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Does a Ribosome Really Read? On the Cognitive Roots and Heuristic Value of Linguistic Metaphors in Molecular Genetics*
Part 1

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Abstract

We discuss the role of linguistic metaphors as a cognitive frame for the understanding of genetic information processing. The essential similarity between language and genetic information processing has been recognized since the very beginning, and many prominent scholars have noted the possibility of considering genes and genomes as texts or languages. Most of the core terms in molecular biology are based on linguistic metaphors. The processing of genetic information is understood as some operations on text – writing, reading and editing and their specification (encoding/decoding, proofreading, transcription, translation, reading frame). The concept of gene reading can be traced from the archaic idea of the equation of Life and Nature with the Book. Thus, the genetics itself can be metaphorically represented as some operations on text (deciphering, understanding, code-breaking, transcribing, editing, etc.), which are performed by scientists.

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At the same time linguistic metaphors portrayed gene entities also as having the ability of reading. In the case of such "bio-reading" some essential features similar to the processes of human reading can be revealed: this is an ability to identify the biochemical sequences based on their function in an abstract system and distinguish between type and its contextual tokens of the same type. Metaphors seem to be an effective instrument for representation, as they make possible a two-dimensional description: biochemical by its experimental empirical results and textual according to the cognitive models of comprehension. In addition to their heuristic value, linguistic metaphors are based on the essential characteristics of genetic information derived from its dual nature: biochemical by its substance, textual (or quasi-textual) by its formal organization. It can be concluded that linguistic metaphors denoting biochemical objects and processes seem to be a method of description and explanation of these heterogeneous properties.

Keywords: epistemology, philosophy of science, genetic code, genetic reading, genetic translation, genetic information, quasi-mind, cognitive metaphor.

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Может ли рибосома «читать»? О когнитивной основе и эвристической значимости лингвистических метафор в молекулярной генетике*

Часть 1

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Аннотация

В статье обсуждается роль лингвистических метафор как когнитивной модели концептуализации процесса обработки генетической информации. Сущностное сходство между языком и обработкой генетической информации было осознано уже со времени становления генетики, многие выдающиеся исследователи отмечали возможность рассматривать гены и геномы как тексты или языки. Большинство базовых терминов в молекулярной биологии основаны на лингвистических метафорах. Процессы обработки генетической информации осмысляются как определенные операции с текстом: запись, чтение, редактирование и их разновидности (кодирование/декодирование, корректура, транскрипция, перевод, считывание). Истоки концепта генетического чтения можно проследить начиная с древних представлений о Жизни и Природе как о Книге. Сама генетика может быть метафорически представлена в качестве выполняемых учеными определенных операций над текстом (декодирование, понимание, взлом кода, транскрибирование, редактирование и т.д.). В то же время лингвистические метафоры представляют гены как объекты, обладающие способностью читать. В случае с «биологическим чтением» могут быть выявлены некоторые существенные черты, сходные с процессами чтения человеком: это способность идентифицировать биохимические последовательности на основе их функции в абстрактной системе и опознавать типы и их контекстуальные варианты. Метафоры видятся как эффективный инструмент репрезентации, поскольку они создают возможность двумерного описания: биохимического по своим экспериментальным эмпирическим результатам и текстуального по когнитивным моделям его осмысления. В дополнение к их эвристической значимости, лингвистические метафоры основаны на базовых свойствах генетической информации, двойственной по своей природе: биохимической по материальной субстанции, текстуальной (или квазитекстуальной) по форме организации. Отсюда делается вывод, что лингвистические метафоры, обозначающие биохимические объекты и процессы, представляются должным методом описания и объяснения этих гетерогенных качеств.

Ключевые слова: эпистемология, философия науки, генетический код, считывание гена, транскрипция гена, генетическая информация, квазисознание, когнитивная метафора.

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Introduction

The article addresses the notion of genetic reading: this evergreen metaphor can be traced from the archaic idea of the likeness of life and nature to the Book till the recent portraying of a genome as the Book of Life and the Language of God. We discuss the influence of linguistic metaphors on the understanding of the processing of genetic information: how intuitive notions were originally formed as linguistic metaphors and then led to experiment-based discoveries. In addition to their heuristic value, linguistic metaphors are based on essential characteristics of genetic information derived from its dual nature: biochemical by its substance, textual by its formal organization. Metaphors seem to be an effective instrument for representation, as they make a two-dimensional description possible: biochemical by its experimental empirical results, and textual according to cognitive models of their comprehension**.**

Metaphors of reading in molecular genetics

In any textbook, one can find an explanation of how a cell or ribosome reads RNA. As a typical example, let us quote Francis Crick's popular book *Life Itself, Its Origin and Nature*: "A ribosome jumps onto each RNA molecule, moving along it, reading off its base-sequence and stringing together amino acids (carried to it by tRNA molecules) to make a polypeptide chain" [Crick 1981, 70].

Sometimes the ability *to read* is attributed to a cell or organism in general, sometimes verbal forms allow to avoid mentioning who is a reader, as it is represented in this simplified explanation: "So, how does a cell know which of these proteins to make?.. Cells decode mRNAs by reading their nucleotides in groups of three, called codons… Codons in an mRNA are read during translation, beginning with a start codon and continuing until a stop codon is reached. mRNA codons are read from 5′ to 3′, and they specify the order of amino acids in a protein”[1].

However, schoolchildren and students are not supposed to ask by whom “codons are read.” The proper answer cannot be found even in scientific papers describing the technique and specific types of reading activities. Based on the data of the National Centre of Biotechnology Information, USA, Wolfgang Raible has systemized and even calculated the frequency of metaphors derived from the concept of reading:

> Four nucleotide bases abbreviated by A, T, G, and C were called the “letters of the genetic alphabet.” RNA-polymerase is *reading* (found in ca. 44,500 documents as of 2000; the numbers always cover a period of ten years) DNA-sequences with their *reading-frame/s* (27,700 docs.). This process is called *transcription* (81,000 docs. in 1997; 148,100 in 2000 and a total of 212,300 for the family transfer* in 2000), and this happens thanks to *transcription factors* (92,300 docs. in 2000). Associated with transcription is an immediate process of *proofreading* or *proof reading* (700 docs.).
>
> The result is called a *copy* (20,000 docs.) subject to further *editing* (2,100) or *copy editing* (52). The resulting string of mRNA will be *translated* (20,000 docs. in 1997, 75,400 for translat* in 2000) into a polypeptide. This is made possible because the triplets of nucleotides *encode* or are *coding for* amino acids (130,000 docs. for code*/coding in 1997, 253,000 in 2000). The whole process is called *gene expression* (245,400 docs. as of 2000). The use of the metaphor does not end here… The genome of lots of species is being *deciphered* actually (830 docs) [Raible 2001, 105–106] (see also: [Avise 2001]).

In spite of the fact that this research covered literature published before 2000, the situation has not essentially changed. As it is demonstrated [O’Keefe et al. 2015], the most common metaphor in use is that of the genome as “text,” though the idea of “editing” now appears to be more valid for public discussion than “reading.” As this is stated in the most recent research, this metaphor still remains the principal and can easily be combined with metaphors of other semantic types: “With these metaphors, we enter a metaphorical field

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[1] *The Genetic Code*. Khan Academy. Retrieved from https://www.khanacademy.org/science/biology/gene-expression-central-dogma/central-dogma-transcription/a/the-genetic-code-discovery-and-properties

governed by a different master metaphor compared to the older 'book of life' metaphors. One might call it the 'circuit of life' metaphor. This metaphor (which links up with the older one of 'programming life') shifts the way we talk and think about genes and genomes away from the book (and cutting and pasting and editing paper) and towards the machine and the computer" [McLeod & Nerlich 2017, 7].

So, it is possible to go further and try to reveal semantic roots of these terminological usages and describe them not only as some linguistic device, but first of all, as a coherent notional system and conceptual tool for comprehension of genetic processing. Such attempts were made before in seminal works of prominent philosophers of science Evelyn Fox Keller (2002) and Lilly Kay (2000), who had chosen as a subject for their research the origin and functioning of this kernel metaphor of genetic reading. In spite of the different bases of their research, both researchers are inclined to consider it as a product of "a Language in operation," or as generated by some discursive practices connected with some dominating notional paradigm: "There were no genetic messages in the 1930s, genes did not transfer information before the 1950s, they only possessed biochemical specificities" [Kay 2000, 18].

One can agree upon that, but at the same time, this explanation does not seem to be exhaustive or comprehensive, as there also was no idea about the genetic code in the 1930s and protein synthesis and genomics in the 1950s. Besides, as it has been mentioned many times, apart from linguistic-oriented metaphors, there are a lot of others (physicalist, mechanical, engineering, architectural, organic, cybernetic, theological, etc.), and all of them can be explained as a result of some discursive paradigm. However, as it seems, the language-based metaphors are the central, systemic and most coherent ones, they describe the whole processes of gene expression on all of its stages and manifestations. The general inconsistency and incompleteness of metaphorical reasoning and understanding, as it seems, does not affect language-based metaphors in molecular biology. It is not that step by step genetic terminology liberates itself from the initial metaphorical connotations and reduces the processing of genetic information to its bio-chemical substratum. One can observe quite the opposite trend: initially emerging just as a comparison, then the reading-based terminology does not lose its linguistic features and is deeply embodied in the theoretical frame of molecular genetics and even gives birth to the new flourishing disciplines (biosemiotics, bioinformatics, and their still non-recognized cousins: bio-hermeneutics, bio-linguistics, even protein linguistics, etc.). All of them are based on the assumption that processing genetic information does not essentially differ from reading and writing. As these metaphors are "more equal" than all the others, so some additional causes should be elucidated as an explanation of their vitality.

Life as a text without an author: more than a metaphor

However, *reading* is not a core concept of the basic terminology of molecular genetics. It is a derivative from the other concept, a written text, which seems to be the central point of this conceptual system. The similarity between text and genetic information was recognized from the very foundation of genetics – since the discovery of the genetic function of the DNA by F. Miesher. At first, this was just a comparison between two recursive systems where an infinite number of derived configurations ("words") from some restricted set of the initial elements ("an alphabet") can be generated. According to Miesher, in these huge molecules all the wealth and variety of heredity transmissions can find expression, "just as all the words and concepts of all languages can find expression in twenty-four to thirty letters of the alphabet" (cited in: [Trifonov 2000, 5]).

Of course, in such usages, the terms "an alphabet" and "words" should be understood in a broad and formal sense (this only happened in the second half of the 20^{th} century, in mathematical linguistics). Nevertheless, the concept of Language remains a prototype for all such denotative and connotative meanings. Miesher's brief observation contains two basic ideas, about finite and minimal sets of formal elements which are blocks for infinite "wealth and variety" of derived constructions. What is missing here is that there should also be rules of formation, a language (the correct notion of grammar seems to be too technical, it occurs not as a metaphor, but only in its literal meaning in special articles on bio-linguistics and bio-semiotics). If processing the genetic information is equated with the processing of verbal text (especially with written, but not oral text), this implies a notion of language (rules of formation and understanding of "words" or "sentences").

Thus, the quest for rules of heredity may be identified with either revealing an unknown language, or deciphering a code. The introduction of the notion "the hereditary code-script" was the first step in this direction. Initially, it is endowed with some features of a supra-natural omniscient being: "In calling the structure of the chromosome fibers a code-script we mean that the all-penetrating mind, once conceived by Laplace, to which every causal connection lay immediately open, could tell from their structure whether the egg would develop, under suitable conditions, into a black cock or into a speckled hen, into a fly or a maize plant, a rhododendron, a beetle, a mouse or a woman" [Schrödinger 2012, 21–22].

Code-script is able to do even more than to predict the further development of a cell: "But the term code-script is, of course, too narrow. The chromosome structures are at the same time instrumental in bringing about the development they foreshadow. They are law-code and executive power – or, to use another simile, they are an architect's plan and builder's craft – in one" [Schrödinger 2012, 22].

The code-script is depicted as a self-acting, self-planning, self-executing, self-referring, self-describing and self-prescribing Being. Of course, this notion initially used as a metaphor, obtains new semantics. At the first stage of conceptualization, the features of a semiotic sign system (code-script) are transferred onto a living organism: a chromosome contains the pattern of its further development, its "script-code." At the second stage, vice versa, the script-code (the-chromosome-as-a-sign-system) is considered as a perfect living Creature endowed with mind, will, abilities to envisage, and even power.

Although Schrödinger's idea on the decisive function of chromosomes was not confirmed, the term "code" that he suggested became an important concept for describing mechanisms of inheritance. With all the differences in their approaches, the experimental researches were subordinated to the logic of revealing and even "cracking" of the secret encryption code. The search for genetic regularities was reformulated in semiotic terms since the biochemical characteristics of heredity can be represented in the form of signs ("digits," "letters" and "words"). The discoveries of the deepest mechanisms of heredity were considered as a semiotic problem, i.e., as identification of rules of mapping of one sign system onto another. In this way the problem was formulated by George Gamow, rightfully considered as the predecessor of the genetic code discovery. According to him, "the hereditary properties of any given organism could be characterized by a long number written in a four-digital system. On the other hand, the enzymes (proteins), the composition of which must be completely determined by the deoxyribonucleic acid molecule, are long peptide chains formed by about twenty different kinds of amino acids, and can be considered as long ‘words’ based on a 20-letter alphabet. Thus, the question arises about the way in which four-digital numbers can be translated into such ‘words’” [Gamow 1954, 318].

Following this logic, Francis Crick characterized his fundamental discovery of the genetic code as a “linkage” between two “languages”: “The elucidation of the genetic code is indeed a great achievement. It is, in a sense, the key to molecular biology because it shows how the two great polymer languages, the acid language, and the protein language, are linked together” [Crick 1966, 9].

Therefore, there are two languages and rules of correspondence between them. Genetic code which was thought by Schrödinger as the all-penetrating mind now is transformed into something like a vocabulary in Gamow’s style: “The genetic code is the small dictionary, which relates the four-letter language of nucleic acids to the twenty-letter language of the proteins” [Crick 1981, 170].

The rapid experimental elucidation of bio-molecular mechanisms of heredity makes it possible to specify the so-called linguistic operations, which were associated with the processing of genetic information. So, instead of the undifferentiated and at the same time “narrow” concept of script-code where characteristics of an author, interpreter, text, and language were blended, the more specific concepts associated with operations on the text have appeared. The equating of the genetic information with text caused the corresponding association. Therefore, the processing of genetic information was likened to operations with text, and different stages and mechanisms for processing genetic information found their correspondences. First of all, the two basic opposing operations with a text, writing and reading, were differentiated and separated. The related stages of these processes are identified and then localized in different areas. Thus, processes associated with writing found their place in DNA, while reading and translation were located in RNA. The protein synthesis was represented as the series of operations meant to convert a sequence of nucleotides into an amino acid sequence, where each triplet (combination of three nucleotides) corresponded to some of the 20 amino acids (or with one of the four nonsense codons, a sort of punctuation mark for benching a beginning or termination of protein synthesis). During this process, some additional operations, as well as possible errors modifying the original message, are also possible: editing, misreading, and even proof-reading (to detect and correct possible mistakes).

In addition to the processes that can be called creative, as they require some "understanding," there are also more mechanical operations with the text – these are different types of its replication[2]. These are the processes of rewriting, copying, and transcription: as when transferring from one strand to another, a triplet of nucleotides is replaced with its mirror copy; thus the same unit of text is rewritten in different letters in the reverse order. Transcription is a general term for this whole process occurring in DNA.

The totality of all these operations, the proper designation of the whole process of protein synthesis is named expression – where the linguistic connotations also are apparent – some initial meaning receives its surface form and is identified with some "expression" (some protein). So, the process of protein synthesis appears as a sequence of operations with text, where DNA and RNA consequently perform the functions of a chirographer, cryptographer, reader, and translator.

However, who is the author of the original text? Taken as it is, this issue can be ignored, as for all the processes mentioned above, it does not matter by whom this "text" was written. Most importantly, it should be adequately "rewritten," "read," and "translated." However, our habit of treating an author as a prime cause of a text urges us to attribute it to someone, even by reconstructing or inventing some imaginary author. The Laplacian "all-penetrating mind" seemed too abstract for claiming authorship. Hence there arise such common expressions as the language of God or the language of Nature. These expressions can be understood both metaphorically and literally. The head of the Human Genome Project, Francis Collins, reproduces a significant dialogue that took place during the ceremony on the occasion of the completion of this project:

"Today," he [Clinton] said, "we are learning the language in which God created life. We are gaining ever more awe for the complexity, the beauty, and the wonder of God's most divine and sacred gift"... When it came time

[2] Cf.: "It is important to note that the process that is called translation in cellular biology differs radically from transcription and replication processes in the cell. While transcription and replication are stereochemical processes in which the molecular matching can be predicted from chemical laws, the correspondence between RNA codons and amino-acids in translation is not deducible from stereochemical laws since this is based on a historically acquired code. This puts the molecular translation process above the lower semiotic threshold, as diferent from transcription and the replication processes in the cell" [Marais & Kull 2016, 174].

for me to add a few words of my own, I echoed this sentiment: "It's a happy day for the world. It is humbling for me, and awe-inspiring, to realize that we have caught the first glimpse of our own instruction book, previously known only to God" [Collins 2006, 2–3].

Later F. Collins published the books *The Language of God* and *The Language of Life* [Collins 2006; Collins 2010]. Thus, there is the language of God, and the book of life is written in this language. Life is a product of God's activity. As one can see, the archaic idea about the Book of Life where God records the names and destinies of all human beings is re-incarnated in one of the greatest scientific projects of the 20th century (cf.: [Weigmann 2004]). However, this idea is entrenched in the culture of the modernity, and the concept of "authorship" was endowed with some theological, if not divine features. In some respect, this attitude was expanded onto persons who can read this sacral message. As it was demonstrated in [Keller 2002], a new differentiation came around: between common people, who are not able to read and understand genetic messages, and professional molecular biologists, who are in a position to read and rewrite genetic texts. E.F. Keller mentioned Crick's comments on the subject "Genetics and Eugenics" (1963): he had foreseen the new social order where the capacity of a molecular biologist to read and rewrite genetic messages would be complemented by power to intervene in order to improve the human race: "We are likely to achieve a considerable improvement (in the human stock through genetics)… that is by simply taking the people with qualities we like and letting them have more children" [Keller 2002, 85–86]. The ongoing success in genomics and synthetic biology achieved after 1963 makes it possible to establish a new order and new power as the actual challenge:

Metaphors of books, machines, and computers are all highly visible in debates about synthetic biology. They frame discussions about life and the living in terms of reading/writing/editing, designing/engineering, and mass production, thus emphasizing the power, but not really the responsibility, of science and scientists. This power is now doubly asserted as "editing" has moved from being a mere metaphor to being a "reality" in the form of "gene editing" – and thus needs to take place responsibly, given that mistakes are as easy to make as the technology is to use [McLeod & Nerlich 2017, 8].

However, another vision seems to be getting more appropriate. In the post-modern epoch, an Author as the main concept is replaced by the concept of a Reader[3] and is now regarded not as a creator, but as something derived from a text as some of the textual functions. The expression "Language of Life" can be understood in another way, where Life itself (or Nature) is portrayed as a creator or speaker of this language. However, as in the case of natural languages, the notion of authorship is contradictory and non-applicable, so it is possible to avoid it. "What does it matter who is speaking?" This final statement of Foucault's famous lecture [Foucault 1977] can also be recalled on this occasion. Such an approach emphasizes the Language and becomes essential for understanding a text. The notion of language also can be understood with different degree of metaphorical or literal, even fundamentalist interpretation. Thus, referring to the Nobel Prize winner's book, one of the most outstanding linguists of the 20th century Roman Jakobson mentioned:

> The title of the book by George and Muriel Beadle, *The Language of Life*, is not a mere figurative expression, and the extraordinary degree of analogy between the systems of genetic and verbal information fully justifies the guiding statement of this volume: "The deciphering of the DNA code has revealed our possession of a language much older than hieroglyphics, a language as old as life itself, a language that is the most living language of all" [Jakobson 1970, 437].

The remarkable fact is that the linguist did not reproduce the continuation of this quotation, he did not go so far as the prominent biologists had done. For them, DNA seemed to be not an analogue of a language, but it was the "DNAese" language: "The unknown language was the molecular one of DNA. Science can now translate at least a

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[3] Cf.: "We know that a text does not consist of a line of words, releasing a single 'theological' meaning (the 'message' of the Author-God), but is a space of many dimensions, in which are wedded and contested various kinds of writing, no one of which is original: the text is a tissue of citations, resulting from the thousand sources of culture, …the unity of a text is not in its origin, it is in its destination; but this destination can no longer be personal: the reader is a man without history, without biography, without psychology; he is only that someone who holds gathered into a single field all the paths of which the text is constituted… The reader has never been the concern of classical criticism; for it, there is no other man in literature but the one who writes. We are now beginning to be the dupes no longer of such antiphrases… we know that to restore to writing its future, we must reverse its myth: the birth of the reader must be ransomed by the death of the Author" [Barthes 1977, 146, 148].

few messages written in DNAese into the chemical language of blood and bone and nerves and muscles" [Beadle & Beadle 1966, 207].

Another Nobel Prize winner, F. Jacob (by the way, he was Jakobson counterpart of in a French TV program) preferred to speak about the linguistic models and their heuristic value in genetics rather than about language, as such models made it possible to account for and describe multiple facts about the heredity process [Jacob 1977]. However, the concept of the DNA language does not cease in his and his prominent co-author J. Monod's conception – it only was replaced by another term, the program, which successfully combines features of the self-written text and self-operated language:

> In the genetic program, therefore, is written the result of all past reproductions, the collection of successes, since all traces of failures have disappeared. The genetic message, the program of the present-day organism, therefore, resembles a text without an author, that a proof-reader has been correcting for more than two billion years, continually improving, refining and completing it, gradually eliminating all imperfections. What is copied and transmitted today to ensure the stability of the species is this text, is ceaselessly modified by time [Jacob 1973, 287] (see also: [Peluffo 2015]).

The new, very peculiar subject has appeared here: a proof-reader of this self-written text instead of an author. Of course, this means more than considering genetic messages as a self-regulating system. A lot of new additional characteristics of the genetic information processing lead to the conclusion that besides being a self-regulated system, an organism can be considered a self-reading text:

> An organism could be viewed as a set of texts, which are translating each other and as a result building new texts. All these texts are components in cycles of replacement or reproduction, thus directly or indirectly also in cycles of self- replacement and self-production. Thus, an organism could be viewed as a set of reading and translating processes, in which some components of the organism read and translate other components of the same organism. Consequently, an organism is a self-reading text [Kull 1998, 94][4].

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[4] Yuri Lotman preferred to use the opposite perspective and regard a text as an intelligent organism: "At this stage of growing structural complexity, a text displays the properties of an intellectual device: it not only conveys the

So, instead of the Author of text, another Being is supposed to be a kernel point of the conceptual system – a "speaker" of this language, or, more definitely, a scripter and reader of the text. An organism, Cell, DNA/RNA, Gene, Genome, Ribosome – these molecular entities can be easier identified by scientists than incomprehensible God or Life, and they are endowed with the ability to read, translate, and (re-)write. Thus, we return to our question: could a ribosome really read, as Francis Crick and many other scientists assume?

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information put into it… but also transforms messages and develops new ones. …a text presents itself not as a realization of a message in some language, but as a complex system storing diverse codes capable of transforming messages received and generating new ones, a generator of information with the traits of an intelligent person" [Lotman 1988, 55].

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To be continued