The Development of Models of Computation with Advances in Technology and Natural Sciences

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Abstract. Present account of models of computation highlights several topics of importance for the development of new understanding of computing, in the first place the development of natural computation (both as physical computation and in a sense of computational models inspired by natural systems) and the relationship between the model and physical implementation. The development beyond the classical Turing machine model proceeds in two directions – as a search for new mathematical structures beyond algorithms which are synonymous with the Turing machine as well as search for different fundamental elements of computational that are not equivalent to actions of human performing calculation: read, write, erase and move left or right in a sequential way. One of the developments builds on interactivity as fundamental feature of complex computational behaviour, which presupposes openness of computational systems. Natural computing widens the domain of computational systems not only to include quantum computing but also living systems, such as living cells, human brains and human societies. In modelling of concurrent information processing systems such as living organisms and their networks, the new developments in both understanding of those systems and in their computational modelling is needed – two processes that converge.

1 INTRODUCTION: WHAT IS COMPUTING?

“The idea behind digital computers may be explained by saying that these machines are intended to carry out any operations which could be done by a human computer.”

Turing in [1] p.436

Turing pioneered the development of first computers, based on several different theoretical models of computation: Logical Calculating Machines (Turing’s name for Turing machines) simulating a human strictly following an algorithm, thus connected to digital computers as described in the quote above, but he also started the development of neural networks and morphological computing. In the background for all those models we can discern his computational natural philosophy. According to Hodges [2], Turing was natural philosopher, and nature – from patterns on the animal skin to functioning of human brains was for him possible to understand in computational terms. Turing lived in a time when computing machinery still was in its beginnings, and we can say there was characteristic dominance of theory over practical devices. Today on the contrary, it appears that the existing computing machinery developed faster than the corresponding theory of computing.

The consequence is that for different directions of the development of computing systems different models of computation apply ranging from classical theories of [3] to steps beyond in [4] [5] [6] to interactive computing of [7], and natural computing in different variations [8], [9] [10] [11] to the view that computing is a natural science [12][13].

The existing diversity of ideas about computing can be confusing and difficult to manage. However, the lack of consensus about the nature of computing is not unique and it has the parallel in the current lack of consensus about the nature of information. Those two are related problems and both have two parts:

a) What is it in the world that corresponds to information/computation?
b) How do we model that information/computation [once we agree upon what in the world they correspond to]?

The answer to the above is not simple, as concepts are theory-laden and we use our existing theories in order to formulate new ones going via phenomena in the real world that we identify as information/computation.

In this context it is instructive to compare with the development of different basic scientific concepts. Ideas about matter, energy, space and time have their history. The same is true of the idea of number in mathematics or the idea of life in biology. So, we should not be surprised to notice the development in the theory of computing that goes along with the development of mathematical methods, new computational devices and new domains of the real world that can be modelled computationally. The aim of this article is to highlight several important lines of the development of computation and to find connections among them.

The rest of the paper is organized as follows. Section 2 gives the brief history of computational devices up to present day’s computers, while Section 3 explores what comes beyond the conventional contemporary computing machinery. Section 4 addresses natural computing and computing nature, while Section 5 describes the development of computational models up to natural computing. In Section 6 interactive computing is outlined. This approach is further extended in Section 7 and related to Info-computational framework in order to answer the question about meaning generation from raw data to semantic information, understood as physical computation by cognitive computational agents. Section 8 discusses the “unreasonable ineffectiveness” of mathematics in biology, and relates it to the Cooper’s notion of mathematician’s bias. Section 9 adds morphological computing to the list of possible directions of development for natural computing. Section 10 investigates further prospects of natural computing and connects to Denning’s view of computing as a natural science. Finally, the short summary is given in Section 11.
2 COMPUTATIONAL DEVICES UP TO ELECTRONIC COMPUTERS

The oldest computational devices were analog. The earliest calculating tools that humans used were fingers (Latin "digit") and pebbles (Latin "calculus") that can be considered as simple means of extended human cognition [14]. Tally stick, counting rods and abacus were the first steps towards mechanization of calculation. The historical development resulted in increasingly more sophisticated machines.

The ancient Greek astronomical analog calculator, Antikythera mechanism, dated to the end of second century BC, was designed to calculate the motions of stars and planets. The device used a differential gear arrangement with over 30 gears, with the complexity comparable to that of 18th century astronomical clocks. [15]

Among the first known constructors of mechanical calculators was Leonardo da Vinci, around year 1500. One notable early calculating machine was Schickard’s calculating clock designed in 1623. In 1645 Pascal invented the mechanical calculator Pascaline that could add and subtract two numbers directly, and multiply and divide by repetition. Leibniz improved the work of Pascal by adding direct multiplication and division in his calculator the Stepped Reckoner, about 1673.

Traditionally, computation was understood as synonymous with calculation. The first computing machines were constructed simply to calculate. The first recorded use of the word "computer" was in 1613 to denote a person who carried out calculations, and the word retained the same meaning until the middle of the 20th century, when the word "computer" started to assume its current meaning, describing a machine that performs computations.

In 1837 Babbage was the first to design a programmable mechanical computer, the general purpose Analytical Engine, based on Jacquard's punched cards for its program storage. 1880 Hollerith was the first to use a punched-card system for data storage – a technology that he sold to the company that will later became IBM.

The first electronic digital computer was built in 1939 by Atanasoff and Berry and it marks the beginning of the era of digital computing. In 1941 Zuse designed the first programmable computer Z3 capable of solving complex equations. This machine was also the first based on the binary system instead of the decimal. Turing built a special-purpose electronic machine Colossus in 1943 to decode secret messages by performing logical and not usual arithmetical operations. In 1950, the UNIVAC was the first computer that was capable of storing and running a program from memory. The first minicomputer PDP was built in 1960 by DEC.

Since 1960s the extremely fast growth of computer use was based on the technology of integrated circuit / microchip, which triggered the invention of the microprocessor, by Intel in 1971. For the further details of historical developments of computing devices, see [16].

3 BEYOND CONVENTIONAL COMPUTING MACHINERY: NATURAL COMPUTING

The development of computing, both machinery and its models, continues. We are accustomed to rapid increase of computational power, memory and usability of computers, but the limit of miniaturization within the present-day concept of computing is approaching as we are getting close to quantum dimensions of hardware. One of the ideals of computing ever since the time of Turing is intelligent computing, which would imply machine capable of not only executing mechanical procedure, but even intelligent problem solving. Thus the goal is a computer able to simulate behaviour of human mathematician, able of making an intelligent insight, unlike historical human computer who only strictly followed a given algorithm. A development of cognitive computing aimed towards human abilities to process/organize/understand information is presented in [17].

At the same time the development of computational modelling of human brain [18] has for a goal to reveal the exact mechanisms of human brain function that will help us understand not only how humans actually perform symbol processing when they follow an algorithm, but also how humans create algorithms or models. Those new developments in computational modelling of brain can be seen as a part of the research within the field of natural computing, where natural system performing computation is human brain.

However, natural computing has much broader scope. According to the Handbook of Natural Computing [11] natural computing is “the field of research that investigates both human-designed computing inspired by nature and computing taking place in nature.” In particular, it addresses: computational models inspired by natural systems, computation performed by natural materials and computational nature of processes taking place in (living) nature. It includes among others areas of cellular automata and neural computation, evolutionary computation, molecular computation and quantum computation and nature-inspired algorithms and general topic of alternative models of computation.

An important characteristic of the research in natural computing is that knowledge is generated bi-directionally, through the interaction between computer science and natural sciences. While natural sciences are adopting tools, methodologies and ideas of information processing, computer science is broadening the notion of computation, recognizing information processing found in nature as computation. [19] [8], [9], [20] That led Denning [12] to argue that computing today is a natural science.

This new concept of computation with inspiration in natural information processing allows among others learning about nondeterministic complex computational systems with self-properties (self-organization, self-configuration, self-optimization, self-healing, self-protection, self-explanation, and self-awareness. Natural computation provides a basis for a unified understanding of phenomena of embodied cognition, intelligence and knowledge generation. [21][22]

The idea of computing nature has several important consequences for our view of computation: “If computation is understood as a physical process, if nature computes with physical bodies as objects (informational structures) and physical laws govern processes of computation, then the computation necessarily appears on many different levels of organization. Natural sciences provide such a layered view of nature. One sort of computation process is found on the quantum-mechanical level of elementary particles, atoms and molecules; yet another on the level of classical physical objects. In the sphere of biology, different processes (computation =
The development of models of computation

As we have seen in Section 2, computational machinery evolved historically from simplest tools of extended human cognition to mechanical computers (calculators) to electronic machines with vacuum tubes and then transistors, to integrated circuits and eventually to microprocessors. During this development of hardware technologies towards ever smaller, faster and cheaper devices, the computational principles remained similar: an isolated computing agent calculating a function, executing an algorithm that can be represented by the Turing machine model.

However, since the 1950s computational machinery has been increasingly used to exchange information and computers gradually started to connect in networks and communicate. In the 1970s ARPANET was used by US research institutions to link their computers via telecommunications. The emergence of networking involved a rethinking of the nature of computation and boundaries of a computer. Computer operating systems and applications were modified to be able to access the resources of other computers in the network. In 1991 the European organization for particle physics CERN created the World Wide Web, which quickly resulted in computer networking as a part of everyday life for common people, not only scientists. By the end of 2011 an estimated 35% of Earth's population used the Internet (according to Wikipedia article Global Internet usage).

With the development of computer networks, two characteristics of computing systems have become increasingly important: parallelism/concurrency and openness – both based on communication between computational units.

Comparing new open-system with traditional closed-system computation models, Hewitt [24] characterizes the Turing machine model as an internal (individual) framework and his own Actor model of concurrent computation as an external (sociological) model of computing.

In the development of unconventional algorithms which is the mathematical branch of the development beyond Turing machine model, presented in [25], Burgin and Dodig-Crnkovic emphasize the complementarity of axiomatics and construction, both elements being necessary for the progress in understanding of computation. They analyze methodological and philosophical implications of algorithmic aspects of unconventional/natural computation that extends the closed classical universe of computation of the Turing machine type. The new model constitutes an open world of algorithmic constellations, allowing increased flexibility and expressive power, supporting constructivism and creativity in mathematical modelling and enabling richer understanding of computation. It is explained how the new models of algorithms and unconventional computations change the algorithmic universe, allowing increased flexibility and expressive power. At the same time, the greater power of new types of algorithms also results in the greater complexity of the algorithmic universe, transforming it into the algorithmic multiverse and demanding new tools for its study. New tools are brought forth by local mathematics, local logics and logical varieties. The article [25] demonstrates how these new tools allow efficient navigation in the algorithmic multiverse. Further work includes study of natural computation by unconventional algorithms and constructive approaches.

5 COMPUTATION AS INTERACTION AND INTERACTIVE COMPUTING

As we have seen in the previous sections, interaction between computational units and processes has become one of the central issues. Wegner developed the interactive model of computation [26] which involves interaction, or communication, with the environment during computation, unlike the traditional Turing machine model of computation which goes on in an isolated system. The interactive paradigm includes concurrent and reactive computations, agent-oriented, distributed and component-based computations. [27] Interestingly, Bohan Broderick [28] argues based on the study of technical notions of communication and computation and finds them practically indistinguishable. “The two notions may be kept distinct if computation is limited to actions within a system and communications is an interaction between a system and its environment.” – Bohan Broderick ascertains.

Goldin and Wegner [27] show, that the paradigm shift from algorithms to interactive computation follows the technology shift from mainframes to networks, and intelligent systems, from calculating to communicating, distributed and often even mobile devices. A majority of the computers today are embedded in other systems and they are continuously communicating with each other and with the environment. The communicative role has definitely prevailed over the initial role of a computer as an isolated calculating machine.

The following characteristics distinguish this new, interactive notion of computation [7]:
- Computational problem is defined as performing a task, rather than (algorithmically) producing an answer to a question.
- Dynamic input and output modelled by dynamic streams which are interleaved; later values of the input stream may depend on earlier values in the output stream and vice versa.
- The environment of the computation is a part of the model, playing an active role in the computation by dynamically supplying the computational system with the inputs, and consuming the output values from the system.
- Concurrency: the computing system (agent) computes in parallel with its environment, and with other agents that may be in it.
- Effective non-computability: the environment cannot be assumed to be static or effectively computable. We cannot always pre-compute input values or predict the effect of the system's output on the environment. Even though practical implementations of interactive computing are several decades old, a general foundational theory, and the semantics and logic of interactive computing is missing. A theoretical foundation analogous to what Turing machines are for algorithmic computing, is under development.

[26] [12] [29] [24]
The advantages of concurrency theory that in the toolbox of formal models is used to simulate observable natural phenomena are according to [30] that:

"it is possible to express much richer notions of time and space in the concur-rent interactive framework than in a sequential one. In the case of time, for example, instead of a unique total order, we now have interplay between many partial orders of events--the local times of concurrent agents--with potential synchronizations, and the possibility to add global constraints on the set of possible scheduling. This requires a much more complex algebraic structure of representation if one wants to "situate" a given agent in time, i.e., relatively to the occurrence of events originated by herself or by other agents."

It is also important to note that theories of concurrency are partially integrating the observer into the model by permitting limited shifting of the inside-outside boundary. By this integration, theories of concurrency might bring major enhancements to the computational expressive toolbox. According to Abramsky [29]:

"An important quality of Petri’s conception of concurrency, as compared with “linguistic” approaches such as process calculi, is that it seeks to explain fundamental concepts: causality, concurrency, process, etc. in a syntax-independent, “geometric” fashion. Another important point, which may originally have seemed merely eccentric, but now looks rather ahead of its time, is the extent to which Petri’s thinking was explicitly influenced by physics (…).

To a large extent, and by design, Net Theory can be seen as a kind of discrete physics: lines are time-like causal flows, cuts are space-like regions, process unfoldings of a marked net are like the solution trajectories of a differential equation. This acquires new significance today, when the consequences of the idea that “Information is Physical” [17] are being explored in the rapidly developing field of quantum informatics. Moreover, the need to recognize the spatial structure of distributed systems has become apparent, and is made explicit in formalisms such as the Ambient calculus [10], and Milner’s bigraphs [23]. “

If the current programme for computation can be formulated as aiming at reconstruction of the computational capabilities of human brain, and not only mechanical symbol manipulation but also innovative reasoning, then it seems unavoidable to further develop interactive computing and natural computing in their different forms. Living systems are essentially open and in constant communication with the environment. New computational models must include interactive, concurrent computation processes in order to be applicable to biological and social phenomena.

6 DIGITAL VS. ANALOG, DISCRETE VS. CONTINUOUS AND SYMBOLIC VS. SUB-SYMBOLIC MODELS OF COMPUTATION

Among many discussions concerning concepts of computation, a prominent place is given to the controversy about the continuous/discrete vs. analogue/digital computation. [31] Some believe in the discrete nature of physical reality and deny any true continuum. Some believe that human cognition can be understood in terms of language and symbol manipulation. Understanding of nature of symbols has relevance for understanding of human cognition and information processing going on in human body (including brain and nervous system).

Trenholme [32] describes the relationship of analog vs. symbolic simulation:

“Symbolic simulation is thus a two-stage affair: first the mapping of inference structure of the theory onto hardware states which defines symbolic computation; second, the mapping of inference structure of the theory onto hardware states which (under appropriate conditions) qualifies the processing as a symbolic simulation.

Analog simulation, in contrast, is defined by a single mapping from causal relations among elements of the simulation to causal relations among elements of the simulated phenomenon.” [32] p.119.

Both symbolic and sub-symbolic simulations depend on causal/analog/physical and symbolic type of computation on some level of abstraction but in the case of symbolic computation it is the symbolic level where information processing is observed. Similarly, even though in the subsymbolic model symbolic representation exists at some high level of abstraction (because language is used for its description), it is the physical agency and its causal structure that define computation.

Freeman characterizes accurately the relationship between physical/sub-symbolic and logical/symbolic level in the following:

“Human brains intentionally direct the body to make symbols, and they use the symbols to represent internal states. The symbols are outside the brain. Inside the brains, the construction is effected by spatiotemporal patterns of neural activity that are operators, not symbols. The operations include formation of sequences of neural activity patterns that we observe by their electrical signs. The process is by neurodynamics, not by logical rule-driven symbol manipulation. The aim of simulating human natural computing should be to simulate the operators. In its simplest form natural computing serves for communication of meaning. Neural operators implement non-symbolic communication of internal states by all mammals, including humans, through intentional actions. (…) I propose that symbol-making operators evolved from neural mechanisms of intentional action by modification of non-symbolic operators.” (Emphasis added) [33]

Consequently, our brains use non-symbolic computing internally in order to manipulate relevant external symbols/objects.

In the words of MacLennan [34], who emphasizes the importance of continuous computation for natural systems:

“We propose certain non-Turing models of computation, but our intent is not to advocate models that surpass the power of Turing Machines (TMs), but to defend the need for models with orthogonal notions of power. We review the nature of models and argue that they are relative to a domain of application and are ill-suited to use outside that domain. Hence we review the presuppositions and context of the TM model and show that it is unsuited to natural computation (computation occurring in or inspired by nature). Therefore we must consider an expanded definition of computation that includes alternative (especially analog) models as well as the TM. “
Mathematician’s contribution to the development of the idea of computing nature is central. Turing was mathematician but also an early proponent of natural computing who put forward two computational models of physical processes – morphological computing and neural networks.

In the context of computing nature, living systems are extraordinary interesting because of their complexity of informational processing, but up to now science haven’t been able to adequately model and simulate the behaviour of even the simplest living organisms. “The unreasonable effectiveness of mathematics” observed in physics by Wigner [35] is missing in biology, according to Gelfand as quoted by Chaitin, see [36].

Not many people today would claim that human cognition (information processing going on in our body, including our brains) can be adequately modelled as a result of computation of one Turing machine, however complex function it might compute. In the next attempt, one may imagine a complex architecture of Turing machines running in parallel as communicating sequential processes exchanging information. We know today that such a system of Turing machines cannot produce the most general kind of computation, as truly asynchronous concurrent information processing going on in our brains. [37]

However, one may object that IBM’s Watson, the winner in man vs. machine "Jeopardy!" challenge, runs on contemporary supercomputer which is claimed to be implementation of the Turing machine. Yet, Watson is connected to the Internet. And Internet is not a Turing machine. It is not even a network of Turing machines. Information processing going on throughout the Internet includes signalling and communication based on complex asynchronous physical processes that cannot be sequentialized. [24] [37] As an illustration see [38] on parasitic complex asynchronous physical processes that cannot be modelled by Turing machine.

Cooper in his article Turing’s Titanic Machine? [39] diagnoses the limitations of the Turing machine model and identifies the following ways of overcoming those limitations:

- Embodiment invalidating the 'machine as data' and universality paradigm.
- The organic linking of mechanics and emergent outcomes delivering a clearer model of supervenience of mentality on brain functionality, and a reconciliation of different levels of effectiveness.
- A reaffirmation of experiment and evolving hardware, for both AI and ex-tened computing generally.
- The validating of a route to creation of new information through interaction and emergence.

The above reflects the fact that computation is physical. Related article by the same author, The Mathematician's Bias and the Return to Embodied Computation, elucidates the character of physical computation compared to universal symbol manipulation. [40]

Besides physical embodiment, one of the important aspects of computing is logic. The underlying logic of Turing’s “Logical Calculating Machine” is fully consistent standard logic. Hintikka proposes Logic as a Theory of Computability, still within the same classical framework. [41] Turing machine is assumed always to be in a well defined state. [24]

In contemporary computing machinery, however, we face both states that are not well defined (in the process of transition) and states that contain inconsistency:

“Consider a computer which stores a large amount of information. While the computer stores the information, it is also used to operate on it, and, crucially, to infer from it. Now it is quite common for the computer to contain inconsistent information, because of mistakes by the data entry operators or because of multiple sourcing. This is certainly a problem for database operations with theorem-provers, and so has drawn much attention from computer scientists. Techniques for removing inconsistent information have been investigated. Yet all have limited applicability, and, in any case, are not guaranteed to produce consistency. (There is no algorithm for logical falsehood.) Hence, even if steps are taken to get rid of contradictions when they are found, an underlying paraconsistent logic is desirable if hidden contradictions are not to generate spurious answers to queries.” [42]

Open, interactive and asynchronous systems have special requirements on logic. [27], and Hewitt [24] argue e.g. that computational logic must be able to model interactive computation, and that classical logic must be robust towards inconsistencies i.e. must be paraconsistent due to the incompleteness of interaction.

As Sloman [37] shows, concurrent and synchronized machines are equivalent to sequential machines, but some concurrent machines are asynchronous, and thus not equivalent to Turing machines. If a machine is composed of asynchronous concurrently running subsystems, and their relative frequencies vary randomly, then such a machine cannot be adequately modelled by Turing machine.

Turing machines are discrete but can in principle approximate machines with continuous changes, yet cannot implement them exactly. Continuous systems with non-linear feedback loops may be chaotic and impossible to approximate discretely, even over short time scales, see [37] and [24].

From all above it is clearly that Turing machine model of computation is an abstraction and idealization. In general, the trend in computing can be discerned towards more and more physics-inspired modelling instead of idealized, symbol-manipulating models.

Theoretical model of concurrent (interactive) computing that would be the counterpart of Turing machine model of algorithmic computing is under development. (Abramsky, Hewitt, Wegner) From the experience with present day networked concurrent computation it becomes obvious that Turing machine model can be seen as a proper subset of a more general computation

8 INFORMATION AND COMPUTATION. INFO-COMPUTATIONALISM

As mentioned in the introduction, not only the idea of computation is under dynamic development, but similar is true of the concept of information. Both processes can be seen as a result of current rapid development of information technology/computing machinery and our newly acquired insights in sciences, largely also based on the development of information
An agent (an entity capable of acting in the world) even as the simplest physical object, can be seen as interacting with the points of inhomogeneities, establishing the connections between those data and the data that constitute the agent itself (a particle, a system). That is how change in the physical world happens through data integration or self-organization in an agent. This is governed by laws of physics and physicists are already working on reformulating physics in terms of information. That development re-cast of physics in terms of information structures and processes can be related to the Wheeler’s idea “it from bit” [45]. A special issue of the journal Information is dedicated to matter/energy and information and elucidates those fundamental relationships [46], with articles by Vedral, Goyal, Brenner, Matsuno and Salthe, Fields, Fiorillo, Yoshitake and Saruwatari Luhn and Zenil. Furthermore, a special issue of the journal Entropy addresses natural/unconventional computing [47] with articles by Chiribella, D’Ariano and Perinotti presenting the topics of informational universe through quantum theory as the theory of information. Ehresmann shows an info-computational model for (neuro-)cognitive systems capable of creativity, Stepney focus on programming unconventional computers: dynamics, development, self-reference. Dodig Crnkovic and Burgin contribute with a rite on unconventional algorithms: complementarity of axiomatics and construction, while Zenil, Gershenson, Marshall and Rosenblueth discuss life as thermodynamic evidence of algorithmic structure in natural environments. All contributions explore the space of natural computation.

As a result of a synthesis of the idea of computing nature (naturalist computationalism/pancomputationalism) [22][48][49][50][51] with the informational structural realism [43][52], the view that nature represents a complex informational structure for a cognizing agent, the framework of info-computationalism is construed [21]. Within info-computationalism the time development (dynamics) of physical states in nature is understood as information processing. Such processes include self-assembly, developmental processes, gene regulation networks, gene assembly, protein-protein interaction networks, biological transport networks, and similar processes found in nature.

Consequently, if computation is understood as physical process, if nature computes with physical bodies as objects (informational structures) and physical laws govern process of computation, then the computation necessarily appears on many levels of organization. Natural sciences provide such a layered view of nature. One sort of computation process is found on the quantum-mechanical level of elementary particles, atoms and molecules; yet another on the level of classical physical objects. In the sphere of biology, different processes (computations = information processing) are going on in biological cells, tissues, organs, organisms, and eco-systems. Social interactions are governed by still another kind of communicative/interactive process. If we compare this to physics where specific “force carriers” are exchanged between elementary particles as messages between elementary agents, in social (many-agent) systems carriers are complex chunks of information such as molecules or sentences or articles, songs, etc. and the nodes might be single cells, organisms or groups. Yet the structure is the same – a network of agents exchanging messages.

In short, within info-computational framework, computation on a given level of organization is realization/actualization of the laws that govern interactions between constituent parts. Consequently, what happens in every next layer of organization is that a set of rules governing the system switch to the new regime. It remains yet to be revealed how this process exactly goes on in nature, how emergent properties occur.

In words of Rozenberg and Karli: “(O)ur task is nothing less than to discover a new, broader, notion of computation, and to understand the world around us in terms of information processing.” [19] From the fields of physics and biology, neuroscience and cognitive science and many more new insights essential for the info-computational universe/nature may be expected in the years to come.

9 MORPHOLOGICAL COMPUTING. MEANING GENERATION FROM RAW DATA TO SEMANTIC INFORMATION

In 1952 Turing wrote a paper on morphogenesis proposing a chemical model as the explanation of the development of biological patterns such as the spots and stripes on animal skin. [53] Turin did not claim that physical system producing patterns actually performed computation. Nevertheless, from the perspective of info-computationalism we can argue that morphogenesis is a process of morphological computing. Physical process – though not „computational” in the traditional sense, presents natural (unconventional), morphological computation. Essential element in this process is the interplay between the informational structure and the computational process - information self-structuring and information integration, both synchronic and diachronic, going on in different time and space scales in physical bodies. Morphology is the central idea in understanding of the connection between computation (morphological/morphogenetical) and information. What is observed as materials on one level of analysis, represents morphology on the lower level – the arrangements of molecular and atomic structures.

Info-computational naturalism describes nature as informational structure – a succession of levels of organization of information. Morphological computing on that informational structure leads to new informational structures via processes of self-organization of information. Evolution itself is a process of morphological computation on a long-term scale. It will be

and communication technology. Even though we are far from having a consensus on the concept of information, the most general view is that information is a structure made of data. Floridi [43] has the following definition of datum: “In its simplest form, a datum can be reduced to just a lack of uniformity, that is, a binary difference.” Bateson’s “the difference that makes the difference” [44] is a datum in that sense. Information is both the result of observed differences (thus the process of differentiation which constitutes data) and the result of synthesis of those data into a common informational structure (thus the result of integration of data). In the process of knowledge generation an intelligent agent moves between those two processes – differentiation and integration of data. It is central to keep in mind that for something to be information there must exist an agent from whose perspective this structure is established. Thus information is like a network of data points connected from an agent’s perspective.
instructive within the info-computational framework to study processes of self-organization of information in an agent (as well as in population of agents) able to re-structure themselves through interactions with the environment as a result of morphological (morphogenetic) computation.

Cognition can be seen as a result of processes of morphological computation on informational structures of a cognitive agent in the interaction with the physical world, processes going on at both sub-symbolic and symbolic levels. This morphological computation establishes connections between an agent’s body, its nervous (control) system and its environment. Through the embodied interaction with the informational structures of the environment, through sensory-motor coordination, information structures are induced in the sensory data of a cognitive agent, thus establishing perception, categorization and learning.

Essential element in this process is the interplay between the informational structures and the computational processes - information self-structuring and information integration, both synchronic and diachronic, going on in different time and space scales. [22][44][45]

From the simple cognizing agents such as bacteria to the complex biological organisms with nervous systems and brains, the basic informational structures undergo transformations through morphological computation. This process causes changes in the informational structures that correspond to the body of an agent, its control mechanisms, its interactions with the world and its inner information processing. Informational structures become strongly semantic information in case of highly intelligent agents for whom truth is well-defined.

10 DEVELOPMENTS AND PROSPECTS OF NATURAL COMPUTATION. COMPUTING AS NATURAL SCIENCE

When we talk about natural computation by “nature” we mean everything that physically exists – not only living organisms, animals, plants and microorganisms, geological formations, astronomical objects but also machines, humans and human societies understood as physical systems – in other words all that can be described as existing in terms of matter/energy and space/time. On different levels of physical organization we find different types of natural computation: on quantum level, there is quantum computation, on the molecular level there is molecular computation, higher up in hierarchy we find nano-computation, networks of proteins are computing in living organisms, DNA code governs variety of computational processes in cells, metabolic processes are at the same time information processing and they are constitutive of life. Maturana and Varela equate cognition with life. [54], [55] Computations of nervous systems resemble neural network models, living organisms as wholes are regulated on variety of levels and so are ecologies. Information processing going on in the physical world can be modelled as computation – some of it on continuous flow of signals, some on discrete signals or symbols, some within living agents without conscious control, whilst other like languages require conscious living organisms for information to be processed. Morphological computing can be considered as a basis for all those physical processes that can be studied as information self-structuring. [23], [48], [49]

11 CONCLUSIONS & FUTURE WORK

Present account of models of computation highlights several topics of importance for the development of new understanding of computing and its role in the physical world: natural computation and the relationship between the model and physical implementation, interactivity as fundamental for computational modelling of concurrent information processing systems such as living organisms and their networks, and the new developments in mathematical modelling needed to support this generalized framework. Even though Turing machine model is well developed and generally established model of computation, variety of new ideas, still under developments are taking shape and have good prospects to extend our understanding of computation and its relationship to physical implementations, which are computational systems.

As Stephen Hawking aptly noticed, in spite of enormous attraction of the idea of final theory of everything (including such theory of everything computational), the progress goes on:

“Some people will be very disappointed if there is not an ultimate theory that can be formulated as a finite number of principles. I used to belong to that camp, but I have changed my mind. I’m now glad that our search for understanding will never come to an end, and that we will always have the challenge of new discovery.” [56]

REFERENCES
