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Article

The Logic of the Physics of Information

Joseph E. Brenner

International Center for Transdisciplinary Research, 19 Villa Curial, 75019 Paris, France;
E-Mail: joe.brenner@bluewin.ch; Tel.: +41-244-922-118; Fax: +41-244-922-118

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Abstract: A consensus is emerging that the multiple forms, functions and properties of information cannot be captured by a simple categorization into classical and quantum information. Similarly, it is unlikely that the applicable physics of information is a single classical discipline, completely expressible in mathematical terms, but rather a complex, multi- and trans-disciplinary field involving deep philosophical questions about the underlying structure of the universe. This paper is an initial attempt to present the fundamental physics of non-quantum information in terms of a novel non-linguistic logic. Originally proposed by the Franco-Romanian thinker Stéphane Lupasco (1900–1988), this logic, grounded in quantum mechanics, can reflect the dual aspects of real processes and their evolution at biological, cognitive and social levels of reality. In my update of this logical system—Logic in Reality (LIR)—a change in perspective is required on the familiar notions in science and philosophy of causality, continuity and discontinuity, time and space. I apply LIR as a critique of current approaches to the physical grounding of information, focusing on its qualitative dualistic aspects at non-quantum levels as a set of physical processes embedded in a physical world.

Keywords: contradiction; duality; dynamics; identity; logic; non-separability; ontology; philosophy; physics; system

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1. Introduction

1.1. The Problem of Information

Information cannot be completely characterized either as a purely high-level epistemological phenomenon or a low-level transfer of energy. There are few conceptual or scientific tools for describing such physical processes that also embody and transport meaning, intentionality and

emotional value. A physics of information should describe phenomena not only at classical and quantum levels but in processes of information generation and transfer at higher biological, cognitive and social levels of reality. In other words, a proper physics of information, like information itself, will likely embody several different forms.

1.2. Current Literature; Rationale for this Paper

The existence of a relationship between physics, logic and information has been discussed in many places in the literature. For an authoritative recent review of the former, see the article by Adriaans in the *Stanford Encyclopedia of Philosophy* [1] and Burgin's *General Theory of Information* [2].

As phenomena, in all but their simplest aspects, information and informational processes display complex recursive, dualistic properties not all of which can be described by standard linguistic logics based on the truth of propositions. As further relevant prior work, I note Volume 8 of the *Handbook of the Philosophy of Science*, edited by Adriaans and van Benthem [3], which includes "Stories of Logic and Information" [4] by van Benthem and Martinez, and "The Physics of Information" by Bais and Farmer [5]. Unfortunately from my perspective, the logic of the former article is an epistemic logic referring to abstractions from states of affairs and whose levels, calculi and dynamics use static, non-relational counters. The authors admit that semantic approaches do not account for the nature of inference, but offer no developed alternative. In general, the logic of quantum information (qbits) is a bivalent, linear logic.

What I ask of a logic of a physics of information is that it capture some of the aspects or form of the evolution of information as a complex physical process and permit inferences about the latter. I therefore start this paper with the briefest possible outline of the novel non-linguistic logic I believe equal to this task. The adjective "non-linguistic" characterizes Logic in Reality. It should not be taken to imply the existence of other non-linguistic logics, and in fact I have never been able to identify any. Mathematical logics are bivalent or multi-valent logics in another form. For readers unfamiliar with it, I first outline my update of this logical system, which I call Logic in Reality (LIR) [6], and its differences from other logics as a first introduction to its application to information.

Note also that many people have refused to accept (1) LIR as a logic; (2) that it has the indicated capability; nor (3) any other proposed well-known logics as alternatives. Upon inspection, all turn out to be variations of modern neo-classical, paraconsistent or paracomplete (intuitionist) logics. Either the law of contradiction *or* the law of the excluded middle (for mathematical entities) is relaxed, but all are propositional, truth-functional logics, without application to real processes.

2. Logic in Reality

2.1. The Fundamental Postulate

LIR is an entirely new kind of non-propositional logic grounded in the fundamental self-dualities and dualities in the nature of energy or its effective quantum field equivalent. It is based on the pioneering extension of logic to real processes of the Franco-Romanian thinker Stéphane Lupasco (1900–1988) [7]. These antagonistic dualities can be formalized as a structural, logical and metaphysical principle of opposition or contradiction instantiated in complex higher level phenomena. The fundamental

postulate of LIR is that all energetic phenomena (all phenomena) alternate between degrees of actualization and of potentialization of themselves and their opposites or contradictions (A and non-A; Axiom of Conditional Contradiction) with which they are associated (Axiom of Functional Association) but without either going to the absolute limits of 0 or 100% (Axiom of Asymptoticity). By phenomena here I in fact mean all complex events, percepts, concepts, processes, theories, *etc.* in which there is a substantial degree of interaction or mutual determination.

At the mid-point of maximum contradiction or interaction between A and non-A, a new third term or entity can emerge at a higher level of reality or complexity (Axiom of the Included Third or Emergence). This axiom was designated by Lupasco as the Principle of Dynamic Opposition (PDO), which is operative in the dynamic structure of the non-separable and inconsistent aspects of complex entities, processes and events at biological, cognitive and social levels of reality.

2.2. The Structure of LIR. Semantics and Calculus

The LIR logical system thus has a formal part—axioms, semantics and calculus; an interpreted part—a metaphysics and a categorial ontology; and a two-level framework for analysis relating levels of reality and levels of explanation. Regarding its semantics, in classical logic, the function of a standard semantics is to ensure truth preservation as a basis for the validity of the logical reasoning. In the semantics of LIR, however, sentences do not *look like* those of a classical logic, and its inferential patterns are different. The semantics of LIR are non-truth-functional in the sense that their elements are not propositions at all, and the concept of truth-functionality (defined as valuations based on homeomorphisms (mappings) between formulas and an algebra of truth functions defined on a given set of values, 0 or 1 in binary logic, several values in many-valued logics) should not be applied. The major aspect of the LIR "dynamic" semantics is to give a sense of the dynamic state of the event, phenomenon, judgment, *etc*. whereby the event is "on the way," more or less as the case may be, between its actualization and the potentialization of its contradiction.

The major consequence of shifting to logical elements that are non-linguistic, defined by the axioms of LIR, is that the dynamic, oppositional relation between two elements will always be expressed by implication, $\supset$. Thus, for any element **e**, I write, where **e** actually implies non-**e** potential, $\mathbf{e}_{A} \supset \overline{\mathbf{e}}_{P}$. I use the bar and not $\neg$ to refer to the real element non-**e** rather than the negation of classical logic. In LIR, the connectives of implication, conjunction and disjunction all correspond to real operators on the parameters of real elements. Accordingly, these operators are, also, subject to being actualized, potentialized or in a T-state. They operate not on theoretical states-of-affairs or propositions, considered as the abstract meaning of statements, but events, relations, processes and properties. The calculus of LIR is based on the concatenation of implications of implications, an event calculus unlike any to be found in the literature.

LIR is neither a physics nor a cosmology but a logic that enables stable patterns of inference (in a mode closest to, but not the same as, abduction in the sense of Magnani) to be made, albeit with reference to metavariables that are something like non-standard (non-Kolmogorovian) probabilities in which the (abstract) limits of 0 and 1 are excluded. The values of logical values being probabilistic reflects the fact that for any real process in progress (being partly actualized and partly potentialized), there is a probability but no certainty that what is still potentialized will be actualized.

In LIR, processes are constituted by a series of series, *etc*., of reciprocally determined actualizations and potentializations of entities and their opposites, and emergent states, driven by the overall energy gradient of the universe. Causality, determinism and indeterminism, time and space, parts and wholes, *etc.* receive non-standard interpretations in this theory.

Real entities can be described as encoding significant energy in potential form, as capacity for interaction. Both the actual and potential states of particles at lower levels—atoms, molecules, biopolymers, cells, *etc*.—are functional. The residual potentialities of entities at any level are the carriers of the information necessary for upward causation and emergence at the next higher level. This grounds, in basic physics, the concepts of "auto"-catalysis and "self"-organization in evolution and morphogenesis.

2.3. Implications for Philosophy: Non-Separability

Many philosophical arguments depend on some form of absolute separability of dichotomous terms *via* the importation, explicit or implicit, of abstract principles of binary logic exemplified in the use of standard notions of time, space and causality. LIR discusses philosophical problems and physical situations in dynamical terms that do not require abstract categorial structures that separate aspects of reality. The critical categorial feature of the LIR process ontology is the *non-separability* of opposing phenomena (two theories) or elements of phenomena, e.g., syntax and semantics, types and tokens.

As discussed by Healey [8], a physics treats systems by assigning them energetic states, and non-separability as a physical principle, functioning at not only quantum but also at biological and cognitive levels is related to holism. Holism is the thesis that the whole is more than the sum of the parts, and non-separability can be defined by the statement that the state of the whole is not fully constituted by the states, properties and relations of the parts. These do not provide the complete basis for the whole, and one says in this case that the whole—an object or process with its own set of properties and relations—does not supervene on its parts. Since I am talking about states of systems, I will use Healey's principle of state separability: the state assigned to a compound physical system at any time is supervenient on the states then assigned to its component subsystems (the latter are the basis for the former).

Since the logical values of LIR that define its states are probabilistic, this formulation and its *negation* should apply to them. A further ascription of non-separability to classical processes such as phase change and the propagation of gravitational energy is possible. Healey then makes the following statement: "Non-separability would be a trivial notion if no qualitative intrinsic physical properties were ever assigned at space-time points or in their neighborhoods. But this would require a thorough-going relationism that took not only geometric but all local features to be irreducibly *relational* (emphasis mine)." This is exactly the "relationalist" thesis of LIR, the local features being the energetic states of actualization and potentialization. Quantum entanglement, which has now been demonstrated over macroscopic distances for pairs of photons, is the paradigm example of non-separability, but so can be the relation between pairs of human beings.

Derrida [9] questioned the structure of binary oppositions, and said that his concept of *différance* "invites us to undo the need for balanced equations, to see if each term in an opposition is not after all an accomplice of the other." LIR takes this intuition and provides a new "structure" of oppositions and

reading of "being an accomplice". The "difference" in the famous statement of Bateson, that information is a difference that makes a difference, can be seen as a *différance*, causally efficient with respect to a term, a process or a person.

In LIR, the structure of reality does not depend on any transcendental notion of human experience (Heidegger; the neo-Kantian phenomenology of Petitot). The dynamics of physical processes may be described without reduction. This logic is not that of logical positivism or of Hempel. It is part, rather, of a new *ontological* turn in philosophy [6].

3. Relation of LIR to Other Logics

It is not possible in this brief overview to show in detail the critical relation of Logic in Reality to important kinds of modern logics, and I limit the discussion to the following points:

- Paraconsistent logic (PCL) is a *linguistic, propositional logic* albeit with a non-truth-functional semantics. Despite some early references to real phenomena by Priest [10], an extension to real processes was never made, by Priest or by others. The result is to drastically limit the application of PCL to the real world, e.g., to the qualitative dualistic aspects of information. In one exception, Da Costa and Krause [11] applied PCL to quantum particles and showed that they both *are* and *are not* individuals, or both parts *and* wholes. The semantics of LIR are non-truth-functional in the different sense that their elements are not propositions at all, and the concept of truth-functionality (defined as valuations based on homeomorphisms (mappings) between formulas and an algebra of truth functions defined on a given set of values, (0 or 1 in binary logic, several values in many-valued logics) should not be applied.
- Quantum logics offer a basis for discussing the dual nature of information in our interpretation. Their elements are similar to non-standard probabilities in that the laws of commutation or distribution are not followed. Aerts' quantum formalism [12] can be applied to complex macroscopic phenomena, including the emergence of biological form and human cognition. Sklar wrote in 1992 [13] that quantum logics were inadequate to resolve quantum paradoxes related to the superposition of states. LIR provides a natural interpretation for quantum superposition in terms of semi-actual and semi-potential states, eliminating the philosophical problems associated with the modified Copenhagen and many-worlds interpretations of quantum mechanics.
- Abduction, defined as reasoning to the best explanation and abductive logic, like paraconsistent logics are closer "in spirit" to LIR, but they are essentially restricted to a place on a linguistic logical map [14], following the rules of propositional, truth-functional logics. The degrees of complexity that are not captured by abductive logic, and some of the facts about real-life abduction that in most theories are suppressed, ignored or idealized can be described by LIR.

4. Information in the Universe: From Philosophy to Physics

As I intimated, it is impossible to discuss any physics of information, classical or quantum, without first establishing some assumptions, if not agreement, about the physical properties of the universe in which informational phenomena unfold. From the beginning, we know that there can be no final position on the relationship due simply to our ignorance of most of the questions about the origin of the

universe. That many of these questions are often considered solely "philosophical" only suggests that absolute classical divisions between philosophy, physics and metaphysics may no longer be justified.

4.1. Where it All Started; One or Many

Since antiquity, human beings have asked whether the universe is single or multiple, ultimately a unity—a "One"—or a diversity. To this intuition of a universe that is both a unity and a duality we may add another; namely, that what there is has emerged from something else. The world, what we can say exists in some manner, is "something" but what it has emerged from may be "nothing." Far from being empty superstition, this statement, together with insights from modern physics, enables inferences to be made that are relevant to the properties and nature of complex real processes, information and life.

The related question of "why is there anything at all?" has never been satisfactorily answered. Science has not yet provided an adequate meaning for such concepts or the implications of "from" which remain the purview of religion and tradition. Another question, as to whether geometry (position, form) or matter (energy) is more fundamental in the universe is still debated today, in the terms of information and quantum physics and cosmology.

4.2. From Quantum Physics to Information Today

The advent of quantum physics, together with General Relativity Theory, has enabled insight into the properties of what *is*, in three domains: the quantum vacuum and its apparent content of zero-point energy and virtual particles; the quantum particle-fields that are the energetic ground of "ordinary existence"; and the thermodynamic world of matter, energy and change that we inhabit. The nature, properties and modes of change or evolution of these domains nevertheless remain subjects of debate.

Information today is somehow associated with or constitutive of what *is* but has proven notoriously difficult to characterize, due to its multiple aspects: it has both physical and apparently non-physical components. It can be described by algorithms but only in part. Information is both meaningful and a carrier of meaning. Information can be viewed as well-defined data [15], or processes [16], referring to what is not or not yet "there" [17] as well as in many other ways. As noted by the philosopher of information, Kun Wu, to approach correctly a concept considered part of standard science—information—we must reexamine the entire philosophical structure of transmitted human knowledge. Strikingly, both Adriaans and Wu [18] independently suggest that a major impact of the philosophy of information is on philosophy itself!

Among the further principles necessary to move towards an understanding of the universe, the principle of self-duality (PSD) seems to be one of those required [19]. The "objects" that, in my interpretation, can be described as instantiating this category-theoretic principle are not only quantum particles and quantum fields but physical theories themselves, as discussed by Majid [20].

I consider that LIR provides, among other things, a theory of reality in terms of the intrinsic fundamental duality of energy; namely, that it instantiates both intensity and extensity. I suggest that the duality of dynamic opposition at macroscopic levels reflects and is the expression of the self-duality of quantum and gravitational fields at the most basic level of existence.

The other defining development of 20th century science has been the availability of the digital computer, capable of processing the enormous amounts of data necessary to characterize the properties of quantum particles and fields. It was thus natural to take concepts from computational science and apply them to the origin of information. The problematics of defining the concept of information have been most clearly delineated by Capurro [21] and Hofkirchner [22] and most recently again by Diaz Nafria and Zimmermann in their paper [23] on the "timing" of the emergence of energy and information from what used to be called the "pleroma."

5. The Physics of Information

If the premises of Logic in Reality are accepted, there is a series of corollaries that change the conclusions of all of the common theories of the physics of information. Here, I can only present these conclusions without the extensive argument that would be desirable. The reader is then asked to consider these conclusions as points for further study and to judge them the extent that they are, at least, internally consistent. The grounding of information in physics, with or without a human-centered perspective, is a major subject of debate. Problems persist in how fundamental physical theories of quantum mechanics, quantum gravity, and cosmology such as the above, apply to information. I propose that self-dualities of the universe at the most fundamental level are reflected at higher levels as the familiar non-separable energetic dualities: positive and negative charge; north and south magnetic poles; "up" and "down" spin of some quantum particles (fermions). Non-separability means that one entity never occurs without the other, regardless of the distance between them. If there is a net negative charge on clouds, for example, there is a net positive charge on the Earth's surface.

On the other hand, any discussion of the physics of information cannot neglect the growing field of quantum information and its physics. Let us then look more closely at the characteristics of classical information, quantum information and the proposals emerging from the LIR perspective.

5.1. Critique of Standard Information Theory

I therefore turn to the critique of standard of information theory that emerges from the principles of LIR. The following outline reflects my initial views of the different common positions, starting with "It-from-Bit":

- *It-from-Bit*
  (1) Immaterial Bits are fundamental and constitute information.
  (2) They have the properties of binary arithmetic digits.
  (3) They support the concept of a digital, computational universe that processes information to produce Its (things).

- *Bit-from-It*
  (1) Its are fundamental.
  (2) They have the properties of energy, better energetic processes, including information and point toward analog, natural computation.
  (3) Bits as information accompany and/or are an integral part of Its and emergent phenomena. They enter into *a posteriori* descriptions of digital computation.

Contra Wheeler, Barbour [24] made a convincing argument for the primacy of things, but left open the possibility that nature is fundamentally digital and continuity an illusion. My theory, outlined below, strongly supports his first position, with the proviso that "things" are primarily understood as dynamic (energetic) processes. However, it offers a significant alternative to the second, based on the self-dualities and dualities of quantum physics which ground LIR and the functional role of the relational properties derived from them at higher levels of reality. As Collier has put it [25], each interaction (1) in quantum mechanics involves a sort of choice (2), and the choice can be represented in terms of bits (3). But this does not prove that the interaction (1) is constituted by bits (3), still less that non-quantum interactions and all forms of information are so constituted. (As discussed by McGinn [26], taking *any* realist position or ontological option about such "things" as fields and particles involves difficulties which I will not attempt to address here.).

- *It-and-Bit*

Thus, going beyond the simple dichotomy, I will discuss some additional positions, which I refer to as It-*and*-Bit:

(1) Energy and information are the most fundamental entities in the universe, but neither is ontologically prior to the other.

(2) Information and energy emerge together from, or are different aspects of, an as yet undefined primordial substrate more fundamental than either.

In my synthesis of these positions, at some level of reality, I suggest that energy is more fundamental than information, and information emerges from but is always functionally associated with it. In the macroscopic world, energy and information, as well as continuity and discontinuity, are non-separable partners, whose evolution follows the "saw-tooth" pattern (skewed sinusoidal) of alternating predominance of actuality and potentiality described by LIR.

In the thermodynamic world, energetic processes are always accompanied by or have the aspect of meaningful information which evolves further with those processes. As was shown by Kolmogorov [27], information can be defined as an operator, constituted by vector differences in energy levels, which changes the distribution of probabilities in a given set of energetic processes, constituted by both their potential as well as actual properties. The former provide the basis for the emergence of new, more complex informational entities. Such "Bits" thus emerge from energy and remain in a dynamic relation with it, a position that I have called It-*and*-Bit.

Diaz Nafria and Zimmermann [23] suggest that both matter-energy and information are two different, associated aspects of the same underlying and still unknown primordial structure of the world. The best picture is that they emerge together from this substrate: the concepts of energy and information are always present in fundamental physics. A major objection to Bit-from-It position, that energy is primitive is that it appears meaningless and its ability to function as a source of meaning difficult to establish. In a computational universe digital information as Bits is fundamental and the "presence" of information would appear to provide a ground of meaning, but no mechanism for its emergence is stated, as for example in Lloyd [28]. Diaz Nafria and Zimmermann therefore opt for an "onto-epistemic" stance. The existence of an onto-epistemology can be seen as a consequence of the absence, according to LIR, of any absolute separation between ontology and epistemology. The ontological ground of information and thus of the meaning that emerges from it, both ontologically and

epistemologically, is energy, an energy that is in some sense the prime expression for (or of) the *potentiality of the system.* As I discuss in [6], data are relational entities, and information, given its relational qualities, always entails meaning.

My critique of the Diaz Nafria–Zimmermann program is that it retains a separation of energy and information as standard categories of irreducibly different phenomena. My final variant of It-and-Bit takes into account that the information of processes and thermodynamic change does not inhere in isolated quantum particles. These must, in my view, be considered as energy, with a structure, but, as in the case of the timeless, pre-thermodynamic quantum vacuum, there is no information associated with their interactions other than the interactions themselves, no *meaningful* data.

I agree with Diaz Nafria and Zimmermann that their "substrate" (systems) is constituted by energy and not an abstraction from energy as in the computational case of It-from-Bit. In my preferred picture, information and energy are the components of all higher level processes, but in contrast to the Diaz Nafria–Zimmermann view, information and energy are not and do not have to be absolutely the same or different, nor emerge in tandem. Because energy is primitive (Bit-from-It), it is the dualistic, oppositional properties of energy that determine the properties of information. In LIR, which describes such a state of affairs, they are the same *and* different, ontologically and also epistemologically, as the mind moves between focus on one or the other aspect to the partial, temporary exclusion of the other.

5.2. Quantum Information Theory

The existence of quantum information corresponding to a quantum entropy does not change my conclusions regarding non-quantum information. As noted by Wilde [29], quantum information has good meaning only in the quantum world: "quantum information applies to the quantum world, to the physical information that is contained in the state of a quantum system". Nevertheless, I am grateful to an anonymous reviewer for suggesting that my discussion should explicitly deal with this rapidly developing field [30].

The quantum world differs from our everyday world in many ways. One major aspect is that any processes which occur are not subject to the laws of thermodynamics, such as the mutual annihilation of particles by their anti-particles. There is no thermodynamic change; quantum objects are timeless. It is not surprising, then, that the nature of quantum information and classical information and their corresponding physics and logics also differ. For example, the unit of quantum information is the qubit (or qbit) which, unlike the discrete bits which constitute classical information, can vary continuously. I therefore wish to re-emphasize that Logic in Reality is not designed and does not apply to the quantum domain.

The theory I am trying to develop here refers to the world, at a macroscopic level which is not describable by classical logic or quantum logic, since although it ultimately depends on the quantum properties of matter-energy, additional principles apply. My theory is thus not in conflict with a theory that *some* information is quantized (quantum physics applies) but not *all* information (non-algorithmic), since some is constituted neither by bits nor qbits and can only be qualitatively described.

5.3. The Causal-Compositional Concept of Information

As I stated above in Section 4.2, information has dual or multiple aspects. The Causal-Compositional concept of information, developed by Luhn [31] enables the discussion of these aspects without conflation by including concepts outlined above of Logic in Reality. In this approach, information is the ensemble of (a) a system in its actual state and (b) its capacity for future states, that is, potential ones, including emergent ones. The abstract level of this description includes the different algorithms that can be written, as noted, in terms of bits for classical Shannon information and qbits for quantum information. But the Causal-Compositional-Concept (CCC) also recognizes the potential of a system for non-algorithmic superpositions and the creation of new rules or causal laws for the evolution of information as a process.

The "physics" of the CCC, like that of LIR, does not require going outside the standard laws of physics. It requires that proper emphasis be given to the informational nature of the symmetry-breaking that occurred at the "start" of the universe and the resulting dualities referred to in the discussion of LIR. The implications of CCC for the ethical dimension are discussed below.

6. Neo-Computationalist Approaches: Natural Computation

My major difficulty with computational theories is that they appear to reflect the ontological properties of information but from the LIR standpoint the necessary foundation in energy is absent, necessary for a physics of states [8]. A group of other recent theories present a view of a universe in which computation is a "natural" process. The form of computationalism developed by Dodig-Crnkovic, informational- or info-computationalism [32], reflects Floridi's view of the universe as an energetic, informational structure [15], in which natural computation governs the dynamics of information. The resulting view, although largely epistemological, has nevertheless a more visible relation to the dialectics of the ontologically oriented Logic in Reality. Together, they constitute a kind of physics in the broad sense of the term.

6.1. Info-Computationalism

As stated by Dodig-Crnkovic [33]: "Info-computationalism is a view according to which the physical universe on a fundamental level can be understood as an informational structure whose dynamics is a computational process. Matter/energy in this model is replaced by information/computation; matter (structure) corresponds to information while the dynamics—constant changes in the informational structure—are computational processes".

I note in this connection the application of computational principles to modeling the universe by Zenil [34]. In his epistemic stance, he states that he believes that everything is computable although not that the universe is necessarily computable. This is his preferred position, however, because he considers it epistemologically the most fruitful and powerful idea in science. The driving force in the universe is that it computes and everything else can be seen either as the result of or as a constraint to computation. In the LIR interpretation, of course, a constraint is not an epistemic abstraction, but an active causal structure, as in the biosemiotics of Kaufmann and Logan [35]. It is thus necessary to

distinguish carefully such approaches from that of a computational universe which assert that the universe is *actually* a digital, Turing-like computer that in fact computes using some digital code.

It is significant that Dodig-Crnkovic herself has moved away from a pan-computationalist position [36]. While remaining agnostic about the question of fundamentality, Dodig-Crnkovic replaces the emphasis where it belongs; namely on understanding *that part* of natural phenomena which may be subsumed under the concept of computation. It is to these ideas that the term natural computation refers, that is, information processing by natural systems. In this view, computationalism is not the world; it is a modeling framework that is acceptable within certain domains and does not exhaust our possibilities to relate to the world.

Within this dual-aspect framework, matter may be viewed as a structure (information), in a permanent process of flow (computation). Mind is the process, which is computational, both in its discrete and in its analog view. This work thus presents its own synthesis of two paradigms within contemporary philosophy—computationalism and informationalism—into a new dual-aspect info-computationalist framework.

6.2. The Role of Logic in Reality

Vis à vis this synthesis, Logic in Reality has both a complementary and a supplementary role. LIR states, as we have seen, that relations are dynamic relations of the energetic properties of the entities or processes under discussion. The phrase "the dynamics of information" in the LIR interpretation points to how the properties and elements of information, as a dynamic process in and of itself, change in response to imposed forces. The meaning of the dualism above might be seen in the analogy with wave-particle or matter-energy dualisms in physics, at the core of Logic in Reality. The dualism itself does not mean that the phenomena are separated, and exclude each other; on the contrary, they are mutually determining, constraining and completely indissoluble. In that sense, one may speak of dual-aspect monism. Thus freed from what I consider the burden of the dogma of the computational universe, computationalism as natural computation appears as an acceptable dialectic "partner" of LIR.

Thus LIR can accept that we are *already* at this point in the part of the universe described by a computational metaphysics. In this framework, information and computation may indeed mutually define one another. In ICON, only, Dodig-Crnkovic has not taken into account the universe as a whole in which non-computational processes may be primary or at least mutually defining at a *more* fundamental level. Mutually defining in LIR is an ontological as well as an epistemological statement, involving the exchange of energy between elements according to the Principle of Dynamic Opposition. Under these circumstances, the kind of Lupascian dialectical interaction between somewhat opposing theories, opposing certainly in their different emphasis on aspects of existence and information, that are better seen as non-computational can take place.

It is necessary to repeat, at this point, that simple process phenomena can be described by standard bivalent or multi-valent logics. The statement that the logic of/in reality reduces to standard binary logic in the case of such phenomena is not empty. It will be correct in all cases in which the interaction between two entities disappears, as when two individuals refuse a dialog, or the interaction never existed, as in the terms of classical dilemmas and paradoxes.

6.3. LIR and the Ethical Dimension

Logic in Reality describes the logical, non-metaphorical content of an antagonistic interaction between the individual and the world, as on-going informational processes in which both actors change and each, alternately, is the predominant cause of further change. This view is an extension of the concept of Floridi's Informational Ethics [37] which I have called Ethical Information [38]. The origin of *non-ethical* behavior can be accommodated in this approach as a consequence of the operation of the fundamental duality of the world at the genetic, individual organism and social levels.

The ontological viewpoint of LIR described in this paper thus contrasts with the predominantly epistemological conceptions of information ethics of Floridi, Dodig-Crnkovic and Zenil. It supports Luhn's view, in his Causal-Computational theory of Information [39], that it is impossible to separate human behavior from the informational processes emerging from their self-referential activities that increase the number of new complex states of the universe. Ethical behavior, then, is behavior that facilitates such emergence, and the drive toward such behavior must in this view have the same grounding in physics as the logic that describes it, that is, LIR and the Principle of Dynamic Opposition (Section 2 above).

Without attempting here to make an exhaustive discussion of ethical issues related to information and its foundations, I note only that Logic in Reality is not topic-neutral as are standard logics, and can address the evolution of qualitative phenomena, permitting a seamless transition between the physics and the ethics of information.

7. Summary and Conclusions

In this paper I have brought together both an interpretation of (1) physical processes in terms of the fundamental self-duality and duality of the matter-energy that constitute them and of (2) the reflection of these properties at higher levels of reality in terms of a dynamic logic that describes their evolution. Logic in Reality (LIR) enables a non-reductionist onto-epistemological picture of information or better informational processes, grounded in physics that answers many of the outstanding problems of previous theories, especially those derived from simple computational models. The supplementary role of LIR *vs.* more complex informational-computational concepts is suggested.

In the framework for analysis of Logic in Reality (LIR), in answer to the questions of ontological priority, my major conclusions are that (1) energy-matter is ontologically prior to, that is, more fundamental than information as digital bits and (2) the properties of that matter-energy are determining for the properties of information. I have contrasted my views with computational models of the universe in which one assumption is that since information is *present* throughout nature it is *more primitive* than energy in nature. I have considered the alternative that matter-energy and information emerge together from some more fundamental underlying but at this time unknown substrate. This picture (It-and-Bit) is conceivable, but it is less parsimonious than my preferred position. It requires a categorial separability between energy and information that is justified essentially on formal rather than physical grounds.

Whether the "unknown substrate" can be equated with the quantum vacuum is a question that I do not believe can yet be answered. My position is that the quantum vacuum does embody energy, the

so-called zero-point energy, constituted by truly random quantum fluctuations. However, as these fluctuations are indistinguishable and do not in and of themselves undergo thermodynamic change, information is absent and only becomes associated with energy at the particle-field level.

I have argued that a picture of the physical universe as fundamentally either continuous or discontinuous can be usefully replaced by one in which both continuity and discontinuity are jointly and dynamically instantiated. Thus, LIR provides a logical-ontological supplement to epistemological theories of natural computation [32], informational-computationalism, which does *not* require that information is ontologically primitive.

Finally, regarding ethical issues related to information and its foundations, I have noted only that Logic in Reality is not topic-neutral as are standard logics. In contrast to standard logics, LIR is normative in the sense the normativity of LIR is engendered not only by its axioms, but also by its categorial ontological features that are a consequence of the axioms.

I therefore claim that, as a consequence of the principle of non-separability applied to human individuals and groups, it provides support to the development of an informational ethics and can address the evolution of qualitative phenomena, permitting a seamless transition between the physics and the ethics of information. Logic in Reality is, accordingly, my proposed candidate as a logic of the physics of complex forms of information.

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Conflicts of Interest

The author declares no conflict of interest.

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