles of physics for our comprehension of nature (Planck 1958, Feynman et al. 1966b, Landau/ Lifshitz 1969). In the sense of logical parity, the same principles may somehow govern the working of mind. The fact that some of the principles of cognitive biology may resemble, or be related, to the extremum principles of physics, may not be a fortuitous coincidence. Duality of ontology and epistemology may turn out to be a major cognitive illusion.

It has been pointed out that Thomas Kuhn's theory of scientific revolutions has not had a good influence on cognitive science. Many cognitive scientists present their theories as new Kuhnian paradigms by discrediting others (Taatgen 1999). Cognitive biology is no paradigm shift. It builds upon the traditional views of a number of scientific disciplines, its only virtue being an attempt at synthesis. Even if not clear at first sight, it should be emphasised that it is mainly out of the deep sources of physics and molecular biology that the idea of the pivotal role of human conscious emotional experience emerges. Implying consequences which, however, may be a revolutionary flash in biological evolution: it is no longer onticity of selfish genes, permanence of self-replicating entities, but a suffering of the individual conscious person that has become - even if possibly just for a short period, and perhaps not for the first time in the history of the universe - the plot of the world drama.

It should be made clear that none of the principles of cognitive biology, not even the principle of the minimisation of suffering, are normative. They are descriptive statements derived from its axioms. It would be premature to try to

axiomatise cognitive biology. Some basic postulates, idealised as are the postulates of Euclidean geometry, may provide sufficient proof of the descriptive character of the principles. Existence, onticity, of human suffering is a distinct initial postulate. The second postulate is empathy as another emotional quality. Minimisation of one's own suffering is, in the ideal case of unlimited empathy, inseparable from the minimisation of suffering of one's neighbour. Science as a specific human invention is instrumental in this action. Neither individual and inclusive fitness, nor reciprocal altruism take part in the reasoning. To claim that this minimisation principle is normative would be equivalent to the claim that extremum principles of physics, such as the principle of minimal action, are normative.

This, of course, does not imply that scientists are driven by compassion and a conscious effort to help or be useful to humankind. The tendency of science to reduce human suffering comes out of its inherent dynamics, in which public acceptance and support of science, as well as of technoscience, play a major role. The trend toward a full elimination of suffering, a triune result of run-away processes of human hyperemotionality, consciousness and meme dynamics (which includes the emergence of science), transcends human biology, including human Darwinian fitness: suffering has been an adaptive device in striving for existence and zero suffering (combined with maximum of artificial pleasure which may soon be provided by techniques of virtual reality) may well reduce the striving to zero. But need survival continue to be the supreme value of that kind of conscious life that has evolved on Earth?

The latter point is crucial for a proper understanding of the scope of cognitive biology. It would be misleading to conceive it just as an attempt at laying down a molecular foundation of cognition. The principle of ratchetting (in addition to the epistemic principle) explains how the unidirectional operation of evolutionary and developmental ratchets generates everincreasing complexity, culminating in human conscious emotionality and in science. Cognitive biology encompasses the analysis of human transcendence, tracing it back and down to its biological, and molecular, roots.

In addition to its status as a science, cognitive biology is also a conceptual program, and as a program it has normative features. The program has its substantiation in the conviction that may have been first voiced by Claude Lévi-Strauss: the 21st century will be the century of science on man - or will not be. The main statement of the program reads: The aim of science *should be* the minimisation

of human suffering *plus* the optimisation of human material and spiritual comfort. (This statement, in contrast to the previous description of the tendency, is normative.) Cognitive biology as a program holds to the tenet that the appropriate way to achieve this, at the present state of our knowledge, is the study of any specific trait of human nature by using organisms, or even purely molecular systems, which are of minimal complexity and still exhibit that trait. The introductory motto of this paper may be slightly modified (and expressed with a slightly normative flavour): The most efficient approach to mankind, to human suffering and happiness, may still be for some time the study of the bacterium.

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References

- Anderson, D. I./Hughes, D. (1996) Muller's ratchet decreases fitness of a DNA-based microbe. *Proc. Natl. Acad. Sci. U. S.* 93: 906-907.
- Astumian, R. D. (1997) Thermodynamics and kinetics of a Brownian motor. *Science* 276: 917-922.
- Bargmann, C. I. (1998) Neurobiology of the *Caenorhabditis elegans* genome. *Science* 282: 2028-2033.
- Bohr, N. (1964) *Atomphysik und menschliche Erkenntnis*, vol. I. Vieweg, Braunschweig.
- Britten, R. J. (1998) Underlying assumptions of developmental models. *Proc. Natl. Acad. Sci. U. S.* 95: 9372-9377.
- Buber, M. (1923) *Ich und Du*. Insel Verlag, Leipzig.
- Butler, D. (1998) Advances in neuroscience „may threaten human rights“. *Nature* 391: 316.

- Campbell, D. T. (1974) Evolutionary epistemology. In: Schilpp, P. A. (ed) The philosophy of Karl Popper. Open Court Publishing Co., La Salle, pp. 413-463.
- C. elegans* sequencing consortium (1998) Genome sequence of the nematode *C. elegans*. A platform for investigating biology. *Science* 282: 2012-2018.
- Chaitin, G. J. (1975) Randomness and mathematical proof. *Sci. Amer.* 232 (5): 47-52.
- Chaitin, G. J. (1990) Algorithmic information theory. Cambridge University Press.
- Darlington, C. D. (1978) The little universe of man. Allen and Unwin, London.
- Dawkins, R. (1987) The blind watchmaker. Norton, New York.
- Desplan, C. (1997) Eye development: governed by a dictator or a junta? *Cell* 91: 861-864.
- Djerassi, K. (1988) Surely you're joking. *New Scientist*, 21 November, p51.
- Drake, F. D. (1990) The Drake equation: a reprisal. Byron Preiss.
- Edelman, G. M. (1987) Neural darwinism. Basic Books, New York.
- Eigen, M./Winkler, R. (1975) Das Spiel. Piper, München/Zurich.
- Feynman, R. P./Leighton, R. B./Sands, M. (1966a) The Feynman lectures in physics. Vol. II. Addison-Wesley, Reading.
- Feynman, R. P./Leighton, R. B./Sands, M. (1966b) The Feynman lectures in physics. Vol. III. Addison-Wesley, Reading.
- Fontana, W./Wagner, G./Buss, L. W. (1997) Beyond digital naturalism. In: Langton, C. G. (ed) Artificial Life. Massachusetts Institute of Technology Press, Cambridge, MA, pp211-227.
- Fontana, W./Schuster, P. (1998) Continuity in evolution: On the nature of transitions. *Science* 280: 1451-1455.
- Gell-Mann, M. (1994) The quark and the jaguar. Freeman, New York.
- Georgescu-Roegen, H. (1971) The entropy law and the economic process. Harvard University Press, Cambridge.
- Gerlach, J. (1988) Gödel-Theorem and Kühlenbeck-Paradox. *Naturwiss.* 75: 393-398.
- Goodwin, B. (1976) Analytical physiology of cells and developing organisms. Academic Press, London.
- Gott III, J. R. (1993) Implications of the Copernican principle for our future prospects. *Nature* 363: 315-319.
- Grassberger, P. (1989) Problems in quantifying self-generated complexity. *Helv. Physica Acta* 62: 489-511.
- Heschl, A. (1998) Das intelligente Genom. Springer, Berlin

- Hofstadter, D. A. (1980) *Godel, Escher, Bach: An eternal golden braid*. Penguin Books, Harmondsworth.
- Husserl, E. (1936) *Die Krisis in der europäischen Wissenschaften und die transzendentale Phänomenologie*. *Philosophia*, Band 1. First published as a book in 1954 by Nijhoff, Hague.
- Jacob, F. (1977) Evolution and tinkering. *Science* 196: 1161-1167.
- Jacob, F. (1981) *Le jeu des possibles*. Fayard, Paris.
- Jaynes, E. T. (1957) Information theory and statistical mechanics. *Phys. Rev.* 106: 620-630.
- Kolmogorov, A. N. (1965) Three approaches to the quantitative definition of information. *Problemy peredachi informatsii* 1(1): 3-11.
- Koshland Jr., D. E. (1977) A response regulator model in a simple sensory system. *Science* 196: 1055-1063.
- Kováč, L. (1982) Evolution of affective evaluation of external stimuli. In: Novák, V. J. A./Mlíkovský, J. (eds) *Evolution and environment*. Czechoslovak Academy of Sciences, Prague, pp867-874.
- Kováč, L. (1986a) Úvod do kognitívnej biológie. (In Slovak. With an abstract in English: Introduction to cognitive biology.) *Biol. listy* 51: 172-190.
- Kováč, L. (1986b) The future of bioenergetics. *EBEC Reports* 4: 26-27.
- Kováč, L. (1987) Overview: Bioenergetics between chemistry, genetics and physics. *Curr. Topics Bioenerg.* 15: 331-372.
- Kováč, L. (1992) The natural world ("Lebenswelt") as a biological problem. *Vesmír* 71: 505-506.
- Kováč, L. (1999) European culture in the global conflict of cultures: a view of a biologist. In: Fukač, J./Chlup, Z./Mizerová, A./Schauerová, A. (eds) *The crossroads of European culture*. Vutium Press, Brno.
- Kuhlenbeck, H. (1982) *The human brain and its universe*. Karger, Basel.
- Kuhn, H. (1972) Selbstorganisation molekularer Systeme und die Evolution des genetischen Apparats. *Angew. Chem.* 18: 838-862.
- Kuhn, H. (1988) Origin of life and physics: Diversified macrostructure - Inducement to form information-carrying and knowledge-accumulating systems. *J. Res. Develop.* 32: 37-46.
- Kupiec, J. J. (1997) A Darwinian theory for the origin of cellular differentiation. *Mol. Gen. Genet.* 255: 201-208.

- Küppers, B. (1979) Towards an experimental analysis of molecular self-organization and precellular Darwinian evolution. *Naturwiss.* 66: 228-243.
- Landau, L. D./Lifshitz, J. M. (1969) *Kratkiy kurs teoreticheskoy fiziki*. Vol. 1. Nauka, Moscow.
- Lloyd, S./Pagels, H. (1988) Complexity as thermodynamic depth. *Ann. Phys.* 188: 186-213.
- Lorenz, K. (1943) Die angeborenen Formen möglicher Erfahrung. *Z. Tierpsychologie* 5: 235-409.
- Lorenz, K. (1973) *Die Rückseite des Spiegels*. Piper, München.
- Lorenz, K. (1983a) *Der Abbau des Menschlichen*. Piper, München.
- Lorenz, K. (1983b) Kants Lehre vom Apriorischen im Lichte gegenwertiger Biologie. In: Lorenz, K./Wuketits, F. M. (eds) *Die Evolution des Denkens*. Piper, München und Zürich, pp95-124. First published in 1941 in *Blätter für deutsche Philosophie* 15: 94-125.
- Mach, E. (1923) Die ökonomische Natur der physikalischen Forschung. In: *Populärwissenschaftliche Vorlesungen*. Barth, Leipzig, pp217-244.
- Maes, P. (1997) Modelling adaptive autonomous agents. In: Laghton C. G. (ed) *Artificial life*. MIT Press, Cambridge, Mass.
- Magnasco, M. O. (1993) Forced thermal ratchets. *Phys. Rev. Lett.* 10: 1477-1481.
- Maynard Smith, J. (1989) *Evolutionary genetics*, Oxford University Press.
- Nagel, E./Newman, J. R. (1958) *Gödel's proof*. Routledge and Kegan, Paul.
- Nagel, T. (1974) What it is like to be a bat. *The Philosophical Review* 83: 435-451.
- Nicolis, G./Prigogine, I. (1987) *Die Erforschung des Komplexen*. Piper, München.
- Pauling, L. (1970) Scientists in Politics. In: Tiselius, A./Nilsson, S. (eds) *The place of values in a world of facts*, Almquist and Wiksell, Stockholm, Willey, New York, London, Sidney, pp97-05.
- Penrose, R. (1989) *The Emperor's new mind*. Oxford University Press.
- Penrose, R. (1994) *Shadows of the mind*. Oxford University Press.
- Peskin, C. P./Garrett M. O./Oster G. F. (1993) Cellular motions and thermal fluctuations: the Brownian ratchet. *Biophys. J.* 65: 316-324.
- Piaget, J. (1967) *Biologie et connaissance*. Gallimard, Paris
- Planck, M. (1958) Das Prinzip der kleinsten Wirkung. In: *Vorträge und Reden*. Vieweg, Braunschweig, pp91-101.

- Plutchik, R. (1991) Emotions and evolution. *Internat. Rev. of Studies on Emotion* 1: 37-58.
- Popper, K. (1957) *The logic of scientific discovery*. Hutchinson, London. (First published in Vienna in 1934 under the title *Logik der Forschung*.)
- Popper, K. (1987) Die erkenntnistheoretische Position der evolutionären Erkenntnistheorie. In: Riedl, R./Wuketits, F. W. (eds) *Die Evolutionäre Erkenntnistheorie*. Parey, Berlin and Hamburg, pp29-37.
- Prigogine, I. (1967) *Introduction to thermodynamics of irreversible processes*. Wiley, New York.
- Radnitzky G./Bartley III, W. W. (1987) (eds) *Evolutionary epistemology, rationality, and the sociology of knowledge*. Open Court, La Salle.
- Riedl, R. (1979) *Biologie der Erkenntnis*. Parey, Berlin.
- Riedl, R. (1992) *Wahrheit und Wahrscheinlichkeit*. Parey, Berlin.
- Riedl, R. (1994) *Darwin, Zeus und Russells Huhn*. Kremayr & Scheriau, Wien
- Riedl, R. (1995) Deficiencies of adaptation in human reason; a constructivist extension of evolutionary epistemology. *Evol. Cogn.* 1: 27-37.
- Riedl, R./Delpos, M. (1996) (eds) *Die Evolutionäre Erkenntnistheorie im Spiegel der Wissenschaften*. WUV Universitätsverlag, Wien.
- Russell, B. (1961) *A history of western philosophy*. Unwin paperbacks, London.
- Schuster, P./Sigmund K. (1983) Replicator dynamics. *J. Theor. Biol.* 100: 533-538.
- Simon, H. A. (1983) *Reason in human affairs*. Stanford University Press
- Sober, E. (1992) Parsimony. In: Keller, E. F./Lloyd, E. A. (eds) *Keywords in evolutionary biology*. Harvard University Press, Cambridge, Mass., pp249-254.
- Spiegelman, S. (1971) An approach to the experimental analysis of precellular evolution. *Quart. Rev. Biophysics* 4: 213.
- Stent, G. S. (1963) *Molecular biology of bacterial viruses*. Freeman, San Francisco and London.
- Taatgen, N. (1999) The atomic components of thought. *Trends in Cogn. Sci.* 3: 82.
- Tarski, A. (1949) The semantic conception of truth and the foundations of semantics. In: Feigl, H./Sellars, W. (eds) *Readings in philosophical analysis*. Appleton-Century-Crofts, New York, pp52-84.
- Tautz, D. (1998) Debatable homologies. *Nature* 395: 17-18.

- Vollmer, G. (1983) Mesokosmos und objektive Erkenntnis - Über Probleme, die von der evolutionären Erkenntnistheorie gelöst werden. In: Lorenz, K./Wuketits, F. M. (eds) Die Evolution des Denkens. Piper, München und Zürich, pp29-91.
- Vollmer, G. (1985) Was können wir wissen? Band 1. Die Natur der Erkenntnis. Hirzel, Stuttgart.
- Vollmer, G. (1987) Evolutionäre Erkenntnistheorie. Hirzel, Stuttgart. (First published in 1975.)
- Wimmer, M. (1995) Evolutionary roots of emotions. *Evol. Cogn.* 1: 38-50.
- Wimsatt, W. C. (1986) Developmental constraints, generative entrenchment, and the innate-acquired distinction. In: Bechtel, W. (ed) Integrating scientific disciplines. Nijhoff, Dordrecht.
- Wray, G. A./Abouheif, E. (1998) When is homology not homology? *Curr. Opinion Genet. Develop.* 8: 675-680.