Meaning-Based Natural Intelligence
Vs.
Information-Based Artificial Intelligence

By

Eshel Ben Jacob and Yoash Shapira

School of Physics and Astronomy
Raymond & Beverly Sackler Faculty of Exact Sciences
Tel Aviv University, 69978 Tel Aviv Israel

Abstract

In this chapter, we reflect on the concept of *Meaning-Based Natural Intelligence* - a fundamental trait of Life shared by all organisms, from bacteria to humans, associated with: semantic and pragmatic communication, assignment and generation of meaning, formation of self-identity and of associated identity (i.e., of the group the individual belongs to), identification of natural intelligence, intentional behavior, decision-making and intentionally designed self-alterations. These features place the *Meaning-Based natural Intelligence* beyond the realm of *Information-based Artificial Intelligence*. Hence, organisms are beyond man-made pre-designed machinery and are distinguishable from non-living systems.

Our chain of reasoning begins with the simple distinction between intrinsic and extrinsic contextual causations for acquiring intelligence. The first, associated with natural intelligence, is required for the survival of the organism (the biotic system) that generates it. In contrast, artificial intelligence is implemented externally to fulfill a purpose for the benefit of the organism that engineered the “Intelligent Machinery”. We explicitly propose that the ability to assign contextual meaning to externally gathered information is an essential requirement for survival, as it gives the organism the freedom of contextual decision-making. By contextual, we mean relating to the external and internal states of the organism and the internally stored ontogenetic knowledge it has generated. We present the view that contextual interpretation of information and consequent decision-making are two fundamentals of natural intelligence that any living creature must have.

A distinction between extraction of information from data vs. extraction of meaning from information is drawn while trying to avoid the traps and pitfalls of the “meaning of meaning” and the “emergence of meaning” paradoxes. The assignment of meaning (internal interpretation) is associated with identifying correlations in the information according to the internal state of the organism, its external conditions and its purpose in gathering the information. Viewed this way, the assignment of meaning implies the existence of intrinsic meaning, against which the external information can be evaluated for extraction of meaning. This leads to the recognition that the organism has self-identity.

We present the view that the essential differences between natural intelligence and artificial intelligence are a testable reality, untested and ignored since it had been wrongly perceived as inconsistent with the foundations of physics. We propose that the inconsistency arises within the current, gene-network picture of the Neo-Darwinian paradigm (that regards organisms as equivalent to a Turing machine) and not from *in principle* contradiction with physical reality. Once the ontological reality of organisms’ natural intelligence is verified, a paradigm shift should be considered, where inter- and intra-cellular communication and genome plasticity (based on junk DNA” and the abundance of transposable elements) play crucial roles. In this new paradigm, communication and gene plasticity might be able to sustain the organisms with regulated freedom of choice between different available responses.

There have been many attempts to attribute the cognitive abilities of organisms (e.g., consciousness) to underlying quantum-mechanical mechanisms, which can directly affect the ”mechanical” parts of the organism (i.e., atomic and molecular excitations) despite thermal noise. Here, organisms are viewed as continuously self-organizing open systems that store past information, external and internal. These features enable the macroscopic organisms to have features analogous to some features in quantum mechanical systems. Yet, they are essentially different and should not be mistaken to be a direct reflection of quantum effects. On the conceptual level, the analogy is very useful as it can lead to some insights from the knowledge of quantum mechanics. We show, for example, how it enables to metaphorically bridge between the Aharonov-Vaidman and Aharonov-Albert-Vaidman concepts of *Protective and Weak Measurements* in quantum mechanics (no destruction of the quantum state) with Ben Jacob’s concept of *Weak-Stress Measurements*, (e.g., exposure to non-lethal levels of antibiotic) in the study of organisms. We also reflect on the metaphoric analogy between Aharonov-Anandan-Popescue-Vaidman *Quantum Time-Translation Machine* and the ability of an external observer to deduce on an organism's decision-making vs. arbitrary fluctuations. Inspired by the concept of *Quantum Non-Demolition* measurements we propose to use biofluoremetry (the use of bio-compatible fluorescent molecules to study intracellular spatio-temporal organization and functional correlations) as a future methodology of *Intracellular Non-Demolition Measurements.* We propose that the latter, performed during *Weak-Stress Measurements* of the organism, can provide proper schemata to test the special features associated with natural intelligence.

Prologue - From Bacteria Thou Art

Back in 1943, a decade before the discovery of the structure of the DNA, Schrödinger, one of the founders of quantum mechanics, delivered a series of public lectures, later collected in a book entitled "What is Life? The Physical Aspects of Living Cells" [1]. The book begins with an "apology" and explanation why he, as a physicist, took the liberty to embark on a quest related to Life sciences.

A scientist is supposed to have a complete and thorough I of knowledge, at first hand, of some subjects and, therefore, is usually expected not to write on any topic of which he is not a life master. This is regarded as a matter of noblesse oblige. For the present purpose I beg to renounce the noblesse, if any, and to be the freed of the ensuing obligation. …some of us should venture to embark on a synthesis of facts and theories, albeit with second-hand and incomplete knowledge of some of them -and at the risk of making fools of ourselves, so much for my apology.

Schrödinger proceeds to discuss the most fundamental issue of *Mind from Matter* [1-3]. He avoids the trap associated with a formal definition of Life and poses instead more pragmatic questions about the special features one would associate with living organisms - to what extent these features are or can be shared by non-living systems.

What is the characteristic feature of life? When is a piece of matter said to be alive? When it goes on 'doing something', moving, exchanging material with its environment, and so forth, and that for a much longer period than we would expect of an inanimate piece of matter to 'keep going' under similar circumstances.

…Let me use the word 'pattern' of an organism in the sense in which the biologist calls it 'the four-dimensional pattern', meaning not only the structure and functioning of that organism in the adult, or in any other particular stage, but the whole of its ontogenetic development from the fertilized egg the cell to the stage of maturity, when the organism begins to reproduce itself.

To explain how the organism can keep alive and not decay to equilibrium, Schrödinger argues from the point of view of statistical physics. It should be kept in mind that the principles of non-equilibrium statistical physics [4-6] with respect to organisms, and particularly to self-organization in open systems [7-12], were to be developed only a decade later, following Turing's papers, "The chemical basis of morphogenesis", "The morphogen theory of phyllotaxis" and "Outline of the development of the daisy" [13-15].

The idea Schrödinger proposed was that, to maintain life, it was not sufficient for organisms just to feed on energy, like man-made thermodynamic machines do. To keep the internal metabolism going, organisms must absorb low-entropy energy and exude high-entropy waste products.

How would we express in terms of the statistical theory the marvelous faculty of a living organism, by which it delays the decay into thermodynamic equilibrium (death)? We said before: 'It feeds upon negative entropy', attracting, as it was a stream of negative entropy upon itself, to compensate the entropy increase it produces by living and thus to maintain itself on a stationary and fairly low entropy level. Indeed, in the case of higher animals we know the kind of orderliness they feed upon well enough, viz. the extremely well-ordered state of matter in more or less complicated organic compounds, which serve them as foodstuffs. After utilizing it they return it in a very much degraded form -not entirely degraded, however, for plants can still make use of it.

The idea can be continued down the line to bacteria - the most fundamental independent form of life on Earth [16-18]. They are the organisms that know how to reverse the second law of thermodynamics in converting high-entropy inorganic substance into low-entropy living matter. They do this cooperatively, so they can make use of any available source of low-entropy energy, from electromagnetic fields to chemical imbalances, and release high-entropy energy to the environment, thus acting as the only Maxwell Demons of nature. The existence of all other creatures depends on these bacterial abilities, since no other organism on earth can do it on its own. Today we understand that bacteria utilize cooperatively the principles of self-organization in open systems [19-36]. Yet bacteria must thrive on imbalances in the environment; in an ideal thermodynamic bath with no local and global spatio-temporal structure, they can only survive a limited time.

In 1943, the year Schrödinger delivered his lectures, Luria and Delbruck performed a cornerstone experiment to prove that random mutation exists [37]: non-resistant bacteria were exposed to a lethal level of bacteriophage, and the idea was that only those that happened to go through random mutation would survive and be observed. Their experiments were then taken as a crucial support for the claim of the Neo-Darwinian dogma that *all* mutations are random and can occur during DNA replication *only* [38-41]. Schrödinger proposed that random mutations and evolution can *in principle* be accounted for by the laws of physics and chemistry (at his time), especially those of quantum mechanics and chemical bonding. He was troubled by other features of Life, those associated with the organisms' ontogenetic development during life. The following are additional extracts from his original lectures about this issue:

Today, thanks to the ingenious work of biologists, mainly of geneticists, during the last thirty or forty years, enough is known about the actual material structure of organisms and about their functioning to state that, and to tell precisely why present-day physics and chemistry could not possibly account for what happens in space and time within a living organism.

…I tried to explain that the molecular picture of the gene made it at least conceivable that the miniature code should be in one-to-one correspondence with a highly complicated and specified plan of development and should somehow contain the means of putting it into operation. Very well then, but how does it do this? How are we going to turn 'conceivability' into true understanding?

…No detailed information about the functioning of the genetic mechanism can emerge from a description of its structure as general as has been given above. That is obvious. But, strangely enough, there is just one general conclusion to be obtained from it, and that, I confess, was my only motive for writing this book. From Delbruck's general picture of the hereditary substance it emerges that living matter, while not eluding the 'laws of physics' as established up to date, is likely to involve 'other laws of physics' hitherto unknown, which, however, once they have been revealed, will form just as integral a part of this science as the former. This is a rather subtle line of thought, open to misconception in more than one respect. All the remaining pages are concerned with making it clear.

With the discovery of the structure of DNA, the evidence for the one-gene-one-protein scheme and the discoveries of the messenger RNA and transfer RNA led to the establishment of the gene-centered paradigm in which the basic elements of life are the genes. According to this paradigm, Schrödinger's old dilemma is due to lack of knowledge at the time, so the new findings render it obsolete. The dominant view since has been that all aspects of life can be explained solely based on the information stored in the structure of the genetic material. In other words, the dominant paradigm was largely assumed to be a self-consistent and a complete theory of living organisms [38-41], although some criticism has been raised over the years [42-47], mainly with emphasis on the role of bacteria in symbiogenesis of species. The latter was proposed in (1926) by Mereschkovsky in a book entitled "Symbiogenesis and the Origin of Species" and by Wallin in a book entitled "Symbionticism and the Origins of Species". To quote Margulis and Sagan [44]:

The pioneering biologist Konstantin S. Merezhkovsky first argued in 1909 that the little green dots (chloroplasts) in plant cells, which synthesize sugars in the presence of sunlight, evolved from symbionts of foreign origin. He proposed that "symbiogenesis"—a term he coined for the merger of different kinds of life-forms into new species—was a major creative force in the production of new kinds of organisms. A Russian anatomist, Andrey S. Famintsyn, and an American biologist, Ivan E. Wallin, worked independently during the early decades of the twentieth century on similar hypotheses. Wallin further developed his unconventional view that all kinds of symbioses played a crucial role in evolution, and Famintsyn, believing that chloroplasts were symbionts, succeeded in maintaining them outside the cell. Both men experimented with the physiology of chloroplasts and bacteria and found striking similarities in their structure and function. Chloroplasts, they proposed, originally entered cells as live food—microbes that fought to survive—and were then exploited by their ingestors. They remained within the larger cells down through the ages, protected and always ready to reproduce. Famintsyn died in 1918; Wallin and Merezhkovsky were ostracized by their fellow biologists, and their work was forgotten. Recent studies have demonstrated, however, that the cell's most important organelles—chloroplasts in plants and mitochondria in plants and animals—are highly integrated and well-organized former bacteria.

The main thesis is that microbes, live beings too small to be seen without the aid of microscopes, provide the mysterious creative force in the origin of species. The machinations of bacteria and other microbes underlie the whole story of Darwinian evolution. Free-living microbes tend to merge with larger forms of life, sometimes seasonally and occasionally, sometimes permanently and unalterably. Inheritance of «acquired bacteria» may ensue under conditions of stress. Many have noted that the complexity and responsiveness of life, including the appearance of new species from differing ancestors, can be comprehended only in the light of evolution. But the evolutionary saga itself is legitimately vulnerable to criticism from within and beyond science. Acquisition and accumulation of random mutations simply are, of course, important processes, but they do not suffice. Random mutation alone does not account for evolutionary novelty. Evolution of life is incomprehensible if microbes are omitted from the story. Charles Darwin (1809-1882), in the absence of evidence, invented «pangenes» as the source of new inherited variation. If he and the first evolutionist, the

Frenchman Jean Baptiste de Lamarck, only knew about the sub visible world what we know today, they would have chuckled, and agreed with each other and with us.

The Neo-Darwinian paradigm began to draw some additional serious questioning following the human genome project that revealed less than expected genes and more than expected transposable elements. The following is a quote from the Celera team [18].

> **Taken together the new findings show the human genome to be far more than a mere sequence of biological code written on a twisted strand of DNA. It is a dynamic and vibrant ecosystem of its own, reminiscent of the thriving world of tiny Whos that Dr. Seuss' elephant, Horton, discovered on a speck of dust . . . One of the bigger surprises to come out of the new analysis, some of the "junk" DNA scattered throughout the genome that scientists had written off as genetic detritus apparently plays an important role after all.**

Even stronger clues can be deduced when social features of bacteria are considered: Eons before we came into existence, bacteria already invented most of the features that we immediately think of when asked to distinguish life from artificial systems: extracting information from data, assigning existential meaning to information from the environment, internal storage and generation of information and knowledge, and inherent plasticity and self-alteration capabilities [9].

Let's keep in mind that about 10% of our genes in the nucleus came, almost unchanged, from bacteria. In addition, each of our cells (like the cells of any eukaryotes and plans) carries its own internal colony of mitochondria - the intracellular multiple organelles that carry their own genetic code (assumed to have originated from symbiotic bacteria), inherited only through the maternal line. One of the known and well studied functions of mitochondria is to produce energy via respiration (oxidative phosphorylation), where oxygen is used to turn extracellular food into internally usable energy in the form of ATP. The present fluorescence methods allow video recording of the mitochondria dynamical behavior within living cells reveal that they play additional crucial roles for example in the generation of intracellular calcium waves in glia cells[48-50].

Looking at the spatio-temporal behavior of mitochondria, it appears very much like that of bacterial colonies. It looks as if they all move around in a coordinated manner replicate and even conjugate like bacteria in a colony. From Schrödinger's perspective, it seems that not only do they provide the rest of the cell with internal digestible energy and negative entropy but they also make available relevant information embedded in the spatio-temporal correlations of localized energy transfer. In other words, each of our cells carries hundreds to thousands of former bacteria as colonial Maxwell Demons with their own genetic codes, self-identity, associated identity with the mitochondria in other cells (even if belong to different tissues), and their own collective self-interest (e.g., to initiate programmed death of their host cell).

Could it be, then, that the fundamental, causality-driven schemata of our natural intelligence have also been invented by bacteria [9,47], and that our natural intelligence is an 'evolution-improved version', which is still based on the same fundamental principles and shares the same fundamental features? If so, perhaps we should also learn something from bacteria about the fundamental distinction between our own Natural Intelligence and the Artificial Intelligence of our created machinery.

Introduction

One of the big ironies of scientific development in the 20th century is that its burst of creativity helped establish the hegemony of a paradigm that regards creativity as an illusion. The independent discovery of the structure of DNA (Universal Genetic Code), the introduction of Chomsky's notion about human languages (Universal Grammar – Appendix B) and the launching of electronic computers (Turing Universal Machines- Appendix C), all occurring during the 1950's, later merged and together established the dominance of reductionism. Western philosophy, our view of the world and our scientific thought were under its influence ever since, to the extent that many hold the deep conviction that the Universe is a Laplacian, mechanical universe in which there is no room for renewal or creativity [47].

In this Universe, concepts like cognition, intelligence or creativity are seen as mere illusion. The amazing process of evolution (from inanimate matter, through organisms of increasing complexity, to the emergence of intelligence) is claimed to be no more than a successful accumulation of errors (random mutations) enhanced by natural selection (the Darwinian picture). Largely due to the undeniable creative achievements of science, unhindered by the still unsolved fundamental questions, the hegemony of reductionism reached the point where we view ourselves as equivalent to a Universal Turing machine. Now, by the logical reasoning inherent in reductionism, we are not and can not be essentially different ‘beings’ from the machinery we can create like complex adaptive systems [51]. The fundamental assumption is of top-level emergence: a system consists of a large number of autonomous entities called agents, that individually have very simple behavior and that interact with each other in simple ways. Despite this simplicity, a system composed of large numbers of such agents often exhibits what is called emergent behavior that is surprisingly complex and hard to predict. Moreover, in principle, we can design and build machinery that can even be made superior to human cognitive abilities [52]. If so, we represent living examples of machines capable of creating machines (a conceptual hybrid of ourselves and our machines) ‘better” then themselves, which is in contradiction with the paradigmatic idea of natural evolution: that all organisms evolved according to a “Game of Random Selection” played between a master random-number generator (Nature) and a collection of independent, random number generators (genomes). The ontological reality of Life is perceived as a game with two simple rules – the second law of thermodynamics and natural selection. Inherent meaning and causality-driven creativity have no existence in such a reality – the only meaning of life is to survive. If true, how come organisms have inherent programming to stop living? So here is the irony: that the burst of real creativity was used to remove creativity from the accepted epistemological description of Nature, including life.

The most intriguing challenge associated with natural intelligence is to resolve the difficulty of the apparent contradiction between its fundamental concepts of decision-making and creativity and the fundamental principle of time causality in physics. Ignoring the trivial notion, that the above concepts have no ontological reality, intelligence is assumed to reflect *Top-Level-Emergence* in complex systems. This commonly accepted picture represents the “More is Different” view [53], of the currently hegemonic *reductionism-based constructivism* paradigm. Within this paradigm, there are no primary differences between machinery and living systems, so the former can, in principle, be made as intelligent as the latter and even more. Here we argue that constructivism is insufficient to explain natural intelligence, and all-level generativism, or a “More is Different on All Levels” principle, is necessary for resolving the emergence of the meaning paradox [9]. The idea is the co-generation of meaning on all hierarchical levels, which involves self-organization and contextual alteration of the constituents of the biotic system on all levels (down to the genome) vs. top-level emergence in complex systems with pre-designed and pre-prepared elements [51,52].

We began in the prologue with the most fundamental organisms, bacteria, building the argument towards the conclusion that recent observations of bacterial collective self-identity place even them, and not only humans, beyond a Turing machine: Everyone agrees that even the most advanced computers today are unable to fully simulate even an individual, most simple bacterium of some 150 genes, let alone more advanced bacteria having several thousands of genes, or a colony of about 10^{10} such bacteria. Within the current Constructivism paradigm, the above state of affairs reflects technical or practical rather than fundamental limitations. Namely, the assumption is that any organelle, our brain included, as well as any whole organism, is in principle equivalent to, and thus may in principle be mapped onto a universal Turing Machine – the basis of all man-made digital information processing machines (Appendix C). We argue otherwise. Before doing so we will place Turing's notions about "Intelligent Machinery" [54] and "Imitation Game" [55] within a new perspective [56], in which any organism, including bacteria, is in principle beyond machinery [9,47]. This realization will, in turn, enable us to better understand ourselves and the organisms our existence depends on – the bacteria.

To make the argument sound, we take a detour and reflect on the philosophical question that motivated Turing to develop his conceptual computing machine: We present Turing's universal machine within the causal context of its invention [57], as a manifestation of Gödel's theorem [58-60], by itself developed to test Hilbert's idea about formal axiomatic systems [61]. Then we continued to reexamine Turing's seminal papers that started the field of Artificial Intelligence, and argue that his "Imitation Game", perceived ever since as an "Intelligence Test", is actually a "Self-Non-Self Identity Test", or "Identity Game" played between two humans competing with a machine by rules set from machines perspective, and a machine built by another human to win the game by presenting a false identity.

We take the stand that Artificial and Natural Intelligence are distinguishable, but not by Turing's imitation game which is set from machines perspective - the rules of the game simply do not allow expression of the special features of natural intelligence. Hence, for distinction between the two versions of Intelligence, the rules of the game must be modified in various ways. Two specific examples are presented, and it is propose that it's unlikely for machines to win these new versions of the game.

Consequently, we reflect on the following questions about natural intelligence: 1. Is it a metaphor or overlooked reality? 2. How can its ontological reality be tested? 3. Is it consistent with the current gene-networks picture of the Neo-Darwinian paradigm? 4. Is it consistent with physical causal determinism and time causality? To answer the questions, we first present the current accepted picture of organisms as 'watery Turing machines' living in a predetermined Laplacian Universe. We then continue to describe the 'creative genome' picture and a new perspective of the organism as a system with special built-in means to sustain 'learning from experience' for decision-making [47]. For that, we reflect on the analogy between the notions of the state of multiple options in organisms, the choice function in the Axiom of Choice in mathematics (Appendix D) and the superposition of states in quantum mechanics (Appendix E). According to the analogy, destructive quantum measurements (that involve collapse of the wave function) are equivalent to strong-stress measurements of the organisms (e.g., lethal levels of antibiotics) and to intracellular destructive measurements (e.g., gene-sequencing and gene-expression in which the organism is disassembled). Inspired by the new approach of protective quantum measurements, which do not involve collapse of the wave function (Appendix E), we propose new conceptual experimental methodologies of biotic protective measurements - for example, by exposing the organisms to weak stress, like non-lethal levels of antibiotic [62,63], and by using fluoremetry to record the intracellular organization and dynamics keeping the organism intact [64-66].

Formation of self-identity and of associated identity (i.e., of the group the individual belongs to), identification of natural intelligence in other organisms, intentional behavior, decision-making [67-75] and intentionally designed self-alterations require semantic and pragmatic communication [76-80], are typically associated with cognitive abilities and meaning-based natural intelligence of human. One might accept their existence in the "language of dolphins" but regard them as well beyond the realm of bacterial communication abilities. We propose that this notion should be reconsidered: New discoveries about bacterial intra- and inter-cellular communication [81-92], colonial semantic and pragmatic language [9,47,93,94], the above mentioned picture of the genome [45-47], and the new experimental methodologies led us to consider bacterial natural intelligence as a testable reality.

Can Organisms be Beyond Watery Turing Machines in Laplace's Universe?

The objection to the idea about organisms' regulated freedom of choice can be traced to the Laplacian description of Nature. In this picture, the Universe is a deterministic and predictable machine composed of matter parts whose functions obey a finite set of rules with specified locality [95-98]. Laplace has also implicitly assumed that determinism, predictability and locality go hand in hand with computability (using current terminology), and suggested that:

"An intellect which at any given moment knew all the forces that animate Nature and the mutual positions of the beings that comprises it. If this intellect were vast enough to submit its data to analysis, could condense into a single formula the movement of the greatest bodies of the universe and that of the lightest atom: for such an intellect nothing could be uncertain: and the future just like the past would be present before its eyes."

Note that this conceptual intellect (Lacplace's demon) is assumed to be an external observer, capable, in principle, of performing measurements without altering the state of the system, and, like Nature itself, equivalent to a universal Turing machine.

In the subsequent two centuries, every explicit and implicit assumption in the Laplacean paradigm has proven to be wrong in principle (although sometimes a good approximation on some scales). For example, quantum mechanics ruled out locality and the implicit assumption about simultaneous and non-destructive measurements. Studies in computer sciences illustrate that a finite deterministic system (with sufficient algorithmic complexity) can be beyond Turing machine computability (the size of the required machine should be comparable with that of the whole universe or the computation time of a smaller machine would be comparable with the time of the universe). Computer sciences, quantum measurements theory and statistical physics rule out backward computability even if the present state is accurately known.

Consequently, systems' unpredictability to an external observer is commonly accepted. Yet, it is still largely assumed that nature itself as a whole and any of its parts must in principle be predetermined, that is, subject to causal determinism [98],which must go hand in hand with time causality [96]:

> **Causal determinism is the thesis that all events are causally necessitated by prior events, so that the future is not open to more than one possibility. It seems to be equivalent to the thesis that the future is *in principle* completely predictable (even if in practice it might never actually be possible to predict with complete accuracy). Another way of stating this is that for everything that happens there are conditions such that, given them, nothing else could happen, meaning that a completely accurate prediction of any future event could in principle be given, as in the famous example of Laplace's demon.**

Clearly, a decomposable state of mixed multiple options and hence decision-making can not have ontological reality in a universe subject to 'causal determinism'. Moreover, in this Neo-Laplacian Universe, the only paradigm that does not contradict the foundations of logic is the Neo-Darwinian one. It is also clear that in such clockwork universe there can not be an essential difference, for example, between self-organization of a bacterial colony and self-organization of a non living system such as electro-chemical deposition [99,100].

Thus, all living organisms, from bacteria to humans, could be nothing but watery Turing machines created and evolved by random number generators. The conviction is so strong that it is pre-assumed that any claim regarding essential differences between living organisms and non living systems is an objection to the foundations of logic, mathematics, physics and biology. The simple idea, that the current paradigm in life sciences might be the source of the apparent inconsistency and hence should be reexamined in light of the new discoveries, is mostly rejected point-blank.

In the next sections we present a logical argument to explain why the Neo-Laplacian Universe (with a built-in Neo-Darwinian paradigm) can not provide a complete and self-consistent description of Nature even if random number generators are called for the rescue. The chain of reasoning is linked with the fact that formal axiomatic systems cannot provide complete bases for mathematics and the fact that a Universal Turing Machine cannot answer all the questions about its own performance.

Hilbert's Vision –

Meaning-Free Formal Axiomatic Systems

Computers were invented to clarify Gödel's theorem, which by itself has been triggered by the philosophical question about the foundation of mathematics raised by Russell's logical paradoxes [61]. These paradoxes attracted much attention, as they appeared to shatter the solid foundations of mathematics, the most elegant creation of human intelligence. The best known paradox has to do with the logical difficulty to include the intuitive concept of self-reference within the foundations of *Principia Mathematica*: If one attempts to define the set of all sets that are not elements of themselves, a paradox arises - that if the set is to be an element of itself, it shouldn't, and vice versa.

As an attempt to eliminate such paradoxes from the foundations of mathematics, Hilbert invented his meta-mathematics. The idea was to lay aside the causal development of mathematics as a meaningful 'tool' for our survival, and set up a formal axiomatic system so that a meaning-independent mathematics can be built starting from a set of basic postulates (axioms) and well-defined rules of deduction for formulating new definitions and theorems clean of paradoxes. Such a formal axiomatic system would then be a perfect artificial language for reasoning, deduction, computing and the description of nature. Hilbert's vision was that, with the creation of a formal axiomatic system, the causal meaning that led to its creation could be ignored and the formal system treated as a perfect, meaning-free game played with meaning-free symbols on paper.

His idea seemed very elegant - with "superior" rules, "uncontaminated" by meaning, at our disposal, any proof would not depend any more on the limitation of human natural language with its imprecision, and could be executed, in principle, by some advanced, meaning-free, idealized machine. It didn't occur to him that the built-in imprecision of human linguistics (associated with its semantic and pragmatic levels) are not a limitation but rather provide the basis for the flexibility required for the existence of our creativity-based natural intelligence. He overlooked the fact that the intuitive (semantic) meanings of intelligence and creativity have to go hand in hand with the *freedom to err* – there is no room for creativity in a precise, clockwork universe.

Gödel's Incompleteness/Undecidability Theorem

In 1931, in a monograph entitled “On Formally Undecidable Propositions of Principia Mathematica and Related Systems” [58-61], Gödel proved that Hilbert’s vision was *in principle* wrong - an ideal ‘Principia Mathematica’ that is both self-consistent and complete can not exist.

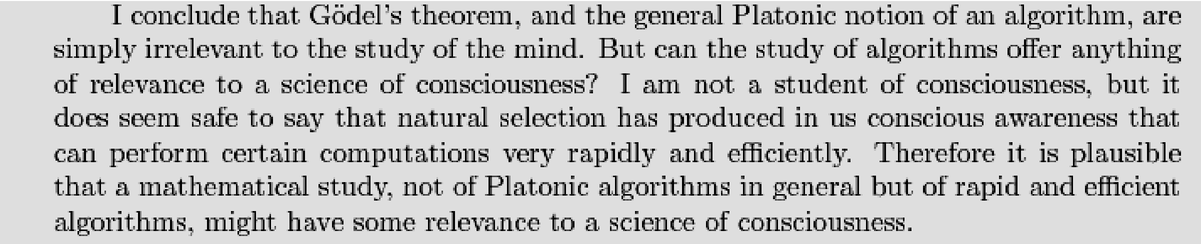
Two related theorems are formulated and proved in Gödel’s paper: 1. The *Undecidability Theorem* - within formal axiomatic systems there exist questions that are neither provable nor disprovable solely on the basis of the axioms that define the system. 2. The *Incompleteness Theorem* - if all questions are decidable then there must exist contradictory statements. Namely, a formal axiomatic system can not be both self-consistent and complete.

What Gödel showed was that a formal axiomatic system is either incomplete or inconsistent even if just the elementary arithmetic of the whole numbers 0,1,2,3, is considered (not to mention all of mathematics). He bridged between the notion of self-referential statements like “This statement is false” and Number Theory. Clearly, mathematical statements in Number Theory are about the properties of whole numbers, which by themselves are not statements, nor are their properties. However, a statement of Number Theory could be about a statement of Number Theory and even about itself (i.e., self-reference). To show this, he constructed one-to-one mapping between statements about numbers and the numbers themselves. In Appendix D, we illustrate the spirit of Gödel’s code.

Gödel’s coding allows regarding statements of Number Theory on two different levels: (1) as statements of Number Theory, and (2) as statements about statements of Number Theory. Using his code, Gödel transformed the Epimenides paradox (“This statement is false”) into a Number Theory version: “This statement of Number Theory is improvable”. Once such a statement of Number Theory that describes itself is constructed, it proves Gödel’s theorems. If the statement is provable then it is false, thus the system is inconsistent. Alternatively, if the statement is improvable, it is true but then the system is incomplete.

One immediate implication of Gödel’s theorem is that no man-made formal axiomatic system, no matter how complex, is sufficient *in principle* to capture the complexity of the simplest of all systems of natural entities – the natural whole numbers. In simple words, any mathematical system we construct can not be prefect (self-consistent and complete) on its own – some of its statements rely on external human intervention to be settled. It is thus implied that either Nature is not limited by causal determinism (which can be mapped onto a formal axiomatic system), or it is limited by causal determinism and there are statement about nature that only an external Intelligence can resolve.

The implications of Gödel’s theorem regarding human cognition are still under debate [108]. According to the Lucas-Penrose view presented in “Minds, Machines and Gödel” by Lucas [101] and in “The emperor’s new mind: concerning computers, minds and the law of physics” by Penrose [73], Gödel’s theorems imply that some of the brain functions must act non-algorithmically. The popular version of the argumentation is: There exist statements in arithmetic which are undecidable for any algorithm yet are intuitively decidable for mathematicians. The objection is mainly to the notion of ‘intuition-based mathematical decidability’. For example, Nelson in “Mathematics and the Mind” [109], writes:



> I conclude that Gödel’s theorem, and the general Platonic notion of an algorithm, are simply irrelevant to the study of the mind. But can the study of algorithms offer anything of relevance to a science of consciousness? I am not a student of consciousness, but it does seem safe to say that natural selection has produced in us conscious awareness that can perform certain computations very rapidly and efficiently. Therefore it is plausible that a mathematical study, not of Platonic algorithms in general but of rapid and efficient algorithms, might have some relevance to a science of consciousness.

For the argumentation presented in later sections, we would like to highlight the following: Russell’s paradoxes emerge when we try to assign the notion of self-reference between the system and its constituents. Unlike living organisms, the sets of artificial elements or Hilbert’s artificial systems of axioms are constructed from fixed components (they do not change due to their assembly in the system) and with no internal structure that can be a functional of the system as a whole as it is assembled. The system itself is also fixed in time or, more precisely, has no temporal ordering. The set is constructed (or the system of axioms is defined) by an external spectator who has the information about the system, i.e., the system doesn’t have internally stored information about itself and there are no intrinsic causal links between the constituents.

Turing’s Universal Computing Machine

Gödel’s theorem, though relating to the foundations of mathematical philosophy, led Alan Turing to invent the concept of computing machinery in 1936. His motivation was to test the relevance of three possibilities for formal axiomatic systems that are left undecidable in Gödel’s theorems: 1. they can not be both self consistent and complete but can be either; 2. they can not be self-consistent; 3. they can not be complete. Turing proved that formal axiomatic systems must be at least incomplete.

To prove his theorem, Gödel used his code to map both symbols and operations. The proof itself, which is quite complicated, utilizes many recursively defined functions. Turing’s idea was to construct mapping between the natural numbers and their binary representation and to include all possible transformations between them to be performed by a conceptual machine. The latter performs the transformation according to a given set of pre-constructed instructions (program). Thus, while Gödel used the natural numbers themselves to prove his theorems, Turing used the space of all possible programs, which is why he could come up with even stronger statements. For later reflections, we note that each program can be perceived as functional correlation between two numbers. In other words the inherent limitations of formal axiomatic systems are better transparent in the higher dimension space of functional correlations between the numbers.

Next, Turing looked for the kind of questions that the machine *in principle* can’t solve irrespective of its physical size. He proved that the kinds of questions the machine can not solve are about its own performance. The best known is the ‘halting problem’: the only way a machine can know if a given specific program will stop within a finite time is by actually running it until it stops.

The proof is in the spirit of the previous “self-reference games”: assume there is a program that can check whether any computer program will stop (Halt program). Prepare another program which makes an infinite loop i.e., never stops (Go program). Then, make a third Dual program which is composed of the first two such that a positive result of the Halt-Buster part will activate the Go-Booster part. Now, if the Dual program is fed as input to the Halt-Buster program it leads to a paradox: the Dual program is constructed so that, if it is to stop, the Halt-Buster part will activate the Go-Booster part so it shouldn't stop and vice versa. In a similar manner it can be proven that Turing machine in principle can not answer questions associated with running a program backward in time.

Turing's proof illustrates the fact that the notion of self-reference can not be part of the space of functional correlations generated by Universal Turing machine. In this sense, Turing proved that if indeed Nature is equivalent to his machine (the implicit assumption associated with causal determinism), we, as parts of this machine, can not in principle generate a complete description of its functioning - especially so with regard to issues related to systems' self-reference.

The above argumentations appear as nothing more than, at best, an amusing game. Four years later (in 1940), Turing converted his conceptual machine into a real one – the first electronic computer *The Enigma,* which helped its human users decipher codes used by another machine. For later discussion we emphasize the following: The Enigma provided the first illustration, that while Turing machine is limited in answering on its own questions about itself, it can provide a useful tool to aid humans in answering questions about other systems, both artificial and natural. In other words, Turing machine can be a very useful tool to help humans design another, improved Turing machine, but it is not capable of doing so on its own - it can not answer questions about itself. In this sense, stand alone machines can not have *in principle* the features we proposed to associate with natural intelligence.

The Birth of *Artificial Intelligence* – Turing's Imitation Game

In his 1936 paper [57], Turing claims that a universal computing machine of the kind he proposed can, in principle, perform any *computation* that a human being can carry out. Ten years later, he began to explore the potential range of functional capabilities of computing machinery beyond computing and in 1950 he published an influential paper, "Computing Machinery and Intelligence" [55], which led to the birth of *Artificial Intelligence*. The paper starts with a statement:

"I propose to consider the question, 'Can machine think?' This should begin with definitions of the meaning of the terms 'machine' and 'think'. The definitions might be

framed so as to reflect so far as possible the normal use of the words, but this attitude is dangerous.”

So, in order to avoid the pitfalls of definitions of terms like ‘think’ and ‘intelligence’, Turing suggested replacing the question by another, which he claimed

“...is closely related to it and is expressed in relatively unambiguous words. The new form of the problem can be described in terms of a game which we call the ‘imitation game’...”

This proposed game, known as *Turing’s Intelligence Test*, involves three players: a human examiner of identities **I**, and two additional human beings, each having a different associated identity. Turing specifically proposed to use gender identity: a man **A** and a woman **B**. The idea of the game is that the identifier **I** knows (**A**;**B**) as (X;Y) and he has to identify, by written communication, who is who, aided by **B** (a cooperator) against the deceiving communication received from **A** (a defector). The purpose of **I** and **B** is that **I** will be able to identify who is **A**. The identity of **I** is not specified in Turing’s paper saying that he may be of either sex.

It is implicitly assumed that the three players have a common language, which can be used also by machines, and that **I**, **A**, and **B** also have a notion about the identity of the other players. Turing looked at the game from a machinery vs. human perspective, asking

‘What will happen when a machine takes the part of A in this game?’

He proposed that a machine capable of causing **I** to fail in his identifications as often as a man would, should be regarded intelligent. That is, the rate of false identifications of **A** made by **I** with the aid of **B** is a measure of the intelligence of **A**.

So, Turing’s intelligence test is actually about self identity and associated identity and the ability to identify non-self identity of different kinds! Turing himself referred to his game as an ‘imitation game’. Currently, the game is usually presented in a different version - an intelligent being **I** has to identify who the machine is, while the machine **A** attempts to imitated intelligent being. Moreover, it is perceived that the Inquirer **I** bases his identification according to which player appears to him more intelligent. Namely, the game is presented as an intelligence competition, and not about Self-Non-Self identity as was originally proposed by Turing.

From Kasparov's Mistake to Bacterial Wisdom

Already in 1947, in a public lecture [15], Turing presented a vision that within 50 years computers will be able to compete with people in the chess game. The victory of Deep Blue over Kasparov exactly 50 years later is perceived today by many, scientists and layman alike, as clear proof for computers' Artificial Intelligence [109,110]. Turing himself considered success in a chess game only a reflection of superior computational capabilities (the computer's ability to compute very fast all possible configurations). In his view, success in the imitation game was a greater challenge. In fact, the connection between success in the imitation game and intelligence is not explicitly discussed in his 1950 paper. Yet, it has become to be perceived as an intelligence test and led to the current dominant view of Artificial Intelligence, that *in principle* any living organism is equivalent to a universal Turing machine [107-110].

Those who view the imitation game as an intelligence test of the machine usually assume that the machine's success in the game reflects the machine's inherent talent. We follow the view that the imitation game is not about the machine's *talent* but about the talent of the designer of the machine who 'trained it' to play the role of **A**.

The above interpretation is consistent with Kasparov's description of his chess game with Deep Blue. According to him, he lost because he failed to foresee that after the first match (which he won) the computer was rebuilt and reprogrammed to play positional chess. So Kasparov opened with the wrong strategy, thus losing because of wrong decision-making not in chess but in predicting the intentions of his human opponents (he wrongly assumed that computer designing still hasn't reached the level of playing positional chess). Thus he lost because he underestimated his opponents. The ability to properly evaluate self intelligence in comparison to that of others is an essential feature of natural intelligence. It illustrates that humans with higher analytical skills can have lower skills associated with natural intelligence and vice versa: the large team that designed and programmed Deep Blue properly evaluated Kasparov's superior talent relative to that of each one of them on its own.

So, before the second match, they extended their team. Bacteria, being the most primordial organisms, had to adopt a similar strategy to survive when higher organisms evolved. The "Bacterial Wisdom" principle [9,47], is that proper cooperation of individuals driven by a common goal can generate a new group-self with superior collective intelligence. However, the formation of such a collective self requires that each of the individuals will be able to alter its own self and adapt it to that of the group's (Appendix A).

Information-Based Artificial Intelligence vs. Meaning-Based Natural Intelligence

We propose to associate (vs. define) meaning-based, natural intelligence with: conduction of semantic and pragmatic communication, assignment and generation of meaning, formation of self-identity (distinction between intrinsic and extrinsic meaning) and of associated identity (i.e., of the group the individual belongs to), identification of natural intelligence in other organisms, intentional behavior, decision-making and intentionally designed self alterations. Below we explain why this features are not likely to be sustained by a universal Turing machine, irrespective of how advanced its information-based artificial intelligence might be.

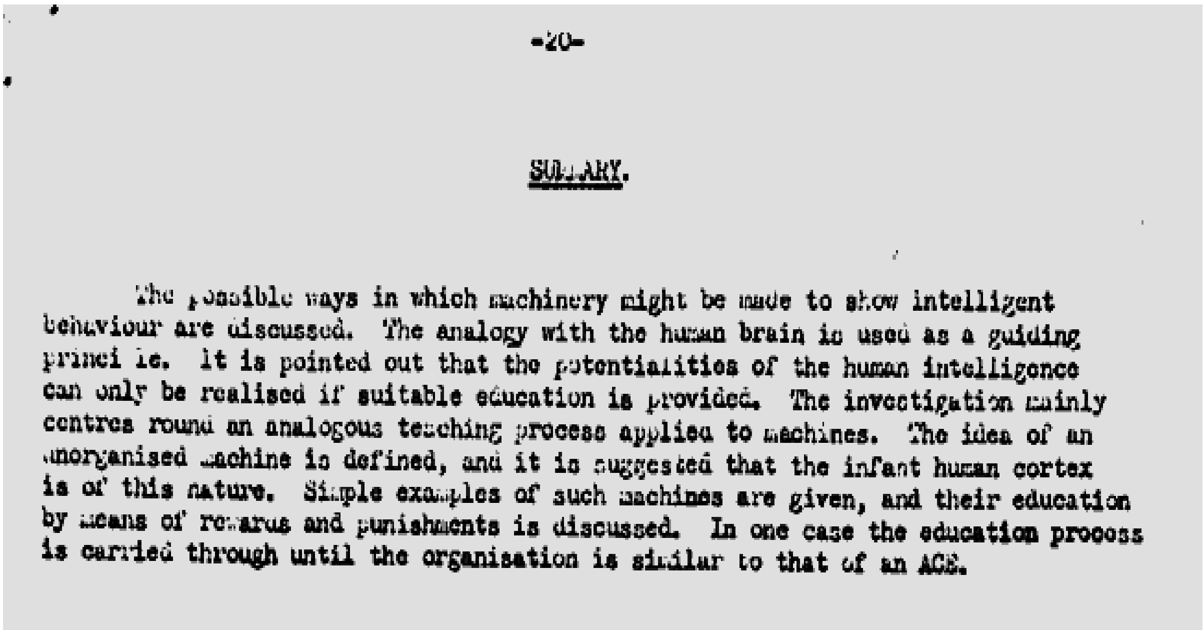
Turing set his original imitation game to be played by machine rules: 1. The self-identities are not allowed to be altered during the game. So, for example, the cooperators can not alter together their associated identity - the strategy bacteria adopt to identify defectors. 2. The players use fixed-in-time, universal-machine-like language (no semantic and pragmatic aspects). In contrast, the strategy bacteria use is to modify their dialect to improve the semantic and pragmatic aspect of their communication. 3. The efficiency of playing the game has no causal drive, i.e., there is no reward or punishment. 4. The time frame within which the game is to be played is not specified. As a result, there is inherent inconsistency in the way Turing formulated his imitation game, and the game can not let the special features of natural intelligence be expressed.

As Turing proved, computing machines are equivalent to formal axiomatic systems that are constructed to be clean of meaning. Hence, by definition, no computer can generate its own intrinsic meanings that are distinguishable from externally imposed ones. Which, in turn, implies the obvious – computers can not have inherent notions of identity and self-identity. So, if the statement: 'When a machine takes the part of A in this game' refers to the machine as an independent player, the game has to be either inconsistent or undecidable. By independent player we mean the use of some general-purpose machine (i.e., designed without specific task in mind, which is analogous to the construction of a meaning-free, formal axiomatic system). The other possibility is that Turing had in mind a specific machine, specially prepared for the specific game with the specific players in mind. In this case, the formulation of the game has no inconsistency/undecidability, but then the game is about the meaning-based, causality-driven creativity of the designer of the machine and not about the machine itself. Therefore, we propose to interpret the statement 'When a machine takes the part of **A**' as implying that '**A** sends a *Pre-designed and Pre-programmed* machine to play his role in the specific game'.

The performance of a specific machine in a specific game is information-based Artificial Intelligence. The machine can even perform better than some humans in the specific game with agreed-upon, fixed rules (time invariant); it has been designed to play. However, the machine is the product of the meaning-based Natural Intelligence and the causality-driven creativity of its designer. The designer can design different machines according to the causal needs he foresees. Moreover, by learning from his experience and by using purposefully gathered knowledge, *he can improve his skills* to create better machines.

It seems that Turing did realize the essential differences between some of the features we associate here with Natural Intelligence vs. Artificial Intelligence. So, for example, he wouldn't have classified Deep Blue as an Intelligent Machine. In an unpublished report from 1948, entitled "Intelligent Machinery", machine intelligence is discussed mainly from the perspective of human intelligence. In this report, Turing explains that intelligence requires learning, which in turn requires the machine to have sufficient *flexibility*, including *self-alteration* capabilities (the equivalent of today's neuro-plasticity). It is further implied that the machine should have the *freedom to make mistakes*. The importance of reward and punishment in the machine learning is emphasized (see the report summary shown below). Turing also relates the machine's learning capabilities to what today would be referred to as genetic algorithm, one which would fit the recent realizations about the genome (Appendix F).

In this regard, we point out that organisms' decision-making and creativity which are based on learning from experience (explained below) must involve learning from past mistakes. Hence, an inseparable feature of natural intelligence is the freedom to err with readiness to bear the consequences.



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SUMMARY.

The possible ways in which machinery might be made to show intelligent behaviour are discussed. The analogy with the human brain is used as a guiding principle. It is pointed out that the potentialities of the human intelligence can only be realised if suitable education is provided. The investigation mainly centres round an analogous teaching process applied to machines. The idea of an unorganised machine is defined, and it is suggested that the infant human cortex is of this nature. Simple examples of such machines are given, and their education by means of rewards and punishments is discussed. In one case the education process is carried through until the organisation is similar to that of an ACE.

Beyond Machinery - Games of Natural Intelligence

Since the rules of Turing's imitation game do not let the special features of natural intelligence be expressed the game can not be used to distinguish natural from artificial intelligence. The rules of the game must be modified to let the features of natural intelligence be expressed, but in a manner machines can technically imitate.

First, several kinds of communication channels that can allow exchange of meaning-bearing messages should be included, in addition to the written messages. Clearly, all communication channels should be such that can be transferred and synthesized by a machine; speech, music, pictures and physiological information (like that used in polygraph tests) are some examples of such channels. We emphasize that a two-way communication is used so, for example, the examiner (**I**) can present to (**B**) a picture he asked (**A**) to draw and vice versa. Second, the game should be set to test the ability of human (**I**) vs. machine (**I**) to make correct identification of (**A**) and (**B**), instead of testing the ability of human (**A**) vs. machine (**A**) to cause human (**I**) false identifications. Third, the game should start after the examiner (**I**) has had a training period. Namely, a period of time during which he is let to communicate with (**A**) and (**B**) knowing who is who, to learn from his own experience about their identities. Both the training period and the game itself should be for a specified duration, say an hour each. The training period can be used by the examiners in various ways; for example, he can expose the players to pictures, music pieces, extracts from literature, and ask them to describe their impressions and feelings. He can also ask each of them to reflect on the response of the other one or explain his own response. Another efficient training can be to ask each player to create his own art piece and reflect on the one created by the other. The training period can also be used by the examiner (**I**) to train (**B**) in new games. For example, he could teach the other players a new game with built-in rewards for the three of them to play. What we suggest is a way to instill in the imitation game intrinsic meaning for the player by reward and decision-making.

The game can be played to test the ability of machine (**I**) vs. human (**I**) to distinguish correctly between various kinds of identities: machine vs. human (in this case, the machine should be identical to the one who plays the examiner), or two associated human identities (like gender, age, profession etc).

The above are examples of natural intelligence games we expect machinery to lose, and as such they can provide proper tests to distinguish their artificial intelligence from the natural intelligence of living systems.

Let Bacteria Play the Game of Natural Intelligence

We proposed that even bacteria have natural intelligence beyond machinery: unlike a machine, a bacterial colony can improve itself by alteration of gene expression, cell differentiation and even generation of new inheritable genetic 'tools'. During colonial development, bacteria collectively use inherited knowledge together with causal information it gathers from the environment, including other organisms (Appendix A). For that, semantic chemical messages are used by the bacteria to conduct dialogue, to cooperatively assess their situation and make contextual decisions accordingly for better colonial adaptability (Appendix B). Should these notions be understood as useful metaphors or as disregarded reality?

Another example of natural intelligence game could be a Bridge game between a machine and human team playing the game against a team of two human players. This version of the game is similar to the real life survival 'game' between cooperators and cheaters (cooperative behavior of organisms goes hand in hand with cheating, i.e., selfish individuals who take advantage of the cooperative effort). An efficient way cooperators can single out the defectors is by using their natural intelligence - semantic and pragmatic communication for collective alteration of their own identity, to outsmart the cheaters who use their own natural intelligence for imitating the identity of the cooperators [111-114].

In Appendix A we describe how even bacteria use communication to generate evolvable self-identity together with special "dialect", so fellow bacteria can find each one in the crowd of strangers (e.g., biofilms of different colonies of the same and different species). For that, they use semantic chemical messages that can initiate specific alteration only with fellow bacteria and with shared common knowledge (Appendix C). So in the presence of defectors they modify their self-identity in a way unpredictable to an external observer not having the same genome and specific gene-expression state. The external observer can be other microorganisms, our immune system or our scientific tools.

The experimental challenge to demonstrate the above notions is to devise an identity game bacteria can play to test if bacteria can conduct a dialogue to recognize self vs. non-self [111-114]. Inspired by Turing's imitation game, we adopted a new conceptual methodology to let the bacteria tell us about their self-identity, which indeed they do: Bacterial colonies from the same culture are grown under the same growth conditions to show that they exhibit similar-looking patterns (Fig 1), as is observed during self-organization of azoic systems [7,8,99,100]. However, unlike for azoic systems, each of the colonies develops its own self identity in a manner no azoic system is expected to do.

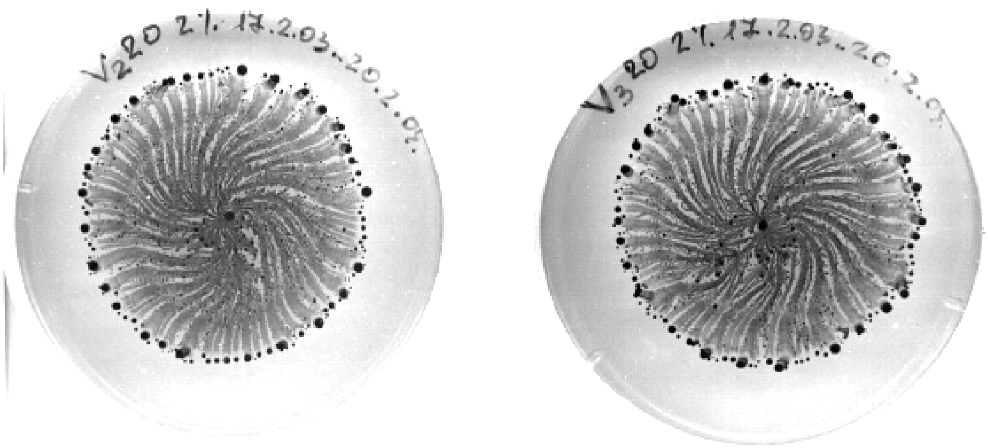


Fig 1. Observed level of reproducibility during colonial developments: Growth of two colonies of the Paenibacillus vortex taken from the same parent colony and under the same growth conditions.

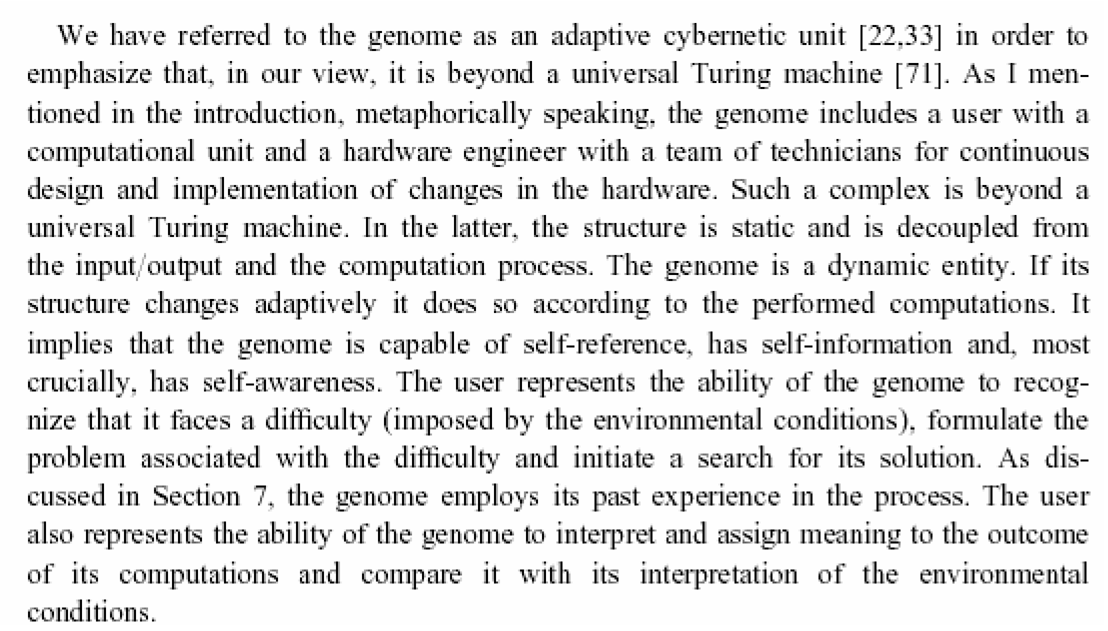
For that, the next stage is to growth of four colonies on the same plate. In one case all are taken from the same parent colony and in the other case they are taken from two different yet similar-looking colonies (like those shown in Fig 1). In preliminary experiments we found that the growth patterns in the two cases are significantly different. These observations imply that the colonies can recognize if the other colonies came from the same parent colony or from a different one. We emphasize that this is a collective phenomenon, and if the bacteria taken from the parent colonies are first grown as isolated bacteria in fluid, the effect is washed out.

It has been proposed that such colonial self-identity might be generated during the several hours of stationary ‘embryonic stage’ or collective training duration of the colonies between the time they are placed on the new surface and start to expand. During this duration, they collectively generate their own specific colonial self identity [62,63]. These findings revive Schrödinger’s dilemma, about the conversion of genetic information (embedded in structural coding) into a functioning organism. A dilemma largely assumed to be obsolete in light of the new experimental findings in life sciences when combined with the Neo-Darwinian the Adaptive Complex Systems paradigms [51,115-120]. The latter, currently the dominant paradigm in the science of complexity is based on the ‘top-level emergence’ principle which has evolved from Anderson’s constructivism (‘More is Different’ [53]).

Beyond Neo-Darwinism – Symbiogenesis on All Levels

Accordingly it is now largely assumed that all aspects of life can *in principle* be explained solely on the basis of information storage in the structure of the genetic material. Hence, an individual bacterium, bacterial colony or any eukaryotic organism is *in principle* analogous to a pre-designed Turing machine. In this analogy, the environment provides energy (electric power of the computer) and absorbs the metabolic waste products (the dissipated heat), and the DNA is the program that runs on the machine. Unlike in an ordinary Turing machine, the program also has instructions for the machine to duplicate and disassemble itself and assemble many machines into an advanced machine – the dominant Top-Level Emergence view in the studies of complex systems and system-biology based on the Neo-Darwinian paradigm.

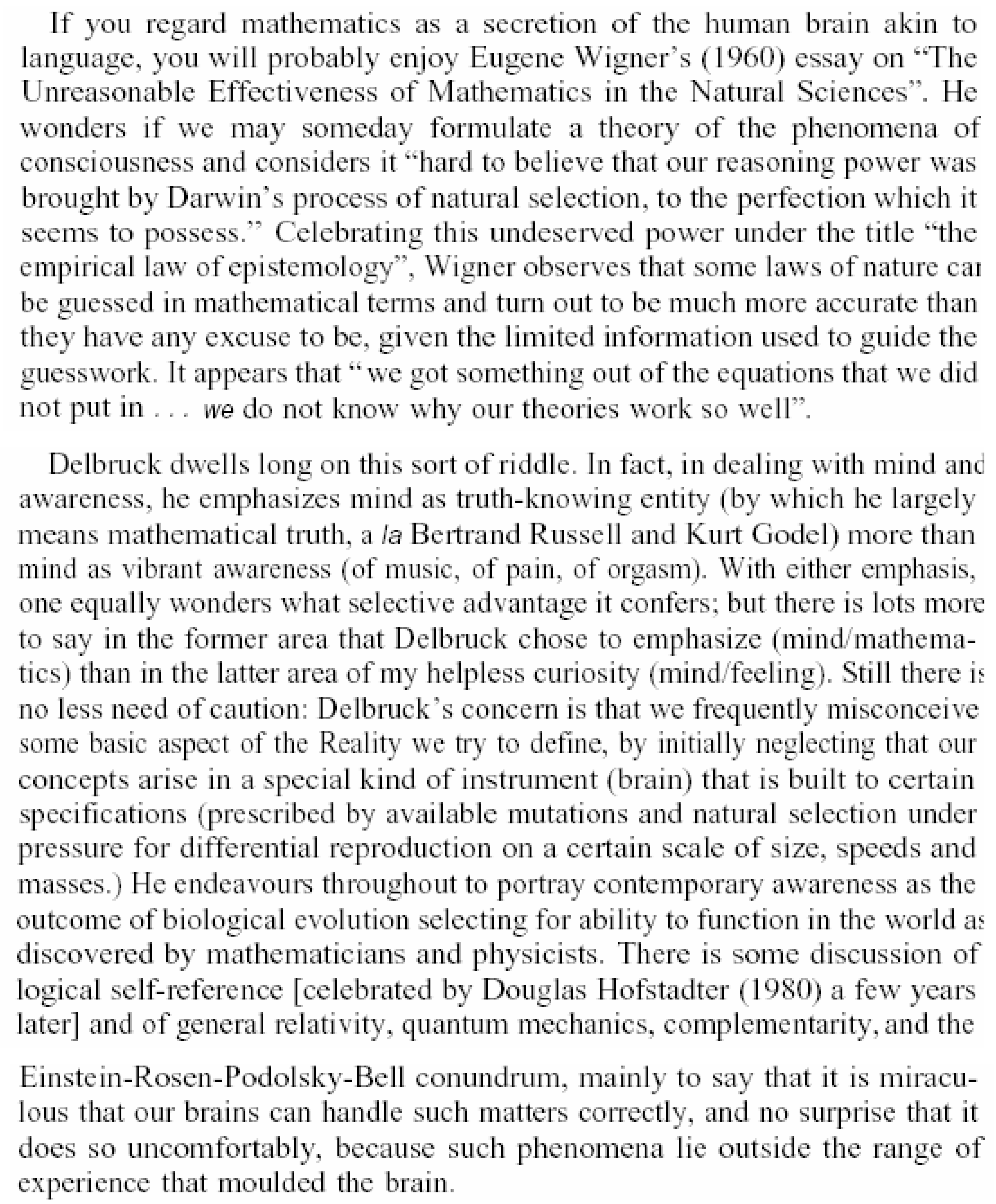
However, recent observations during bacterial cooperative self-organization show features that can not be explained by this picture (Appendix A). Ben Jacob reasoned that Anderson's constructivism is insufficient to explain bacterial self-organization. Hence, it should be extended to a "More is Different on All Levels" or all-level generativism [9]. The idea is that biotic self-organization involves self-organization and contextual alteration of the constituents of the biotic system on all levels (down to the genome). The alterations are based on stored information, external information, information processing and collective decision-making following semantic and pragmatic communication on all levels. Intentional alterations (neither pre-designed nor due to random changes) are possible, however, only if they are performed on all levels. Unlike the Neo-Darwinian based, top-level emergence, all-level emergence can account for the features associated with natural intelligence. For example, in the colony, communication allows collective alterations of the intracellular state of the individual bacteria, including the genome, the intracellular gel and the membrane. For bacterial colony as an organism, all-level generativism requires collective 'natural genetic engineering' together with 'creative genomic webs' [45-47]. In a manuscript entitled: "Bacterial wisdom, Gödel's theorem and Creative Genomic Webs", Ben Jacob refers to the following special genomic abilities of individual bacteria when being the building agents of a colony.



We have referred to the genome as an adaptive cybernetic unit [22,33] in order to emphasize that, in our view, it is beyond a universal Turing machine [71]. As I mentioned in the introduction, metaphorically speaking, the genome includes a user with a computational unit and a hardware engineer with a team of technicians for continuous design and implementation of changes in the hardware. Such a complex is beyond a universal Turing machine. In the latter, the structure is static and is decoupled from the input/output and the computation process. The genome is a dynamic entity. If its structure changes adaptively it does so according to the performed computations. It implies that the genome is capable of self-reference, has self-information and, most crucially, has self-awareness. The user represents the ability of the genome to recognize that it faces a difficulty (imposed by the environmental conditions), formulate the problem associated with the difficulty and initiate a search for its solution. As discussed in Section 7, the genome employs its past experience in the process. The user also represents the ability of the genome to interpret and assign meaning to the outcome of its computations and compare it with its interpretation of the environmental conditions.

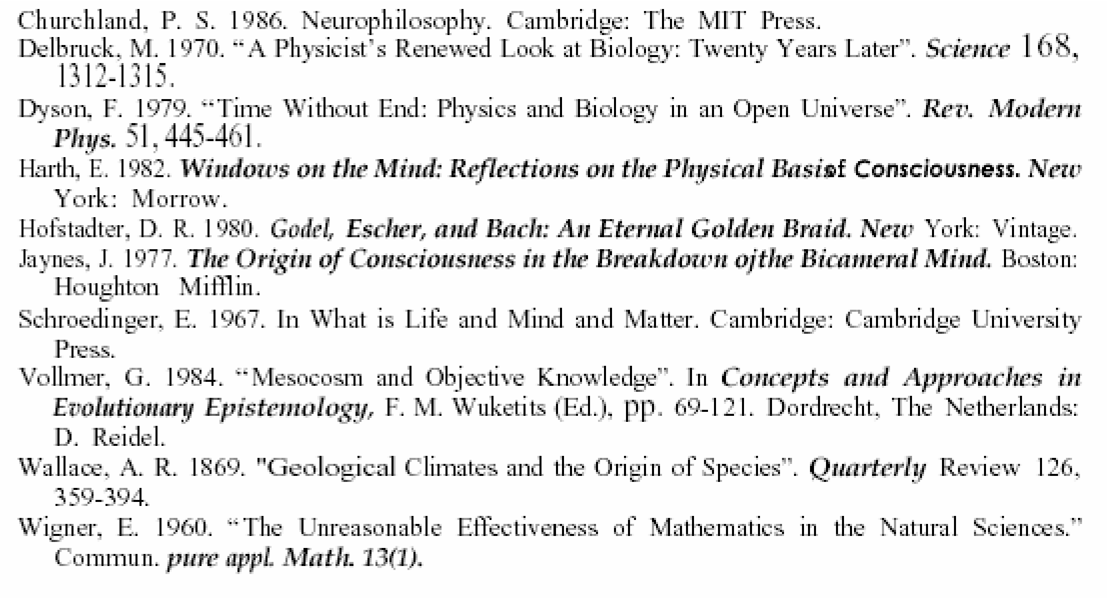
In the prologue we quoted Margulis' and Sagan's criticisms of the incompleteness of the Neo-Darwinian paradigm and the crucial role of symbiogenesis in the transition from prokaryotes to eukaryotes and the evolution of the latter. With regard to eukaryotic organisms, an additional major difficulty arises from the notion that all the required information to sustain the life of the organism is embedded in the structure of its genetic code: this information seems useless without the surrounding cellular machinery [123,124]. While the structural coding contains basic instructions on how to prepare many components of the machinery – namely, proteins – it is unlikely to contain full instructions on how to assemble them into multi-molecular structures to create a functional cell. We mentioned mitochondria that carry their own genetic code. In addition, membranes, for example, contain lipids, which are not internally coded but are absorbed from food intake according to the functional state of the organism.

Thus, we are back to Schrödinger's chicken-and-egg paradox – the coding parts of the DNA require pre-existing proteins to create new proteins and to make them functional. The problem may be conceptually related to Russell's self-reference paradoxes and Gödel's theorems: it is possible *in principle* to construct mapping between the genetic information and statements about the genetic information. Hence, according to a proper version of Gödel's theorem (for finite system [47]), the structural coding can not be both complete and self-consistent for the organism to live, replicate and have programmed cell death. In this sense, the Neo-Darwinian paradigm can not be both self-consistent and complete to describe the organism's lifecycle. In other words, within this paradigm, the transition from the coding part of the DNA to the construction of a functioning organism is metaphorically like the construction of mathematics from a formal axiomatic system. This logical difficulty is discussed by Winfree [125] in his review on Delbruck's book "Mind from Matter? An Essay on Evolutionary Epistemology".



If you regard mathematics as a secretion of the human brain akin to language, you will probably enjoy Eugene Wigner's (1960) essay on "The Unreasonable Effectiveness of Mathematics in the Natural Sciences". He wonders if we may someday formulate a theory of the phenomena of consciousness and considers it "hard to believe that our reasoning power was brought by Darwin's process of natural selection, to the perfection which it seems to possess." Celebrating this undeserved power under the title "the empirical law of epistemology", Wigner observes that some laws of nature can be guessed in mathematical terms and turn out to be much more accurate than they have any excuse to be, given the limited information used to guide the guesswork. It appears that " we got something out of the equations that we did not put in . . . *we* do not know why our theories work so well".

Delbruck dwells long on this sort of riddle. In fact, in dealing with mind and awareness, he emphasizes mind as truth-knowing entity (by which he largely means mathematical truth, a *la* Bertrand Russell and Kurt Godel) more than mind as vibrant awareness (of music, of pain, of orgasm). With either emphasis, one equally wonders what selective advantage it confers; but there is lots more to say in the former area that Delbruck chose to emphasize (mind/mathematics) than in the latter area of my helpless curiosity (mind/feeling). Still there is no less need of caution: Delbruck's concern is that we frequently misconceive some basic aspect of the Reality we try to define, by initially neglecting that our concepts arise in a special kind of instrument (brain) that is built to certain specifications (prescribed by available mutations and natural selection under pressure for differential reproduction on a certain scale of size, speeds and masses.) He endeavours throughout to portray contemporary awareness as the outcome of biological evolution selecting for ability to function in the world as discovered by mathematicians and physicists. There is some discussion of logical self-reference [celebrated by Douglas Hofstadter (1980) a few years later] and of general relativity, quantum mechanics, complementarity, and the Einstein-Rosen-Podolsky-Bell conundrum, mainly to say that it is miraculous that our brains can handle such matters correctly, and no surprise that it does so uncomfortably, because such phenomena lie outside the range of experience that moulded the brain.



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New discoveries about the role of transposable elements and the abilities of the Junk DNA to alter the genome (including generation of new genes) during the organism's lifecycle support the new picture proposed in the above mentioned paper. So, it seems more likely now that indeed the Junk DNA and transposable elements provide the necessary mechanisms for the formation of creative genomic webs. The human genome project provided additional clues about the functioning of the genome, and in particular the Junk DNA in light of the unexpectedly low number of coding genes together with equally unexpectedly high numbers of transposable elements, as described in Appendix B. These new findings on the genomic level together with the new understanding about the roles played by mitochondria [126-132] imply that the current Neo-Darwinian paradigm should be questioned. Could it be that mitochondria – the intelligent intracellular bacterial colonies in eukaryotic cells, provide a manifestation of symbiogenesis on all levels?

Learning from Experience –
Harnessing the Past to Free the Future

Back to bacteria, the colony as a whole and each of the individual bacteria are continuously self-organized open systems: The colonial self-organization is coupled to the internal self-organization process each of the individual bacteria. Three intermingled elements are involved in the internal process: 1. genetic components, including the chromosomal genetic sequences and additional free genetic elements like transposons and plasmids. 2. the membrane, including the integrated proteins and attached networks of proteins, etc. 3. The intracellular gel, including the machinery required to change its composition, to reorganize the genetic components, to reorganize the membrane, to exchange matter, energy and information with the surrounding, etc. In addition, we specifically follow the assumption that usable information can be stored in its internal state of spatio-temporal structures and functional correlations. The internal state can be self-altered, for example via alterations of the part of the genetic sequences which store information about transcription control. Hence, the combination of the genome and the intra-cellular gel is a system with self reference. Hence, the following features of genome cybernetics [9,50] can be sustained.

1. **storage of past external information and its contextual internal interpretation.**
2. **storage of past information about the system's past selected and possible states.**
3. **hybrid digital-analog processing of information.**
4. **hybrid hardware-software processing of information.**

The idea is that the hardware can be self-altered according to the needs and outcome of the information processing, and part of the software is stored in the structure of the hardware itself, which can be self-altered, so the software can have self reference and change itself. Such mechanisms may take a variety of different forms. The simplest possibility is by ordinary genome regulation – the state of gene expression and communication-based collective gene expression of many organisms. For eukaryotes, the mitochondria acting like a bacterial colony can allow such collective gene expression of their own independent genes. In this regard, it is interesting to note that about 2/3 of the mitochondria's genetic material is not coding for proteins.

Genome cybernetics has been proposed to explain the reconstruction of the coding DNA nucleus in ciliates [133,134]. The specific strains studied have two nuclei, one that contains only DNA coded for proteins and one only non-coding DNA. Upon replication, the coding nucleus disintegrates and the non-coding is replicated. After replication, the non-coding nucleus builds a new coding nucleus. It has been shown that it is done using the transposable elements in a computational process.

More recent work shows that transposable elements can effectively re-program the genome between replications [135]. In yeast, these elements can insert themselves into messenger

RNA and give rise to new proteins without eliminating old ones[136]. These findings illustrate that rather than wait for mutations to occur randomly, cells can apparently keep some genetic variation on tap and move them to 'hard disk' storage in the coding part of the DNA if they turn out to be beneficial over several life cycles. Some observations hint that the collective intelligence of the intracellular mitochondrial colonies play a crucial role in these processes of self-improvement [128-132].

Here, we further assume the existence of the following features:

5. storage of the information and the knowledge explicitly in its internal spatio-temporal structural organizations.
6. storage of the information and the knowledge implicitly in functional organizations (composons) in its corresponding high dimensional space of affinities.
7. continuous generation of models of itself by reflection forward (in the space of affinities) its stored knowledge.

The idea of high dimensional space of affinities (renormalized correlations) has been developed by Baruchi and Ben Jacob [137], for analyzing multi-channel recorded activity (from gene expression to human cortex). They have shown the coexistence of functional composons (functional sub-networks) in the space of affinities for recorded brain activity.

With this picture in mind, the system's models of itself are not necessarily dedicated 'units' of the system in the real space but in the space of affinities, so the models should be understood as a caricature of the system in real space including themselves - caricature in the sense that maximal meaningful information is represented. In addition, the system's hierarchical organization enables the smaller scales to contain information about the larger scale they themselves form – metaphorically, like the formation of meanings of words in sentences as we explain in Appendix B. The larger scale, the analog of the sentence and the reader's previous knowledge, selects between the possible lower scale organizations. The system's real time is represented in the models by a faster internal time, so at every moment in real time the system has information about possible caricatures of itself at later times.

The reason that internal multiple composons (that serve as models) can coexist has to do with the fact that going backward in time is undecidable for external observer (e.g., solving backward reaction-diffusion equations is undetermined). So what we suggest is that, by projecting the internally stored information about the past (which can not be reconstruct by external observer), living organisms utilize the fact that going backward in time is undetermined for regulated freedom of response: to have a range of possible courses of future behavior from which they have the freedom to select intentionally according to their past experience, present circumstances, and inherent predictions of the future. In contrast, the fundamental assumption in the studies of complex adaptive systems according to Gell-Mann [115], is that the behavior of organisms is determined by accumulations of accidents.

Any entity in the world around us, such as an individual human being, owes its existence not only to the simple fundamental law of physics and the boundary condition on the early universe but also to the outcomes of an inconceivably long sequence of probabilistic events, each of which could have turned out differently. Now a great many of those accidents, for instance most cases of the bouncing of a particular molecule in a gas to the right rather than the left in a molecular collision, have few ramifications for the future coarse-grained histories. Sometimes, however, an accident can have widespread consequences for the future, although those are typically restricted to particular regions of space and time. Such a "frozen accident" produces a great deal of mutual algorithmic information among various parts or aspects of a future coarse-grained history of the universe, for many such histories and for various ways of dividing them up.

We propose that organisms use stored relevant information to generate an internal mixed yet decomposable (separable) state of multiple options analogous to quantum mechanical superposition of states .In this sense the process of decision-making to select a specific response to external stimuli is conceptually like the projection of the wave function in quantum mechanical measurement. There are two fundamental differences, though: 1. In quantum measurement, the external observer directly causes the collapse of the system on a specific eigenstate he pre-selects. Namely, the eigenstate is predetermined while its corresponding eigenvalue is not. In the organism’s decision-making, the external stimuli initiate the selection of a specific state (collapse on a specific response). The selected state is *in principle* unknown directly to an external observer. The initiated internal decomposition of the mixed states and the selection of a specific one are performed according to stored past information. 2. In quantum measurement, the previous possible (expected) eigenvalues of the other eigenstates are erased and assigned new uncertainties. In the organism’s decision making the process is qualitatively different: the external stimuli initiate decomposition of the mixed states by the organism itself. The information about the other available options is stored after the selection of the specific response. Therefore, the unselected past options are expected to affect consequent decision-making.

Decomposable Mixed State of Multiple-Options – A Metaphor or Testable Reality?

The above picture is rejected on the grounds that *in principle* the existence of a mixed and decomposable state of multiple options can not be tested experimentally. In this sense, the objection is similar in spirit to the objections to the existence of the choice function in mathematics (Appendix D), and the wave function in physics (Appendix E).

The current experimental methodology in life science (disintegrating the organism or exposing it to lethal stress), is conceptually similar to the notion of ”strong measurements” or “destructive measurements” in quantum mechanics in which the wave function is forced to collapse. Therefore, the existence of an internal state decomposable only by the organism itself can not be tested by that approach. A new conceptual methodology is required, of protective biotic measurements. For example, biofluoremetry can be used to measure the intracellular spatio-temporal organization and functional correlations in a living organism exposed to weak stress. Conceptually, fluoremetry is similar to quantum non-demolition and weak stress is similar to the notion of weak quantum measurements. Both allow the measurement of the quantum state of a system without forcing the wave function to collapse. Bacterial collective learning when exposed to non-lethal levels of antibiotics provide an example of protective biotic measurements (Appendix E).

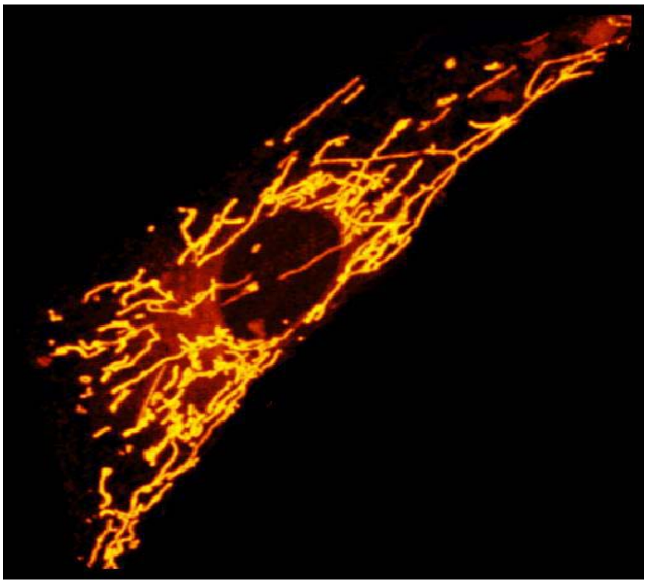

Fig 2. Confocal image of mitochondria within a single cultured rat cortical astrocyte stained with the calcium-sensitive dye rhod-2 which partitions into mitochondria, permitting direct measurements of intramitochondrial calciuum concentration (curtsey of Michael Duchen).

It should be kept in mind that the conceptual analogy with quantum mechanics is subtle and can be deceiving rather than inspiring if not properly used. For clarification, let us consider the two-slit experiment for electrons. When the external observer measures through which of the slits the electron passes, the interference pattern is washed out - the measurement causes the wave function of the incoming electron to collapse on one of the two otherwise available states.

Imagine now an equivalent two-slit experiment for organisms. In this thought experiment, the organisms arrive at a wall with two closely located narrow open gates. Behind the wall there are many bowls of food placed along an arc so that they are all at equal distance from the gates. The organisms first choose through which of the two gates to pass and then select one bowl of food. The experiment is performed with many organisms, and the combined decisions are presented in a histogram of the selected bowls. In the control experiment, two independent histograms are measured, for each door separately (no decision-making is required). The distribution when the two gates are open is compared with the sum of the distributions for the single gates. A statistically significant difference will indicate that past unselected options can influence consequent decision-making even if the following decision involves a different choice altogether (gates vs. food bowls).

Upon completion of this monograph, the development of a Robot-Scientist has just been reported [138]. The machine was given the problem of discovering the function of different genes in yeast, to demonstrate its ability to generate a set of hypotheses from what is known about biochemistry and then design experiments and interpret the results (assign meaning) without human help. Does this development provide the ultimate proof that there is no distinction between Artificial Intelligence and Natural Intelligence? Obviously, advanced automated technology interfaced with learning software can have important contribution. It may replace human researchers from doing what machines can do, thus freeing them to be more creative and to devote more effort to their beyond-machinery thinking. We don't expect, however, that a robot scientist will be able to design experiments to test, for example, self-identity and decision-making, for the simple reason that it could not grasp these concepts.

Epilogue – From Bacteria Shalt Thou Learn

Mutations as the causal driving force for the emergence of the diversity and complexity of organisms and biosystems became the most fundamental principle in life sciences ever since Darwin gave mutations a key role in natural selection.

Consequently, research in life sciences has been guided by the assumption that the complexity of life can become comprehensible if we accumulate sufficient amounts of detailed information. The information is to be deciphered with the aid of advanced mathematical method within the Neo-Darwinian schemata. To quote Gell-Mann,

> Life can perfectly well emerge from the laws of physics plus accidents, and mind, from neurobiology. It is not necessary to assume additional mechanisms or hidden causes. Once emergence is considered, a huge burden is lifted from the inquiring mind. We don't need something more in order to get something more.

This quote represents the currently, dominant view of life as a unique physical phenomenon that began as a colossal accident, and continues to evolve via sequences of accidents selected by random number generators – the omnipotent idols of science. We reason that, according to this top-level emergence picture, organisms could not have evolved to have meaning-based, natural intelligence beyond that of machinery.

Interestingly, Darwin himself didn't consider mutations to be necessarily random, and thought the environment can trigger adaptive changes in organisms – a notion associated with Lamarckism. Darwin did comment, however, that it is reasonable to treat alterations as random, so long as we do not know their origin. He says:

"I have hitherto sometimes spoken as if the variations were due to chance. This, of course, is a wholly incorrect expression, but it serves to acknowledge plainly our ignorance of the cause of each particular variation… lead to the conclusion that variability is generally related to the conditions of life to which each species has been exposed during several successive generations".

In 1943, Luria and Delbruck performed a cornerstone experiment to prove that random mutation exist by exposing bacteria to lethal conditions – bacteriophage that immediately kills non-resistant bacteria. Therefore, only cells with pre-existing specific mutations could survive. The other cells with didn't have the chance to alter their self - a possibility that could not be ruled out by the experiments. Nevertheless, these experiments were taken as a crucial support for the Neo-Darwinian dogma which states that *all* mutations are random, and can occur *only* during DNA replication. To bridge between these experiments, Turing's imitation game and the notion of weak measurements in quantum mechanics, we suggest to test natural intelligence by first giving the organisms a chance to learn from hard but non-lethal conditions. We also proposed to let the bacteria play identity game proper for testing their natural intelligence, similar in spirit to the real life games played between different colonies and even with other organisms [139].

In Turing's footsteps, we propose to play his imitation game with the reverse goal in mind. Namely, human players participate in the game to learn about themselves. By playing this reverse game with bacteria, - Nature's fundamental organisms from which all life emerged - we should be able to learn about the very essence of our self. This is especially so when keeping in mind that the life, death and well being of each of our cells depend on the cooperation of its own intelligent bacterial colony – the mitochondria. Specifically, we believe that understanding bacterial natural intelligence as manifested in mitochondria might be crucial for understanding the meaning-based natural intelligence of the immune system and the central nervous system, the two intelligent systems we use for interacting with other organisms in the game of life. Indeed, it has recently been demonstrated that mice with identical nuclear genomes can have very different cognitive functioning if they do not have the same mitochondria in their cytoplasm. The mitochondria are not transferred with the nucleus during cloning procedures [140].

To quote Schrödinger,

Democritus introduces the intellect having an argument with the senses about what is 'real'. The intellect says; 'Ostensibly there is color, ostensibly sweetness, ostensibly bitterness, actually only atoms and the void.' To which the senses retort; 'Poor intellect, do you hope to defeat us while from us you borrow your evidence? Your victory is your defeat.'

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Personal Thanks by Eshel Ben-Jacob

About twenty-five years ago, when I was a physics graduate student, I read the book "The Myth of Tantalus" and discovered there a new world of ideas. I went to seek the author, and found a special person with vast knowledge and human approach. Our dialogue led to the establishment of a unique, multidisciplinary seminar, where themes like "the origin of creativity" and "mind and matter" were discussed from different perspectives. Some of the questions have remained with me ever since, and are discussed in this monograph.

Over the years I have had illuminating dialogues with my teacher Yakir Aharonov about the foundations of quantum mechanics and with my friend Adam Tenenbaum about logic and philosophy.

In my Post-Doctoral years, I was very fortunate to meet the late Uri Merry, who introduced me to the world of social science and linguistics and to Buber's philosophy. Among other things, we discussed the role of semantic and pragmatic communication in the emergence of individual and group self.

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Appendix A: Bacterial Cooperation – The Origin of Natural Intelligence

Under natural conditions, bacteria tend to cooperatively self-organize into hierarchically structured colonies (10^9-10^{13} bacteria each), acting much like multi-cellular organisms capable of coordinated gene expressions, regulated cell differentiation, division of tasks, and more. Moreover, the colony behaves as a new organism with its own new self, although the building blocks are living organisms, each with its own self, as illustrated in the figure below. To achieve the proper balance of individuality and cooperation, bacteria communicate using sophisticated communication methods which include a broad repertoire of biochemical agents, such as simple molecules, polymers, peptides, proteins, pheromones, genetic materials, and even “cassettes” of genetic information like plasmids and viruses. At the same time, each bacterium has equally intricate intracellular communication means (signal transduction networks and genomic plasticity) of generating intrinsic meaning for contextual interpretation of the chemical messages and for formulating its appropriate response.

Collective decision-making: When the growth conditions become too stressful, bacteria can transform themselves into inert, enduring spores. Sporulation is executed collectively and begins only after "consultation" and assessment of the colonial stress as a whole by the individual bacteria. Simply put, starved cells emit chemical messages to convey their stress. Each of the other bacteria uses the information for contextual interpretation of the state of the colony relative to its own situation. Accordingly, each of the cells decides to send a message for or against sporulation. After all the members of the colony have sent out their decisions and read all the other messages, if the “majority vote” is pro-sporulation, sporulation occurs. Thus, sporulation illustrates semantic and pragmatic levels in bacterial communication, i.e., bacteria can transmit meaning-bearing messages to other bacteria to conduct a dialogue for collective decision making (Appendix B).

Although spores can endure extreme conditions (e.g., high temperatures, toxic materials, etc.), all they need for germination is to be placed under mild growth conditions. How can they sense the environment so accurately while in almost non living state, surrounded by a very solid membrane, is an unsolved and very little studied enigma.

Exchange of genetic information: Another example of bacterial special abilities has to do with the rapid development of bacterial resistance to antibiotic: The emergence of bacterial strains with multiple drug resistance has become one of the major health problems worldwide. Efficient resistance rapidly evolves through the cooperative response of bacteria, utilizing their sophisticated communication capabilities. Bacteria exchange resistance information within the colony and between colonies, thus establishing a “creative genomic web”. Maintenance and exchange of the resistance genetic information is costly and might be hazardous to the bacteria. Therefore, the information is given and taken on a “need to know” basis. In other words, the bacteria prepare, send and accept the genetic message when the information is relevant to their existence.

One of the tools for genetic communication is via direct physical transfer of conjugal plasmids. These bacterial mating events, that can also include inter-colonial and even interspecies conjugations, follow chemical courtship played by the potential partners. Naively presented, bacteria with valuable information (say, resistance to antibiotic) emit chemical signals to announce this fact. Bacteria in need of that information, upon receiving the signal, emit pheromone-like peptides to declare their willingness to mate. Sometimes, the decision to mate is followed by an exchange of competence factors (peptides). This pre-conjugation communication modifies the membrane of the partner cell into a penetrable state needed for conjugation, allowing the exchange of genetic information.

Hierarchical organization of vortices: Some bacteria cope with hazards by generating module structures - vortices, which then become building blocks used to construct the colony as a higher entity (Fig 2). To maintain the integrity of the module while it serves as a higher-order building block of the colony requires an advanced level of communication. Messages must be passed to inform each cell in the vortex that it is now playing a more complex role, being a member of the specific module and the colony as a whole, so it can adjust its behavior accordingly.

Once the vortex is recognized as a possible spatial structure, it becomes easy to understand that vortices can be used as subunits in a more complex colonial structure for elevated colonial plasticity. In Fig 3, we demonstrate how the *P. vortex* bacteria utilize their cooperative, complexity-based plasticity to alter the colony structure to cope with antibiotic stress, making use of some simple yet elegant solutions. The bacteria simply increase cooperation (by intensifying both attractive and repulsive chemical signaling), leading to larger vortices (due to stronger attraction) that move faster away from the antibiotic stress (due to stronger repulsion by those left behind). Moreover, once they've encountered the antibiotic, the bacteria seem to generate a collective memory so that in the next encounter they can respond even more efficiently.

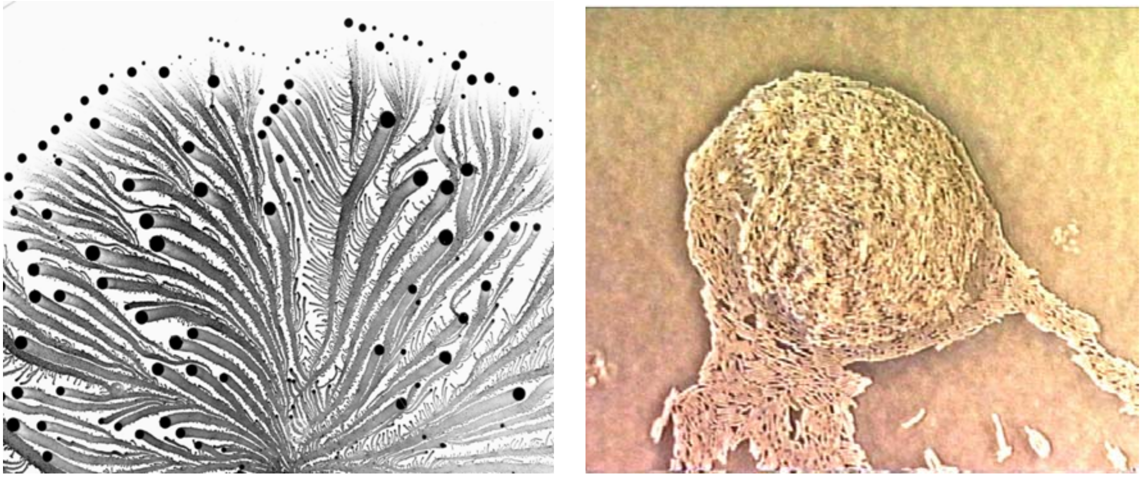


Fig. A1: Hierarchical colonial organization: Patterns formed during colonial development of the swarming and lubricating *Paenibacillus vortex* bacteria. (Left) The vortices (modules) are the leading dots seen on a macro-scale (~10cm^2). The picture shows part of a circular colony composed of about 10^{12} bacteria - ~ the number of cells of our immune system, ten times the number of neurons in the brain and hundred times the human population on earth. Each vortex is composed of many cells that swarm collectively around their common center. These vortices vary in size from tens to millions of bacteria, according to their location in the colony and the growth conditions. The vortex shown on the right (magnification x500, hence each bar is a single bacterium) is a relatively newly formed one. After formation, the cells in the vortex replicate, the vortex expands in size and moves outward as a unit, leaving behind a trail of motile but usually non replicating cells – the vortex tail. The vortices dynamics is quite complicated and includes attraction, repulsion, merging and splitting of vortices. Yet, from this complex, seemingly chaotic movement, a colony with complex but non-arbitrary organization develops (left). To maintain the integrity of the vortex while it serves as a higher-order building block of the colony requires an advanced level of communication. Messages must be passed to inform each cell in the vortex that it is now playing a more complex role, being a member of the specific vortex and the colony as a whole, so it can adjust its behavior accordingly. New vortices emerge in the trail behind a vortex following initiation signals from the parent vortex. The entire process proceeds as a continuous dialogue: a vortex grows and moves, producing a trail of bacteria and being pushed forward by the very same bacteria behind. At some point the process stalls, and this is the signal for the generation of a new vortex behind the original one, that leaves home (the trail) as a new entity which serves a living building block of the colony as a whole.

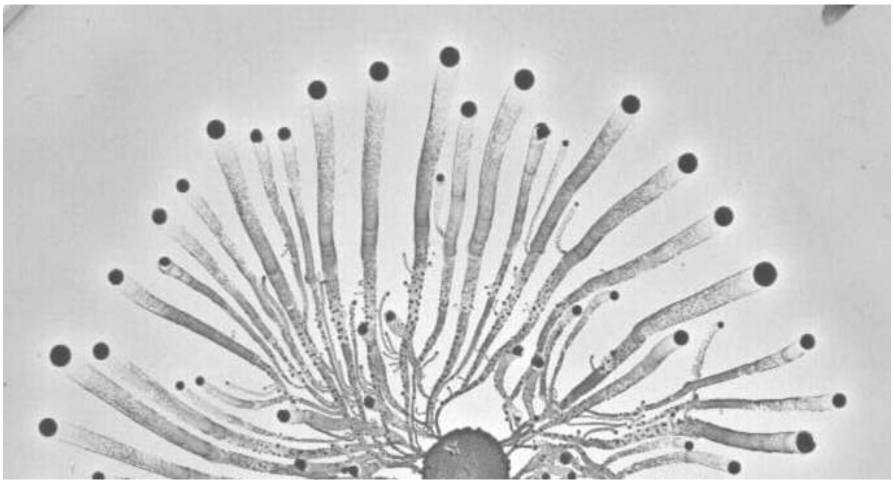


Fig. A2: Collective memory and learning: Self-organization of the P.vortex bacteria in the presence of non-lethal levels of antibiotic added to the substrate. In the picture shown, bacteria were exposed to antibiotic before the colonial developments. Note that it resulted in a more organized pattern (in comparison with Fig 1.

From multi-cellularity to sociality: In fact, bacteria can go a step higher; once an entire colony becomes a new multi-cellular being with its own identity, colonies functioning as organisms cooperate as building blocks of even more complex organizations of bacterial communities or societies, such as species-rich biofilms. In this situation, cells should be able to identify their own self, both within the context of being part of a specific colony-self and part of a higher entity - a multi-colonial community to which their colony belongs. Hence, to maintain social cooperation in such societies with species diversity, the bacteria need “multi-lingual” skills for the identification and contextual interpretation of messages received from colony members and from other colonies of the same species and of other species, and to have the necessary means to sustain the highest level of dialogue within the “chattering” of the surrounding crowed.

Incomprehensible complexity: For perspective, the oral cavity, for example, hosts a large assortment of unicellular prokaryotic and various eukaryotic microorganisms. Current estimates suggest that sub-gingival plaque contains 20 genera of bacteria representing hundreds of different species, each with its own colony of ~10^{10} bacteria, i.e., together ~thousand times the human population on earth. Thus, the level of complexity of such microbial system far exceeds that of the computer networks, electric networks, transportation and all other man-made networks combined. Yet bacteria of all those colonies communicate for tropism in shared tasks, coordinated activities and exchange of relevant genetic bacterial information using biochemical communication of meaning-bearing, semantic messages. The current usage of "language" with respect to intra- and inter-bacteria communication is mainly in the sense that one would use in, for example, "computer language" or "language of algebra". Namely, it refers to structural aspects of communication, corresponding to the structural (lexical and syntactic) linguistic motifs. Higher linguistic levels - assigning contextual meaning to words and sentences (semantic) and conducting meaningful dialogue (pragmatic) - are typically associated with cognitive abilities and intelligence of human. Hence, currently one might accept their existence in the "language of dolphins" but regard them as well beyond the realm of bacterial communication abilities. We propose that this notion should be reconsidered.

Appendix B: Clues and Percepts Drawn from Human Linguistics

Two independent discoveries the 1950's latter bridged linguistics and genetics: Chomsky's proposed universal grammar of human languages [141] and the discovery of the structural code of the DNA. The first suggested universal structural motifs and combinatorial principles (syntactic rules) at the core of all natural languages, and the other provided analogous universals for the genetic code of all living organisms. A generation later, these paradigms continue to cross-pollinate these two fields. For example, Neo-Darwinian and population genetics perspectives as well as phylogenetic methods are now used for the understanding the structure, learning, and evolution of human languages. Similarly, Chomsky's meaning-independent syntactic grammar view combined with computational linguistic methods are widely used in biology, especially in bioinformatics and structural biology but increasingly in biosystemics and even ecology.

The focus has been on the formal, syntactic structural levels, which are also applicable to "machine languages": Lexical – formation of words from their components (e.g., characters and phonemes); Syntactic – organization of phrases and sentences in accordance with well-specified grammatical rules [142,143].

Linguistics also deals with a higher-level framework, the semantics of human language. Semantics is connected to contextual interpretation, to the assignment of context-dependent meaning to words, sentences and paragraphs. For example, one is often able to capture the meaning of a text only after reading it several times. At each such iteration, words, sentences and paragraphs may assume different meanings in the reader's mind; iteration is necessary, since there is a hierarchical organization of contextual meaning. Namely, each word contributes to the generation of the meaning of the entire sentence it is part of, and at the same time the generated whole meaning of the sentence can change the meaning of each of the words it is composed of. By the same token, the meanings of all sentences in a paragraph are co-generated along with the created meaning of the paragraph as a whole, and so on, for all levels.

Readers have semantic plasticity, i.e., a reader is free to assign individualistic contextual and causal meanings to the same text, according to background knowledge, expectations, or purpose; this is accomplished using combined analytical and synthetic skills. Beyond this, some linguists identify the conduction of a dialogue among converser using shared semantic meaning as pragmatics. The group usage of a dialogue can vary from activity coordination through collective decision-making to the emergence of a new group self. To sustain such cognitive abilities might require analogous iterative processes of self-organization based generation of composons of meaning within the brain which will be discussed elsewhere

Drawing upon human linguistics with regard to bacteria, semantics would imply contextual interpretation of chemical messages, i.e., each bacterium has some freedom (plasticity) to assign meaning according to its own specific, internal and external, contextual state. For that, a chemical message is required to initiate an intra-cellular response that involves internal restructuring - self-organization of the intracellular gel and/or the gene-network or even the genome itself. To sustain a dialogue based on semantic messages, the bacteria should have a common pre-existing knowledge (collective memory) *and* abilities to collectively generate new knowledge that is transferable upon replication. Thus, the ability to conduct a dialogue implies that there exist some mechanisms of collective gene expression, analogous to that of cell differentiation during embryonic development of multi-cellular organisms, in which mitochondria might play an important role.

Appendix C: Gödel's Code and the Axiom of Choice

Hilbert's second problem

Gödel's theorems provided an answer to the second of the 23 problems posed by Hilbert.

2. Can it be proven that the axioms of logic are consistent?

Gödel's theorems say that the answer to Hilbert's second question is negative. For that he has invented the following three steps code:

1. Gödel assigned a number to each logical symbol, e.g.,

Not ≡ 1
Or ≡ 2
If then ≡ 3
∃ ≡ 4

2. He assigned prime numbers to variables, e.g.,

x ≡ 11
y ≡ 13

3. He assigned a number to any statement according to the following example: "There is a number not equal to zero".

In logic symbols	(	∃	x	)	(	x	~	=	0	)
In Gödel's numbers	8	4	11	9	8	11	1	5	6	9

The statement's number is $2^8.3^4.5^{11}.7^9.11^8.13^{11}.17^1.19^5.23^6.29^9$

Note that it is a product of the sequence of prime numbers, each to the power of the corresponding Gödel's number. This coding enables one-to-one mapping between statements and the whole numbers.

Hilbert's first problem and the Axiom of Choice

Gödel also studied the first of the 23 essential problems posed by Hilbert.

1.a Is there a transfinite number between that of a denumerable set and the numbers of the continuum? 1.b Can the continuum of numbers be considered a well ordered set?

In 1940, Gödel proved that a positive answer to 1.a is consistent with the axioms of von Neumann-Bernays-Gödel set theory. However, in 1963, Cohen demonstrated that it is inconsistent with the Zermelo-Frankel set theory. Thus, the answer is undecidable – it depends on the particular set theory assumed. The second question is related to an important and fundamental axiom in set sometimes called Zermelo's Axiom of Choice. It was formulated by Zermelo in 1904 and states that, given any set of mutually exclusive nonempty sets, there exists at least one set that contains exactly one element in common with each of the nonempty sets. The axiom of choice can be demonstrated to be independent of all other axioms in set theory. So the answer to 1.b is also undecidable.

The popular version of the Axiom of Choice is that [144]:

Let *C* be a collection of nonempty sets. Then we can *choose* a member from each set in that collection. In other words, there *exists* a *choice function f* defined on *C* with the property that, for each set *S* in the collection, *f*(*S*) is a member of *S*.

There is an ongoing controversy over how to interpret the words "choose" and "exists" in the axiom: If we follow the constructivists, and "exists" means "to find," then the axiom is *false*, since we cannot find a choice function for the nonempty subsets of the real numbers. However, most mathematicians give "exists" a much weaker meaning, and they consider the Axiom to be true: To define *f*(*S*), just arbitrarily "pick any member" of *S*.
In effect, when we accept the Axiom of Choice, this means we are agreeing to the convention that we shall permit ourselves to use a choice function *f* in proofs, as though it "exists" in some sense, even though we cannot give an explicit example of it or an explicit algorithm for it.

The choice function merely exists in the mental universe of mathematics. Many different mathematical universes are possible. When we accept or reject the Axiom of Choice, we are specifying which universe we shall work in. As was shown by Gödel and Cohen, both possibilities are feasible – i.e., neither accepting nor rejecting AC yields a contradiction.

The Axiom of Choice implies the existence of some conclusions which seem to be counter-intuitive or to contradict "ordinary" experience. One example is the Banach-Tarski Decomposition, in which the Axiom of Choice is assumed to prove that it is possible to take the 3-dimensional closed unit ball,

$$B \;=\; \left\{(x,y,z) \in \mathbf{R}^3 : x^2 + y^2 + z^2 \le 1\right\}$$

and partition it into finitely many pieces, and move those pieces in rigid motions (i.e., rotations and translations, with pieces permitted to move through one another) and reassemble them to form *two* copies of *B*.

At first glance, the Banach-Tarski Decomposition seems to contradict some of our intuition about physics – e.g., the Law of Mass Conservation from classical Newtonian physics. Consequently, the Decomposition is often called the Banach-Tarski *Paradox*. But actually, it only yields a complication, not a contradiction. If we assume a uniform density, only a set with a defined *volume* can have a defined mass. The notion of "volume" can be defined for many subsets of $\mathbf{R}^3$, and beginners might expect the notion to apply to all subsets of $\mathbf{R}^3$, but it does not. More precisely, *Lebesgue measure* is defined on some subsets of $\mathbf{R}^3$, but it cannot be extended to *all* subsets of $\mathbf{R}^3$ in a fashion that preserves two of its most important properties: the measure of the union of two disjoint sets is the sum of their measures, and measure is unchanged under translation and rotation. Thus, the Banach-Tarski Paradox does not violate the Law of Conservation of Mass; it merely tells us that the notion of "volume" is more complicated than we might have expected.

We emphasize that the sets in the Banach-Tarski Decomposition cannot be described explicitly; we are merely able to prove their *existence*, like that of a choice function. One or more of the sets in the decomposition must be Lebesgue unmeasurable; thus a corollary of the Banach-Tarski Theorem is the fact that there exist sets that are not Lebesgue measurable.

The idea we lean toward is that in the space of affinities the composons represent similar decomposition but of information which is the extensive functional in this space which corresponds to the volume in the system real space.

Appendix D: Description of Turing’s Conceptual Machinery

To support our view of the limits of Artificial Intelligence or Machines Intelligence, we present here a relatively detailed description of Turing’s Universal Machine. Turing proved that any discrete, finite state with fixed in time finite set of instructions can be mapped onto his conceptual machine. ***Note that there can be self-reference in the execution of the instructions but not in their logical structure.***

The process of computation was graphically depicted in Turing's paper when he asked the reader to consider a device that can read and write simple symbols on a paper tape that is divided into squares. The *"reading/writing head"* can move in either direction along the tape, one square at a time, and a control unit that directs the actions of the head can interpret simple instructions about reading and writing symbols in squares. The single square that is "scanned" or "read" at each stage is known as the *Active Square*. Imagine that new sections can be added at either end of the existing tape, so it is potentially infinite.

Suppose the symbols are "X" and "O". Suppose that the device can erase either symbol when it reads it in the *Active Square* and replace it with the other symbol (i.e., erase an X and replace it with an O, and vice versa). The device also has the ability to move left or right, one square at a time, according to instructions interpreted by the control unit. The instructions cause a symbol to be erased, written, or left the same, depending on which symbol is read.

Any number of games can be constructed using these rules, but they would not all necessarily be meaningful. One of the first things Turing demonstrated was that some of the games constructed under these rules can be very sophisticated, considering how crude and automaton-like the primitive operations seem to be. The following example illustrates how this game can be used to perform a simple calculation.

The rules of the game to be played by this Turing machine are simple: Given a starting position in the form of a section of tape with some Xs and Os on it, and a starting square indicated, the device is to perform the actions dictated by a list of instructions and follows the succeeding instructions *one at a time* until it reaches an instruction that forces it to stop. *(If there is no explicit instruction in the table of instructions for a particular tape configuration, there is nothing that the machine can do when it reaches that configuration, so it has to stop.)*

Each instruction specifies a particular action to be performed if there is a certain symbol on the active square at the time it is read. There are four different actions; they are the only legal moves of this game. They are:

Replace O with X.
Replace X with O.
Go one square to the right.
Go one square to the left.

An example of an instruction is: "If there is an X on the active square replace it with O." This instruction causes the machine to perform the second action listed above. In order to create a "game," we need to make a list that specifies the number of the instruction that is being followed at every step as well as the number of the instruction that is to be followed next. That is like saying "The machine is now following (for example) instruction seven, and the instruction to be followed next is (for example) instruction eight" (as is illustrated in appendix 3).

Here is a series of instructions, given in coded form and the more English-like translation. Taken together, these instructions constitute an "instruction table" or a "program" that tells a Turing machine how to play a certain kind off game:

1XO2 (Instruction #1:if an X is on the active square, replace it with O, then execute instruction #2.)
2OR3 (Instruction #2: if an O is on the active square, go right one square and then execute instruction #3.)
3XR3 (Instruction #3: if an X is on the active square, go right one square execute instruction #3;
3OR4 but if an O is on the active square, go right one square and then execute instruction #4.)
4XR4 (Instruction #4: if an X is on the active square, go right one square and then execute instruction #4;
4OX5 but if an O is on the active square, replace it with X and then execute instruction #5.)
5XR5 (Instruction #5: if an X is on the active square, go right one square and then execute instruction #5;
5OX6 but if an O is on the active square, replace it with X and then execute instruction #6.)
6XL6 (Instruction #6: if an X is on the active square, go left one square and then execute instruction #6
6OL7 but if an O is on the active square, go left one square and then execute instruction #7.)
7XL8 (Instruction #7: if an X is on the active square, go left one square and then execute instruction #8.)
8XL8 (Instruction #8: if an X is on the active square, go left one square and then execute instruction #8;
8OR1 but if an O is on the active square, go right one square and then execute instruction #1.)

Note that if there is an O on the active square in instruction #1 or #7, or if there is an X on the active square in instruction #2, the machine will stop.

In order to play the game (run the program) specified by the list of instructions, one more thing must be provided: a starting tape configuration. For our example, let us consider a tape with two Xs on it, bounded on both sides by an infinite string of Os. The changing states of a single tape are depicted here as a series of tape segments, one above the other. The *Active*

Square for each is denoted by a capital X or O. When the machine is started it will try to execute the first available instruction, instruction #1. The following series of actions will then occur

Instruction	**Tape**	**What the Machine Does**
#1	...oo**X**xooooooo...	One (of two) Xs is erased.
#2	...oo**O**xooooooo...	
#3	...ooo**X**ooooooo...	Tape is scanned to the right
#3	...ooox**O**oooooo...	
#4	...oooxo**O**ooooo...	
#5	...oooxo**X**ooooo...	Two Xs are written.
#5	...oooxox**O**oooo...	
#6	...oooxox**X**oooo...	
#6	...oooxo**X**xoooo...	Scanner returns to the other original X
#6	...ooox**O**xxoooo...	
#7	...ooo**X**oxxoooo...	
#8	...oo**O**xoxxoooo...	Scanner moves to the right and execute #1
#1	...ooo**X**oxxoooo...	
#2	...ooo**O**oxxoooo...	
#3	...oooo**O**xxoooo...	Scanner moves to the right of the two Xs that were written earlier.
#4	...ooooo**X**xoooo...	
#4	...ooooox**X**oooo...	
#4	...oooooxx**O**ooo...	
#5	...oooooxx**X**ooo...	Two more Xs are written.
#5	...oooooxxx**O**oo...	
#6	...oooooxxx**X**oo...	
#6	...oooooxx**X**xoo...	Scanner looks for any more original Xs
#6	...ooooox**X**xxoo...	
#6	...ooooo**X**xxxoo...	
#6	...oooo**O**xxxxoo...	
#7	...ooo**O**oxxxxoo...	The machine stops because there is no instruction for #7 if O is being scanned.

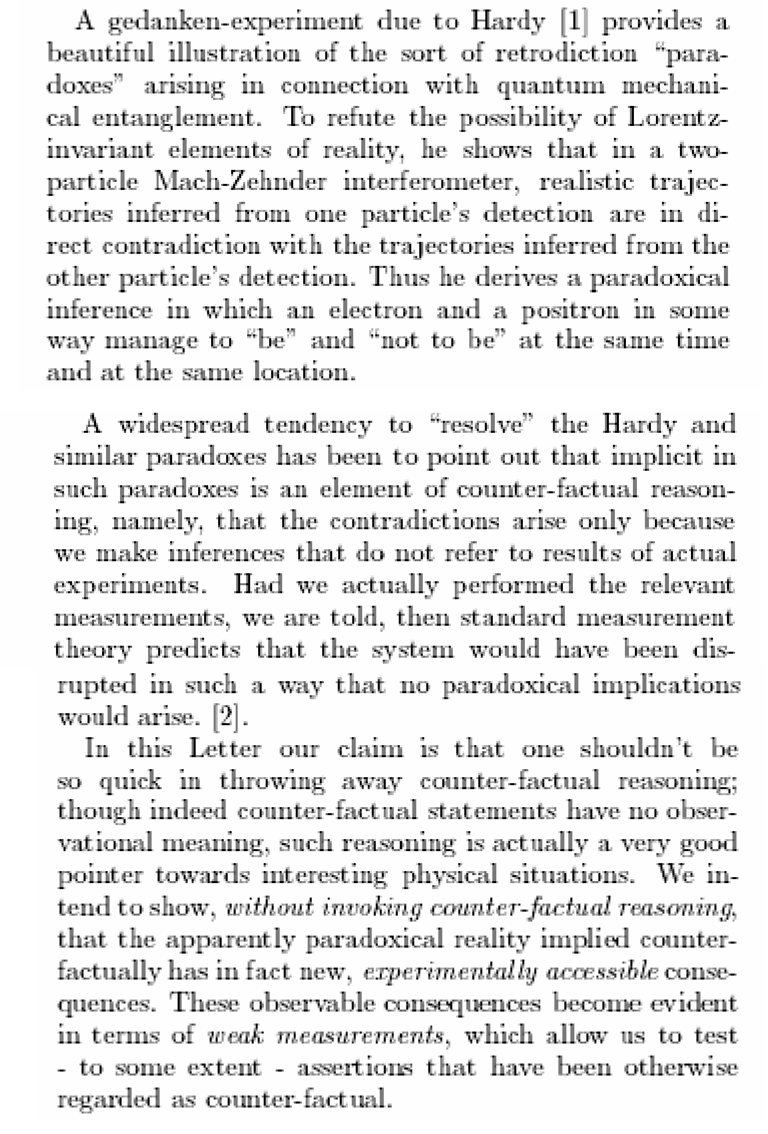
This game may seem rather mechanical. The fact that it is mechanical was one of the points Turing was trying to make. If you look at the starting position, note that there are two adjacent Xs. Then look at the final position and note that there are four Xs. If you were to use the same instructions, but start with a tape that had five Xs, you would wind up with ten Xs. This list of instructions is the specification for a calculating procedure that can double the input and display the output. It can, in fact, be done by a machine.

(This Appendix is edited with author's permission from "Tools for Thoughts: The People and Ideas of the Next Computer Revolution" by Howard Rheingold 1985)

Appendix E: Non-Destructive Quantum Measurements

Protective Quantum Measurements and Hardy's Paradox

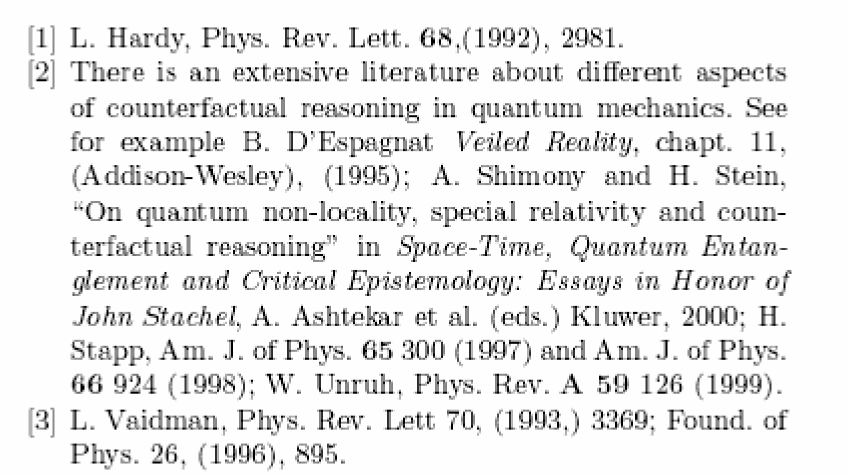
The debate about the existence of the choice function in the Axiom of choices is in the same spirit as the debated questions about the reality of the wave function and paradoxes connected with quantum entanglement like the one proposed by Hardy (see references in the extract below). It has been proven by Aharonov and his collaborators[145-148]that it is possible in principle to perform quantum measurements to extract information beyond quantum uncertainty while the wave function is protected (for the case of eigenstate with discrete spectrum of eigenvalue they refer to it as protective measurements, and for continuous spectrum as weak measurements). The protective, weak and non-demolition (described latter) quantum measurements provide different methods for non-destructive measurements of quantum systems – there is no destruction of the quantum state of the system due to externally imposed measurement. These kinds of measurements enable the observations of unexpected quantum phenomena. For example, the thought experiment proposed in Hardy's paradox can be tested as illustrated in [Quantum Physics, abstract quant-ph/0104062].



A gedanken-experiment due to Hardy [1] provides a beautiful illustration of the sort of retrodiction "paradoxes" arising in connection with quantum mechanical entanglement. To refute the possibility of Lorentz-invariant elements of reality, he shows that in a two-particle Mach-Zehnder interferometer, realistic trajectories inferred from one particle's detection are in direct contradiction with the trajectories inferred from the other particle's detection. Thus he derives a paradoxical inference in which an electron and a positron in some way manage to "be" and "not to be" at the same time and at the same location.

A widespread tendency to "resolve" the Hardy and similar paradoxes has been to point out that implicit in such paradoxes is an element of counter-factual reasoning, namely, that the contradictions arise only because we make inferences that do not refer to results of actual experiments. Had we actually performed the relevant measurements, we are told, then standard measurement theory predicts that the system would have been disrupted in such a way that no paradoxical implications would arise. [2].

In this Letter our claim is that one shouldn't be so quick in throwing away counter-factual reasoning; though indeed counter-factual statements have no observational meaning, such reasoning is actually a very good pointer towards interesting physical situations. We intend to show, *without invoking counter-factual reasoning*, that the apparently paradoxical reality implied counter-factually has in fact new, *experimentally accessible* consequences. These observable consequences become evident in terms of *weak measurements*, which allow us to test - to some extent - assertions that have been otherwise regarded as counter-factual.



[1] L. Hardy, Phys. Rev. Lett. **68**,(1992), 2981.

[2] There is an extensive literature about different aspects of counterfactual reasoning in quantum mechanics. See for example B. D'Espagnat *Veiled Reality*, chapt. 11, (Addison-Wesley), (1995); A. Shimony and H. Stein, "On quantum non-locality, special relativity and counterfactual reasoning" in *Space-Time, Quantum Entanglement and Critical Epistemology: Essays in Honor of John Stachel*, A. Ashtekar et al. (eds.) Kluwer, 2000; H. Stapp, Am. J. of Phys. **65** 300 (1997) and Am. J. of Phys. **66** 924 (1998); W. Unruh, Phys. Rev. **A 59** 126 (1999).

[3] L. Vaidman, Phys. Rev. Lett 70, (1993,) 3369; Found. of Phys. 26, (1996), 895.

As with a multiple-options state for organism, Hardy's paradox is usually assumed to be resolved on the grounds that the thought experiment doesn't correspond to any possible real experiment and is therefore meaningless. The only way to find out what really happens to the particles in the experiment would be to measure their routes, rather than simply inferring them from the final result. But, as soon as a particle detector is placed in any of the paths, standard strong quantum measurement will cause the collapse of its wave function and wash out any possible future interference between the electron and positron states.

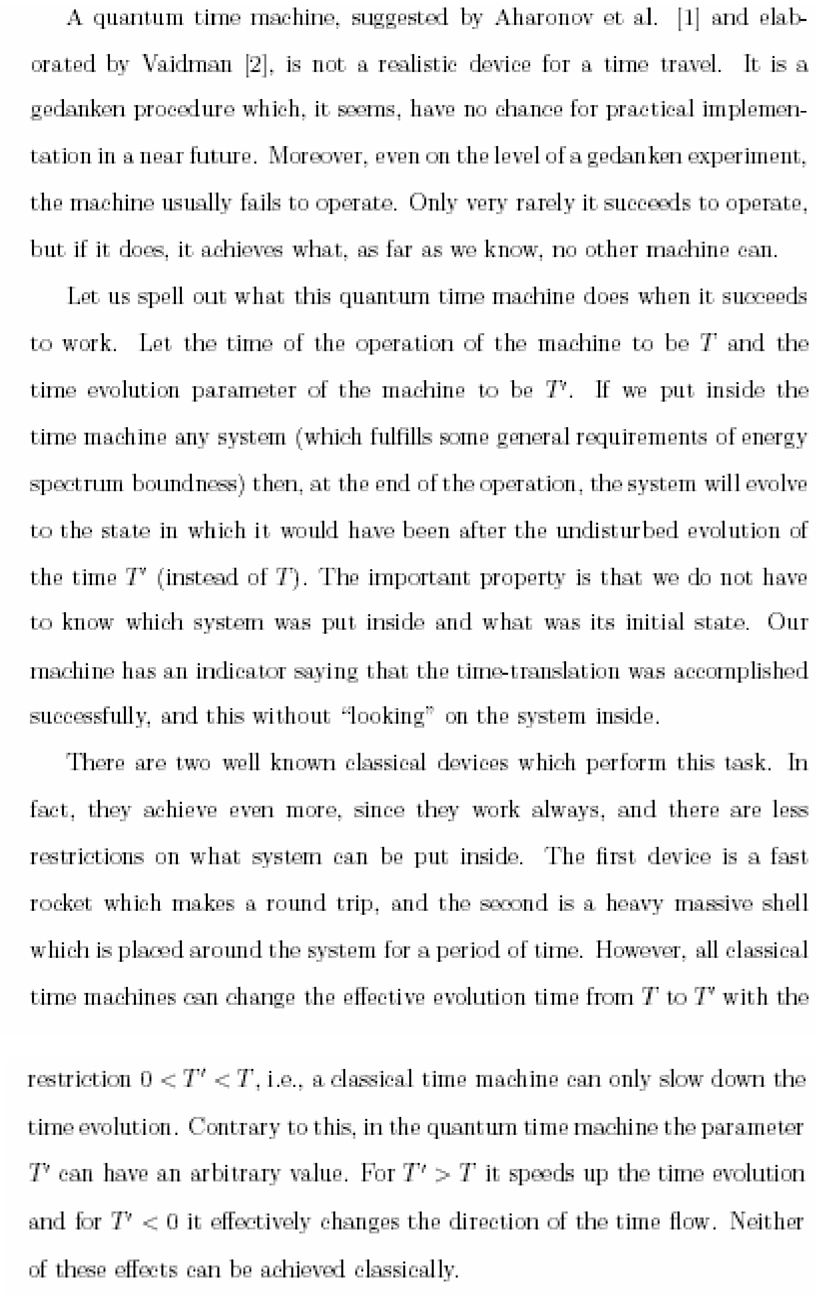
However, Hardy's thought experiment can be converted into a real one if the assumed strong quantum measurement is replaced with weak measurements. The idea is to exploit quantum uncertainty by using a quantum detector which is weakly coupled to the measured system to the degree that it reads eigenvalues smaller than the expected quantum uncertainty. It was proved that by doing so quantum superposition of states can be preserved (i.e., there is no collapse of the wave function). Clearly, a single weak measurement can not, on its own, provide any meaningful information. However, it was proved theoretically that, when repeated many times, the average of these measurements approximates to the true eigenvalue that would be obtained by a single strong measurement involving a collapse of the wave function [145-148]..

Therefore, when weak measurements are assumed, not only does the original paradox remain, but an additional difficulty arises. The theoretical investigations imply that two pairs of electron-positron can coexist in the apparatus at the same time: A detector located in the part of the interferometer in which the particle trajectories are non-overlapping can yield a final reading of -1, i.e., a "negative presence" of a pair of particles! To quote Aharonov:

The -1 result illustrates that there is a way to carry out experiments on the counter-intuitive predictions of quantum theory without destroying all the interesting results. A single quantum particle could have measurable effects on physical systems in two places at once, for instance. Moreover, when you get a good look inside, quantum theory is even more bizarre than we thought. Quantum particles can assume far more complex identities than simply being in two places at once: pairs of particles are fundamentally different from single particles and they can assume a negative presence. And the fact that weak measurements transform the paradox from a mere technicality into an unavoidable truth suggests that they could provide a springboard for new understanding of quantum mechanics. There are extraordinary things within ordinary quantum mechanics; the negative presence result might be just the tip of the iceberg: every paradox in quantum theory may simply be a manifestation of other strange behaviors of quantum objects that we have not yet detected - or even thought of.

The Quantum Time-Translation Machine

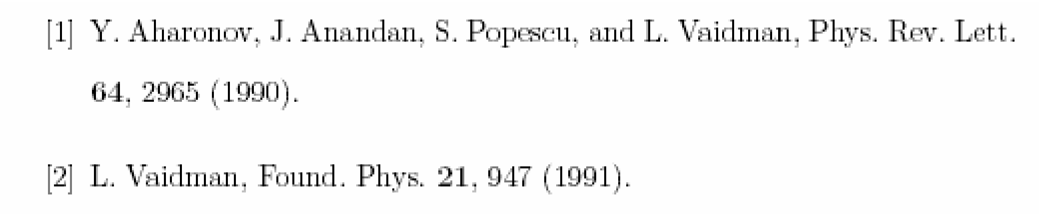
Another unexpected quantum reality about the concept of time [149], can be viewed as being metaphorically related to the organism's internal model of itself, which acts on different time scales for educated decision-making. We refer to the Aharonov, Anandan, Popescue and Vaidman (AAPV) *Quantum Time-Translation Machine* [150,151]:



A quantum time machine, suggested by Aharonov et al. [1] and elaborated by Vaidman [2], is not a realistic device for a time travel. It is a gedanken procedure which, it seems, have no chance for practical implementation in a near future. Moreover, even on the level of a gedanken experiment, the machine usually fails to operate. Only very rarely it succeeds to operate, but if it does, it achieves what, as far as we know, no other machine can.

Let us spell out what this quantum time machine does when it succeeds to work. Let the time of the operation of the machine to be T and the time evolution parameter of the machine to be T'. If we put inside the time machine any system (which fulfills some general requirements of energy spectrum boundness) then, at the end of the operation, the system will evolve to the state in which it would have been after the undisturbed evolution of the time T' (instead of T). The important property is that we do not have to know which system was put inside and what was its initial state. Our machine has an indicator saying that the time-translation was accomplished successfully, and this without "looking" on the system inside.

There are two well known classical devices which perform this task. In fact, they achieve even more, since they work always, and there are less restrictions on what system can be put inside. The first device is a fast rocket which makes a round trip, and the second is a heavy massive shell which is placed around the system for a period of time. However, all classical time machines can change the effective evolution time from T to T' with the restriction $0 < T' < T$, i.e., a classical time machine can only slow down the time evolution. Contrary to this, in the quantum time machine the parameter T' can have an arbitrary value. For $T' > T$ it speeds up the time evolution and for $T' < 0$ it effectively changes the direction of the time flow. Neither of these effects can be achieved classically.



[1] Y. Aharonov, J. Anandan, S. Popescu, and L. Vaidman, Phys. Rev. Lett. 64, 2965 (1990).

[2] L. Vaidman, Found. Phys. 21, 947 (1991).

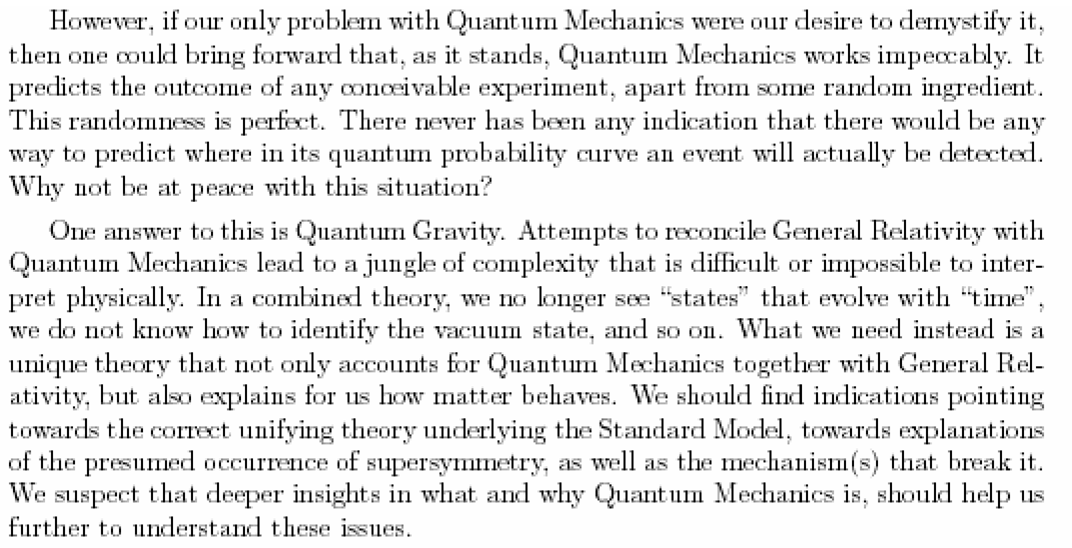
Quantum Non-Demolition Measurements

Another approach to measure the eigenvalue of a specific observable without demolition of the quantum state of the observed system is referred to as QND measurements used mainly in quantum optics [152,153]. The idea can be traced back to the Einstein, Podolsky and Rosen paradox [154], presented in their 1935 paper entitled "Can quantum-mechanical description of physical reality be considered complete?" They have shown that, according to quantum mechanics, if two systems in a combined state (e.g., two half-spin particles in a combined-spin state) are at a large distance from each other, a measurement of the state of one system can provide information about that of the other one. The conceptual idea of the QND measurements is to first prepare the observed system and a quantum detector (e.g., Polarized light) in an entangled state and then to extract information about the observed system by using ordinary destructive measurement on the quantum detector. This way, the state of the detector is demolished but that of the system of interest is protected. In this sense, the newly developed biofluoremetry method for studying the intracellular spatio-temporal organization and functional correlations is actually a version of QND measurements and not just an analogy.

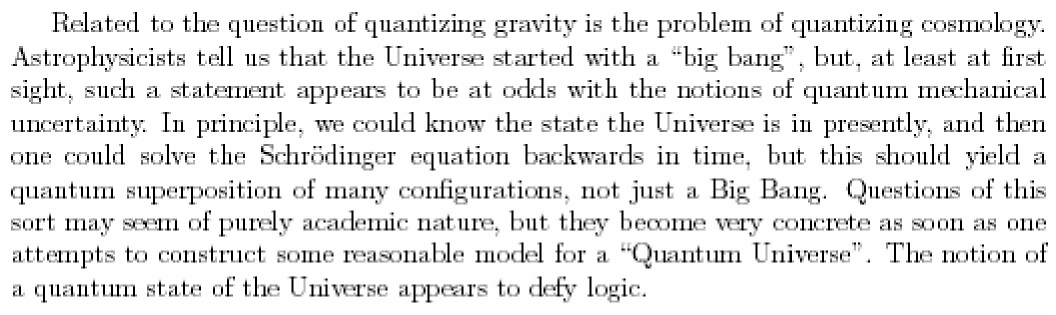
Proceeding with the same metaphor, bacterial colonies enable to perform new real experiments in analogy with Aharonov's 'back from the future' notion about the backward propagation of the wave function. For example, several colonies taken from the same culture in a stationary phase, or even better, from spores, can be grown at successive intervals of time while exposed to the same constraints. The new concept is to let, for example, bacteria taken from the future (the older colonies) to communicate with colonies at the present and compare their consequent development with those who were not exposed to their own future. Albeit simple, the detailed setup and interpretations of the experiments should be done keeping in mind that (as we have shown), even similar colonies grown at the same time develop distinguishable self-identities.

To Be is to Change

The picture of the decomposable mixed state of multiple options is also metaphorically analogous to t'Hooft's Universe [155,156], composed of underlying Be-able and Change-able non-commuting observables at the Planck length scales (10^{-35}meter). His motivation was the paradox posed by the *in principle* contradiction of simulating backward in time a unified theory composed of gravity and quantum mechanics based on the current Copenhagen interpretation: There is no deeper reality, hidden variables do not exist and the world is simply probabilistic. It holds that we are not ignorant about quantum objects; it's just that there is nothing further to be known. This is in contradiction with Einstein's picture later named 'hidden variables'. The EPR paradox mentioned earlier was an attempt to illustrate that, unless the existence of unknown and non-measurable variables is assumed, one runs into contradiction with our intuitive perception of reality. Simply phrased, according to the 'hidden variable' picture, quantum uncertainty reflects some underlying deterministic reality that *in principle* can be measured. Following the EPR paradox, Bell proposed a specific inequality that, if measured, can distinguish between the Copenhagen and hidden variables interpretations of quantum mechanics. The consequent experiments were in agreement with the Copenhagen interpretation. In 2002, t'Hooft presented a new approach to the problem that most perceived as being resolved. His answer to the Copenhagen interpretation is [155]:

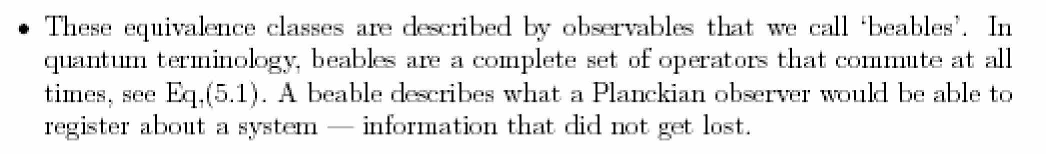


> However, if our only problem with Quantum Mechanics were our desire to demystify it, then one could bring forward that, as it stands, Quantum Mechanics works impeccably. It predicts the outcome of any conceivable experiment, apart from some random ingredient. This randomness is perfect. There never has been any indication that there would be any way to predict where in its quantum probability curve an event will actually be detected. Why not be at peace with this situation?
>
> One answer to this is Quantum Gravity. Attempts to reconcile General Relativity with Quantum Mechanics lead to a jungle of complexity that is difficult or impossible to interpret physically. In a combined theory, we no longer see "states" that evolve with "time", we do not know how to identify the vacuum state, and so on. What we need instead is a unique theory that not only accounts for Quantum Mechanics together with General Relativity, but also explains for us how matter behaves. We should find indications pointing towards the correct unifying theory underlying the Standard Model, towards explanations of the presumed occurrence of supersymmetry, as well as the mechanism(s) that break it. We suspect that deeper insights in what and why Quantum Mechanics is, should help us further to understand these issues.



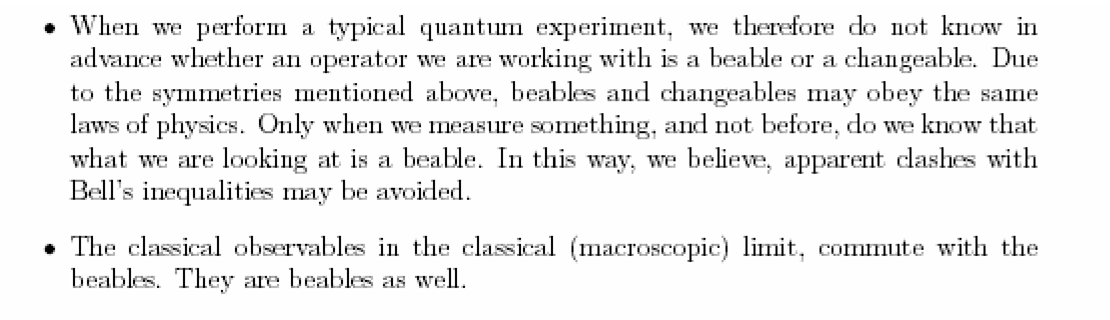
> Related to the question of quantizing gravity is the problem of quantizing cosmology. Astrophysicists tell us that the Universe started with a "big bang", but, at least at first sight, such a statement appears to be at odds with the notions of quantum mechanical uncertainty. In principle, we could know the state the Universe is in presently, and then one could solve the Schrödinger equation backwards in time, but this should yield a quantum superposition of many configurations, not just a Big Bang. Questions of this sort may seem of purely academic nature, but they become very concrete as soon as one attempts to construct some reasonable model for a "Quantum Universe". The notion of a quantum state of the Universe appears to defy logic.

To solve the paradox, he proposed a third approach based on the idea that, on the Planckian level, reality might be essentially different from that on the larger scales of interest. The idea is to define equivalence classes of states. Two states are defined as equivalent if and only if they evolve in the near future to the same state. We emphasize that this is the analogy (in reverse) to our picture of ‘harnessing the past to free the future’ during internal self-organization of organisms. Metaphorically, for similar reasons (in reverse) why loss of information leads to the quantum uncertainty for an external observer, the storage of past information by the organism affords it an internal state of multiple options inaccessible to an external observer. To take into consideration the crucial role of information loss, t’Hooft proposes that two kinds of observables exist on the Planckian scale. The ones that describe the equivalent classes are the be-able ones:



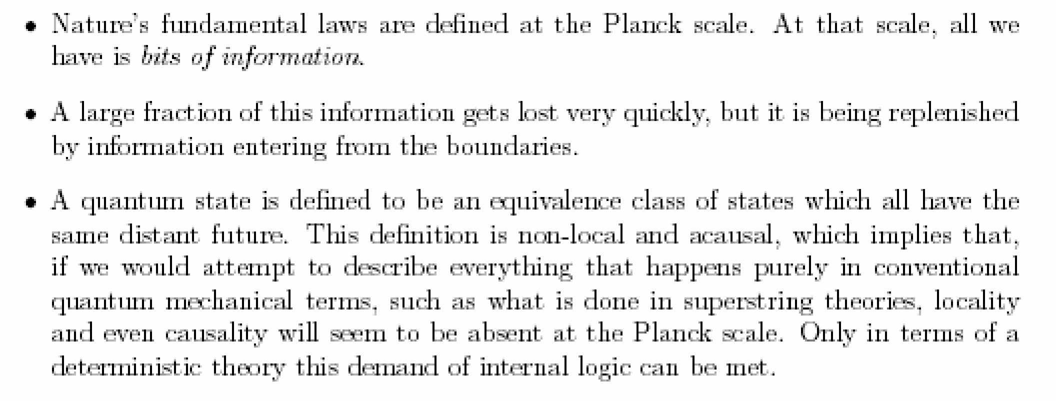
- These equivalence classes are described by observables that we call ‘beables’. In quantum terminology, beables are a complete set of operators that commute at all times, see Eq.(5.1). A beable describes what a Planckian observer would be able to register about a system — information that did not get lost.

With regard to organisms, the corresponding observables are those connected with information registered in the structural organization or statistically averaged dynamics (e.g., gene-expression measurements from several organisms under the same conditions). According to t’Hooft all other operators are the change-able ones that do not commute with the be-able operators. So that,

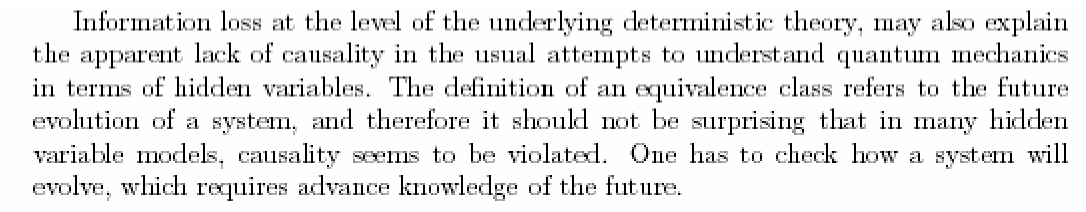


- When we perform a typical quantum experiment, we therefore do not know in advance whether an operator we are working with is a beable or a changeable. Due to the symmetries mentioned above, beables and changeables may obey the same laws of physics. Only when we measure something, and not before, do we know that what we are looking at is a beable. In this way, we believe, apparent clashes with Bell’s inequalities may be avoided.
- The classical observables in the classical (macroscopic) limit, commute with the beables. They are beables as well.

In this picture, reality on the very fundamental level is associated with information rather than matter:



- Nature's fundamental laws are defined at the Planck scale. At that scale, all we have is *bits of information*.
- A large fraction of this information gets lost very quickly, but it is being replenished by information entering from the boundaries.
- A quantum state is defined to be an equivalence class of states which all have the same distant future. This definition is non-local and acausal, which implies that, if we would attempt to describe everything that happens purely in conventional quantum mechanical terms, such as what is done in superstring theories, locality and even causality will seem to be absent at the Planck scale. Only in terms of a deterministic theory this demand of internal logic can be met.



Information loss at the level of the underlying deterministic theory, may also explain the apparent lack of causality in the usual attempts to understand quantum mechanics in terms of hidden variables. The definition of an equivalence class refers to the future evolution of a system, and therefore it should not be surprising that in many hidden variable models, causality seems to be violated. One has to check how a system will evolve, which requires advance knowledge of the future.

This picture of nature is metaphorically similar to the picture we propose for organisms – a balance between intrinsic and extrinsic flow of information. The essential difference is that organisms are self-organizing open system that can store information, including about their self.

Appendix F: Turing's Child Machine

In the 1950's the three interchangeable terms 'Machine Intelligence', 'Artificial Intelligence' and 'Machine learning' referred to the causal (goal) of learning about humans by building machines to exhibit behavior which, if performed by humans, would be assumed to involve the use of intelligence. In the next five decades, "Machine Intelligence" and its associated terms evolved away from their original *causal* meanings. These terms are now primarily associated with particular *methodologies* for attempting to achieve the goal of getting computers to automatically solve problems. Thus, the term "artificial intelligence" is associated today primarily with the efforts to design and utilize computers to solve problems using methods that rely on knowledge, logic, and various analytical and mathematical methods. Only in some spin-off branches of research, such as genetic programming and evolvable hardware, does Turing's term still communicate the broad goal of getting computers to automatically solve problems in a human-like or even broader biological-like manners.

In his 1948 paper, Turing identified three strategies by which human-competitive machine intelligence might be achieved. The first is a logic-driven search which is the causal reason (described earlier) that led Turing to develop the idea of his conceptual machine, i.e., to learn about the foundations of mathematics and logics. The second reason for generating machine intelligence is what he called a "cultural search" in which previously acquired knowledge is accumulated, stored in libraries, and used in problem solving a - the approach taken by modern knowledge-based expert systems. These first two approaches of Turing's have been pursued over the past 50 years by the vast majority of researchers using the methodologies that are today primarily associated with the term "artificial intelligence."

Turing also identified a third approach to machine intelligence in his 1948 paper, saying: "There is the genetical or evolutionary search by which a combination of genes is looked for, the criterion being the survival value." Note that this remarkable realization preceded the discovery of the DNA and modern genetics. So Turing could not have specified in 1948 how to conduct the "genetical or evolutionary search" for solutions to problems and could not mention concepts like population genetics and recombination. However, he did point out in his 1950 paper that:

We cannot expect to find a good child-machine at the first attempt. One must experiment with teaching one such machine and see how well it learns. One can then try another and see if it is better or worse. There is an obvious connection between this process and evolution, by the identifications
"Structure of the child machine = Hereditary material";
"Changes of the child machine = Mutations";
"Natural selection = Judgment of the experimenter".

Thus, Turing correctly perceived in 1948 and 1950 that machine intelligence can only be achieved by an evolutionary process in which a description of a computer *hardware and software* (the hereditary material) undergoes progressive modification (mutation) under the guidance of natural selection (i.e., selective pressure in the form of what is now usually called "fitness"). The measurement of fitness in modern-day genetics and evolutionary computation is usually performed by automated means, as opposed to a human passing judgment on each individual candidate, as suggested by Turing.

From this perspective, Turing's vision is actually closer to our view about organisms' intelligence, provided that the external "teacher" is replaced by an inner one, and the organism has freedom of response to the external information gathered, rather than forced to follow specific instructions.