Forthcoming in: THINKING MACHINES AND THE PHILOSOPHY OF COMPUTER SCIENCE: CONCEPTS AND PRINCIPLES

Biological Information and Natural Computation

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Abstract

The dynamics of natural systems, and particularly organic systems, specialized in self-organization and complexity management, presents a vast source of ideas for new approaches to computing, such as natural computing and its special case organic computing. Based on *paninformationalism* (understanding of all physical structures as informational) and *pancomputationalism or natural computationalism* (understanding of the dynamics of physical structures as computation) a new approach of *info-computational naturalism* emerges as a result of their synthesis. This includes naturalistic view of mind and hence naturalized epistemology based on evolution from inanimate to biological systems through the increase in complexity of informational structures by natural computation. Learning on the info-computational level about structures and processes in nature and especially those in intelligent and autonomous biological agents enables the development of advanced autonomous adaptive intelligent artifacts and makes possible connection (both theoretical and practical) between organic and inorganic systems.

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Biological Information and Natural Computation

Introduction

Information has become a conceptual tool above others and it is found everywhere across research disciplines and in everyday use. Physics may be founded on informational grounds, and so other sciences involving physical objects (*paninformational stance, informational structural realism, Floridi*). *Pancomputationalism (natural computationalism)* at the same time views the physical universe as a computational system. According to *pancomputationalists* (Zuse (1967) , Fredkin (2009) , Wolfram (2002) , Chaitin (2007) , Lloyd (2006) and others) the dynamics of the universe is a computational process; universe on the fundamental level may be conceived of as a computer which from the current state, following physical laws computes its own next state. The computation that pancomputationalism presupposes is *natural computation*, defined by MacLennan as ”computation occurring in nature or inspired by that in nature”, where the structure of the universe may be assumed as both discrete and continuous at different levels of abstraction. Our present day computing machinery is a proper subset of natural computing.

Combining informational structures as the fabric of the universe and natural computation as its dynamics leads to the idea of *info-computationalism (info-computationalist naturalism),* the framework which builds on two fundamental concepts: information as a structure and computation as its dynamics.

As both physical structures and processes can be expressed in terms of info-computationalism, a new means arise of smoothly connecting two traditionally disparate spheres: bodies and their minds, and so naturalizing epistemology. The unified framework presents the epistemological feed-back loop between theoretical model – simulation – experimental tests – data analysis - theory. It opens the possibility to integrate the human as natural being with the rest of the physical world into the common framework by integrating current knowledge from neurosciences, biology, physics, complexity etc.

For complex systems such as biological ones, both the analysis of experiments and theory is increasingly done by computer simulations. Life itself on a fundamental level may be viewed as a process of computation, where hardware at the same time is the software (such as DNA). Our studying of life as information processes leads to production of simulations able to mimic relevant characteristics and behaviors of living biological systems: dynamic and recursive behavior, morphogenetic patterns, emergency phenomena etc. A good example of computer simulation aimed at reverse-engineering of the brain is a Blue Brain project which will be described later on.

This paper will highlight current developments and trends within the field of natural computing in the framework of info-computational naturalism.

Interesting to observe is epistemic productiveness of natural computing as it leads to a significantly bidirectional research (Rozenberg & Kari, 2008); while natural sciences are rapidly absorbing ideas of information processing, field of computing concurrently assimilates ideas from natural sciences. There is thus an interesting synergy gain in the relating of human designed computing with the computing going on in nature.

Fundamental Questions

Promises of info-computational programme rely on learning from nature using predictability of its physical processes and structures as a means to improve our understanding of computation and its counterpart information.

The following questions are of interest:

- Learning from natural computation, is non-algorithmic computation possible?
- Is there a universal model (for which the TM model is a special case) underlying all Natural computation?
- What can be learned about intelligence, cognition and our epistemological and ontological premises within info-computational naturalism?
- What computational problems can our understanding of natural self-organization and management of complexity help to solve?
- If our brains and nervous systems are info-computational networks, what can we say about mind?
- How to develop artifactually intelligent autonomous systems based on insights from organic computing?

Those questions are best approached on the inter-disciplinary/trans-disciplinary ground as a study of the foundational issues of computing and information at the intersection of computing and philosophy, a present-day Natural Philosophy.

What is Computation?

Computation is in general defined as any kind of information processing. It includes processes such as human cognition, cell metabolism as well as calculations performed by computing devices. For a process to be a computation a model must exist such as algorithm, network topology, physical process or in general any mechanism which ensures predictability of its behavior.

The three-dimensional characterization of computing can be made by classification into orthogonal types: digital/analog, interactive/batch and sequential/parallel computation.

Nowadays digital computers are used to simulate all sorts of natural processes, including those that in physics are described as continuous. In this case, it is important to distinguish between the mechanism of computation and the simulation model.

Computation as a Physical Process

According to physics of computation (the branch of theoretical physics), computation can be seen as a physical phenomenon occurring inside physical systems (digital computers, quantum computers, DNA computers, molecular computers, analog computers, organic computers, etc).

Mathematical Models of Computation

In the theory of computation, a diversity of mathematical models of computers has been developed, among others state models such as Turing Machine, functional models such as lambda calculus and concurrent models such as process calculi.

Turing Machine Model and Computing Beyond Turing Machine

The rapid development of the computing field in the past half a century was based on the classical understanding of computation as symbol manipulation performed by a Turing Machine. Ever since Turing proposed his model which identifies computation with the execution of an algorithm, there have been questions about how widely the model is applicable. Church-Turing Thesis after establishing the equivalence between a Turing Machine and an algorithm claims that all of computation must be algorithmic. However, with the advent of computer networks, the model of a computer in isolation, represented by a Turing Machine, has become insufficient[1].

A number of contemporary philosophers and scientists have noticed the necessity of considering computation beyond currently governing Turing machine model. New research results from computer science, physics, logics, bioinformatics, neurosciences, biology, chemistry and related research fields provide strong and increasing support for this claim.

Generalization of Turing model of computation is addressed in essentially two ways:

1. Generalization of *the physical realization* of computation process (Copeland, Lloyd, MacLennan, Cooper, Hogarth).
2. Generalization of *the model*, such as extending the idea of algorithm to a non-halting process (Wegner, Burgin, Rice).

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[1] By now there is a vast literature on computing beyond Turing limit, hypercomputation and superrecursive algorithms.

The two above are necessarily linked. As soon as a new kind of physical process is identified as computation we will need an adequate theoretical model. Likewise, a new model will necessarily be linked with its implementations.

In search for a new generalized model of computation, interactive computation is proposed by (Wegner, 1998), (Goldin , Smolka, & Wegner, 2006) which unlike Turing machine implies communication of the computing process with the external world during the ongoing process of computation.

The search for new physical computation processes aims at enrichment of the conventional computing repertoire. Present-day computers have developed from the tools for mechanizing calculations into adaptive devices interacting with the physical world, which itself may be conceived of as a computer. In that sense natural computing represents the extension of the domain of physical phenomena which are understood as computational processes and it goes beyond Turing model of computation.

Turing Machine as Mechanistic Idealization

The mechanistic world view is based on the following principles, Dodig Crnkovic and Müller in Dodig Crnkovic and Burgin (2010):

(M1) The ontologically fundamental entities of the physical reality are [*space-time & matter* (mass-energy)] defining physical structures and *motion* (or change of physical structures).

(M2) All the properties of any complex physical system can be derived from the properties of its components.

(M3) Change of physical structures is governed by laws.

Mechanistic models assume that the system is closed, i.e. isolated from the environment, which has for the consequence that laws of conservation (energy, mass, momentum, etc.) hold. Environment (if modelled at all) is treated as a perturbation for the steady state of the system. Implicitly it is assumed that the observer is outside of the system observed. Organic systems pose insurmountable problems for mechanistic/reductionist modelling because of their inherent complexity.

Turing model as it consists of an isolated computing device operating over an input of atomic symbols represents a typical mechanistic idealisation.

Complexity, Computing, Algorithms and Hypercomputation

In order to not only understand, but also to be able to interact in real time with the physical world, computation must match its environment, which, according to Ashby (1964) means to correspond to the complexity of the environment. Ashby's Law of requisite variety states namely, that to control a state, the variety of system responses must at least match the variety of disturbances. This amounts to the claim that in order for a computer to achieve adequate control of a complex system, the complexity of the repertoire of its responses must correspond to the complexity of the environment.

If we compare Turing machines with the physical world (including biological organisms) the latter exhibit a much higher degree of complexity. That would imply that we need more powerful machines than what is represented by Turing model in order to be able to control by computers the real world phenomena on those levels of organization.

A New Paradigm of Computation: Natural Computing

> In these times brimming with excitement, our 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. Rozenberg and Kari (2008)

Computing beyond Turing limit or hypercomputing, Copeland (2002), seen as the possibility of carrying on infinitely many (computational) steps in a finite time is a question of our idea of the infinity and our understanding of the nature of the world (continuous, discrete). The problem of hypercomputation can be seen as the problem of induction. *Inductive Turing machines* described Burgin (2005) always give results after a finite number of steps, do not use infinite objects such as real numbers and are more powerful than Turing machines.

In general the approach the question of computing beyond the Turing model goes under different names and has different content: natural computing, unconventional computing, analog computing, organic computing, sub-symbolic computing, etc. (for an introduction see http://en.wikipedia.org/wiki/Natural_Computing) Common strategy of this approach is Simon's *satisficing* (Simon 1978), that focus on *adequacy*, rather than searches an *optimal* solution.

Natural computing is a new paradigm of computing (MacLennan, Rozenberg, Calude, Bäck, Bath, Müller-Schloer, de Castro, Paun) which includes the following:

1) *Theoretical* computational methods *inspired by nature* (such as artificial neural networks,

computing on continuous data, evolutionary algorithms, swarm intelligence, artificial immune systems). This includes computer simulations used to functionally synthesize natural phenomena (artificial life, engineering of semi-synthetic organisms)

2) *Physical computing methods* based on new *natural materials* besides present-day electronic hardware (such as organic/biological computing, DNA computing and quantum computing)

The above computational approaches are abstracted from the range of natural phenomena - characteristics of living organisms such as the defining properties of life forms, cell membranes, and morphogenesis, self-replication, self-defense, self-configuration and self-repair; the information processing mechanisms of the brain, evolution, autonomy and automatic coordination of group behavior, self-explaining and context-awareness. Processes like self-assembly, developmental processes, gene regulation networks, protein-protein interaction networks, biological transport networks, and gene assembly in unicellular organisms are at present studied as information processing. Understanding of biological organisms as information processing systems is a part of understanding of the universe as a whole as an information processing computational structure.

Natural computing has different criteria for success of a computation. Unlike Turing model, the halting problem is not a central issue[2], but instead the adequacy of the computational response. Organic computing system adapts dynamically to the current conditions of its environment by self-organization, self-configuration, self-optimization, self-healing, self-protection and context-awareness. In many areas, we have to computationally model emergence

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[2] In the Turing model a computation must halt when execution of an algorithm has finished.

not being algorithmic, Sloman and Cooper in (Dodig Crnkovic & Burgin , 2010), which makes it interesting to investigate computational characteristics of non-algorithmic natural computation (sub-symbolic, analogue).

The research in theoretical foundations of natural computing aims at improving our understanding on the fundamental level of *computation* as *information processing* which underlie all of computing in nature. Importantly, Solutions are being sought in natural systems with evolutionary developed strategies for handling complexity in order to improve complex networks of massively parallel autonomous engineered computational systems.

Natural computational models are most relevant in applications that resemble natural systems, as for example real-time control systems, autonomous robots, and distributed intelligent systems in general.

If computation is to be able to match the observable natural phenomena, such as: adequacy, generality and flexibility of real-time response, adaptability and robustness, relevant characteristics in natural computation should be incorporated in new models of computation. Maclennan (2004).

Illustrative Examples of Research Projects Inspired by Natural Computing

BIO-ICT

> New perspectives in ICT exploit the understanding of information processing in biological systems that have demonstrable advantages in terms of functionality, operating conditions, resilience or adaptability or lead to systems that can be naturally combined

> with biological systems. BIO-ICT Projects integrate some of the following topics: Novel computing paradigms, derived from the information representation and processing capabilities of biological systems (networks of neurons or other cells), or from the computational interpretation of biological processes (molecular signaling, metabolism) and with measurable advantages over current approaches to difficult problems in information processing. Biomimetic artefacts: ad hoc hardware implementations of bio-inspired systems in areas where standard devices do not provide the required performance. This may use analogue and digital circuits, evolvable hardware, artificial cells, neuro-morphic chips or sensors for achieving life-like functionality or properties such as self organisation, robustness or growth. Bidirectional interfaces between electronic or electro-mechanical systems and living entities, at or close to the cellular level, with adequate control and/or signal processing algorithms, enabling direct interfacing to the nervous system or to other types of cells. Biohybrid artefacts, involving tightly coupled ICT and biological entities (e.g. neural or other types of biological tissue) for new forms of computation, sensing, communication or physical actuation or adaptation http://www.bio-ict.org

IBM Autonomic Computing

> Over the past forty years (…) the focus has been on raw processing power and the individual components that allow ever smaller and greater capacity to store, process and move data. And while scientists and researchers have met this demand with astonishing regularity, we have missed an opportunity to look at the evolution of computing from a more holistic perspective.

> There are a number of immediate needs that require us to adjust our thinking and reinterpret our approach to computing in general, and specifically to the interaction between computer hardware, software and networks. The current strain on I/T services demands that we turn our best minds to developing computer systems to be more automated and less reliant on human intervention.
> http://www.research.ibm.com/autonomic/research/

The above examples show that the research within natural computing is already going on and we can expect in the near future a substantial paradigm shift from present day Turing machine-centric view of computing towards natural computing, both in terms of new models of computation and in terms of new computational devices.

Natural Computationalism (Pancomputationalism): The Universe is a Computer

Pancomputationalism (Pan-computationalism, Natural computationalism) is a view that the universe is a huge computational machine or rather a network of computational processes which following fundamental physical laws compute (dynamically develop) its own next state from the current one. In this approach the stuff of the universe is:

- Essentially informational
- Both digital and analog – depending on the level of abstraction

Pancomputationalism claims that all physical processes can be understood as computational processes. In principle, there seems to be no ontological hindrance to our including the system or process we try to compute among the models we use. We then get what I take to be the fundamental idea of pancomputationalism: The function governing a process is calculated by the process itself[3]. The following remark by Richard Feynman explains lucidly the idea and our hopes about natural computing:

> It always bothers me that according to the laws as we understand them today, it takes a computing machine an infinite number of logical operations to figure out what goes on in no matter how tiny a region of space and no matter how tiny a region of time ... I have often made the hypothesis that ultimately physics will not require a mathematical statement, that in the end the machinery will be revealed and the laws will turn out to be simple. Richard P. Feynman, The Character of Physical Law (1965), 57. [4]

Digital vs. Analog and Continuum vs. Discrete

Georg Leopold Kronecker believed that, while everything else was made by man, the natural numbers were given by God. For the logicists the natural numbers were sufficient for deriving of all of mathematics.We can see this subject re-surface in Chaitin's question about the existence of real numbers, see Chaitin *How real are real numbers,* Chaitin (2007) 276. For Chaitin real numbers are chimeras of our own minds, they just simply do not exist!

Even though pragmatic minded people would say that discrete set can always be made dense enough to mimic continuum for all practical purposes, on purely principal grounds we

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[3] For this formulation I thank KB Hansen.

[4] Used as the motto for the 2008 Midwest NKS Conference, http://www.cs.indiana.edu/~dgerman/2008midwestNKSconference/index.html

cannot dispense with only one part in a dyadic pair for continuum and discrete are mutually defining.[5]

Discrete – continuum problem lies in the underpinning of calculus and Bishop George Berkeley in his book "The analyst: or a discourse addressed to an infidel mathematician" argued that, although calculus led to correct results, its foundations were logically problematic. Of derivatives (which Newton called fluxions) Berkley wrote:

> And what are these fluxions? The velocities of evanescent increments. And what are these same evanescent increments? They are neither finite quantities, nor quantities infinitely small, nor yet nothing. May we not call them ghosts of departed quantities?[6]

Philosophical problems closely attached to the idea of infinity in mathematics are classical ones. From physics on the other hand, there are persistent voices, such as (Lesne 2007) witnessing for the necessity of continuum in physical modeling of the world. Here is the summary:

> This paper presents a sample of the deep and multiple interplay between discrete and continuous behaviours and the corresponding modellings in physics. The aim is to show that discrete and continuous features coexist in any natural phenomenon, depending on

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[5] This dyadic function seems to come from our cognitive apparatus which makes the difference in perception of discrete and continuous. It is indirectly given by the world, in a sense that we as a species being alive in the world have developed those dyadic/binary systems for discrete (number) and continuous (magnitude) phenomena as the most effective way to relate to that physical world.

[6] Berkeley talks about *the relationship between the model and the world*, not about the inner structure of the model itself. Worth noticing is KB Hansen's remark that "problems observed by Berkeley have been solved by Bolzano, Cauchy, Riemann, Weierstrass, and Robinson. Modern mathematical analysis rests on solid foundations."

> the scales of observation. Accordingly, different models, either discrete or continuous in time, space, phase space or conjugate space can be considered. Lesne (2007)

The question of continuum vs. discrete nature of the world is ages old and it is not limited to the existing technology. Digital philosophy as well as Turing machine has been epistemologically remarkably productive (see Stephen Wolframs work, e.g. (Wolfram 2002) along with Ed Fredkin and number of people who focused on the digital aspects of the world). Digital is undoubtedly one of the levels we can use for the description, but from physics it seems to be necessary to be able to handle continuum too (as we do in Quantum Mechanics). For a very good account, see Lloyd (2006) .

Finally it should be remembered (as already pointed out) that both digital and analog systems can be discrete or continuous, depending on the level of description/level of description or organization.

Paninformationalism - Informational Structural Realism

According to Floridi (2008) the ultimate nature of reality is an informational structure, a view called informational realism. Using the methodology of the levels of abstractions Floridi shows that, within the debate about structural realism, epistemic and ontic structural realism are reconcilable.

Floridi (2009) goes a step further arguing that digital ontology (the ultimate nature of reality is digital, and the universe is a computational system equivalent to a Turing Machine) should be carefully distinguished from informational ontology (the ultimate nature of reality is informational). His conclusion is that digital ontology does not cover all aspects of physical reality while informational ontology does:

> Digital vs. analogue is a Boolean dichotomy typical of our computational paradigm, but digital and analogue are only “modes of presentation” of Being (to paraphrase (...) Kant), that is, ways in which reality is experienced or conceptualized by an epistemic agent at a given level of abstraction. A preferable alternative is provided by an informational approach to structural realism, according to which knowledge of the world is knowledge of its structures. The most reasonable ontological commitment turns out to be in favor of an interpretation of reality as the totality of structures dynamically interacting with each other. Floridi (2009)

This dynamic interaction of informational structures is what is called natural computation. *Pancomputationalism does not automatically imply digital (discrete) computing*. As the whole of the universe computes, both sorts of computing are part of natural computation, discrete and continuous. As Seth Lloyd points out, on the basic quantum-mechanical level both discrete and analogue, digital and continuous computing is going on. See more about the question of digital/analog universe in Dodig Crnkovic (2006).

Info-Computational Naturalism

Info-computational naturalism unifies pancomputationalism with paninformationalism, the view that the fabric of the universe is informational. Its claim is that while the structure of the universe is informational, its dynamics (change) is computation i.e. information processing, see

Dodig Crnkovic (2006) and Dodig Crnkovic (2008). This computation process is natural computing, see MacLennan in Dodig Crnkovic and Burgin (2010) . Burgin's article, *Information Dynamics in a Categorical Setting*, in the same volume, offers a common framework for information and computation, building a mathematical stratum of the general theory of information based on category theory.

The main feature of info-computationalist naturalism is that it makes possible unification of nonliving and living physical world within the same framework, thus even providing clues to mental (information processing) capacities in humans and animals. Of all grand unifications or *système du monde* as Greg Chaitin says in his *Epistemology as Information Theory: From Leibniz to Ω,* Chaitin (2007), this is the first one holding promise to be able to explain and simulate not only non-living universe but also the structure and behavior of living organisms including the human mind.

Complexity is an essential characteristic of life, the domain in which info-computational approach best shows its explanatory power. Living organisms are complex, goal-oriented autonomous information-processing systems with ability of self-organization, self-reproduction (based on genetic information) and adaptation. They evolved through pre-biotic and biological evolution from inanimate matter. Understanding of basic info-computational features of living beings has consequences for many fields, especially information sciences, cognitive science, neuroscience, theory of computing, artificial intelligence and robotics but also biology, sociology, economics and other fields where informational complexity is essential.

The info-computational idea is based on the following principles:

(IC1) The ontologically fundamental entities of the physical reality are *information* (structure) and *computation* (change).

(IC2) Properties of a complex physical system cannot be derived solely from the properties of its components. Emergent properties must be taken into account.

(IC3) In general, the observer is a part of the system observed.

Info-computational models include *open systems* in communication with the environment. Environment is a constitutive element for an open complex info-computational system. *Network* of interconnected parts is a typical configuration, where understanding is sought on the meta-level with respect to constituent parts. Info-computational models include mechanistic ones as a special case when the internal interaction between the parts of the system and the interaction of the system with the environment may be neglected.

Epistemological Consequences of Info-Computational Naturalism

One might suspect that the computationalist idea is vacuous, and if everything is info-computational, then it says nothing about the world. The computationalist claim however should be understood as similar to the claim that universe is made of atoms. Atom is a very useful concept which helps understanding the world in many fields. So is the info-computational approach. Universe is NOT “nothing but atoms”, but on some view (level of organization, level of abstraction) may be seen as atoms.

As already emphasized, physical reality can be addressed at many different levels of organization. Life and intelligence are the phenomena especially characterized by info-computational structures and processes. Living systems have the ability to act autonomously and store information, retrieve information (remember), anticipate future behavior in the environment with help of information stored (learn) and adapt to the environment in order to survive. In Epistemology Naturalized, Dodig Crnkovic (2007), I present a model which connects mechanisms of information processing and knowledge generation in an organism. Thinking of us and the universe as a network of computational structures and processes allows easier approaching of the question about boundaries between living and non-living beings.

Info-computationalism views our bodies as advanced computational machines in constant interaction with the environmental computational processes and structures. Our brains are informational architectures undergoing computational processes on many levels of organization. On the levels of basic physical laws there is a computation going on. All which physics can conceptualize, describe, calculate, simulate and predict can be expressed in info-computationalist terms. On the level of molecules (with atoms and elementary particles as structural elements) there are computational processes going on. The nerve cell level can be understood as the next level of relevance in our understanding of the computational nature of the brain processes. Neurons are organized in networks, and with neurons as building blocks new computational phenomena appear on the level of neural network. The intricate architecture of informational structures in the brain, implementing different levels of control mechanisms are not unlike virtual machines on higher level running on the structure below, Sloman and Chrisley (2003) . What we call "informational architecture" is fluid and interactive, not so much crystal-lattice-type rigid construction but more like networks of agents, Minsky's society of minds, Minsky (1988) .

The development is going on into two directions: analyzing living organisms as info-computational systems/agents, and implementing natural computation strategies (organic computing, bio computing) into artifacts. Lessons learned from the design and implementation of our understanding of living natural computational agents through iterative process of improvements will lead to artifacts that in increasingly higher degree will be capable of simulating characteristics of living organisms.

Naturalist Understanding of Cognition

According to Maturana and Varela (1980) even the simplest organisms possess cognition and their meaning-production apparatus is contained in their metabolism. Of course, there are also non-metabolic interactions with the environment, such as locomotion, that also generates meaning for an organism by changing its environment and providing new input data.

Maturana's and Varelas' understanding of cognition is most suitable as the basis for a computationalist account of the naturalized evolutionary epistemology. A great conceptual advantage of cognition as a central focus of study is that all living organisms possess some cognition, in some degree.

Theoretical Advances in Learning From Nature Through Info-Computation

In what follows examples are given of the research where we learn through info-computational approaches about cognition and functions of the brain.

Epistemology Naturalized

Naturalized epistemology (Feldman, Kornblith, Stich) is, in general, an idea that knowledge may be studied as a natural phenomenon; that the subject matter of epistemology is not our concept of knowledge, but the knowledge itself, knowledge in the world.

> The stimulation of his sensory receptors is all the evidence anybody has had to go on, ultimately, in arriving at his picture of the world. Why not just see how this construction really proceeds? Why not settle for psychology? Quine (1985)

Why not settle for info-computational naturalism?

> Indeed, cognitive ethologists find the only way to make sense of the cognitive equipment in animals is to treat it as an information processing system, including equipment for perception, as well as the storage and integration of information; that is, after all, the point of calling it cognitive equipment. That equipment which can play such a role confers selective advantage over animals lacking such equipment no longer requires any argument. Kornblith (2003)

Evolutionary Development

> One cannot account for the functional architecture, reliability, and goals of a nervous system without understanding its adaptive history. Consequently, a successful science of knowledge must include standard techniques for modeling the interaction between evolution and learning. Harms (2004)

A central question is thus what the mechanism is of the evolutionary development of cognitive abilities in organisms. Critics of the evolutionary approach mention the impossibility of "blind chance" to produce such highly complex structures as intelligent living organisms. Proverbial monkeys typing Shakespeare are often used as an illustration; an interesting account is given by Gell-Man (1994). However, (Lloyd, 2006) mentions a very good counterargument, originally due to Chaitin and Bennet. The "typing monkeys" argument does not take into account physical laws of the universe, which dramatically limit what can be typed. Moreover, the universe is not a typewriter, but a computer, so a monkey types random input into a computer. The computer interprets the strings as programs.

> Quantum mechanics supplies the universe with "monkeys" in the form of random fluctuations, such as those that seeded the locations of galaxies. The computer into which they type is the universe itself. From a simple initial state, obeying simple physical laws, the universe has systematically processed and amplified the bits of information embodied in those quantum fluctuations. The result of this information processing is the diverse, information-packed universe we see around us: programmed by quanta, physics give rise first to chemistry and then to life; programmed by mutation and recombination, life gave rise to Shakespeare; programmed by experience and imagination, Shakespeare gave rise to Hamlet. You might say that the difference between a monkey at a typewriter and a monkey at a computer is all the difference in the world. Lloyd (2006)

The universe/computer on which a monkey types is at the same time the hardware and the program, in a way similar to the Turing machine. An example from biological computing is the DNA where the hardware (the molecule) is at the same time the software (the program, the code). In general, each new input restructures the computational universe and changes the preconditions for the future inputs. Those processes are interactive and self-organizing. That makes the essential speed-up for the process of getting more and more complex structures.

Based on natural phenomena understood as info-computational, computing in general is conceived on an open interactive system (digital or analogue; discrete or continuous) in communication with the environment. The classical Turing machine is seen as a subset of a more general interactive/adaptive/self-organizing universal natural computer. A "living system" is defined as an "open, coherent, space-time structure maintained far from thermodynamic equilibrium by a flow of energy through it" Chaisson (2001). On a computationalist view, organisms are constituted by computational processes, implementing computation in vivo. In the open system of living cells an info-computational process takes place using DNA, exchanging information, matter, and energy with the environment.

All cognizing beings are in constant interaction with their environment. The essential feature of living organisms is their ability to manage complexity and to handle diverse environmental conditions with a variety of responses that are results of adaptation, variation, selection, learning, and/or reasoning. As a consequence of evolution, increasingly complex living organisms arise. They are able to register inputs (data) from the environment, to structure those into information and, in more developed organisms, into knowledge. The evolutionary advantage of using structured, component-based approaches (data – information – knowledge) is improving response time and the computational efficiency of cognitive processes.

The main reason for choosing info-computationalist view for naturalizing epistemology is that it provides a unifying framework that makes it possible for different research fields such as philosophy, computer science, neuroscience, cognitive science, biology, and a number of others to communicate, exchange their results, and to build a common knowledge.

It also provides the natural solution to the old problem of the role of representation in explaining and producing information, a discussion about two seemingly incompatible views: a symbolic, explicit, and static notion of representation versus an implicit and dynamic (interactive) one. Within the info-computational framework, those classical (Turing-machine type) and connectionist views are reconciled and used to describe different aspects of cognition.

The info-computationalist project of naturalizing epistemology by defining cognition as an information-processing phenomenon is based on the development of multilevel dynamical computational models and simulations of intelligent systems and has important consequences for the development of artificial intelligence and artificial life, the subject of the next chapter.

Intelligence, Chess, Computing and AI from Deep Blue to Blue Brain

Chess Relevance for AI and Deep Blue

Many people would even today agree with the following claim made in 1958:

> If one could devise a successful chess machine, one would seem to have penetrated to the core of human intellectual endeavor. Newell, Shaw, and Simon (1958)

Chess play is by Ross (2006) even called “the Drosophila of Cognitive Science” for its frequent use in cognitive experiments, Charness (1992). The story of IBM’s Chess supercomputer Deep Blue winning in 1997 the match against the world chess champion Gary Kasparov is therefore a very instructive one. The computer was programmed by a computer scientists assisted by a chess grandmaster. They developed the evaluation function to assess every given position. The method may be described as combinatorial “brute force”.

It turned out that what was believed to be “at the core of human intellectual endeavour” could be better performed by a programmed machine applying basically simple strategy. This was the beginning of a development of machines dedicated to mimic what would be considered to be intelligent behaviour.

Descendant of Deep Blue, Blue Gene an Engine of Scientific Discovery

The methods devised in Deep Blue project were employed as a foundation of Blue Gene supercomputer and used among others for protein folding, genetic and brain research. The project was exceptionally fruitful. [7] Searching for the optimum configurations of systems consisting of simple elements is typical of not only chess play but also of a range of other scientific problems. Solving this category of problems brings us closer to constructing intelligent computers and facilitates scientific progress in general.

Blue Brain Project

In 2005 EPFL and IBM initiated a research project analogous in scope to the Genome Project, with the aim to create a biologically accurate model of the brain using Blue Gene

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[7] For comparison, Deep Blue had 32 processors and could process about 200 million chess moves per second in its match against Kasparov. Today Blue Gene uses 131000 processors to perform 280 trillion operations per second. http://www-03.ibm.com/servers/deepcomputing/bluegene.html

supercomputer. This project has already delivered important results with biologically accurate computational neurons made on the basis of experimental data. These neurons are automatically connected in a network by positioning around 30 million synapses in exact 3D locations. Such networks have been used to simulate the basic functional unit of the brain, the neocortical column, http://news.bbc.co.uk/2/hi/science/nature/8012496.stm.

This development from Deep Blue via Deep Gene to the Blue Brain demonstrates how scientific progress can be made through learning by construction. There is a clear paradigm shift in computing as a scientific discipline with respect to classical scientific fields, Dodig Crnkovic (2003). Understanding neocortical information processing by reverse-engineering the mammalian brain makes foundation for simulation of the whole brain and is an essential step in our understanding of brain functions including intelligence in info-computational terms, Dodig Crnkovic (2008).

Promises of the Info-Computational Naturalist Research Programme

The central question is how *epistemologically productive* this paradigm is, as info-computational naturalism really is a *research programme* whose role is to mobilize researchers to work in the same direction, within the same global framework. The majority of natural sciences, formal sciences, technical sciences and engineering are already based on computational thinking, computational tools and computational modelling, Wing (2008).

So the time has come for paradigm change in computing. Following are some of the promises of info-computationalism:

The synthesis of (presently disconnected) knowledge from different fields within the common info-computational framework which will enrich our understanding of the world as a whole. Present day narrow specialization into different isolated research fields has gradually led into impoverishment of the common world view.

Integration of scientific understanding of the phenomena of life (structures, processes) with the rest of natural world helping to achieve “the unreasonable effectiveness of mathematics” such as in physics (Wigner) even for complex phenomena like biology that today lack mathematical effectiveness (Gelfand)[8]. In this case, mathematical effectiveness will be replaced by computational effectiveness.

Understanding of the semantics of information as a part of data-information-knowledge-wisdom sequence, in which more and more complex relational structures are created by computational processing of information. An evolutionary naturalist view of semantics of information in living organisms is given based on interaction (information exchange) of an organism with its environment.

A unified picture of fundamental dual-aspect information/computation phenomenon applicable in natural sciences, information science, cognitive science, philosophy and number of others.

Relating phenomena of information and computation understood in interactive paradigm makes it possible for investigations in logical pluralism of information produced as a result of

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[8] See Chaitin, Mathematics, Biology and Metabiology (Foils, July 2009)

interactive computation. [9] Of special interest are open systems in communication with the environment and related logical pluralism including paraconsistent logic. Japaridze (2003)

Advancement of our computing methods beyond the Turing-Church paradigm, computation in the next step of development becoming able to handle complex phenomena such as living organisms and processes of life, knowledge, social dynamics, communication and control of large interacting networks (as addressed in *organic computing* and other kinds of *unconventional computing*), etc.

Of all manifestations of life, mind seems to be information-theoretically and philosophically the most interesting one. Info-computationalism (pancomputationalism + paninformationalism) has a potential to support (by means of models and simulations) our effort in learning about mind. On the practical side, understanding and learning to simulate and control functions and structures of living organisms will bring completely new medical treatments for all sorts of diseases including mental ones which to this day are poorly understood. Understanding of our information-processing features of human brain will bring new insights into such fields as education, media, entertainment, cognition etc.

Conclusions

Today's software-intensive and intelligent computer systems have become large, consisting of massive numbers of autonomous and parallel elements across multiple scales. At the nano-scale they approach programmable matter; at the macro scale, multitude of cores

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[9] This logical pluralism is closely related to phenomena of consistency and truth; see also de Vey Mestdagh & Hoepman in Dodig Crnkovic and Burgin (2010).

compute in clusters, grids or clouds, while at the planetary scale, sensor networks connect environmental data to track climate and other global-scale phenomena. The common for these modern computing systems is that they are *ensemble-like* (as they form one whole in which the parts act in concert to achieve a common goal like an organism that is an ensemble of its cells) and *physical* (as ensembles act in the physical world and interact with their environment through sensors and actuators).

Info-computationalism will help us answering the focal research questions and understanding the potential and the limits of the emerging computational paradigm which will have significant impact on the research in both computing and sciences. It has high relevance for the development of future computing theories and technologies as well as for the improvement of computational models of natural and phenomena. Applications such as BIO-ICT and Autonomic computing show possible domains of practical use.

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Key terms

Pancomputationalism (Pan-computationalism, Natural computationalism) is a view that the universe is a huge computational machine or rather a network of computational processes which following fundamental physical laws compute (dynamically develop) its own next state from the current one. In this approach the stuff of the universe is essentially informational and both digital and analog – depending on the level of abstraction.

Paninformationalism (Informational structural realism) According to this view, the ultimate nature of reality is an informational structure.

Info-computational naturalism (Info-computationalism) unifies pancomputationalism with paninformationalism. Within this framework the structure of the universe is informational while its dynamics (change) is computation i.e. information processing

Computation is in general defined as any kind of information processing. It includes processes such as human cognition, cell metabolism as well as calculations performed by computing devices. For a process to be a computation a model must exist such as algorithm, network topology, physical process or in general any mechanism which ensures predictability of its behavior.

Natural computation (Natural computing) includes theoretical computational methods inspired by nature and physical computing methods based on new natural materials besides present-day electronic hardware.

Digital physics is a set of theoretical perspectives that the universe is computable. It can be conceived as either the output of some computer program or as being some sort of vast *digital* computation device.

Hypercomputation refers to computation beyond Turing model, capable of computing non-Turing-computable functions, following super-recursive algorithms. It also includes other forms of computation interactive computation. The term was first introduced Jack Copeland.

Naturalized epistemology is, in general, an idea that knowledge may be studied as a natural phenomenon; that the subject matter of epistemology is not our concept of knowledge, but the knowledge itself, knowledge in the world.

Forthcoming in: THINKING MACHINES AND THE PHILOSOPHY OF COMPUTER SCIENCE: CONCEPTS AND PRINCIPLES

Biographical sketch

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