Simon Fraser University Undergraduate Journal of Philosophy, Volume 1, Issue 2. 2017.
Towards a Biologically-Inspired Formal Semantics
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The classical logical analysis of language, dependent on logical translation and a general logical analysis of grammatical connectives in natural language has been shown to be forced at best and tenuous at worst. However, more recent research in biology and in formal semantics has shown that a more nuanced approach to natural language by means of logic may be possible. In this essay, an argument is given for a biologically-inspired formal semantics inspired by the abstract tile assembly model for DNA origami. Tilings provide a rigorous and flexible middle ground between logic and molecules such as DNA. An argument is presented that establishes the possibility of a transitivity of tiling properties between logic, biology, and language, allowing for a logical analysis of natural language in terms of formal semantics built on tiling models, provided this hypothesis is empirically sound. Some further attention is given to the explanatory appeal of such a hypothesis, along with a response to an initial objection centred on the unpredictability of emergent properties.

Keywords: Formal Semantics, Experimental Philosophy, Biology, Language, Linguistics, First-order Logic, Roger Penrose, Wang Tiles, Abstract Tile Assembly Model, DNA Origami, Slime Mold, Microfluidic Gates, Quasicrystals, Aperiodic Crystals, Information Theory.

Introduction

A central pedagogic element of any course on logic is that we can 'translate' natural language into a logical language, and that somehow this clears up any imprecise linguistic notions which lead to misunderstandings. For the logical positivists, this was more than mere pedagogy: it was a driving force of their philosophy. They believed that logicizing every aspect of our lives would lead to knowledge of the world, purified from imprecision, implicit premises, and, as Wittgenstein famously said, the '[B]ewitchment of our intelligence by means of language.' Such hopes were to be dashed because the very precision of logical languages showed they were an entirely different beast than natural languages. Recursive definitions, truth-conditional analysis, and an emphasis on truth-functionality aren't hallmark properties of natural languages, but of logical languages. Affixing a certain order of symbols to a particular mathematical object doesn't sound like what we're talking about when we think of constructing a sentence in a natural language. Furthermore, natural languages evolve while logical languages are static unless otherwise specified.

While this was seen as a mark against the logicization of language, a middle way may be had whereby a logical analysis of language is possible but only when we increase the expressivity and nuance of logics so as to parallel the same qualities in natural languages.

Headway has been made in this direction by way of modal logics and machine learning, but a formal-semantical parallel to natural language would have to be of a complexity over and above simple directed graphs and weighted graphs that have become so ubiquitous in modal logic and machine learning, respectively. In this paper I will present an argument for developing a semantic capture of natural language by way of natural language supervening on biology. I will argue that biological matter at the molecular, cellular, tissue, organ, and organ-functional levels displays structures similar to that of our formal-semantical mathematical objects, and that a close analysis of these structures can help logicians to develop more precise ways of modeling natural language through logical languages. The core of my argument rests on a transitivity of specific mathematical properties from the molecular level to the organ-functional level, and that if this transitivity holds, then a biological basis may be had for formal semantics.

1. Motivation

When one first learns logic, they're asked to translate a very narrow set of sentences into their formal-logical equivalents and vice-versa. One later learns that, no, there is no real equivalence between a natural language and a logical language, and that the original sentences in the natural language had a semantic content which was already highly precise. In some ways, translation is a stepping stone to learning the deeper aspects of proofs, and for learning how to reason through and follow mathematical proofs written in natural language.

Despite the pedagogic power of translating natural language sentences into logical language sentences, the reality is roughly analogous to chemistry where Bohr orbits are used to teach students the structure of valence bonds, when in fact Bohr orbits are an entirely wrong model and it is in fact atomic orbitals — a quantum phenomenon — that better describe the way atoms behave. An illustration of the disconnect between logical and natural languages comes from Wittgenstein: Wittgenstein is famous for promoting the notion of language games that act as different semantic 'covers' of formally identical sets of sentences. When it comes to natural language, we can already see a difference between natural language and the structure and interpretation of logical languages in the context of language games.

Perhaps one of the most decisive illustrations of the disconnect between natural and logical language comes from this university, namely from the work of Ray Jennings. In his book The Genealogy of Disjunction, Jennings shows how the interpretation of the word 'or' has changed over time, going from having a spatial meaning, namely 'outside of', to the strong disjunctive meaning we have in today's colloquial usage, namely 'either-or', which is the logical connective XOR.[1] In another work of his, The Descent of Logic, Jennings also

[1] Jennings, Raymond Earl. *The Genealogy of Disjunction*, Oxford University Press, New York, 1994.

shows how the logical interpretation of natural language results in a linguistic trivialization, whereby the multivalent meanings of a sentence and its connectives are reduced to a bivalent meaning.[2] A simple example might be the usage of the word 'as long as', and observing how its usage has changed from a durational or temporal one, to a usage where we interpret it as a conditional.[3] Finding further examples of such disconnects is only a matter of our comparing and contrasting the usage of natural and logical language.

This impasse provides us with the opportunity for expanding our variety of formal semantical systems. The consequence is that we can enrich the structure of various logical models, enhancing our understanding of logic, natural language, and even biology. A logical language is simply a set of symbols with a precise order of manipulation, and this order of manipulation is affixed to some mathematical object(s), such as sets or graphs. The precision and manipulability of the symbols is ensured so long as we can make sure its manipulation is non-arbitrary, and having a mathematical structure for these symbols to 'latch onto' forms the nuts and bolts of formal semantics. Yet, our semantical models are too simple for natural languages, so, our springboard for expanding the expressivity of formal logic is this question: what would it take to have a formal semantics 'behave' in a fashion similar to that of natural languages?

2. Linguistic Supervenience Thesis

The foundation of my argument for enriching formal logic and formal semantics depends on a supervenience of language upon biology. Although the extent to which natural language is determined strictly by biology continues to be a matter of debate, the least controversial thesis needed for my argument is a weak form of biological determinism. To elaborate further, the primary tension arising from our assuming biological determinism in the strictest sense is that of the social influence of language development in children. Nowhere is there a gene that tells us to speak English, French, Mandarin, or Spanish, but there are certainly genes that seem to contribute to our linguistic intelligence. Further, language development can be delayed or even entirely prevented through lack of social interaction, showing that a strict genetic determination of language isn't a tenable thesis. The obvious caveat here is that our social activity is indeed influenced by our genes, but my thesis about determinism aims at something more subtle: the influence that the structure and composition of our biology have on the expression of natural language.

The reason for believing that our usage of language is influenced or 'filtered' by the structure and composition of our biology arises from the fact that we, as creatures within a physical universe of determinate form, are at least as determinate as the structures of the laws of physics. One can think of this as an externalist, epistemological thesis, and

[2] Jennings, Ray. *The Descent of Logic*. The Laboratory for Logic and Experimental Philosophy. Simon Fraser University, 2015. 59. Accessed 9 Sept 2015.
[3] Ibid.

something of the sort was originally put forward by Erwin Schrödinger in his lecture What is Life? Schrödinger suggested that the reason why we can reason so precisely about phenomena is because our cognitive constitution is so precisely formed that it's inevitable we come to precise theses as well.[4] In short, our witnessing of higher-order patterns should be the result of some very fundamental basis patterns, and we should expect these basis patterns to reappear at various orders of scale as is the case with many other complex systems displaying emergent phenomena.

For instance, our thoughts and actions — including those related to speech — are certainly determined by our atomic, molecular, cellular, etc. compositions. Even though we cannot exist as human beings without the laws of physics, we also cannot exist as human beings without the particular DNA that we have, the proteins that it codes for, and the cells and tissues that make up our cognitive and speech faculties. More generally, it shouldn't be controversial that the very structure of this composition should influence the structure of our speech, as well as our thoughts. When looking for a more biologically-inspired formal semantics, studying the mathematical properties of our biological composition and its structure seems to be the perfect place to start for answering the above question about formal semantics and natural languages.

3. Information Theory: The Tertium Quid Allowing for a Parallel Between Logic and Biology

The transitivity argument begins with information theory. Information theory is a common language between logic and biology, so it's the perfect place to begin an argument for why properties of structures apparent at the microscopic level to structures are also apparent at the meso- or macroscopic level. Information theory concerns itself with the study of what signals can be communicated between senders and receivers, and how these signals may be ordered and how to quantify said order.

Central to information theory is information entropy, which in simple terms is the degree in which a signal can encode a given variety of messages. For instance, sending a sequence of 1's is a signal with very low entropy because very little can be said. Suddenly, by adding 0's and allowing for a variety of combinations of 1's and 0's, the entropy can become staggeringly high, meaning that a lot can be said in a string of 1's and 0's of arbitrary length and an arbitrary ordering of 1's and 0's. Measuring entropy in terms of isomeric combinations and studying isomeric combinations as a matter of decidability is our entry point for seeking a biological inspiration to a future formal semantics.

When Erwin Schrödinger first proposed the notion of a molecule of heredity in What is Life?, he suggested that the mechanism for heredity should be preserved within a one-

[4] Erwin Schrödinger. What is Life? With Mind and Matter and Autobiographical Sketches. Cambridge University Press, 1992. 13.

dimensionally ordered 'aperiodic' crystal with a size of roughly 300 angstroms.[5,6] By 'aperiodic crystal', Schrödinger meant that it is a structuring of matter exhibiting a complete plane tiling with the special property that the same pattern never repeats, which is not the case with ordinary crystals. Suggesting that a hereditary molecule must be an aperiodic crystal was a unique in- sight at the time—one that few people outside of a small circle of physicists and information theorists could appreciate. An aperiodic crystal allows for a very high informational entropy with very few isomeric elements; in layman's terms, this lets one say a lot with very few words.[7] Although DNA has since been discovered to not be crystalline, it still has an aperiodic structure exhibiting exactly the same informational properties of quasicrystals.[8]

There are two ways that this can already be related to formal semantics. The first way, which I call the 'easy' way, is that DNA, genes, and genetic combinations may already be studied in terms of higher-order logics. It turns out that quantifying over sets and sets of sets allows for computers to discover regularities and correlations between various genes by brute force. This is still in the realm of standard formal semantical models of set theory and higher-order logics. The second way, which I call the 'hard' way — and the one I want to build on in this paper — is that the rules of self-assembly and isomeric combination (that are so often studied in genetics and bioinformatics) already have a very general relationship to contemporary formal semantics, and that teasing out the details of this relationship can help us to better understand genetics, logic, and also natural language.[9,10]

3.1 The Downward Transitivity Argument

The first step of such an endeavour is to establish a common ground between logic and biology, and already we have seen that this basis may be had with higher-order logics, but the easy objection may be made here about such a basis, namely that it seems to be too 'forced' of a common ground. However, there are mathematical structures with degrees of similarity at various levels of abstraction, and which are present in both genes and organic tissues, as well as logics. Logical 'models' of formal languages such as modal logics, for instance, may be expressed graph-theoretically. The analysis of such models according to Kripke semantics involves the building-up of a series of directed edges and vertices whereby the validation of a well-formed string of symbols depends on the structure of the graphs at hand and the assignment of said strings of symbols to given vertices. One can already study such a logical language in terms of isomeric elements and combination rules in the same way we can study anything else with such combinatory properties.

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[5] Ibid., 60.
[6] Ibid., 30.
[7] René Doursat, Hiroki Sayama, and Olivier Michel, eds. *Morphogenetic Engineering: Toward Programmable Complex Systems*. Springer, 2012. 160-1.
[8] Gunther S. Stent. "The Aperiodic Crystal of Heredity." Annals of the New York Academy of Sciences 758.1, (1995): 28-9.
[9] Christoph Adami. "Information Theory in Molecular Biology." *Physics of Life Reviews 1.1* (2004): 7-8.
[10] Werner Ebeling and Miguel A. Jiménez-Montaño. "On Grammars, Complexity, and Information Measures of Biological Macromolecules." *Mathematical Biosciences,* 52.1 (1980): 61.

We can now tease out a similarity between graphs and crystals: if we fix the graph's structure to that of a planar graph, and assign rules to the building-up of such a graph, we can already develop graphs that can completely tile a plane exactly like a crystal, both periodic and aperiodic.[11] Indeed, a study of this has already been done in terms of the decidability of Wang tilings, which allow for an aperiodic tiling following a rather uninteresting planar structure.[12] What makes Wang tilings so interesting is that the colourabiltiy of the tiling determines the rules of assembly, allowing us to ask questions about the rules of assembly, such as whether they are decidable or not. In fact, Wang tilings and tiling games in general are already used to study the decidability, satisfiability, validity, etc. of various sorts of logics, such as modal, propositional, and first-order logics.[13]

My thesis here is that we already have a basis to study DNA and logic with the same tools, namely tilings and, more generally, rules of self-assembly of isomeric elements. My point here is that there are very likely fragments of already-existing logics buried in the rules of self-assembly of biological structures like DNA, RNA, proteins, cells, etc. One question that might be asked is whether or not the iterative growth of a semantic tree can parallel iterative growth and self- assembly of proteins into cells and beyond. The answering of this question might shed light on exactly what fragments of logical languages may best represent biological behaviour on the meso and macro levels, and whether or not this should bear any similarity to the study of natural language as a matter of biological behaviour.

That such a similarity exists between certain formal semantical models and that this similarity can be established, even as a possibility, is a weak-enough starting point for a biologically- inspired formal semantics. The way that such a relationship is established is through a colloquial homology between patterns found in logic and patterns found in nature. The fact that this exists is enough to show that some properties of logics may also carry over into properties in nature, and vice-versa.

3.2 The Upward Transitivity Argument

Now that a relationship between logic and biology is established by appeal to facts, the next relationship to be established is one between biology at the micro-level, to biology at the meso- level and, as a consequence, to natural language. By natural language here we mean language insofar as it is an expression of the structural sophistication of our biological apparatus. By relating logic to biology, and biology to language, we have the means to establishing at the very least a possibility of there being a relationship between very specific logical models and the way in which natural language is expressed. If such a relationship is established, a way to modelling natural language and studying it via formal semantics is

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[11] Jonathan L. Gross and Jay Yellen, eds. *Handbook of Graph Theory*. CRC Press, 2004. 1352.
[12] Taati Siamak. "Wang Tiles." Siamak Taati, 2006. Accessed 30 March 2017. <http://www.math.ubc.ca/ staati/articles/tilings06.pdf>
[13] Bogdan S. Chlebus. Chlebus, Bogdan S. "Domino-Tiling Games." *Journal of Computer and System Sciences*, vol. 32, no. 3, (1986): 386-390, Accessed 15 March 2017, doi:10.1016/0022-0000(86)90036-X.

open again, over and above merely forcing natural language to fit the requirements of a logical language. Since there are no direct examples of such a relationship as of yet, the transitivity requirement will depend on a proof of concept that this relationship is at the very least possible.

If this seems reminiscent of a universal grammar, it certainly is, but only on the surface. Chomsky and Pinker had suggested that, at least in principle, grammar and other pattern- forming processes are external to one's own learned natural language(s) rather than being inherent within the language(s) that one learns. This is to say that a linguistic animal is not entirely responsible for its linguistic capacities insofar as it is socially conditioned to speak a specific language, but rather that there is some other process responsible for the animal's linguisticity. What Chomsky, Pinker, and others don't consider is that the structural 'kernel' of such pattern- forming processes shouldn't have a reason to generate speech that is inherently grammatical, but only something patterned. It may very well be that we, as linguistic creatures, simply take a pattern and, given the associations we make with it, call it 'grammatical' and then search for a grammar-like structure. Grammar and syntax may very well be just resultant patterns supervening on more fundamental ones.

To see how this may happen, we can think of any chain of iterations produced according to a series or some recursive algorithm: one iteration becomes the input of the next iteration, etc. In biology, we can think of macromolecules as acting like 'functions', taking smaller molecules as inputs and rearranging them into proteins, other molecules, and waste products. Genes kick off this iteration process by having some genetic code copied, and then this is used to form the basis pattern for proteins. Proteins carry on this iterative process by coalescing to form larger and more complex structures, the latter of which, in turn, organize themselves into higher- order structures. Humans, as linguistic animals, are an inevitable result of such a process given sufficient genetic material.

The existing models for studying DNA molecules happen to be tiling models, such as the 'abstract tile assembly model' (aTAM), using aperiodic tilings such as the Robinson tiling. The aTAM is used to study the way in which base pairs interact, and is even used to study the information-theoretic properties of DNA. One such usage of the aTAM is for studying 'DNA origami', whereby DNA folds and organizes into complex structures.[14] The aTAM, as an aperiodic tiling model with rules of assembly (that is, rules of substitution, etc.) happens to model DNA origami with impressive accuracy and predictive power. The question, then, is if such a tiling model may be adapted to higher-order organic structures, such as proteins, tissues, organs, and even to the behaviours of creatures like human beings and the societies they form.

[14] Jennifer E. Padilla, Wenyan Liu, and Nadrian C. Seeman. "Hierarchical Self Assembly of Patterns from the Robinson Tilings: DNA Tile Design in an Enhanced Tile Assembly Model." *Natural Computing*, vol. 11, no. 2, 2012, (2011): 331-5, doi:10.1007/s11047-011-9268-7

Most certainly, the aTAM is insufficient for describing protein folding and tissue formation as it stands, since the aTAM is specifically designed with DNA in mind. However, the phenomenon of aperiodicity continually recurs in higher levels of scale. One such explanation by a group of scientists led by Sharon Glotzer is that quasicrystalline structures are a very common consequence of simple thermodynamical properties, and that this, on its own, is sufficient to show that physical structures self-organize into quasicrystalline structures, if not for any other reason than simply maximizing thermodynamic entropy.[15,16] In other words, maximizing thermodynamic entropy means maximizing information entropy. The consequence of this for DNA and proteins is actually quite simple: we should expect there to be further aperiodic structures (proteins) formed from lower-order aperiodic structures (like DNA), if for no other reason than humble thermodynamics. For the purposes of this essay, this consequence fits neatly with what has been conjectured so far, namely that at higher orders of scale in biological creatures, we should expect further self-assembly rules and more variegated aperiodic structures. The possibility of language being such a phenomenon isn't so dim after all.

One response that may be had would be to say that the self-assembly rules of tilings are already implicit in logical languages and that such an algorithm may be extended to context- free grammars as well, making the novelty of self-assembly a moot point because it can be subsumed by the application of recursive definitions. However, there actually is a difference between recursive definitions and self-assembly rules in that self-assembly rules present a far stronger structure while recursive definitions in the general case do not de facto guarantee a deductive framework strong enough for self-assembly rules in tilings. Another response would be to say that a tile assembly model is less abstract insofar as it concerns geometric properties directly inherent in a number of material objects, while recursive definitions don't carry the same concreteness. Furthermore, one may go from a set of self-assembly rules to logic just as easily as one may go from logic to self-assembly rules. Taken together, these responses amount to a counter-argument that self-assembly rules seem much more amenable to a material grounding and a much better biological account of logic and context-free grammar than the other way around.

One caveat is that I cannot specify what such a tile assembly model should look like, but on noting the extent of intimate connection between tile assembly models and formal semantics, we should expect there to be some fragment of a first- or higher-order logic that can approximate such a model. For all intents and purposes, if we are to look at what can more accurately describe natural language, a logical fragment based off of such an assembly model would have a better chance of success for studying the logical properties of natural

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[15] Peter Palffy-Muhoray, et al. "Disordered, Quasicrystalline and Crystalline Phases of Densely Packed Tetra- hedra." *Nature*, vol. 462, no. 7274, (2009): 774-6, doi:10.1038/nature08641.
[16] Pablo F. Damasceno, et al. "Predictive Self-Assembly of Polyhedra into Complex Structures.? *Science* 337, 453 (2012): 453. Accessed 30 March 2017. doi: 10.1126/science.1220869.

languages than, say, just FOL plain and simple. This might even help us to identify certain truth-functions that better match up to their connective analogues in natural language, and ones that may even allow for change over time. We are, of course, by no means modelling language exactly when we attempt any of this, but at least we have more to say after we have shed the naïveté of a classical logical analysis of language.

The immediate consequences of this line of thought are that language is not only a result of genetics, but that the 'grooves' upon which languages operate are not inherent in the language as a social phenomenon, but rather they are inherent within the structure that the language faculty happens to supervene on. We are not linguistic creatures in the sense that language floats freely from our physical makeup. Rather, we are primarily creatures of patterns, and we receive these patterns from our genes and our environment. One may think of the language faculty through an evolutionary perspective in that a natural language exapts patterns present in our physical makeup and our environment, and that a significant portion of the basis patterns we've come to use in language come from the self-assembly rules present in genetics and microbiology.

4. Initial Criticism

There is one significant initial criticism to be made against the current conjecture, namely: why should there be a property that re-emerges across various levels of scale? Furthermore, why should the given property — no matter how generally construed — follow a structure affirming sufficient material and qualitative similarity? I will admit that here the rules of self- organization for one level may not be the same for the next. However, the kicker here is that emergent properties such as these often display scale invariance, and they can also emerge at higher scales. There is a lot of contingency to be had here that can only be deferred to empirical investigation. Regardless of whether the transitivity argument is right or not, this is still an open avenue for investigation and for potential formal-semantical research.

5. Explanatory Appeal

In seeking a mathematical analysis of language, particularly one according to a logical fragment inspired by tiling rules, there are four examples of explanatory appeal that may be had. The first is that the thesis of tiling rules influencing linguisticity happens to give us a way to get a sort of 'universal grammar', but without presupposing any particular grammar. The second is that the increasing symmetry and self-organization of structures so as to form a tiling accounts for a tendency towards symmetry, and upon accepting this tiling-linguisticity thesis, we have a way to account for the case of a lexical-to-grammatical shift seen in the development of human vocabulary. The third is that the global ordering of tiles influences the local ordering of tiles, meaning that such a logical analysis of language gives us a more mechanical means of studying the holistic qualities of natural language. The fourth example is that such a thesis in the most general case explains the behaviour of creatures such as slime molds that display logical behaviour, namely how a certain slime mold, Physarum polycephalum, happens to be an excellent natural computational device for polyadic logics.[17]

With regards to the universal grammar hypothesis, a tile assembly-inspired explanation can account for recursive and other structural regularities in natural languages without positing a specific language gene. There are, for instance, genes that contribute to linguisticity such as FOXP2, as well as other genes partly responsible for linguistic intelligence.[18] However, to say that there is a gene somewhere specifying our grammatical structure is to attribute too much to genomes. The fast response has been that, no, such grammatical structure is more of a social phenomenon, but the path remains open for a partial biological explanation in tandem with a social one. In this case, language, insofar as it is a behavioural phenomenon arising from the ordering of tissues, which are in turn ordered by proteins and DNA, would be a phenomenon akin to self-assembly rules. In this case, it would just be that language does not concern the self-assembly of anything as concrete as proteins, but rather the emergence and self-assembly of vocabulary. Universal grammar, under this hypothesis, is a result of repetition of local and highly ordered patterns, interspersed within more irregular ones. These patterns have their source in biology, and do not need an appeal to standalone linguistic explanations. The origin of grammar would then be accounted for in more fundamental patterns embedded in our biology that shape our behaviour, and not some standalone universal grammar.

This hypothesis also gives us the ability to account for the transition from a lexical to a grammatical vocabulary, and the differences between a grammatical and a lexical vocabulary. Nicholas Rescher once suggested that in nature there is a force of 'symmetry tropism' — that is, a tendency towards greater symmetry.[19] Such asymmetry tropism might beat work in the case of a mechanical explanation for a transition from a more lexically-dominant to a more grammatically- dominant vocabulary. For instance, the thermodynamic hypothesis discussed in the transitivity argument gives a basis for re-imagining language as a thermodynamic phenomenon—one that self-organizes into patterns that maximize information entropy. In crystals and tilings, we might think of this as a phase change from an irregular pattern to a regular but dynamically ordered pattern. Crystal-formation is indeed a tendency towards symmetry.

With regards to the holistic qualities of natural language, there is also a certain holism to aperiodic tilings and their assembly rules. Roger Penrose suggests that aperiodic tilings have a 'global' order in that the chance of a local arrangement of tiles affects the

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[17] "Computing with slime: Logical circuits built using living slime molds." ScienceDaily, Elsevier. 27 March 2014. Accessed 30 March 2017. <www.sciencedaily.com/releases/2014/03/140327100335.htm>.

[18] Gary F. Marcus, and Simon E. Fisher. "FOXP2 in Focus: What can Genes Tell Us About Speech and Lan- guage?." Trends in Cognitive Sciences 7.6 (2003): 261. Accessed 5 Nov 2015. doi:10.1016/S1364-6613(03)00104-9.

[19] Nicholas Rescher. *Nature and Understanding: The Metaphysics and Method of Science*. Oxford University Press, 2003. 73.

global ordering of tiles and vice-versa. This is to say that if I were to remove a certain tile and rotate it another way and still insist that I preserve the aperiodic structure, then I will have to either move the tile back to its original orientation or rearrange the entire tiling so as to fit the new orientation and placement of the tile I moved. In this way, tilings can experience phase changes whereby a local change can result in a global change. Aperiodic tilings can undergo phase changes, and so one can transform one tiling pattern into another while preserving the structural similarities between one phase and the other—the assembly rules remain the same, but can encode a great variety of information in this way. Such tilings can have a 'holistic' nature in that they cannot be thought of merely as assemblies of discrete parts, but also have to be thought of as parts whose order is influenced by the way they fit into a larger pattern. The above insights are very useful for describing natural languages in that changes in words and interpretations have affinity to global and local phase changes, and the understanding of a word cannot be had in the word alone, but only in the context of the rest of the language as it is understood by a person.

Finally, a more general version of this tiling-language hypothesis can be had, namely that behaviour in organisms should exhibit behaviour akin to that of self-assembly rules in tilings, can account for the unusual behaviour of a certain slime mold known as Physarum polycephalum.[20] This mold can be arranged in such a way as to have it perform logical computations, and thus serve as the basis for a truly biological computer, capable of performing computations for plane tessellations, logical calculi, etc.[21] If the slime mold's metabolism or feeding behaviour exhibit patterns akin to these tile assembly rules, and if such assembly rules are sufficient for being combined in sequence to produce a more broader scale of computations, then we have an explanatory basis for why such organisms display this behaviour.

6. Conclusion

What has been established here is the possibility of a transitivity of specific properties between logic, biology, and language. This has been argued for in terms of the 'downwards' and an 'upwards' transitivity argument. The former establishes a connection between logic and DNA in terms of the mutual uses of tilings for studying logical fragments as well as self-organizing patterns in DNA; the latter establishes a connection between DNA and language in terms of the abstract tile assembly model, by way of thermodynamical considerations. This connection gives us a starting point for examining how we can better analyze natural languages in terms of a logical language, specifically a logical fragment with a formal-semantical basis in terms of self- assembly rules for tilings. The main hurdle that this

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20 Adamatzky, Andrew, Theresa Schubert, "Slime mold microfluidic logical gates", *Materials Today*, Volume 17, Issue 2, March 2014: 86-91. Accessed 30 March 2017. doi: 10.1016/j.mattod.2014.01.018. <http://www.sciencedirect.com/science/article/pii/S136970211400025X>.

21 "Slime Mould Computers: Prototypes, Models, Algorithms and Applications? ECAL 2015. Accessed 30 March, 2017. <https://www.cs.york.ac.uk/nature/ecal2015/slime.html>

hypothesis needs to clear is an empirical one, demonstrating that emergence of phenomena across various levels of scale are relatively constant and that the tile assembly structure is largely preserved. Finally, the explanatory appeal to this hypothesis is that a number of disparate phenomena — such as the emergence of language, the holistic structure of language, and even the distinctly logical behaviour of other creatures — may be explained using one general hypothesis, giving this explanation an advantage by way of parsimony and plenitude. It is hoped that all of these above considerations should be at least a tentative way forward to a new and biological inspiration for formal semantics.

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