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Morphological Computation as Morphogenesis: From Leibniz and Goethe to René Thom and Beyond †

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Abstract: The paper is intended as an exploration of the potential methodology for hypercomputing using the long intellectual experience of the study of morphology and morphogenesis. The first part of the paper shows that the missing element of the process of computation in the studies searching for the generalization of computation is encoding. Turing Machines can work only on information encoded in a very specific way. When we look for ways to generalize computation, the analysis of encoding is the most likely source of ideas for the extension of this concept. The second part of the paper is an exploration of the history of morphogenesis from the perspective of the search for a method of unconventional encoding information.

Keywords: morphological computation; morphogenesis; analog information; digital information; information encoding

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1. Introduction

The paper is intended as an exploration of the potential methodology for hypercomputing using the long intellectual experience of the study of morphology and morphogenesis. The first part of the paper shows that the missing element of the process of computation in the studies searching for the generalization of computation is encoding. Turing Machines can work only on information encoded in a very specific way. When we look for ways to generalize computation, the analysis of encoding is the most likely source of ideas for the extension of this concept. The main source of confusion regarding the matters of encoding is in the distinction between digital and analog forms of information that has to be clarified.

The second part of the paper is an exploration of the studies of morphology and morphogenesis from the perspective of the search for a method of unconventional encoding of information.

2. Encoding: Digital, Morphological, or Other

The pairs of adjectives “analog”—“digital” and “qualitative”—“quantitative” entered the everyday language and in the common belief, the latter in each pair is better, more progressive, and future-oriented. There is another belief, this time among those who know the theoretical model of computing introduced by Alan Turing called now Turing Machine that this model sets the boundaries for computing that cannot be crossed. This belief is not universal and there is continuous effort to design hypercomputing, i.e., computing free from the limits set in the orthodox model. Turing himself challenged the limits, first with his oracle machines, later by exploration of chemical morphogenesis.

To go beyond Turing's model of computation requires a generalization of the concept of computing. Of course, computing understood as a process modeled by Turing Machine excludes hypercomputing. The strong attachment to the existing orthodox model of computation generates emphatic denials of its feasibility. In the absence of any clear vision of the generalization, the claim that hypercomputation is not a discipline is obvious [1], but the claim that it is impossible can be only an expression of the belief. On the other hand, without having any idea about the process which could have orthodox computing as a special case, but which exceeds its boundaries the task is formidable. Thus far, attempts were made to engage some elements of analog computing within the orthodox digital paradigm [2].

If we want to go beyond the existing paradigm of computation we have to have a clear view of the existing model. We have to identify what exactly we want to transcend. Turing's model of computation is very clear, precise, and surprisingly simple. It may seem impossible to find in it anything which requires an additional explanation or clarification. However, the question is whether the Turing Machine accurately describes the entire process of computation. More specifically, does it describe the entire process of information transformation with all its aspects? This question can be reformulated using a different perspective on computation. Can Turing Machine be autonomous? What does it need for its functioning?

The answer is obvious. Information processed by the Turing Machine has to be in digital form. It is a less obvious question of what "digital form" means. Von Neumann in 1948 described analog computing as based on the idea that the representation of numbers in the processing units is not digital (i.e., is not based on the finite number of classes of states of the physical processor associated with digits and their combination into numerals), but analog (numbers are represented directly by the physical magnitudes characterizing the states of processor). Its disadvantage in comparison to digital computing is in the lack of universality and the need for reconfiguration for different tasks [3]. Later the distinction between digital and analog processing of information (not only in the context of computation, but also storage, transmission, and retrieval) entered the everyday vocabulary and became associated with the distinction between the discrete and continuous characteristics of information.

My distinction between analog and digital computing can be formulated in terms of the distinction between states and observables introduced in physics after the influence of quantum mechanics. Analog computing is performed directly and exclusively on the states of the processing unit without the mediation of observables and their measurement, i.e., numbers. Digital computing involves the mediation of observables, i.e., numbers. In the Turing Machine, in each step, the head observes the cell of the tape, and the transition to the next step is based on the result of this observation. The dynamic of the process of computing is based on the outcomes of these observations. In analog computing, the observation is engaged only in the identification of the result. Of course, this distinction is slightly different from von Neumann's in which processing is in both cases of the numbers which are represented in the analog or digital forms.

Thus, in digital computing, we have an important engagement of encoding information in the process of information dynamic. This encoding is not arbitrary. The work of the Turing Machine is heavily dependent on the specific encoding in a digital-positional way. If we use different symbols for each piece of information, the model of computation fails. The description of the process of computation assumes that the variety of information items is represented by finite sequences of pre-selected digits (characters). This approach was inherited by computation from the human use of the language, in particular of the written language. We use a finite number of basic units (letters or characters) from which compound units carrying meaning are formed as sequences. The rules of formation of these compound units of higher levels are governed by syntactic and logic. Yet another aspect of processing information is semantics. Turing Machine has to get as its input already encoded information and the result of computing has to be decoded and interpreted externally, typically by a human programmer. It is a natural choice to look for the models for hypercomputation in the extension or generalization of encoding.

However, this tells us about the exploration of information systems with alternative encoding, but it does not answer the question about the generalization of computing. Before entering the exploration of morphological computing, let me briefly recall my proposal of generalized computing by the so-called Symmetric Turing Machine presented in earlier publications in which computing is defined as the construction of information structures in the interaction of two or more information systems carrying information [4]. The main point of my approach is that computing is understood as a dynamical process involving more than one information system with equal status and that the outcome of the process is information which is a nontrivial function of information from the interacting systems. The requirement of involvement in the interaction of more than one system prevents the overgeneralization in which every process, such as the motion of a stone could be considered computation. On the other hand, it is clear that the work of Turing Machine is a form of computing understood this general way with the added specification of the digital encoding together with the one-way goal-oriented action, so orthodox computing is a special case. The model of the symmetric Turing Machine in which the interaction is Turing-noncomputable may achieve the goals of hypercomputing.

3. Morphological Computing and Morphogenesis

To avoid the mediation of digital encoding, we can explore information systems based on morphology, not necessarily structures of sequences of digits. At first sight, the task may seem easy. "Morphological computing" is sometimes described as computing involving shape as a carrier of information. However, the concept of shape, although very intuitive and often used in the common sense discourse, is actually very difficult to define and systematize. The word "shape" in topological shape theory initiated and developed by K. Borsuk in "Concerning homotopy properties of compacta," 1968 is misleading [5], as it is not concerned with anything which can be expected from the intuitive meaning of the word "shape". For instance, the so-called Warsaw circle is shape equivalent to a circle, but its appearance is of a circle after a very serious accident in which it was bent infinitely many times. Shape theory developed by D. G. Kendall was intended as a tool for numerical characterization and statistical analysis of shape understood in the common sense way: "We here define 'shape' informally as all the geometrical information that remains when location, scale, and rotational effects are filtered out from an object" [6]. It is however disputable whether this theory can meet all expectations of the theory of shape in all contexts. For instance, the fact that the object whose shape is considered is reduced to the finite number of quite arbitrary "landmark points" and that the shape is an invariant of rotations around some axis makes it questionable that this approach grasps the essential features of the concept of shape. Whether these objections are justified or not, it is quite clear that the reduction of morphology to the analysis of shape would not make understanding of morphology easier or more useful. We can only observe that the introductory explanation of Kendall's concept refers to shape as "geometrical information". Whatever understanding would be of morphological computing or computing in general, it is a legitimate assumption that they refer to information in its dynamical aspect. Therefore any attempt to characterize morphological computing requires prior study of the relationship between morphology and information.

Morphology as a study of organic forms was initiated by J. W. Goethe and independently by C. F. Burdach at the turn of the 18th and 19th centuries. Goethe defined it in 1817 "On Morphology" as the science of the form (Gestalt), formation (Buildnung), and transformation (Umbildung) of organic beings. Significantly, he conceived it as a study of the form and at the same time as a study of its changes. The tradition of the study of organic forms in terms of their transformations initiated by Goethe became the central paradigm of biology reinforced and redirected by the influential work of D'A. W. Thompson ("On Growth and Form," 1917).

There is less known, but the equally interesting 1894 study of William Bateson, "Materials for the Study of Variation" with very deep insights into the matters of morphogenesis which his son Gregory Bateson linked directly with the concept of information in his 1971 article "A Re-examination of 'Bateson's Rule'" [7].

Henri Poincaré in his 1905 "Science and Hypothesis" analyzed the mechanism of human perception engaging different organs distributed all over human organism to show that geometry is conventional. His study is essentially describing a form of morphological computing of spatial information implemented in the human organism.

This direction of inquiry entered the context of information and computing indirectly in the work of A. Turing ("The Chemical Basis of Morphogenesis," 1952) and directly and explicitly in the celebrated book of R. Thom ("Structural Stability and Morphogenesis," 1972). Thom explicitly presents his book as a study of information alternative and superior to the approach of E. C. Shannon. For Thom morphology of a process is defined by its points of singularity (catastrophic points) as distinct from regular points. He describes the relationship between morphology and information "[A]ny geometric form whatsoever can be the carrier of information, and in the set of geometric forms carrying information of the same type the topological complexity of the form is the quantitative scalar measure of information" [8].

The work of Thom is of special value. He showed that we can investigate dynamic processes from the point of view of differential topology. These processes of morphogenesis and the study of their structural stability provide the tools for the design of morphological computing. On the other hand, we also get a warning in the fact that Thom did not achieve any breakthrough in his study of semiosis (information processing!) His failure (which he admitted [9]) was the result of not being able to reject traditional principles of the quantitative methodology. It seems that we should follow the dream of Leibniz to develop an entirely new structure of human thought based on a general form of algebra (as expressed in his own words).

The origins of ideas expressed in the current morphological study of information are much older than the term "morphology" or "computing". Probably the most influential among the early studies of the morphology of information predating these terms was the work of G. W. Leibniz (e.g., "On the Art of Combination," 1690). His *characteristica universalis* is a language based on morphological information directly reflecting thinking without the mediation of the alphabet and his *calculus ratiocinator* operating on *characteristica universalis* is a process of computing. Leibniz wrote in the letter to Nicolas Remond in 1714 that the integration of science, mathematics, and metaphysics through the use of *characteristica universalis* requires "a kind of general algebra in which all truths of reason would be reduced to a kind of calculus" [10]. He did not understand it as a simple extension of arithmetic. In earlier work ("On Universal Synthesis and Analysis," 1679) Leibniz presented *calculus ratiocinator* as "that science in which are treated the forms or formulas of things in general, that is, quality in general" [11]. Leibniz did not know that a sub-discipline of mathematics called "general algebra" would be developed. He did not give a clear view of what he expected.

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