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ORIGINAL PAPER

Response by H. H. Pattee to Jon Umerez's Paper: "Where Does Pattee's *"How Does a Molecule Become a Message?"* Belong in the History of Biosemiotics?"

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Abstract Umerez's analysis made me aware of the fundamental differences in the culture of physics and molecular biology and the culture of semiotics from which the new field of biosemiotics arose. These cultures also view histories differently. Considering the evolutionary span and the many hierarchical levels of organization that their models must cover, models at different levels will require different observables and different meanings for common words, like symbol, interpretation, and language. These models as well as their histories should be viewed as complementary rather than competitive. The relation of genetic language and human language is the central issue. They are separated by 4 billion years and require entirely different models. Nevertheless, these languages have in common a unique unlimited expressive power that allows open-ended evolution and creative thought. Understanding the nature of this expressive power and how it arises remains a basic unsolved problem of biosemiotics.

Keywords Symbol-matter problem · Genetic language · Interpretation · Metaphor · Physical laws · Boundary conditions · Constraints · Evolution · Emergence

Conceptual Resonance and Cultural Discord

Umerez's historical analysis of my "resonance" with biosemiotics is well documented, and Jon has a clearer recollection of my papers than I do myself, so

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I have little reason to question his evaluation. Perhaps others will. While I agree that some of my ideas resonate with the aims of biosemiotics, Jon's review reinforced my awareness of the gulf between the culture that formed the new field of biosemiotics and the cultures of physics and biology that formed my concept of genetic language. One aspect of the gulf is unavoidable—the 4 billion years between the origin of genetic language and the origin of human language. The culture of biosemiotics began at the human end; the physicists' study of life began at the molecular beginning.

From my side of the gulf I see an adversarial stance toward physics and molecular biology in some of the biosemiotics literature. Perhaps this stance provides a motivation for developing a new biosemiotics. On the other hand this may be an obstacle to the integration of biosemiotic models with these more empirical sciences. This is what I will discuss.

Umerez is correct that until recently I was unaware of the new field of biosemiotics. In fact, until I read Kull's (2007a) and Favareau's (2007) histories I had no idea of how the current discipline of biosemiotics originated or how it had been promoted by Sebeok, Hoffmeyer, Barbieri, and others. As judged by its current literature, Umerez is also justified in concluding, "that Pattee is not properly a biosemiotician." I have no problem being an improper biosemiotician as long as I pass as a proper physicist and evolutionary biologist. Jon continues, "His [Pattee's] perspective has not been and it is not semiotic. His use of linguistic vocabulary: language, code, symbol, etc, is just in plain terms and not as part of a specialized terminology." That is true. The symbol-matter problem that I consider fundamental is primarily a physics problem. I use conventional terminology from the culture of physics, and I do not coin words. In my papers I try to credit the experts who influenced my thinking, and none of them are semioticians.

It so happens I can use the mathematician Peter Winkler's misquote of Newton's metaphor: "If I have seen a little further it is by standing on the shoulders of Hungarians." In my case, some Hungarians I credit with essential ideas are John von Neumann, Michael Polanyi, Eugene Wigner, Albert Szent Geörgyi, and George Polya.

A History from a Different Culture

Kull recently reminded me that I was reluctant at first to accept his invitation to contribute to the special *Semiotica* issue honoring von Uexküll. There were two reasons. First, I knew little about von Uexküll, and second, my encounters with linguists over many years were unproductive to say the least. I found them immune to any concept of genetic language and not interested in the molecular basis of life. For example, when I first met Sebeok I could not convince him that the genetic system formed any kind of language. He doubted that it rose to the level of semiosis. If I recall correctly, this was at an American Institute, of Biological Sciences meeting in St. Louis, ca. 1980. At the time Sebeok was promoting zoosemiotics, and he felt that semiosis required a nervous system. I understand now that he thought this was necessary to implement a von Uexküll function cycle.

In my other limited experiences with linguists and semioticians (e.g., Pattee 1980) I found they were also unconvinced by the unique expressive power of genetic and

human language. Also, the linguists I met were not interested in the origin of life, and many were not even interested in the origin of language! Furthermore, linguists dismiss physics as irrelevant to their studies of language. That is understandable in their culture—physics has no relevance if you simply assume that language exists. To a physicist it is just the existence of language—how molecules become messages—that is the problem.

My Introduction to the New Biosemiotics

It was therefore a great surprise and pleasure to read (at Kull's suggestion) some of the recent biosemiotic literature and to discover that a few of my ideas had recently been noticed, most often by those who, like Hoffmeyer, had a biochemical background. I was gratified to find that Hoffmeyer and Emmeche (1991) recognize the fundamental symbol-matter problem of connecting discrete symbols with continuous dynamics, although I am not clear how their code-duality solves it.

Based on the small fraction of the biosemiotic literature I have read, Umerez is correct that my interest in the physics of symbols arose from a different culture. My perspective began with the problem of the origin of symbols and evolution rather than with human language and animal signs. Most of what I read of the history of biosemiotics has little connection with how physicists and biologists have interpreted genetic information. I get the impression that the new biosemioticians have tried to distance themselves from the informational terminology used by those physicists and molecular biologists who discovered the genetic memory and the genetic code. This is another indication of the "two cultures" problem.

As I read it, the modern history of biosemiotics was not motivated by the physical basis of life, as it was with physicists, but with the nature of sign function beginning with concepts from philosophy, especially C. S. Peirce, ethology, especially von Uexküll, and semiotics, especially Sebeok. These disciplines initially made sense only for the late stages of evolution after animals had well-developed nervous systems, sensorimotor controls, and cognition. Over many years with the growth of molecular biology, sign function was gradually accepted at lower and lower branches of the evolutionary tree until in the 1980s sign function was interpreted by some semioticians as the sign of life itself. In that decade the new biosemiotics was born.

Physicists Recognition of the Genetic Language

For physicists the nature of life has always been recognized as a problem, because the so-called universal laws do not describe local controls—the informational structures or boundary conditions that define life (e.g. Polanyi 1968). For physicists the concept of genetic language appeared naturally with the recognition that DNA was the locus of control information. The discovery of the discrete, linear structure of the gene suggested how information could be recorded, copied, and communicated, but it gave few clues on how the information was actually interpreted by the cell. This problem—how genetic information controls material construction—attracted a large group of physicists and biochemists from 1953 (discovery of the

double helix) to 1966 (discovery of the code and the basics of protein synthesis). It was during that period that the academic fields of molecular biology and biophysics began to flourish, as well as studies on the origin of life. During that period the concept of genetic language was in common use among physicists and biologists.

For example, in 1959 I attended a Biophysics Study Program at University of Colorado at which many physicists and biologist informally discussed the gene-language similarity and speculated about the code. One participant, the neurophysiologist F. O. Schmidt (1961), "saw a direct homology between the logic of molecular and phonemic codes." It was a geneticist, H. Kalmus (1965) who published one of the earliest critical discussions of the similarities and differences of genetic and human language. I know of only one early discussion between a biologist and a linguist about the significance of genetic and human language similarity. That was between François Jacob (1977) and Roman Jakobson. Jacob's view was that the analogous structures resulted only from the requirements of analogous functions, i.e., convergent evolution—a view with which I agree because of the enormous differences between the two languages (See Sec. 9). Jakobson (1970) felt there was more of a structural relation, i.e., genes as a proto-language (See Katz 2008).

As I have pointed out, my question in the paper Umerez discusses, the matter-to-symbol process is equivalent to the problem of the origin of life. However, the converse problem of gene expression must have arisen simultaneously: How do genetic messages control the dynamics of material structures? How do thoughts cause actions? This type of question includes a large class of well-known problems that I call the general symbol-matter problem.

My earliest recollection of becoming aware of this problem was at meeting with Albert Szent-Gyorgyi (1956) who faced the symbol-matter problem at the molecular level long before the discovery of the genetic code. After winning the Nobel Prize in 1938 for discovering vitamin C, he chose to work on the biophysics of muscle (he later discovered the actin-myosin-ATP complex that produces contraction). He chose to study muscle because he knew that (pace Spinoza) "mind cannot cause the body to move"—unless there is muscle. Muscles are complicated mechanisms, and as he aptly explained: "You cannot build a mechanism out of marbles." This interdependence of biosemiotics and biophysics was my first recognition of the irreducible symbol-matter complementarity at the molecular level. No amount of semiotic information, thought, or discourse alone can cause the body to move. It takes some physics. As Waddington has pointed out, the first function of language was to cause actions, not to make statements.

Two Responses to the Genetic Language Metaphor

In contrast to the negative responses from linguists and semioticians to the concept of genetic language, there were no objections from biologists or physicists. The question of whether it was only a metaphor never arose, which is understandable because this had become common usage. Physicists and biologist use metaphors and analogies freely because they are a source of creative ideas. They are "safe" if they are grounded empirically by operationally defined observables. From the literature I

have read, semioticians tend to see danger in metaphors because without empirical grounding they generate undecidable controversies over definitions and ambiguous metaphysical concepts such as realism and idealism.

In the culture of physics, the only issue over a metaphor is whether it is a good metaphor. This is judged, broadly speaking, on its power to suggest more precise formal theories, make predictions, or explain observable behavior. Aristotle said, "a good metaphor implies an intuitive grasp of the similarities in dissimilars." He also said that while the proper use of words is a great skill, "the greatest thing by far is to be master of metaphor." A good metaphor reveals a crucial but otherwise obscure similarity between two systems that also have obvious dissimilarities.

Consequently, for the physicist it is irrelevant if what he calls particles, waves, fields, and spin are metaphors. They are good metaphors just because they have led to formal models with observable consequences, and they are now part of the conventional terminology. Metaphor and analogy are powerful linguistic tools for generating novel images that have more implicit cognitive structure than is easily described or directly observable. For the same reasons, molecular biologists have found metaphorical language conceptually revealing and empirically useful.

Semioticians on the other hand tend to be wary of metaphors. A simple metaphor like "DNA contains information" causes disputes over the definition of information and the "reality" of the metaphor. For example, Barbieri does not want to accept the genetic code as a metaphor because that implies that it is not a "real code." He associates metaphor with a statement that is not literally true. That is correct by definition. Then he associates what is not literally true with not being real. That is only one metaphysical interpretation of "real." He suggests that when one uses metaphor, *"it is not meant to be serious"* (his italics). He wants to "prove" the reality of the code by "generalizing" the physicists' concept of measurement. He says, "Whereas the physical quantities are evaluated by measuring, our biological entities are evaluated by naming their components, but in both cases the entities in question are defined by the operations that evaluate them, and this is the essence of the evaluative approach" (Barbieri 2007).

In the culture of physics, a good metaphor does not imply unreality; rather it reveals an important aspect of reality. Physicists could not get along without metaphors. Imagery, analogies, and metaphors are essential in the creation of scientific models (e.g., Kuhn 1993; Way 1991; Polanyi and Prosch 1975). Physicists often benefit from the associative power of natural language because it promotes analogs and metaphors, even though the source of creative ideas often does not involve language (e.g., Miller 1984; Ghiselin 1952). The same is the case for mathematicians (e.g., Hadamard 1943). My teacher George Polya (1945) points out that the associative power of language results largely from its inherent ambiguity and this is often the source of analogies as well as provocative problems, like Zeno's and Russell's paradoxes.

Metaphors that have become part of conventional language are sometimes called "dead" metaphors, but a more accurate term is a tacit metaphor. It is well known that a good metaphor if it is used repeatedly simply becomes part of the conventional language, with the consequence that most of human language is tacitly metaphoric (e.g., Lakoff and Johnson 1980). For example, when Schrödinger used the term "code script" in 1944 it was clearly a live metaphor.

Today "genetic code" is explicitly defined in most dictionaries and therefore it is now a tacit metaphor. For that reason biologists today do not worry about whether the genetic code is a "real code."

As Umerez indicates, my 1969 paper under discussion was presented to developmental biologists at a conference titled "Communication in Development." Even then, none of these biologists questioned my concept of the genetic language because it was "merely a metaphor." In a postscript to the proceedings, Anton Lang (1969), the organizer of the conference, favorably elaborated on my views and agreed that "we may expect to find some principles of molecular languages, just as we have them in our own higher languages." I also had a similar response at all four of Waddington's Bellagio Conferences. Umerez quotes Waddington at length on his support of the genetic language analogy.

The biologists I know have been using these linguistic terms since the 1950s to describe

communication among cells as well as species, as in the "universal chemical discourse" among bacteria (e.g., Bassler 2006). This linguistic terminology is now a well-established convention. At its root it remains a tacit metaphor because human discourse and genetic discourse, while intuitively similar in one fundamental aspect (see Sec. 7), are explicitly dissimilar in many ways (see Sec.9).

Suggestions on How to Alleviate the Two-Culture Problem

Historically, linguists and semioticians have been resistant and even vehemently opposed to extending concepts like language, messages, and meaning beyond their strict human context. The new biosemiotics arose largely because of the gradual acceptance of a more inclusive use of linguistic terminology.

On the other hand, biosemioticians apparently do not recognize the physicists' inclusive use of information. They claim that physicists interpret information narrowly and, as such, call it an "outdated paradigm." If the new biosemiotics hopes to complement biophysics, it is not helpful to trivialize the physicist's concept of information by defining it narrowly (as in Shannon Communication Theory) so that it is devoid of meaning. From the literature I have read, the new biosemiotics appears to be unaware of how long physicists have struggled with semantic information, and the necessary empirical consequences of informational control of dynamical systems. This problem began with Maxwell's demon that conceptually uses information to control single molecules (e.g., Leff and Rex 1990). The physicists' concept of semantic information is neither simple nor trivial. In my opinion, no physically coherent theory of semiosis can ignore it (e.g., Pattee 2006). That is because semantic information is, by definition, semiotic information.

The concept of complementary hierarchical models is essential for modeling complex systems (e.g., Pattee 1973a). Every level of biological organization requires a different operational definition of information and interpretation. It should be clear that a model of the cell's interpretation of molecular information in the gene must be different from a model of the brain's interpretation of the information in this sentence. It is a waste of time arguing over concepts like information, interpretation, and function without specifying the domain of the model. Many new disciplines of

biology are now engaged at many levels studying the complex problems of how organisms interpret information, including how genes influence the linguistic structures of the brain (e.g., Thompson, et al. 2001).

It appears to me that biosemiotics in some of its literature is trying to support its novelty as a "new paradigm" by charging physics with pejorative metaphysical assumptions like reductionism, physicalism, mechanism, as well as determinism. This is not a way to promote biosemiotics. None of these charges will stand up. For well over a century physics has been forced by theory and experiment to revise fundamental concepts about determinism, reductionism and the nature of reality. Modern physics is certainly not deterministic, and it has strong arguments against reductionism (e.g., Wigner 1982; Anderson 1972). Laws cannot describe information, function, and language. Laws cannot even describe measurement! These are all considered emergent constraints on the laws. How they emerge and evolve is still the fundamental problem. I should add that physicists' use of metaphor has no necessary relation to reductionism or any other metaphysical stance.

For the same reasons, biosemiotics will not find it helpful to characterize molecular biologists as reductionists, physicalists, mechanists, or organicists on the basis of how they study genetic information. Their work will stand or fall by empirical evidence, not by philosophical interpretation. Molecular biologists are experts in many sophisticated technologies that are essential for understanding how organisms actually interpret the enormous complexities of genetic and epigenetic discourse. Biosemiotics can contribute to this understanding by asking the right questions, some of which have been recently outlined by Kull et al. (2008). However what appears as gratuitous characterization of biologists as "non-semiotic" and "mired in a self-defeating metaphysics" does not give a fair picture of how biologists work, and will certainly not promote biosemiotics among biologists. A more helpful approach was given earlier by Kull (2007b) in which he stresses the irreducible complementarity of biophysics and biosemiotics.

The Unique Similarity of Genetic and Human Language

I do not believe biosemiotic models will be persuasive for biologists if they ignore Dobzhansky's (1973) principle: "Nothing in biology makes sense except in the light of evolution." That is because evolution and creative thought depend on the unlimited number of constructions, functions, and meanings that these two languages allow. In both languages, this crucial power, the basis of which is still poorly understood, is achieved by interpreting a remarkably small number of fixed units concatenated in physically unrestricted recursive sequences of indefinite length. It is this broad expressive power that is the unique and essential feature that allows both open-ended evolution and—after 4 billion years—human speech.

In "The Necessity of Biosemiotics" (Pattee 2007), I restated my earlier claim that von Neumann (1966) gave the first plausible explanation (ca. 1951) for this necessity of language for evolution. His underlying problem was the origin of open-ended evolution. As he expressed it, the problem was explaining the, "critical size below which the process of synthesis is degenerative, but above which the phenomenon of synthesis, if properly arranged, can become explosive." He argued that this requires a

type of self-replication that is controlled by quiescent symbolic description as distinct from the dynamic material construction it controls. This is his semiotic threshold. Von Neumann did not pursue the implication of physical laws on his logic, although he suspected that its molecular realization was the "more important half" of the problem—that is why I have pursued it. The fundamental physical basis for von Neumann's logic is the necessary epistemic separation of laws and initial conditions, as explained elsewhere (e.g., Pattee 2008; Wigner 1964).

It is also significant that von Neumann's argument arose from the culture of formal languages, not from human language. He was thinking of a physical analog of Turing's precisely defined formal idea of a universal (symbolic) computer that defines the domain of computable functions. Computation also has a "syntactic threshold" (a minimum state-symbol product) to reach universality. However, von Neumann knew that the idea of a "universal" (material) physical constructor, and its corresponding "universal" language, could not be precisely defined without involving physical laws. Even then, the evolutionary domain of constructible organisms is not predictable. Von Neumann imagined his universal constructor metaphorically as a "general purpose" machine shop that together with a reservoir of parts could construct any new machine given its explicit description. This in turn implies a corresponding language with the expressive power necessary to describe an endless number of new machines in this intuitive physical domain.

Von Neumann (1951) was well-aware of where this metaphor breaks down. He warned that it was "clear at which point the analogy with the Turing Machine ceases to be valid," which was the fact that construction is not algorithmic. Any analogy of a formal Turing Machine with a material organism would break down just because algorithmic computation requires complete, unambiguous instructions for every step, while genetic description is not complete and therefore not algorithmic. Genes provide only enough explicit information to survive by constructing proteins. These in turn control the structural, enzymatic, and communication networks of the organism, which ultimately includes their own expression. The potential physical domain describable by genetic language is therefore not predictable.

The concept of expressive power in the domain of formal language theory was developed largely by Chomsky (1959)—the Chomsky hierarchy—but this does not touch on the physical interpretation of symbols. The only linguist I found that comes close to expressing "universals of language" broadly enough is Zelig Harris (1968). Genetic language conforms to most of his conditions for a human language. That includes discrete, one-dimensional sequences, small alphabet, syntax (not all sequences meaningful), functional units (sentences), and most important, rewriting (recursion) and self-reference (metalanguage and semiotic closure (Pattee 1995)).

Because material computers can only approximate Turing's formal universal computer, instead of calling them a "universal computer" we speak more modestly (and correctly) of a "general-purpose programmable computer." Here again, the programming languages must have the expressive power as interpreted by the hardware to cover the domain of computable functions. In practice, translating human language to machine language requires a hierarchy of adaptor languages related by codes.

Only Two Languages Have This Unique Creative Power

It is by virtue of this evolutionary criterion of expressive power that the genetic language should be called a general-purpose language because it has the expressive power as interpreted by the cell or organism to describe the essential molecules and controls that distinguish all the species that have existed, or will exist, on the Earth.

The genetic language and human language are the only general-purpose languages that are known, according to this principle of evolutionary potential (Pattee 1973b). This potential is the crucial metaphorical similarity. They both have unpredictable potential expressive power because of their unlimited information capacity for generating functions and meanings. Again, by this evolutionary criterion, other symbol systems and codes, including all forms of signal transduction, cell signaling and chemical messengers, and all communication forms, such as bee-dances, spider drumming, and bird songs, should be recognized as special purpose languages, or better, special symbol systems that are limited to specific functions (e.g., Hauser et al. 2002). Except for very limited learning potential, like imprinting, these symbol systems depend on genetic information for their construction and for their evolution.

Sebeok (2000) clearly appreciated this distinction between a general-purpose language and a special-purpose symbol system, but he applied it only to animal and human languages. As he expressed it, "All animals paleontologists classify generically as Homo, and only such, embody, in addition to a primary [special-purpose] modeling system (Theorem I), a secondary [general-purpose] modeling system, equivalent to a natural language. The difference amounts to this: while the Umwelten of other animals model solely a (for each) 'existent world', man can, by means of the secondary system, also model a potentially limitless variety of 'possible worlds' (containing sentences with alethic, deontic, or epistemic modalities)."

Of course I would agree with Sebeok that the rich modalities of human expressions cannot be compared with the primitive modalities of genetic expressions. Perhaps this lack of human modalities is why Sebeok did not want to call genetic information a language; but it is still the case that only these languages have the crucial potential to describe a limitless variety of possible worlds.

The fact remains that no matter how important the modalities of human language appear to linguists, they are not necessary for evolution or even for intelligent behavior. We cannot even be confident that the technologies based on human language will promote the survival of the species. Whatever the case, genetic language will exist as long as life exists. Genetic language is the primal general-purpose language from which all other symbol systems and human language evolved.

The Differences Between Genetic and Human Language—The Limits of the Metaphor

All metaphors have limits. There are other analogies of genetic and human language (e.g., Sereno 1991), but these similarities should not obscure the enormous differences between genetic and human language. Those differences are why their

relation is still a tacit metaphor. The crucial linguistic similarities that account for their great expressive power are few and simple, while the differences in their production, interpretation, and functions are many and complex, as you would expect after 4 billion years of evolution.

With respect to language production and understanding in the human brain the details are enormously complex and still a major mystery. We do not even understand the basis of memory. There are no internal informational strings or localized memory, no simple alphabet, no explicit code, and no replication. The observed one-dimensional sequences of speech and writing we call human language are only the tip of an iceberg—the final output of a complex neuromuscular dynamical system; and that is not even the source of the thought behind the linguistic sequences. Genetic language has nothing like the complex grammar of human language, no tenses, no propositions, no figures of speech, and no displacement (unless someone discovers some new metaphors).

We know the brain achieves its speed of learning and communication by a coherent dynamics of distributed processing in networks with many millions of neurons. This is entirely different from the local sequential reading of genes. This parallel processing along with fast neural circuitry gives natural language a type of expressive power far beyond the limits of the much simpler and slower linear genetic language processing. The essential semiotic functions of writing, reading, and interpreting symbols in genetic language and in the brain's language have different material substrates, different functions, and operate by completely different processes. Consequently, the domain of human meanings is far removed from the domain of genetic meanings. We may hope to understand the details of how genes are interpreted by organisms, but the neural events that produce human thoughts are probably too complex to ever model in detail.

Opinions and Questions

These cultural and evolutionary differences between the molecular language of genes and neuronal languages of nervous systems, make it unlikely that molecular biologists and semioticians will find models with many common observables or terminologies; but their models should be viewed as complementary not competitive. I agree with Umerez that the metaphor of "resonance" is appropriate for relating the physics of symbols to biosemiotics. However, from a broader historical perspective, I would say that the biosemioticians' "new paradigm" has turned out to resonate with the established knowledge of genetic language and cell communication that has been developed over the past 50 years by physicists and molecular biologists.

The new biosemiotics originated with a culture associated with human language, and it has more of a philosophical outlook than the material focus of the molecular biologist. Nevertheless, from an evolutionary perspective, no matter how unphysical, and immaterial higher level semiotics and linguistics may appear, these levels must have emerged from lower levels. If biosemiotics hopes to influence biology it will need to find more testable connections with lower level models.

One motto of the new biosemiotics, "the sign is the basis of life, not the molecule" is provocative; but physicists and biologists will rightly claim it is a half-

truth that obscures the basic questions: When does a molecule become a sign? Why do signs become messages? How do messages become a general purpose language? In my view these fundamental biosemiotic questions have not been adequately answered. They cover the entire evolutionary time scale, and they raise many other important complementary and non-competitive questions—enough to keep the members of several cultures fully occupied.

References

Anderson, P. W. (1972). More is different. *Science, 177*(4047), 393–396.

Barbieri, M. (2007). Is the cell a semiotic system? In M. Barbieri (Ed.), *Introduction to biosemiotics* (p. 200). Dordrecht: Springer.

Bassler, B. L. (2006). Cell-to-cell communication in bacteria: a chemical discourse. *Harvey Lectures, 2004-2005*(100), 123–142. PubMed.

Chomsky, N. (1959). On certain formal properties of grammars. *Information and Control, 2*(2), 137–167.

Dobzhansky, T. (1973). Nothing in biology makes sense except in the light of evolution. *American Biology Teacher, 35*, 125–129.

Favareau, D. (2007). The evolutionary history of biosemiotics. In M. Barbieri (Ed.), *Introduction to biosemiotics* (pp. 1–67). Dordrecht: Springer.

Ghiselin, B. (1952). *The creative process*. Berkeley: University of California Press. Paperback reprint, 1985.

Hadamard, J. (1943). The *Psychology of Invention in the Mathematical Field*. Princeton University Press. (Dover edition, 1954).

Harris, Z. (1968). *Mathematical structures of languages*. New York: Wiley (Intersciernce).

Hauser, M. D., Chomsky, N., & Fitch, W. T. (2002). The faculty of language: what is it, who has it, and how did it evolve? *Science, 298*, 1569–1579.

Hoffmeyer, J., & Emmeche, C. (1991). Code duality and the semiotics of nature. In M. Anderson & F. Merrell (Eds.), *Semiotic modeling*. Berlin: Mouton de Gruyter. Reprinted in Biosemiotics: Information, Codes and Signs in Living Systems, M. Barbieri, (Ed.), New York: Nova Science.

Jacob, F. (1977). The linguistic model in biology. In D. Armstrong & C. van Schooneveld (Eds.), *Roman Jakobson: Echoes of his scholarship* (p. 187). The Netherlands: Peter de Ridder Press.

Jakobson, R. (1970). *Linguistics. In main trends of research in the social and human sciences I, Paris* (p. 438). Mouton-UNESCO: The Hague.

Kalmus, H. (1965). Analogies of language to life. In J. J. Good, A. J. Mayne & J. Maynard-Smith (Eds.), *The scientist speculates* (pp. 274–279). New York: Capricorn Books.

Katz, G. (2008). The hypothesis of a protolanguage: an epistemological investigation. *Biosemiotics, 1*(1), 57–73.

Kuhn, T. S. (1993). Metaphor in Science. In A. Ortony (Ed.), *Metaphor and thought* (2nd ed.). New York: Oxford University Press.

Kull, K. (2007a). A brief history of biosemiotics. In M. Barbieri (Ed.), *Biosemiotics, information, codes, and signs in living systems* (pp. 1–25). New York: Nova Science.

Kull, K. (2007b). Biosemiotics and biophysics—the fundamental approaches to the study of life. In M. Barbieri (Ed.), *Introduction to biosemiotics*. Dordrecht: Springer.

Kull, K., Emmeche, C., & Favareau, D. (2008). Biosemiotic questions. *Biosemiotics, 1*(1), 41–55.

Lakoff, G. and Johnson, M, (1980). *Metaphors We Live By.* Chicago University Press.

Lang, A. (1969). *Communication in development* (p. 249). NY: Academic.

Leff, H. S., & Rex, A. F. (1990). *Maxwell's demon: Entropy.* Information, Computing, Princeton, NJ: Princeton University Press.

Miller, A. I. (1984). *Imagery in scientific thought*. Inc: Birkhaüser Boston.

Pattee, H. H. (2008). Physical and functional conditions for symbols, codes, and languages. *Biosemiotics, 1*(2), 146–168.

Pattee, H. H. (2007). The necessity of biosemiotics: matter-symbol complementarity. In M. Barbieri (Ed.), *Introduction to biosemiotics* (pp. 115–132). Springer, Dordrecht: The Netherlands.

Pattee, H. H. (2006). The physics of autonomous biological information. *Biological Theory, 1*(3), 1–3.

Pattee, H. H. (1995). Evolving self-reference: matter, symbols, and semantic closure. *Communication and Cognition—Artificial Intelligence, 12*(1–2), 9–27.

Pattee, H. H. (1980). Clues from molecular symbol systems. In *Signed and Spoken Language: Biological Constraints on Linguistic Form,* U. Bellugi and M. Studdert-Kennedy, (Eds.), Dahlem Konferenzen 1980. Weinheim: Verlag Chemie GmbH. pp. 261-274.

Pattee, H. H. (1973a). In H. Pattee (Ed.), *Hierarchy theory.* New York: George Braziller.

Pattee, H. H. (1973b). Postscript — Unsolved problems and potential applications of hierarchy theory. In H. Pattee (Ed.), *Hierarchy theory* (p. 153). New York: George Braziller.

Polanyi, M. and Prosch, H. (1975). *Meaning*. University of Chicago Press. p. 75.

Polanyi, M. (1968). Life's irreducible structure. *Science, 160*, 1308–1312.

Polya, G. (1945). *How to Solve It*. Princeton University Press.

Schmidt, F. O. (1961). Quoted in "Concluding remarks", p. xxviii. In A. Sovijärvi & P. Aalto (Eds.), *Proceedings of the 4th International Congress of Phonetic Sciences*. The Hague, Netherlands: Mouton & Co.

Sebeok, T. A. (2000). Semiotics as Bridge Between Humanities and Science. In P. Perron, L. G. Sbrocchi, P. Colilli & M. Danesi (Eds.), *Semiotics and information sciences* (p. 86). Ottawa: Legas Press.

Sereno, M. I. (1991). Four analogies between biological and cultural/linguistic evolution. *Journal of Theoretical Biology, 151*, 467–507.

Szent-Gyorgyi, A. (1956). Bioenergetics. *Science, 124*(3227), 873–875.

Thompson, P. M., Cannon, T. D., Narr, K. L., van Erp, T., Poutanen, V., Huttunen, M., et al. (2001). Genetic influences on brain structure. *Nature Neuroscience, 4*, 1253–1258.

von Neumann, (1951). General logical theory of automata. In L. A. Jeffress (Ed.), *Cerebral Mechanisms of Behavior—The Hixon Symposium*, vol. 5, no. 9, New York: Wiley, p. 315. Also in *John von Neumann—The Collected Works*, vol 5, A. H. Taub, (Ed.), New York: Macmillan 1963, p. 288.

von Neumann, J. (1966). *Theory of Self-reproducing Automata*. Edited and completed by A. W. Burks, University of Illinois Press, Urbana and London, pp.74–87 and pp. 121–123. (Original lectures, ca. 1952.)

Way, E. C. (1991). *Knowledge representation and metaphor*. Dordrecht: Kluwer Academic Publishers. Studies in Cognitive Systems 7.

Wigner, E. P. (1982). *The limitations of the validity of present-day physics. In: Mind in Nature. Nobel Conference XVII* (p. 119). San Francisco: Harper & Row.

Wigner, E. P. (1964). Events, laws, and invariance principles. *Science, 145*, 995–999.