Semantics of Information as Interactive Computation

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Abstract. Computers today are not only the calculation tools - they are directly (inter)acting in the physical world which itself may be conceived of as the universal computer (Zuse, Fredkin, Wolfram, Chaitin, Lloyd). In expanding its domains from abstract logical symbol manipulation to physical embedded and networked devices, computing goes beyond Church-Turing limit (Copeland, Siegelman, Burgin, Schachter). Computational processes are distributed, reactive, interactive, agent-based and concurrent. The main criterion of success of computation is not its termination, but the adequacy of its response, its speed, generality and flexibility; adaptability, and tolerance to noise, error, faults, and damage. Interactive computing is a generalization of Turing computing, and it calls for new conceptualizations (Goldin, Wegner). In the info-computationalist framework, with computation seen as information processing, natural computation appears as the most suitable paradigm of computation and information semantics requires logical pluralism.

Keywords: Semantic Information, Computationalism, Philosophy of Computing, Hypercomputating, Philosophy of Information

1 Introduction

Every epoch and culture has a different conception of the universe. For some (numerous ancient myths, Thales, Spinoza) universe was a living organism. For Ptolemy, Descartes, and Newton it was a huge machine. Our current understanding of information and computing has led to a conception of the universe as a computer. On such a pancomputational and paninformational view (Zuse, Fredkin, Wolfram, Chaitin, Lloyd) we can consider information as a result of (natural) computation, and the universe as a network of computing processes that are defined by the information they manipulate and produce. Within a computationalist framework information is that which constitutes the structure of the universe, at any given moment (Dodig-Crnkovic 2006). The structure changes continuously and that process of change can be understood as computation. Information and computation are elements of a dual-aspect theory, much like energy/matter dualism. Currently we are changing the concept of universe to an increasingly more pronounced computationalism, which hopefully will help us both to understand the functioning of the physical universe and learn more about the nature of computation. The universe as a computer is a dynamic system, a huge network of interacting computational processes. (Dodig-Crnkovic 2006)

Contrary to traditional Turing computation, in which the computer was an isolated box provided with a suitable algorithm and an input, left alone to compute until the algorithm halted, interactive computation (Wegner 1988, Goldin et al. 2006) implies interaction i.e. communication of the computing process with the environment during the computation. Interaction consequently provides a new conceptualization of computational phenomena which involves communication and information processing.

The essential novelty that interactive computing brings about is its capability of articulation of *the difference between an open and a closed system*, the distinction being equally relevant for physics, mathematics as for computing itself. The traditional theories are about *isolated systems* where environment is represented by some average behavior, and treated as a perturbation. An observer is external to the system. In the interactive framework on the other hand, the system is in general communicating with the explicitly expressed environment (which system does not control) that also allows for the integration of the observer into the model.

Even though practical implementations of interactive computing are several decades old, a foundational theory, and in the first place semantics and logic[1] of interactive computing is only in its beginning. A theoretical base analogous to what Turing machines are for algorithmic computing, is under development for interactive computing. (Wegner 1998, Abramsky 2003, Japaridze 2006)

Goldin and Wegner (2002) argue e.g. that computational logic must be able to model interactive computation, that classical logic does not suffice and that logic must be paraconsistent due to the incompleteness of interaction.

"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." (Priest, Tanaka 2004)

Through the analysis of information semantics also Allo (2005) puts forward arguments in favor of non-classical logics requiring logical pluralism. Having in mind complementarity of information/computation, both arguments point into the same direction – necessity of non-classical logical approaches in the computationalist theoretical framework.

There are several entangled strands of ideas presented here which suggest a necessity of a new general view of computing, information, and logic, also having consequences for mathematics, physics, and related fields. What is then the role of

[1] Games with their distributed, reactive, agent-based concurrency present a very suitable formalism (Abramsky, Hintikka) for the modeling of interactive computing, i.e. of information flow and multi-agent interaction (Van Benthem, Japaridze, Wegner).

semantics in this new emerging informational – computational world? Here is a possible answer:

"According to computability logic philosophy, syntax - the study of axiomatizations or any other, deductive or nondeductive string-manipulation systems - exclusively owes its right of existence to semantics, and is thus secondary to it. Computability logic believes that logic is meant to be the most basic, general-purpose formal tool potentially usable by intelligent agents in successfully navigating real life. And it is semantics that establishes that ultimate real-life meaning of logic." (Japaridze, 2006)

2 Information Semantics - Open Problems

In his Open Problems in the Philosophy of Information Floridi (2004) lists the five most interesting areas of research for the field of Philosophy of Information (and Computation), containing eighteen fundamental questions as follows:

I) *Information definition* [What is Information? What is the dynamics of information? Is a grand unified theory of information (GUTI) possible?]

II) *Information Semantics* [The data grounding problem: How can data acquire their meaning? Truth problem: How can meaningful data acquire their truth value? Informational truth theory: Can a theory of information explain truth? Informational semantic problem: Can information theory explain meaning?]

III) *Intelligence/Cognition* [Descartes' problem: Can cognition be fully analyzed in terms of information processing at some level of abstraction? Dennett's reengineering problem: Can natural intelligence be fully analyzed in terms of information processing at some level of abstraction? Turing's problem: Can natural intelligence be fully and satisfactorily implemented non-biologically? The MIB (mind-information-body) problem: Can an informational approach solve the Mind-Body problem? The informational circle: If information cannot be transcended but can only be checked against further information - if it is information all the way up and all the way down - what does this tell us about our knowledge of the world? The Information Continuum Conjecture: Does knowledge encapsulate truth because it encapsulates semantic information? Should epistemology be based on a theory of information? The semantic view of science: Is science reducible to information modeling?]

IV) *Informational Universe/Nature* [Wiener's problem: Is information an independent ontological category, different from the physical/material and the mental? The problem of localization: Could information be neither here (intelligence) nor there (natural world) but on the threshold, as a special relation or interface between the world and its intelligent inhabitants (constructionism)? The "It from Bit" hypothesis: Is the universe essentially made of informational stuff, with natural processes, including causation, as special cases of information dynamics?]

V) *Values/Ethics* [Are computing ethics issues unique or are they simply moral issues that happen to involve ICT? What kind of ethics is CE? What is the contribution of CE to the ethical discourse?]

Information semantics (II) is of special interest here, but we will come back to a number of closely related questions from the Floridi program.

According to Floridi (2006, 2005) declarative, objective and semantic information must be true (strongly semantic information). Consequently, for this kind of information “The Information Continuum Conjecture: Does knowledge encapsulate truth because it encapsulates semantic information?” has always an affirmative answer.

Now what about non-declarative objective semantic information? Non-declarative information is of great relevance for epistemology. Natural sciences e.g. in their generation of knowledge handle extensively non-declarative information represented by empirical data. Non-declarative information is abundant in nature and processed in a variety of natural computation processes.

This paper will relate to several points of Floridi’s program for Philosophy of Information, and suggest a general approach to information/computation logic, that includes the classical approaches as a proper subset. There are many related questions that might be answered in interesting ways if we define information as the result of computing, the definition mirroring the complementary description of computing as information processing. (Dodig-Crnkovic 2006, Dodig-Crnkovic & Stuart 2007) Computational/Informational turn might also be seen as a practical basis of a program of naturalizing epistemology. Starting from info/computational universe with adaptive (info/computational) agents in varying environments, building informational structures by means of exchanges with the environment, agents with increasing capabilities to predict and control the environment emerge, see Dodig-Crnkovic, 2007.

If we accept the pancomputational stance (Zuse, Fredkin, Wolfram, Chaitin, Lloyd) as a point of departure, and if all physics may be expressed as computation, meaning the whole universe might be represented as a network of computing processes at different scales or levels of granularity then we may see information in the first place as a result of (natural) computation.

Information (structure) and computation (process) are two ideas complementary in a similar way as continuum and a discrete and can be applied to the same physical phenomena, depending on the level of description. In its turn continuum – discrete set dichotomy may be seen in a variety of disguises such as: time – space; wave – particle; geometry – arithmetic; computation – information. Two elements in each pair presuppose each other, and are inseparably bounded to each other. (Dodig-Crnkovic 2006)

The field of Philosophy of Information is so closely interconnected with the Philosophy of Computation that it would be appropriate to call it Philosophy of Information and Computation, having in mind the dual character of information-computation phenomena. Burgin (2005) puts it in the following way:

“It is necessary to remark that there is an ongoing synthesis of computation and communication into a unified process of information processing. Practical and theoretical advances are aimed at this synthesis and also use it as a tool for further development. Thus, we use the word computation in the sense of information processing as a whole. Better theoretical understanding of computers, networks, and other information processing systems will allow us to develop such systems to a higher level. “

3 Computation as Information Processing

Our civilization is more and more the world of information processing – we are surrounded by computer systems connected in global networks of multitasking, often mobile, communicating devices. A mechanical symbol manipulation going on in a computer is basically processing of information, with its syntactic and semantic aspects attached.

It is interesting to note that both computation and communication imply the transformation and preservation of information. Bohan Broderick (2004) compares notions of communication and computation which leads him to the conclusion that the two are not conceptually distinguishable. He shows that computation and communication may be distinguished if computation is limited to actions within a system and communication is an interaction between a system and its environment. The interesting problem of distinction arises when the computer is conceived as an open system in communication with the environment, where the boundary between the system and the world allows for a dynamic relationship, as in biological computing where system exchanges energy and information with the environment.

Burgin (2005) identifies three distinct components of information processing systems: hardware (physical devices), software (programs that regulate its functioning) and infoware which represent information processed by the system. Infoware is a shell built around the software-hardware core which was the traditional domain of automata and algorithm theory.

Compared to new computing paradigms, Turing machines form the proper subset of the set of information processing devices, in much the same way as Newton's theory of gravitation forms a subset of Einstein's theory or the Euclidean geometry appears as a limit case of non-Euclidean geometries.

4 Complexity, Computing, Algorithms and Hypercomputation

Having the ambition of not only describing, but also taking part in the universe, computational systems must be able to match and directly connect to the environment. According to Ashby (1964) it is therefore for them necessary to match the complexity of the environment. Ashby's "Law of Requisite Variety" states namely, that to control a situation and to perform up to requirements, 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 match the complexity of the system.

The theory of information and communication technology of today is based on algorithms. The Church-Turing thesis is the basic tenet of the algorithmic model that claims that all of computation can be expressed by recursive algorithms (Turing machines). However, generally speaking, the semantics of mathematical models are relative to a domain of application and they are usually not well-defined outside that domain (Kuipers, 2006 gives some interesting examples of the domain dependence of a theory). Even traditional computing has its domain, and the discussion of the presuppositions and context of the Turing machine model is therefore in order. In spite of its validity within a given domain, the Turing machine model is not appropriate for some applications (levels of granularity of the description).

As is well known, the Turing machine model was developed in a reply to Hilbert's program in mathematics, which attempted to reduce mathematics to a finitary formal system. Turing machines were an attempt to give a mathematically precise definition of "algorithm" or "mechanical procedure". In Turing's words:

"A man provided with paper, pencil, and rubber, and subject to strict discipline, is in effect a universal machine."

Nevertheless, a thesis concerning the extent of effective procedures that a human being unaided by machinery is capable of carrying out has no implication concerning the extent of the procedures *that other computing systems* are capable of carrying out. *Among a "machine's" (computing physical system's)*[2] *repertoire of atomic operations there may be those that no human being unaided by "computing machinery" can perform.*

The definition of computation is still under debate, and an entire issue of the journal Minds and Machines (1994, 4, 4) was devoted to the question "What is Computation?" It has been argued that Turing computation is what we mean by computation, but MacLennan (2004) proposes a broader definition of computation that includes both Turing computation and alternative (in Burgin's terminology super-recursive) hypercomputing models. If we compare Turing machines with the physical universe, including quantum physics, the latter exhibits a much higher order of complexity. A living cell is an example of a real-world information-processing mechanism for which Turing machine model is not appropriate. That would imply that we need more powerful computers, than what is described by Turing machine models in order to be able to represent, simulate and better control the real world phenomena.

In exceeding Turing limit, the new area of computing theory called the theory of super-recursive algorithms or hypercomputation addresses two distinct problems (Burgin 2005, Minds and Machines (1994, 4, 4)): the nature of the computing mechanism and the nature of the halting problem. The first problem could be answered by natural computation, see next chapter. Computing has an ambition to not only calculate but also simulate phenomena, which is best done by natural computation in the case of natural phenomena.

The second question is answered by the insight that computing in general has no need of halting. The Internet neither computes any function nor is it expected to halt. Another way to see the halting problem is conceiving the original question of uncomputability as the internalized problem of induction, (Kelly 2004). Induction, now in a sense of the learning process, is stopped at a certain point, decided on semantic (pragmatic) grounds.

[2] Here of course the machine is not a Turing machine, otherwise it would be circular: TM defined as a human, which is then compared with a TM.

5 Natural Computation

MacLennan, (2004) defines natural computation as ”computation occurring in nature or inspired by that in nature”, which includes quantum computing and molecular computation, and might be represented by either discrete or continuous models. Examples of computation occurring in nature comprise information processing in evolution by natural selection, in the brain, in the immune system, in the self-organized collective behavior of groups of animals such as ant colonies, and particle swarms. Computation inspired by nature include genetic algorithms, artificial neural nets, simulated immune systems, ant colony optimization, particle swarm optimization, and similar. 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. There is an interesting synergy gain in relating the human designed computing with the computing going on in nature.

If computation is to be able to simulate the observable natural phenomena, relevant characteristics in natural computation should be incorporated in new models of computation. Natural computational systems have the following important features (MacLennan, 2004): adequacy of real-time response, generality of response, flexibility in response to novelty, adaptability and robustness in the presence of perturbations – used to the advantage of the system in developing new features - all of which can be implemented in future computational devices aimed to function as embedded computing tools in direct interaction with physical environment. That is why in natural computation, the same features are becoming important characteristics of computation.

6 Concurrent Interactive Computing

If the semantics for the behavior of a concurrent system is defined by the functional relationship between inputs and outputs, as within the Church-Turing framework, then the concurrent system can be simulated by a Turing machine. The Turing machine is a special case of a more general computation concept.

The added expressiveness of concurrent interactive computing may be seen as a consequence of the introduction of time within the perspective. Time seen from a system is defined through the occurrence of external events, i.e. through interaction with the environment. In a similar way, spatial distribution, (between an inside and an outside of the system, also between different systems) gets its full expression through interaction. Different distributed agents, with different behaviors, interact with different parts of the environment. In interactive computing, time distribution and generally also (time-dependent) spatial distribution are modeled in the same formalism (Milner 1989 and Wegner 1998).

The contribution of concurrency theory to the toolbox of formal models of computing that may be used to simulate observable natural phenomena, are according to Schachter (1999):

“Furthermore, it is possible to express much richer notions of time and space in the concurrent 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.“

Theories of concurrency are integrating the observer into the model by permitting shifting of the inside-outside boundary. By this integration, theories of concurrency might bring major enhancements to the computational expressive resources, and capture phenomena beyond the Church-Turing framework.

7 Philosophy of Computing and Logical Pluralism

One can see the historical development of science as successive abandonment of absolutes: first the divine as a source of all truth, earth’s central position in the universe, the idea of absolute space and the concept of absolute time. Now we are ready to leave the ideal of absolute truth, which is connected to the abandonment of the idea of one and only true logic (logical monism). The process of leaving absolutes parallels our ability to produce more and more complex models in which we can control and examine more and more parameters and simulate increasingly complex structures and behaviors.

How does the change in logic towards accepting logical pluralism relate to computing, computers and information? Those elements influence each other and the development within one field induces the development in the others, which in its turn, influences the original field, and so on.

There are several points of departure one can take in order to explore the alternatives of logical monism in the context of Philosophy of Information and Computation. Focusing on information instead of knowledge can be the smooth way to go from logical monism. The alternative, logical pluralism (Beall and Restall, 2000, 2005) is motivated by an analysis of disagreement within the classical first-order logic, relevant logic and intuitionistic logic in the account of logical consequence (and hence of logical truth). Allo (2006) is arguing that logical pluralism could also entail semantic informational pluralism as informational content depends upon the underlying logic one assumes. Furthermore:

“An elementary consequence of this point of view is that, when a formal account of semantic information is elaborated, the absolute validity of logic cannot be taken for granted. Some further — external — evidence for its applicability is needed.”

Allo presents an interesting, and for practical purposes relevant, case of communication between agents adhering to different logics in a multi-agent system. This is the central point: information is something that is characteristic of a dynamical system; while knowledge presupposes static, steady states. Further arguments for logical pluralism and non-classical logic will be found in (Allo, 2005).

"Moreover it turns out that in an adaptive logic for acceptance and rejection a weak but sufficient notion of truthfulness is obtained for the limiting case of final derivability (this solves the problem of contingent falsities). Contrary to the motivations of Carnap & Bar-Hillel [1952], the presented approach outlines a theory of information based on information handling, not the other way around as a theory of semantic information as a preliminary for a future theory of pragmatic information." Allo (2005)

The need for new logic, including logical pluralism, in this context is obvious. In terms of interactive paradigm computational processes are conceived as distributed, adaptable, agent-based and concurrent. Agents, in general, may use different logics. Interaction provides a new conceptualization of computational phenomena which involves communication and information exchange, and presupposes logical pluralism. Pluralist logics are developing within the theory of computing (Allo, 2006) and they will soon show as a tool we can not do without in computationalism.

8 Conclusions

According to pancomputational/paninformational view (Zuse, Fredkin, Wolfram, Chaitin, Lloyd), the universe is a computer, or rather a network of distributed communicating computing processes, which come as a result of the multitude of changes occurring in an informational structure.

Philosophy of Information (Floridi, 2004) is a paradigm shift in philosophy, with ontology and epistemology being based on information, instead of following the tradition of ontological and epistemological foundation on the idea of knowledge. That means that the fine structure of both philosophical disciplines becomes explicit, and opens up for fundamentally new conceptualizations and interpretations. Philosophy of Information, with information conceived as a flow of data, structured and exchanged between varieties of cognizing agents, represents the ideal field of logical pluralism, Allo (2005).

In the domain of objective non-declarative information, Floridi's open problem (17) [*The* It *from* Bit *hypothesis*: Is the universe essentially made of informational stuff, with natural processes, including causation, as special cases of information dynamics?] has the positive answer: the universe is made of information that is in a constant flow, transformed and communicated through processes of computation/communication under the assumption of paninformationalism, i.e. computational mechanism (matter/energy plus physical laws) is informational. Pancomputationalism settles problems about the character of information and its dynamics.

Information semantics (the research area II in Floridi program) in the present unified informational/computational framework has its foundation in interactive computing and pluralist computability logic. (Dodig-Crnkovic, 2007) What becomes especially visible in this interactive framework is the intentionality of the agent, even the intentionality implicit in technologies. The possibility of choice and its consequences makes value systems one of the critical questions (problem 18) with consequences not only for ethics but also clearly for epistemology.

Intelligence/cognition (the research area III) also may be seen as a part of the computational/informational turn in naturalizing epistemology, to which a special chapter in (Dodig-Crnkovic 2006) is devoted. In effect, computationalism presents a way to generalized theory of information, where not only semantic objective declarative but also non-declarative information are included

In sum, this essay addresses several strands of intertwined ideas, suggesting a new view of computing, information, and logic, with consequences that affect number of related fields. Following is discussed: the duality of information and computation; pancomputationalism and paninformationalism; natural computation and hypercomputation; interactive computing, paraconsistent logic and logical pluralism. The arguments are presented for the need of a new approach to the semantics of information, where information is defined as a result of a computing process.

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