Chapter

LAWS OF SCIENCE AND LAWS OF NATURE IN AN EVOLUTIONARY KNOWLEDGE ECOLOGY

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ABSTRACT

This chapter presents an evolutionary ecological approach in which human knowledge is studied as the ecology of interacting data-information-knowledge systems developing in time as a consequence of incessant learning from interactions with the environment on a variety of levels of organization. Within the framework of evolving knowledge ecology, we address Laws of Nature and how they relate to Laws of Science with examples of taxonomies as open-ended relation-based Laws of Science. Dynamical processes in the ecology of knowledge are observed in real/actual time as well as in evolutionary time. The creative nature of sciences is found in its generative principles, mutual interactions between sciences and in their interactions with other knowledge fields. As an illustration of an interdisciplinary knowledge production approach, an info-computational framework is presented with the unconventional notion of computation as natural information processing.

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INTRODUCTION

Science stands as a pillar supporting our highly technological civilization, providing our best present knowledge about hundreds of specific knowledge areas within the domains of Life and Health Sciences; Exact Sciences and Engineering; Natural and Environmental Sciences and Social Sciences and the Humanities.

Scientific fields developed for centuries in isolation, have resulted in ever increasing specialization and division into isolated islands of knowledge. However, recent developments of ICT with the internet connecting researchers, providing quick access and exchange of information has lead to the new mutual awareness of the research fields and to an increase of interdisciplinarity and multidisciplinarity. Concurrently, a number of complex problems (such as global warming and environmental problems) need urgent solutions that can only be found in transdisciplinary problem solving and team work across and beyond disciplinary borders. Real-world problems necessitate the involvement of a variety of stakeholders, and thus, the question arises of connecting different heterogeneous kinds of knowledge into a meaningful and harmoniously orchestrated whole – ecology of knowledge. Typically, such complex problems are not "solved," but "controlled," which means monitoring and the awareness of ever changing contexts and mutual relationships within the systems and their contexts – thus there is a time dimension. We also discuss the relationship between knowledge and "unknowable" and how unknowable can be tackled by a collaborative effort of research within a variety of domains belonging to the common ecology of knowledge.

SCIENCES AND LAWS

Science is typically described as a *unique notion* in encyclopedias and dictionaries, usually as a body of knowledge and related activities with an emphasis on systematic study using specific, scientific methods. However, in practice, “science” contains a multifaceted network of notions that stand for a variety of related human activities and their results, connected in a network of networks. Figure 1 gives an idea about the complexity of the term “science,” suggesting that we talk about the family of related notions. Some of them refer to scientific knowledge, some to scientific disciplines or professions and yet others to specific scientific theories and scientists. There is an ecology of related networked processes that interact, develop and co-adapt and we should keep this complexity in mind when we talk about the “nature of science.”

There is also a question of what would be good to have under the umbrella of “science” and how sharp demarcation is necessary to non-scientific knowledge fields that has been widely debated, notably in the work of Karl Popper, (Popper 1963, 1959, 1999, 1972, 1984). The recent transdisciplinary work on projects of acute importance to the society that must involve various stakeholders with practical non-scientific domain knowledge, leads to more inclusive approaches.

Science is closely connected to knowing and reality. Branches of science can be systematized according to the scale and fundamentality into Formal-, Physical-, Life-, Social- and Earth & Space Sciences, (Wikipedia authors 2019a). During its history, science has developed into tens of thousands of disciplines and specialties (Wikipedia authors 2019b).

Consequently, as discussed in Dodig-Crnkovic and Schroeder (2018a), there is an expressed need for connecting disparate islands of deep specialist knowledge into a new common world view of an emerging contemporary Natural Philosophy:

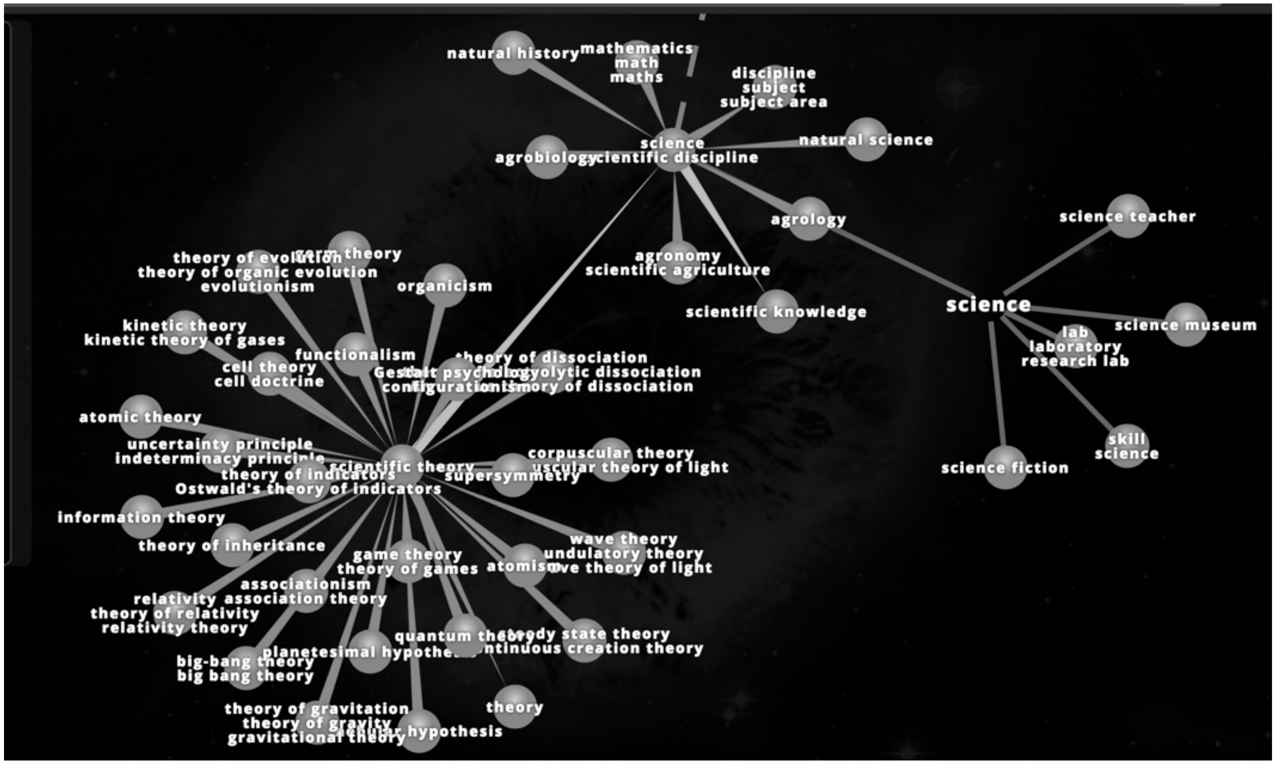

Figure 1. Visual thesaurus Visuwords, term “science,” https://visuwords.com/science.

> “to help establish a new unity in diversity of human knowledge, which would include both “Wissen” (i.e., “Wissenschaft”) and “scīre” (i.e., “science”). As is known, “Wissenshaft” (the pursuit of knowledge, learning, and scholarship) is a broader concept of knowledge than “science”, as it involves all kinds of knowledge, including philosophy, and not exclusively knowledge in the form of directly testable explanations and predictions. The broader notion of scholarship incorporates an understanding and articulation of the role of the learner and the process of the growth of knowledge and its development, rather than only the final product and its verification and validation. In other words, it is a form of knowledge that is inclusive of both short-term and long-term perspectives; it is local and global, critical and hypothetical (speculative), breaking new ground. This new synthesis or rather re-integration of knowledge is expected to resonate with basic human value systems, including cultural values.”

The question that remains is to address is how to establish this new ecology of knowledge where different branches and types of knowledge can mutually and constructively inform each other and contribute to the common development. The recent special issue of the journal Philosophies is dedicated to the establishment of new Natural Philosophy, where not only sciences and philosophies, but other types of scholarships are invited to contribute to the ecology of knowledge, theoretical as well as practical (Dodig-Crnkovic and Schroeder 2018a). Unlike the classical Natural Philosophy of Newton and Leibniz, which constituted a foundation of natural sciences with heavy emphasis on physics, new Natural Philosophy has a much wider scope of knowledge, including recognition of values and ethics and recognizing arts as contributing to the expression of knowledge.

A part of the question about the nature of science, is the question of *the goals of science*. The classical view is presented in Friedland and Yamauchi (2011):

> “The goal of natural science is to identify the laws that govern nature, like Newton’s law. Nature works according to these laws, although they are always open to falsification—e.g., Newton’s law does not apply to quantum physics. On the other hand, social science seeks to understand rules that are normatively maintained.”

Similarly, Anderson and Brady (van Holten 2017) maintain that the goal of science is the understanding of *"the deepest physical nature of the world in which we live."* This deepest physical nature is assumed to be governed by the Laws of Nature. Philosophers distinguish *Laws of Nature* from *Scientific Laws or Laws of Science* that are their approximations. Both of them are separate from *Natural Laws* expressed in legal or ethical theories, based on the assumption that moral standards are derived from the nature of human beings.

LAWS OF NATURE

> " ... there is at least one philosophic problem in which all thinking men are interested. It is the problem of cosmology: the problem of understanding the world including ourselves, and our knowledge, as part of the world." (Popper 1959) p. XVIII.

There are two basic axioms presupposed by the scientific method: the existence of objective reality (*realism*) and the existence of observable stable Laws of Nature.

The idea of a Law of Nature was developed in the seventeenth century in the work of Descartes. In 1644, in the Principia Philosophiae (Descartes 1644) he proposed three physical laws governing nature, originating in a divine mind ruling the universe. It was Newton (Newton 1687) who first left out the theological connotations of the concept of the Law of Nature and focused on the question *how things are* instead of *why they are*. Later on Mill (Mill 1882) formulated Laws of Nature as the smallest set of simple assumptions/propositions from which all the regularities of the universe might be deductively derived.

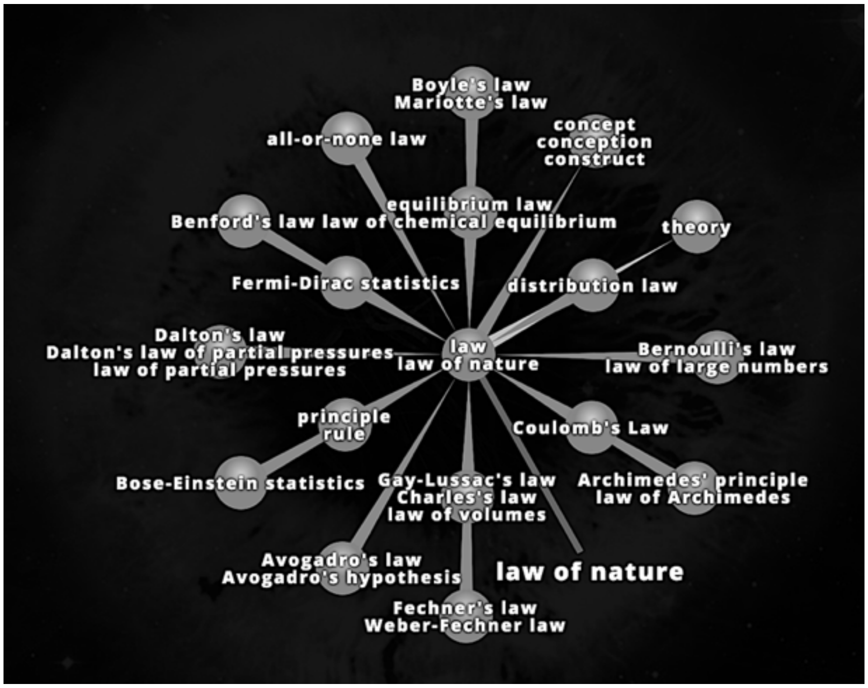

Figure 2. Visuwords representation of the term "law of nature"
https://visuwords.com/law%20of%20nature.

In a recent work, Johansson attributed two functions to fundamental natural laws: they provide implicit definitions of theoretical concepts, and they enable derivation of empirical regularities (Johansson 2016). Contemporary pragmatic proposals are suggesting that laws are simply explanatory tools. A special case is that Laws of Nature are basic principles on which scientific theories are built. Current debate by Ott and Patton (Ott and Patton 2018) presents a number of views ranging from *Best System* (that laws are generalizations that best systematize knowledge), *Perspectival* (nomic necessity as the resilience of lawful scientific knowledge claims across different scientific perspectives), *Kantian* (our ability of understanding is the basic source of lawfulness of nature, through the a priori categories that constitute principles for our experience of nature), to (causal) *Powers- or Mechanisms*-based accounts — as the current ideas of the of Laws of Nature.

According to the Internet Encyclopedia of Philosophy, (Swartz 2019):

> "There are two competing theories of Laws of Nature. On one account, in the Regularity Theory, Laws of Nature are statements of the uniformities or regularities in the world; they are mere descriptions of the way the world is. On the other account, in the Necessitarian Theory, Laws of Nature are the "principles" which govern the natural phenomena of the world. That is, the natural world "obeys" the Laws of Nature. This seemingly innocuous difference marks one of the most profound gulfs within contemporary philosophy, and has quite unexpected, and wide-ranging implications."

Even though the Regulatory and Necessitarian theories focus on different aspects of the Laws of Nature, they are not mutually exclusive. It is perfectly plausible that laws that govern nature produce regular structures. In our argument for taxonomies as natural laws, we will rely on the regularity interpretation, as taxonomies stand for regularities in the world, and we can stay agnostic regarding the cause of regularities.

Simplicity of Mechanisms Governing (Fundamental) Physics and the Complexity of Mechanisms Governing Biology

One interesting difference has been pointed out (Ott and Patton 2018) and (Massimi and Breitenbach 2017) between generative laws in Physics and generative laws of Biology[1] regarding the lawfulness of nature, its systematicity, nomic necessity and the metaphysics. While fundamental Physics has simple generative laws, and even an expectation that the "Theory of Everything" (from which all of physics could be derived) is simple, nature itself is complex. Complexity of nature is especially visible in living systems that are the subject of Biology.

The difference is striking between closed, isolated systems in the state of equilibrium, with conservation of energy, typically studied in physics, and the behavior of living organisms resulting from the interactions within the

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[1] We should mention that there are three descriptive Laws of Biology (1. All living organisms obey the laws of Thermodynamics; 2. All living organisms consist of membrane-encased cells; 3. All living organisms arose in an evolutionary process), but they are insufficient to derive structures and behaviors of biological systems.

open systems of many components that evolve into complex states on the edge of chaos. (Bak 1996). Theoretical biology models levels of organization in living systems, from molecular (which encompasses physics and chemistry) to cellular with emerging biological laws with several levels of organization (tissues, organs up to the level of organism). The research field of origins of life explores the self-organization of physical-chemical matter and its transition into a highly organized biological organism.

Stephan Hawking declared in January 2000 that "the next century will be the century of complexity" in an interview with San Jose Mercury News. Indeed, complexity is the defining feature of our century (Rzevski 2015). The more complex system under investigation, is with less focus on the role of "Laws of Nature" in explaining its structures and behaviors. As illustrated in Figure 3, the use of the concept "Laws of Nature" is in decline in books where it is typically mentioned in the philosophy of science. We see it rising with Descartes and falling today under the frequency of the period before Descartes.

Figure 3. Usage of the term "Laws of Nature" from Google Books Ngram Viewer https://books.google.com/ngrams.

LAWS OF SCIENCE - SCIENTIFIC LAWS

There is an important distinction between the Laws of Nature and the Laws of Science, the latter being seen as an approximation to the Laws of Nature.

Regarding their form, scientific laws can be equational, implicational, descriptive, operational and representational. Taxonomies are very important and an often forgotten form of scientific laws, the best examples being biological taxonomy of Linnaeus that is a law of biology, Mendeleev's periodic table as a law of chemistry and the Standard Model's taxonomy of elementary particles. They are scientific laws in the same way as Newton's law or Maxwell's equations are laws of physics (Burgin and Dodig-Crnkovic 2017) (Burgin and Dodig-Crnkovic 2019) (Burgin and Dodig-Crnkovic 2019). What makes taxonomies especially interesting in contemporary science is their open-endedness and their form of network representation that can be used to represent multidisciplinary, ecological as well as evolutionary aspects of knowledge.

Historically, the focus on the eternal Laws of Nature, reflecting simplicity and perfection, has been shifting towards complexity, evolution and other forms of dynamic phenomena. To the difference from the classical picture of *passive, inert* matter that obeys the laws imposed from the outside, modern sciences reveal *active aspects of matter* capable of complex self-organization.

Newton's absolute space, time and matter turned out to be *related to the system of reference*. At different spatial and temporal scales, under microcosmic and macrocosmic conditions, Newton's laws must be modified. With the extensions of the domains of study, probability, indeterminacy and undecidability have become concepts commonly used in scientific accounts.

Development of sciences since the time of Descartes, Newton and Leibnitz, led the exploration of nature and development of logic and other tools of scientific discovery to formulations of a variety of new models, theories and frameworks, technologies and techniques which changed radically the original understanding of nature as simple, law-governed, eternal and perfect.

Regarding simplicity, we can observe that Wikipedia gives a list of 170 scientific laws named after people, and there are of course many more scientific laws. So we can conclude that the picture of the perfect, simple, monolithic, eternally given, deterministic, decidable universe governed by Laws of Nature that are possible for humans to comprehend is being replaced by the more complex view.

Change and evolution, as well as indeterminacy and undecidability are not only real but also essential for our understanding of nature. Contemporary sciences thus bring into the picture *sources of the unknowable* such as uncertainties, indeterminism and probabilistic processes, undecidability including paradoxes, incompleteness, and emergence (White and Banzhaf 2019).

Scientific explanatory models today are using all three elements of classical Greek cosmogony: *cosmos* (order), *chaos* (formlessness, amorphousness, emptiness, space), and *logos* (discourse, reason) – in a common account of the existing world/universe/nature.

We should also mention the fundamental role of logic. Scientific accounts, for centuries, have been based on classical logic. That is radically changing, as a variety of non-classical logics have developed, especially in the field of philosophical logic and computing, such as *many-valued logic*, *modal logic, paraconsistent logic*, *quantum logic* and more. Specifically targeting the whole of nature, both its entities/structures and events/processes and abstract, formal logical analysis, constructive synthetic "logic in reality" (Brenner 2008), presents a view of the structure and dynamics of reality - its philosophy, metaphysics and science.

Model View of Sciences. The Fragmentarity of Domain Specific Knowledge

According to the traditional covering law model (the Hempel–Oppenheim model, or the Popper–Hempel model), scientific explanation is deduced from the observed starting conditions with the help of general laws and logico-mathematical apparatus. Nancy Cartwright (Cartwright 1983) argued against this idealized view of scientific explanation and laws of science. For Cartwright, the adequate account of explanation in science is not the covering law, but the 'simulacrum'.

> "The fundamental laws of physics do not govern objects in the real world, but rather only objects in models. Consequently, the proper account of explanation in science is the 'simulacrum' view."

Moreover, apart from sciences being about models, they do not cover all possible knowledge domains. Cartwright (Cartwright 1999) argues that "we live in dappled world, it seems, characterized by a patchwork of laws." Gregory Chaitin (Dodig-Crnkovic 2007b) describes the situation with sciences as consisting of islands of knowledge divided by the ocean of unknown. Even Peterson (Peterson 1990) elaborates on the picture of the mathematical islands of truth. Recently, Chaitin (Chaitin 2019) addresses the issue of *unknowable* hinting at some of the content of the "ocean of unknown" such as probability theory, metamathematics, algorithmic information theory, metabiology, from the point of view of theory of science/philosophy of science. On the other hand, he addresses research on cold fusion and dark matter from the point of view of the sociology of science, illustrating the role of scientific organization and systemic support in the choice of subject and possibility of research, for the understanding of nature and its laws.

Stanley Salthe (Salthe 2019) comments on the limits of knowledge coming from several sources: In *Logic*, it is shown by Gödel's incompleteness theorems. A more encompassing system is needed to demonstrate the consistency of a system of axioms. This invites use of the subsumptive hierarchy; {{ }} In *Computation*, Church-Turing's undecidability shows the limits of Mechanicism. *Measurement problem demonstrated* Heisenberg uncertainty relations. Salthe proposes the subsumptive hierarchy: { logic → { mechanicism projected onto material world → { contingency in material world }}}.

TIME AND THE EVOLUTIONARY PARADIGM OF NATURE/UNIVERSE

In contrast to the Platonic picture of the *perfect universe* of eternal and unchangeable ideas or forms governed by mathematical laws, of which our actual world is only an imperfect realization of lesser interest for philosophers of nature. Modern sciences focus exactly on the dynamic view of the actual universe as *unfinished, always evolving* and in a process of restructuring. Deacon (2011) pictures nature as *incomplete,* consisting of open interacting thermodynamic systems far from equilibrium that constitute a basis for the emergence and evolution of biological organisms with cognitive abilities, and thus allowing mind to emerge from matter. Unlike Plato's proposal of *mind over matter*, Deacon argues for the *mind from matter, in matter*.

The physical universe as a whole has its history and evolution. According to the current Big Bang account, the universe was born in a gigantic explosion from singularity about 15 billion years ago. It evolved from that singularity through several stages of the development in which all physical structures have been formed, together with fundamental physical forces.

There is an idea that all physical forces evolved from the one fundamental force that existed in the beginning. Grand unified theories (GUT) of physics propose models for unifying present-days strong and weak nuclear force with the electromagnetic force at very high energies corresponding to the conditions that existed 10^{-35} seconds after the Big Bang. It is anticipated eventually, at 10^{-43} seconds*,* to merge even gravity, resulting in a unified theory of everything (TOE). The ideal of physics is to derive all physics from the minimal number of elements connecting elementary particles and their interactions.

The article discussing the evolution of the Laws of Nature (Balashov 1992) describes the situation, a result of a self-organization on a cosmic scale, from the perspective of the interplay between the *diachronic* and *synchronistic* descriptions of cosmic processes. This leads to not only the evolution of material substrate, but also nomic evolution, that is evolution of the Laws of Nature:

> "… described by the unified gauge theories immersed in the 'flow of time', i.e. in the non-stationary expanding and cooling environment." (…) In the present situation, physics may transcend the trivial idea of the evolutionary origin of the substratum aspects of the Universe. It may be quite possible to extend evolutionary notions to the nomic features of our world, e.g. the particles' quantum parameters and the values of coupling-constants. Some of these quantities could perhaps vary during the early stages of cosmic evolution (…). In view of this, the idea of the possible evolution of the laws of nature in real historical time suggests itself quite naturally."

The paradigm of generative evolutionary models is strongly established in many sciences, from biological evolution, to linguistic, social theory and ecology (Corne and Bentley 2002).

Time, given the constructive role in the evolution of matter, life, intelligence and human culture opened possibility to scientifically address dynamics and uncover the new Laws of Nature (Prigogine 1997). This ever-changing universe brings about the end of certainty as Prigogine observed. Prigogine's study of self-organizing systems shows how new vistas open when the concept of determinism gets questioned that was ruling Western science for centuries, since pre-Socratic Greek philosophers. The consequence of the dynamic, unfinished, evolving nature is that the future of the universe is not uniquely given by its present state, it is under continual construction. Entropy for Prigogine is the arrow of time that brings order and life to the evolving dynamic universe, it is not leading to its heat death in a thermodynamic equilibrium. In the evolving universe, unfathomably large numbers of particles interact with each other forming varieties of structures, in a layered architecture of emerging levels, constructing ever new states with a history of relationships – a fundamental "memory" in a sense of Leyton: shape = memory storage (Leyton 2005). In (Prigogine 1981, 1997; Nicolis and Prigogine 1977; Prigogine and Stengers 1984), Prigogine with his coauthors develop the view of the universe evolving in real, natural time. (Prigogine 1997) explains how this has close connection to learning and knowledge:

> "Knowledge presupposes that the world affects us and our instruments, that there is an interaction between the knower and the known, that this interaction creates a difference between past and future. Becoming is the sine qua non of science, and indeed of knowledge itself."

Unlike defenders of timeless universe like Barbour (Barbour 2005) who believes that time is an illusion, (which seems to be Einstein's position as well), Prigogine demonstrates why and how time is absolutely essential for our universe, for its being and becoming. The world is neither predetermined nor is it random; lawful chains of cause and effect form patterns, while chance brings novelty on top of regularity. Life presents especially interesting types of complex systems, in which interactions between living system governed by physical, chemical and biological laws, and chance brought by the environment develop into a many-leveled self-organized, goal-directed wholes. Dobzhansky (1973) underlines this central role of (evolutionary) time for living beings in his famous adage: "Nothing in biology makes sense except in the light of evolution".

Understanding Dynamics by Descriptive vs. Executable Explanatory Models

While reconstructing reality as a time-dependent process, Morrison (2015) studies modelling and simulation and how they provide means of understanding of the world/nature. She addresses fictional models in science, mathematical models producing physical information, and the problem of mutual inconsistency of models. She questions the role of simulation as a replacement of traditional methods of theoretical and experimental science and investigates how simulation can be used, including the problem of its verification and validation.

From the analysis of CERN experiments, which regularly combine simulations with empirical measurements, Morrison concludes that the *distinction between simulation and experiment is in general no longer justifiable*. Casacuberta and Vallverdú (2014) analyze the role of software in LHC (Large Hadron Collider) of CERN and find out that ”the role of software is crucial, because it: a) filters data coming from the detectors (there are four different experiments running at the LHC); b) monitors the performance of the detectors; c) calibrates and aligns the detector components; d) simulates detector responses from known physics processes; and e) carries out user analysis leading to physics results.”

In the case of e-science, the (essentially Socratic) idea of *scientific method* (observation of the world, hypothetical explanation, test) gets fundamentally changed (ibid.) with the impossibility of humans to perform such research without computers, and impossibility of reproduction because of the complexity of the experiment and uniqueness of the facility, the situation of the human mind extended by computational resources and radically distributed cognition.

The question Morrison (2015) addresses is how exactly simulation relates to both theoretical and empirical knowledge. While physics provides fertile ground for mathematization, biology still presents a field with challenges for both mathematical models and computer simulations. Simulations bring the possibility to study dynamical behavior of a simulated system under controlled conditions. Time enters into the picture through the manipulations performed by the observer.

Time plays a constitutive role in natural processes. White and Banzhaf (2019) discuss the relationship between and differences with respect to the role and form of time in science, identifying “two sciences that provide modeling tools for others to use in their effort to model the material universe, mathematics and computer science.” However, there is an essential difference between mathematical and computational models, and that is their time dependence. (ibid.)

> "For instance, a mathematical proof is a set of transformations of a statement into the values "true" or "false," that are unchanging and not dynamic. This reliability is its strength. Once a statement is established to be true, it is accepted into the canon of mathematically proven statements and can serve as an intermediate for other proof transformations."

Fisher, Piterman, and Bodik (2014) illustrate this difference on the *executable (computational) models in biology*. The difference between mathematical and computational models can be summarized as distinction between denotational and operational semantics models given in the following (Fisher and Henzinger 2007):

- *Denotational (mathematical) semantics models*: Set of equations showing relationships between different quantities and how they change over time. They are approximated numerically. (Differential Equations etc.)
- *Operational semantics models*: Algorithm (list of instructions) executable by an abstract machine whose computation resembles the behavior of the system under study. (i.e., Finite State Machines).

The two semantics have different roles – while executable algorithms (operational semantics) connect directly to the physical process and can be used for interactions with them in natural time, mathematical models (denotational semantics) are descriptive and can be used to reason about systems using a description of time.

Barry Cooper characterized this difference between mathematical and computational approaches (Cooper 2012) in his article identifying the historical "mathematician's bias" and the current return to embodied (physical, natural) computation.

Resembling a living organism, a city is an example where dynamics and natural time are essential. White (2019) illustrates how abstract mathematics are used in the formal treatment of urban morphology, as the complexity of urban form is best represented (described) as a mathematical object, a fractal. Mathematics is equally important in models of the genesis of form – morphogenesis.

Nevertheless, mathematics alone is unable to start the morphogenetic processes itself and must be embedded in executing algorithms in order to capture the temporality of morphogenesis. In the case of straightforward processes of urban self-organization, conventional simulation models are sufficient. However, to capture the creativity of cities— their ability to generate new agents and new types of agents with new rules of behavior—*unconventional algorithms are required, algorithms that alter themselves during execution*. Ultimately algorithms, not mathematics, provide the natural language of morphogenesis.

COMPUTING NATURE

Fundamental natural laws govern the fundamental level of the universe. But what is the universe? (Dodig-Crnkovic and Stuart 2007) p. xi:

> "Every epoch and culture has a different conception of the Universe. For Ptolemy, Descartes, and Newton, the Universe was best conceived in a mechanistic way as some vast machine. For others it is, in its entirety, a living organism [Viz. Thales of Miletus, Spinoza, and Kafatos & Nadeau 1999]. Our current understanding in terms of information and computing has led to a conception of the Universe as, more or less explicitly, a computer. On such a pancomputational and paninformational view (Zuse 1967; Lloyd 2006; Chaitin this volume), if all physics is expressible as computation – so the whole universe can be represented as a network of computing processes at different levels of granularity – then 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."

Many of the ancient myths described nature as a living and developing (growing) being - as a tree or an egg. In more recent times, Nature ceased being an organism and became a machine. In the early 13th-century, John of Sacrobosco has written an introduction to astronomy, speaking of the universe as the *machina mundi*, the machine of the world. Gottfried Leibniz was a known supporter of this idea. Based on Newton's physics, mechanistic

Nature was envisaged as the *clockwork universe*, a perfect machine governed by the laws of (classical, deterministic) physics. With further development of physics and introduction of quantum mechanics and relativity, the fundamental underlying mechanism changed, but it was still a *mechanism* governed by physical laws (Glennan 2010).

Morphological Info-computation and Computational Discovery[2] in Nature

The belief in mathematical/geometrical essence of the world can be traced back to Plato and the Pythagoreans, which later reappears with Galileo, in his 1632 *Dialogue Concerning the Two Chief World Systems*, where he argues that the book of nature is written in the language of mathematics. Plato's ideal of eternal, unchangeable forms can be found in mathematics to this day. Even though mathematical formulas can be used to compute time-dependent processes, equations themselves are symbolic structures, specified and immovable. Time dependency comes from human performing computation, actively using static structures of mathematical algorithms to trace time behaviors of the real-world.

Platonic ideal forms, however remote from the physical realizations and questions of finite material resources, were long considered to represent the true nature of the world, while changes were supposed to be something ephemeral, uninteresting and too earthly for a mathematician or a scientist to bother about. Up to quite recently this detachment from the "real time" or "natural time" aspects of the world was commonly taken for granted and justified.

The shift happened with computing machinery getting integrated with dynamically changing physical objects, such as in embedded systems / cyber-physical systems or process control, where real-time computation processes must match real-time behaviors of the physical environment. This situation radicalized even more with the mobile distributed ICT for which

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[2] The introductory part of this section follows essentially the narrative from (Dodig-Crnkovic and Cicchetti 2017).

the *system dynamics and bounded resources* are the central characteristics. Rapidly, eternal forms are becoming something remote and less important.

The focus is on the process of change, communication, timely response, and resource optimization, as this new world of embodied and embedded computation is physical in nature and thus substrate-dependent. The whole field of cyber-physical systems is emerging, at different levels of organization, from nano to macroscopic. In this critical transition from idealized abstract forms towards concrete material processes, computation has come close to the messy and complex world of concurrent and context-dependent processes in living beings (Navlakha and Bar-Joseph 2015). One important shift is also in the role of an "observer." According to *(Denning 2014)*:

> "Computational expressions are not constrained to be outside the systems they represent. The possibility of self-reference makes for very powerful computational schemes based on recursive designs and executions and also for very powerful limitations on computing, such as the non-computability of halting problems. Self-reference is common in natural information processes; the cell, for example, contains its own blueprint."

One important aspect of modeling is the direction of their generation – bottom up or top down. Mathematical models are typically top down while computational models are frequently bottom up or generative, described by Wolfram as a "new kind of science" (Wolfram 2002). Fields modeling living organisms like synthetic biology present the challenge of bridging the gap between the two, enabling the circular motion from bottom up to top down and back.

Computation beyond the Turing Machine Model

Already in the early days of the Turing Model of abstract computation, there were critical voices pointing out the abstract and eminently reductionist nature of the Turing machine model. Georg Kampis claimed that the Church-Turing thesis applies only to simple systems (Kampis 1991).

According to Kampis, complex systems such as those found in biology must be modeled as self-organizing, self-referential structures called component-systems whose behavior goes far beyond the simple Turing machi.ne model as a more general model of computation.

The following is a quote from Kampis (1991) p. 223:

> "a component system is a computer which, when executing its operations (software), builds a new hardware.... [W]e have a computer that re-wires itself in a hardware-software interplay: the hardware defines the software and the software defines new hardware. Then the circle starts again."

I would add an obvious remark. The Turing machine is supposed to be given from the outset – its logic, its (unlimited) physical resources, and the meanings ascribed to its actions. The *Turing machine essentially presupposes a human as a part of a system* – the human is the one who poses the questions, provides resources and interprets the answers."

Computing can provide modeling tools for biomolecular systems in which a system of interacting molecules is modeled as a system of interacting computational agents (Regev and Shapiro 2002). Petri nets, State charts and the Pi-calculus, developed for systems of interacting computations, can successfully be used for the modeling of biomolecular systems, such as signaling-, regulatory-, and metabolic- pathways and even multicellular processes. "Processes, the basic interacting computational entities of these languages, have internal state and interaction capabilities. Process behavior is governed by reaction rules specifying the response to an input message based on its content and the state of the process. The response can be a state change, a change in interaction capabilities, and/or sending messages. Complex entities are described hierarchically."

In Dodig-Crnkovic (2012) and Dodig-Crnkovic (2017) a view is presented of nature as a network of info-computational agents organized in a dynamical hierarchy of levels. Information is conceived as a structure, differences in one system that cause the differences in another system, while computation is the dynamics of information, i.e., physical process of morphological change in the informational structure. There are frequent misunderstandings regarding the natural computational models and their relationships to physical systems, especially cognitive systems such as living beings.

Natural morphological info-computation as a conceptual framework presents generalization of models of computation beyond the traditional idealized model of the Turing machine representing symbol manipulation with unlimited computational resources. Morphological info-computation is physical computation implemented as agent-based concurrent resource-sensitive signal-processing model of computation, where symbol manipulation emerges from signal processing. Grounding in physical substrate and data-processing is necessary in order to be able to cover the whole range of phenomena, heterarchically organized from basic physical processes to cognition (Dodig-Crnkovic 2011). Zenil (2012) offers a similar proposal for exploring nature as computation in a computable universe. Zenil also presents research on new approaches to computation.

As already illustrated by the work on simulation presented in Morrison (2015), computational approaches are being extensively used in scientific research and their role is studied in the philosophy of science. In this case it is conventional computing that is used in simulations. There are also attempts, as e.g., in Kuipers (2001) to formulate the computational Philosophy of Science.

Present day computational models with distributed, asynchronous, heterogeneous, and concurrent networks are becoming increasingly well suited for modeling of cognitive systems with their dynamic properties, and can be used in Model-Based Reasoning, and for the study of mechanisms of abduction and scientific discovery (Dodig-Crnkovic and Cicchetti 2017). Dodig-Crnkovic (2007a) presents an attempt to understand epistemology as computation (information processing). Both cognitive computing and computational discovery are fields that can be expected to grow, especially with the big data explosion and the development of artificial intelligence.

UNITY OF SCIENCES IN UNITY OF KNOWLEDGE

Knowledge Ecology

In hindsight, Popper's most profound and original ideas in philosophy of science are not those searching for the means of demarcation, but those exposing the *evolutionary nature of science* (Popper 1972). Especially novel and fresh, he feels his evolutionary epistemology which frames all kinds of knowledge, problem solving and learning, in evolutionary terms is based on interactions with the environment, trials and errors. This includes not only scientific knowledge in all its forms, but also knowledge, learning and problem-solving abilities embodied in all living organisms, both animals and plants. Unlike plants and animals who mainly learn by direct responses to the environment and other organisms from their own ecological niches, humans have developed on top of direct responses, also complex communicative tools providing both long-range communication as well as long-term memory through culture in which even sciences participate as an important contributor. Interestingly, while apes can learn to use many human words and communicate complex concepts, they are not transferring this knowledge to their next generation. That is the most important difference distinuishing human species from other life forms, far more than the genetic code – our ability to learn from each other and to preserve knowledge for many coming generations. This evolutionary, learning, adaptive character of human knowledge in general and scientific knowledge in particular is one of the most prominent features that constitute the nature of science.

Ecology of Knowledge and Interdisciplinarity

The ambition to unify all sciences is a very old one. Historically, natural sciences started as Natural Philosohy and then diverged into specific fields as the amount of knowledge increased. The process of differentiation started by the mathematization of Natural Philosophy in the seventeenth century (Gorham et al. 2016). However, contrary to common belief, Morrison (2000) argues that unification often does not increase explanatory power. I would argue that it must depend on the type of unification. Physicists dream of the Unified Theory of Everything which pressuposes the discovering of a unique mechanism that may be used to generate all of the existing physics as well as the new one.

The problem of excessive amounts of knowledge, information and data which made it impossible for a scientist to know in depth more than a few scientific fields, might be solved by help of ever increasing information processing/computing power in combination with efficient communication and storage capabilities.

The trend is towards bigger and bigger teams of scientists collaborating on common research projects and working across the disciplinary borders. This is a new kind of unity of knowledge through interdisciplinarity, transdisciplinarity, and multidisciplinarity such as in Human Brain Project, LHC or the projects concerning the solution of environmental problems. This is unity through diversity in a manner of distributed cognition. The question is do we better understand the world when we can generate its correct descriptions (according to the present state data we have) and possibly its predictions based on a single generative mechanism (if it exists)? On what cognitive level is our expectation of understanding? I mentioned earlier the symbiosis of computing and human cognition in LHC experiments. This topic is new and open for future research.

There is an additional aspect to the result of interaction between different research fields: *More is different*, as Anderson (1972) rightly argued, along the lines of Aristotle, who in Metaphysics asks: “What is the reason for a unity/oneness? For however many things have a plurality of parts and are not merely a complete aggregate but instead some kind of a whole beyond its parts” and goes explaining *the reason for unity as being the result of the interaction between parts*.

Anastas (2019) identifies big questions of chemistry and science in general when it comes to complex systems that must be seen beyond reductionists simplifications, especially when applying chemistry on sustainability problems. If we neglect the interactions and divide the problem in separate isolated units, something essential is lost that accounts for the whole.

Scientific reductionism has its applications on isolated systems (and that is why physicists study elementary particles in an absolute vacuum) but when we want to address real world problems, mutual dependencies of the parts must be carefully studied if we want to understand the whole based on the understanding of its parts.

This need of a wholistic view led Nowotny, Scott, and Gibbons (2001) to propose a rethinking of science, especially the classical preconception about the certainty of science in the view of increasing awareness of uncertainty inherent to science. The way out of reductionist myopic perspective is to embrace interdisciplinarity and work on establishing relationships between disparate research fields. Nicolescu (2008), Brier (2015a, 2008), Burgin and Hofkirchner (2017) addressed theoretical aspects of interdisciplinarity/transdisciplinarity, while Solomon Marcus in his research made contributions at the intersection of computer science with biology, chemistry and physics (Paun et al. 2017). Julie Thompson Klain offers a taxonomy of interdisciplinarity (Klein 2010).

Given the preceding discussion of knowledge expressed in the Laws of Nature and Laws of Science that typically stand for specific domains, it is also important to see the knowledge as influenced by its ecology, the evolutionary processes based on interactions with the environment/context. In physics, systems are typically closed and context-independent while in biology, cognitive science, sociology and ecology systems are essentially open and often in symbiotic relationships with the environment. In the introduction we mentioned the current fast process of establishing connections between disparate fields of scientific knowledge as they developed historically and even to this day constitute isolated domains of data, research, publications, academic institutions, practical applications and social networks.

As an interesting illustration, we can mention the European Open Science Cloud project (EOSC) for research data management, that will connect present and future research data centers providing “a free point of use, open and seamless services for storage, management, analysis and re-use of research data”. The process of digitalization of European research data have namely clearly revealed disciplinary “knowledge silos” with practically no connections. That must and will be changed in the years to come, when technology will make access possible between those knowledge silos. In order to connect separate data repositories, EOSC will include: “the design of a micro-service architecture, the introduction of standards for metadata, the design of a central search index to allow cross-repository search and retrieval as well as the large storage and computing capacities.”

As Klaus Tochtermann (Tochtermann 2018) presented in his keynote talk at Informatics Europe conference.

Together with this process of connecting databases and creating overarching, encompassing metadata, dictionary definitions of terms used in knowledge production must be revisited. Among other terms important for knowledge production and organization that need to be updated to reflect contemporary state are the notions of Laws of Nature and Laws of Science. The example of Visual thesaurus Visuwords shows that terms such as "Science" still are represented in a rudimentary and old-fashioned way. The same goes for the Laws of Nature. Terms "Laws of Science" and "Scientific Laws" do not even exist in this dictionary. Big work on reorganization of the research infrastructure remains to be done, and it will boost the development of interdisciplinary/ transdisciplinary/ multidisciplinary knowledge production and even more important, actualize the need of common frameworks.

Knowledge Production in the Study of Information

Among present-day examples of emerging general frameworks with the potential to embrace sciences, (including social sciences), humanities, and even arts and other kinds of embodied knowledge is Philosophy of Information and Computation (Dodig-Crnkovic and Burgin 2019). It is studying the world as an informational/computational system, where all physical processes represent computation over informational structures. Computation is understood in its most general form as natural computation which finds computational processes in nature, ranging from quantum physics, to self-organizing, self-sustaining phenomena such as living organisms or cognitive systems. The info-computational framework allows us to understand mechanisms of science on both object and meta-levels. The object level is a sense of describing different phenomena within science such as biology, physics, chemistry, etc. as manifestations of informational-computational processes. Meta levels are a sense of understanding scientific theories of different sciences translated into the same info-computational language. One more level of understanding is given by the study of mechanisms of cognition in the same info-computational conceptual space. If we are to search for a path of unification of sciences, it should go via common language and conceptual apparatus, and info-computationalism is providing both. It offers even more than classical scientific theories, through simulations and even physical info-computational devices such as virtual reality and internet of things which offer paths of further development of our understanding of science and their embracing into the common worldview (Dodig-Crnkovic 2006).

Kun and Brenner (2017) propose Philosophy of Information as a means of unifying the Informational Metaphilosophy of Science. This proposal differs from info-computational in that Metaphilosophy is a philosophical approach and in that descriptive/denotational, while info-computational approach is more interested in generative mechanisms and thus operational. On the other hand, Brier is working on a different unification project: *"to define a universal concept of information covering subjective experiential and meaningful cognition"* (Brier 2015b).

Ecology of knowledge comes in the work of Zhong (2017); Burgin and Zhong (2018); Zhong (2011) emphasizing the *system approach* to the generation of knowledge with the process of transformation of data to information and to knowledge, that later on can be used for decision making and as a basis for further knowledge generation.

FUTURE WORK

In the future, it will be necessary to make a more systematic study of conceptual analyses and taxonomies of various concepts such as Laws of Nature and Laws of Science(s). Projects of unification such as Incomplete Nature (Deacon 2011), Cybersemiotics (Brier 2008), Unified Theory of Information (Hofkirchner 2013), Philosophy of Information (Floridi 2011) (Kun and Brenner 2017), Logic in Reality (Brenner 2008), Contemporary Natural Philosophy (Dodig-Crnkovic and Schroeder 2018a), Computing Nature (Dodig-Crnkovic 2011) (Zenil 2012), and similar approaches should be systematized. It is also a next step to clarify relationships between different approaches, their underlying assumptions, what phenomena they are designed to tackle, and how they are used. Nature and life with their manifestations such as cognition and knowledge are complex phenomena and it is expected that they will manifest themselves in different approaches. We cannot claim that one approach is "wrong," but it can be more or less suitable for a certain purpose. TOE for example is a view taken from the perspective of cosmology and in that perspective life is invisible. And yet, they are related and it is interesting to know how. We need more connections and mutual relationships between currently, weakly related knowledge fields.

The paradigm of generative evolutionary models is strongly established in many sciences, from biological evolution, to linguistics, social theory and ecology (Corne and Bentley 2002). The modern evolutionary view of the physical Universe should conceive of the Laws of Nature as evolving concurrently with the things constituting the environment. Thus, the conception of the Universe as an evolving subject to be fixed, eternal laws regulating all behavior should be abandoned (Whitehead 1967 p. 112).

Better insight into the knowledge production as a result of digitalization will also help understand both the research data and scientific models built upon them. The Open Science Cloud mentioned earlier is the important first step in the creation of practical *open knowledge ecology*.

CONCLUSION

After the impressive success of Newton's laws of physics (while he was still a natural philosopher, and not a professional scientist), Natural Philosophy started to give rise to a variety of scientific fields that continued to develop in separation, based on (domain specific) "scientific method(s)." That has led to ever increasing specialization and division into isolated islands of scientific knowledge. The advantage of this development was the production of in depth, specialist knowledge. The shortcoming was *fragmentation, and lost common perspective*.

However, recent technology development enabled effective processing of data, information, and knowledge, together with quick access and exchange. That triggered new mutual awareness of the research fields resulting in a continual increase of interdisciplinarity, transdisciplinarity, multidisciplinarity, pluridisciplinarity and other forms of collaborations across the disciplinary borders. Such networks of collaborations can be seen as ecologies where each science gets into symbiotic relationships with the others and with the environment.

Already Bateson (1973), identified the problem of fragmentation of knowledge in the modern era and proposed building bridges between different knowledge disciplines as a remedy. Bateson has envisaged a new epistemology resulting from systems theory and ecology in which *relationships* were the central interest and context of a system naturally connected to the system itself, forming *systems of systems* and *patterns of patterns*.

There are several present strategies in the search for common frameworks for knowledge. One of them goes via contemporary Natural Philosophy, where the human is studied as a natural being, embedded in Nature as described in sciences, with inclusion of humanities, arts and cultures (Dodig-Crnkovic and Schroeder 2018a, 2018b). Some other approaches generate a unified framework starting with fundamental physics, up to cosmology (TOE). Others still emphasize the succession of levels of organization of increasing complexity from basic physics to chemistry, biology, cognition, sociology to ecology (Prigogine).

Yet another parallel to natural sciences, modern unification approach goes via information as fundamental to our epistemology and cognition. Instead of isolated objects, information stands for *relationships*, the networks of "*differences that make a difference*"[3] which was Bateson's definition of information (Bateson 1979 p.110). Structures and processes are centered in cognizing agents such as humans and other living organisms, as a locus of information interpretation, and the origin of all relationships of those agents with the world, including the reflective relationships with themselves (von Uexküll's Umwelt - life-world).

A more recent take on the ecology of information and knowledge can be found in the work of Zhong (2017); Burgin and Zhong (2018); Zhong (2011) who study human life-world as the ecology of interacting data-information-

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[3] It would be more exact to say that differences which make a difference *for another system* constitute information. Data present the smallest units of information.

knowledge systems. Within an ecological framework, Laws of Nature and their representation in Laws of Science have their given place as fundamental building blocks of a complex and fine-tuned eco-system of life based on information. The awareness is increasing about the benefits of the ecological approach to knowledge of all possible kinds, including not only natural sciences, social sciences and humanities but also arts, as argued by Solomon Marcus (Solomon 1999).

With the developments of artificial intelligence, and people with their promises and challenges, questions of values moved to the fore of the scientific and technical debate. Integration of values into the enterprise of knowledge production, gains legitimacy from the insight that there is an inevitable coupling between ethics and epistemology (Tuana 2015). In the Science as Social Knowledge, Longino (1990) argues for the *integrity* of a science not as *purity* but as *wholeness*:

> "When purged of assumptions carrying social and cultural values, observation and reason are too impoverished to produce scientific theories of the beauty and power that characterize even the theories we do have. If we understand integrity not as purity but as wholeness, the integrity of the scientist is honored when she permits her values to play a role in her scientific work."

In sum: in the dynamic world, ever changing on both spatial and temporal scales, from micro- to macro cosmic dimensions, production of knowledge is a result of interactions in networks of networks of information processing agents – from the simplest elementary particles to the most complex ones - humans.

For humans, information has many properties that reflect Umwelt/ life-world, in interaction with the embodied human information-processing structures. Some of the information properties are functional (directly connected to the function), the others are nonfunctional (referring to properties that are not directly connected to function) - to borrow the expression from computing. Among nonfunctional properties of information there are aspects of ethics and esthetics. What we may hope to see in the future is a rich account of agency and knowledge ecology that would be able, in a unified framework, to account for a variety of human agency and experience. In that framework, science has the important role of providing the (descriptive) information about how the world is, and generating executable models of behavior of systems under consideration, in natural/actual time.

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REFERENCES

Anastas, Paul T. 2019. "Beyond Reductionist Thinking in Chemistry for Sustainability." *Trends in Chemistry* 1 (2): 145–48.

Anderson, Philip W. 1972. "More Is Different." *Science* 177: 393–396.

Bak, Per. 1996. *How Nature Works*. NewYork: Springer.

Balashov, Yury V. 1992. "On the Evolution of Natural Laws." *The British Journal for the Philosophy of Science* 43 (3): 343–70.

Barbour, Julian. 2005. *The End of Time: The Next Revolution in Our Understanding of the Universe*. Oxford: Oxford University Press.

Bateson, Gregory. 1973. *Steps to an Ecology of Mind*. London: Granada.

———. 1979. *Mind and Nature: A Necessary Unity*. London: Wildwood House.

Brenner, Joseph. 2008. *Logic in Reality*. Springer Netherlands.

Brier, Søren. 2008. *Cybersemiotics: Why Information Is Not Enough*. Toronto: Toronto University Press.

———. 2015a. "Can Biosemiotics Be a 'Science' If Its Purpose Is to Be a Bridge between the Natural, Social and Human Sciences?" *Progress in Biophysics and Molecular Biology. Integral Biomathics: Life Sciences, Mathematics, and Phenomenological Philosophy* 119 (3): 576–87.

———. 2015b. "Finding an Information Concept Suited for a Universal Theory of Information." *Progress in Biophysics and Molecular Biology*. Elsevier Ltd. https://doi.org/10.1016/j.pbiomolbio. 2015.06.018.

Burgin, Mark, and Gordana Dodig-Crnkovic. 2017. "Prolegomena to Information Taxonomy." *Proceedings, Volume 1, Issue 3 (August 2017)* 1 (3): 210–13.

———. 2019. "A Multiscale Taxonomy of Information in the World." In *Theoretical Information Studies. Information in the World. World Scientific Series in Information Studies: Volume 11.*, edited by Mark Burgin and Gordana Dodig-Crnkovic. Singapore: World Scientific.

Burgin, Mark, and Wolfgang Hofkirchner. 2017. *Information Studies and the Quest for Transdisciplinarity. Unity through Diversity*. Singapore: World Scientific.

Burgin, Mark, and Yixin Zhong. 2018. "Information Ecology in the Context of General Ecology." *Information* 9: 57.

Cartwright, Nancy. 1983. *How the Laws of Physics Lie*. Oxford: Oxford University Press.

———. 1999. *The Dappled World: A Study of the Boundaries of Science*. Cambridge: Cambridge University Press.

Casacuberta, David, and Jordi Vallverdú. 2014. "E-Science and the Data Deluge." *Philosophical Psychology* 27 (1): 126–40.

Chaitin, Gregory. 2019. "Unknowability in Mathematics, Biology and Physics. The New School." *Social Research* 87 (1).

Cooper, Barry S. 2012. "The Mathematician's Bias - and the Return to Embodied Computation." In *A Computable Universe. Understanding Computation & Exploring Nature as Computation*, edited by Hector Zenil, 125–42. Singapore: World Scientific.

Corne, David, and Peter Bentley. 2002. *Creative Evolutionary Systems*. The Morgan. San Francisco, CA: Morgan Kaufmann.

Deacon, Terrence. 2011. *Incomplete Nature. How Mind Emerged from Matter*. New York. London: W. W. Norton & Company.

Denning, Peter. 2014. "Structure and Organization of Computing." In *Computing Handbook. Computer Science and Software Engineering*, edited by J. Tucker, A., Gonzalez, T., Topi, H. and Diaz-Herrera. Chapman & Hall/CRC.

Descartes, René. 1644. *Principia Philosophiae (Principles of Philosophy)*. Reprint 19. Dordrecht: Reidel.

Dobzhansky, Theodosius. 1973. “Nothing in Biology Makes Sense Except in the Light of Evolution.” *The American Biology Teacher* 35 (3): 125–29.

Dodig-Crnkovic, Gordana. 2006. “Investigations into Information Semantics and Ethics of Computing.” *Mälardalen University Press*.

———. 2007a. “Where Do New Ideas Come From? How Do They Emerge? Epistemology as Computation (Information Processing).” In *Randomness and Complexity, From Leibniz to Chaitin*, edited by Cristian Calude, 263–279. World Scientific.

———. 2007b. “Where Do New Ideas Come From? How Do They Emerge? Epistemology as Computation (Information Processing).” In , edited by Christian Calude, 263–71. World Scientific.

———. 2011. “Significance of Models of Computation, from Turing Model to Natural Computation.” *Minds and Machines* 21 (2): 301–22. https://doi.org/10.1007/s11023-011-9235-1.

———. 2012. “Physical Computation as Dynamics of Form That Glues Everything Together.” *Information (Switzerland)*. https://doi.org/10.3390/info3020204.

———. 2017. “Nature as a Network of Morphological Infocomputational Processes for Cognitive Agents.” *European Physical Journal: Special Topics*. https://doi.org/10.1140/epjst/e2016-60362-9.

Dodig-Crnkovic, Gordana, and Mark Burgin. 2019. “The Study of Information in the Context of Knowledge Ecology.” In *Philosophy and Methodology of Information: The Study of Information in the Transdisciplinary Perspective*. Singapore: World Scientific.

Dodig-Crnkovic, Gordana, and Antonio Cicchetti. 2017. “Computational Aspects of Model-Based Reasoning.” In *Springer Handbook of Model-Based Science*, edited by Lorenzo Magnani and Tomaso Bertolotti, 695–718. Springer International Publishing.

Dodig-Crnkovic, Gordana, and Marcin Schroeder. 2018a. “Contemporary Natural Philosophy and Philosophies.” *Philosophies* 3: 42.

———. 2018b. “Special Issue ‘Contemporary Natural Philosophy and Philosophies.’” Philosophies. 2018.

Dodig-Crnkovic, Gordana, and Susan Stuart. 2007. *Computation, Information, Cognition: The Nexus and the Liminal*. Newcastle: Cambridge Scholars Press.

Fisher, Jasmin, and Thomas A. Henzinger. 2007. "Executable Cell Biology." *Nature Biotechnology* 25 (11): 1239–1249.

Fisher, Jasmin, Nir Piterman, and Rastislav Bodik. 2014. "Toward Synthesizing Executable Models in Biology." *Frontiers in Bioengineering and Biotechnology* 2: 75.

Floridi, Luciano. 2011. *The Philosophy of Information*. *The Philosophy of Information*. Oxford University Press. https://doi.org/10.1093/acprof:oso/9780199232383.001.0001.

Friedland, Barton, and Yutaka Yamauchi. 2011. "Reflexive Design Thinking: Putting More Human in Human-Centered Practices." *Interactions* 18 (2): 66–71.

Glennan, Stuart. 2010. "Mechanisms, Causes, and the Layered Model of the World." *Philosophy and Phenomenological Research* 81 (2): 362–81.

Gorham, Geoffrey, Benjamin Hill, Edward Slowik, and C. Waters Kenneth. 2016. *The Language of Nature: Reassessing the Mathematization of Natural Philosophy in the Seventeenth Century*. Minneapolis: University of Minnesota Press.

Hofkirchner, Wolfgang. 2013. *Emergent Information: A Unified Theory of Information Framework*. Singapore: World Scientific.

Holten, Theo van. 2017. *The Atomic World Spooky? It Ain't Necessarily So! Emergent Quantum Mechanics, How the Classical Laws of Nature Can Conspire to Cause Quantum-Like Behaviour*. Paris: Atlantis Press.

Johansson, Lars-Göran. 2016. *Philosophy of Science for Scientists*. Springer International Publishing.

Kampis, George. 1991. *Self-Modifying Systems in Biology and Cognitive Science: A New Framework for Dynamics, Information, and Complexity*. Amsterdam: Pergamon Press.

Klein, Julie Thompson. 2010. "A Taxonomy of Interdisciplinarity." In *The Oxford Handbook of Interdisciplinarity*, edited by Robert Frodeman, Julie T. Klein, and Carl Mitcham, 15–30. Oxford: Oxford University Press.

Kuipers, Theo A. F. 2001. "Computational Philosophy of Science." In *Structures in Science. Synthese Library (Studies in Epistemology, Logic, Methodology, and Philosophy of Science), Vol 301*. Springer, Dordrecht.

Kun, Wu, and Joseph Brenner. 2017. "Philosophy of Information: Revolution in Philosophy. Towards an Informational Metaphilosophy of Science." *Philosophies* 2 (4): 22.

Leyton, Michael. 2005. "Shape as Memory Storage." In *Ambient Intelligence for Scientific Discovery. Lecture Notes in Computer Science, Vol 3345.*, edited by Cai Y. (eds). Berlin, Heidelberg: Springer.

Longino, Helen. 1990. *Science as Social Knowledge*. Princeton: Princeton University Press.

Massimi, Michela, and Angela Breitenbach. 2017. *Kant and the Laws of Nature*. Cambridge: Cambridge University Press.

Mill, John Stuart. 1882. *A System of Logic*. 8th ed. New York: Harper & Brothers.

Morrison, Margaret. 2000. *Unifying Scientific Theories. Physical Concepts and Mathematical Structures*. Cambridge: Cambridge University Press.

———. 2015. *Reconstructing Reality: Models, Mathematics and Simulations*. Oxford: Oxford University Press.

Navlakha, Saket, and Ziv Bar-Joseph. 2015. "Distributed Information Processing in Biological and Computational Systems." *Communications of the ACM* 58 (1): 94--102.

Newton, Isaac. 1687. *Philosophiae Naturalis Principia Mathematica*. Digital. http://cudl.lib.cam.ac.uk/view/PR-ADV-B-00039-00001/14.

Nicolescu, Basarab. 2008. *Transdisciplinarity - Theory and Practice*. New York: Hampton Press.

Nicolis, Gregoire, and Ilya Prigogine. 1977. *Self-Organization in Nonequilibrium Systems: From Dissipative Structures to Order Through Fluctuations*. New Jersey: Wiley.

Nowotny, Helga, Peter B. Scott, and Michael T. Gibbons. 2001. *Re-Thinking Science. Knowledge and the Public in the Age of Uncertainty*. Cambridge: Blackwell publishers.

Ott, Walter, and Lydia Patton. 2018. *Laws of Nature*. Oxford: Oxford University Press.

Paun, Gheorghe, Ion Petre, Grzegorz Rozenberg, and Arto Salomaa. 2017. “At the Intersection of Computer Science with Biology, Chemistry and Physics - In Memory of Solomon Marcus.” *Theoretical Computer Science* 701: 1–234.

Peterson, Ivars. 1990. *Islands Ot Truth: A Mathematical Mystery Cruise*. New York: W H Freeman & Co.

Popper, Karl. 1959. *The Logic of Scientific Discovery*. London: Hutchinson.

———. 1963. *Conjectures and Refutations: The Growth of Scientific Knowledge*. Fifth edit. London: Routledge.

———. 1972. *Objective Knowledge: An Evolutionary Approach*. Oxford: Oxford University Press.

———. 1984. *Unended Quest: An Intellectual Autobiography*. Fontana.

———. 1999. *All Life Is Problem Solving*. London: Routledge.

Prigogine, Ilya. 1981. *From Being to Becoming: Time and Complexity in the Physical Sciences*. New York: W. H. Freeman and Co.

———. 1997. *The End of Certainty*. New York: Simon and Schuster.

Prigogine, Ilya, and Isabelle Stengers. 1984. *Order out of Chaos: Man’s New Dialogue with Nature*. Bantam Books.

Regev, Aviv, and Ehud Shapiro. 2002. “Cellular Abstractions: Cells as Computation.” *Nature* 419: 343.

Rzevski, George. 2015. “Complexity as the Defining Feature of the 21st Century.” *Int. J. of Design & Nature and Ecodynamics* 10 (3): 191–98.

Salthe, Stanley N. 2019. “The Limits, Mail Communication in FIS (Foundations of Information Science) Discussion.”

Solomon, Marcus. 1999. “The Art-Science Marriage, From Quarrel to Understanding.” In *Bridges: Mathematical Connections in Art, Music, and Science*, edited by Reza Sarhangi, 279--290. Winfield, Kansas: Bridges Conference. http://archive.bridgesmathart.org/1999/bridges1999-279.html.

Swartz, Norman. 2019. “Laws of Nature.” Internet Encyclopedia of Philosophy. 2019. https://www.iep.utm.edu/lawofnat/.

Tochtermann, Klaus. 2018. “Towards the European Open Science Cloud - The Role of Computer Science.” ECSS 2018 Informatics Europe Conference - Keynote Talk. 2018. http://www.informatics-europe.org/images/ECSS/ECSS2018/Slides/ECSS2018_Tochtermann.pdf.

Tuana, Nancy. 2015. "Coupled Ethical-Epistemic Analysis in Teaching Ethics. Critical Reflection on Value Choices." *CACM* 500 (12): 27–29.

White, Roger. 2019. "Urban Morphogenesis: Putting Mathematics in Its Place." In *The Mathematics of Urban Morphology*, edited by Luca D'Acci, Book Serie. Springer International Publishing.

White, Roger, and Wolfgang Banzhaf. 2019. "Putting Natural Time into Science." In *A. Adamicky and V. Kendon, "From Astrophysics to Unconventional Computing. Essays Presented to Susan Stepney on the Occasion of Her 60th Birthday",* 1–21. Springer Nature Switzerland.

Whitehead, A. N. 1967. *Adventures of Ideas*. First edit. Cambridge: Cambridge University Press.

Wikipedia authors. 2019a. "Branches of Science." Wikipedia, The Free Encyclopedia. 2019. https://en.wikipedia.org/wiki/Branches_of_science.

———. 2019b. "List of Academic Fields." Wikipedia, The Free Encyclopedia. 2019. https://en.wikipedia.org/wiki/List_of_academic_fields.

Wolfram, Stephen. 2002. *A New Kind of Science*. Wolfram Media.

Zenil, Hector. 2012. *A Computable Universe. Understanding Computation & Exploring Nature as Computation*. Singapore: World Scientific.

Zhong, Yixin. 2011. "Unity-Based Diversity. System Approach to Defining Information." *Information* 2 (3): 406–16.

———. 2017. "Information Ecology and Information Studies." *Proceedings* 1 (3): 200.

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Dodig Crnkovic, G. and Burgin, M. (2019) Philosophy and Methodology of Information: The Study of Information in the Transdisciplinary Perspective. *World Scientific Series in Information* Studies, Vol 10. World Scientific, Singapore. https://www.worldscientific.com/worldscibooks/10.1142/11190.

Dodig Crnkovic, G. and Burgin, M. (2019) The Study of Information in the Context of Knowledge Ecology. In: Dodig Crnkovic & Burgin (2019) *Philosophy and Methodology of Information: The Study of Information in the Transdisciplinary Perspective*. World Scientific Series in Information Studies, Vol 10. World Scientific, Singapore. https://www.worldscientific.com/worldscibooks/10.1142/11190.

Giovagnoli, R., Crucitti, A., Dodig Crnkovic, G. (2019) *Robotics and the quality of life: the case of robotics assisted surgery.* philinq VII, 1-2019, pp. 71-82. https://www.philinq.it/index.php/philinq/article/view/240 ISSN (print) 2281-8618-ETS.

2018

Dodig Crnkovic, G. (2018) Cognition as Embodied Morphological Computation. *Philosophy and Theory of Artificial Intelligence* 2017: 19-23. http://dx.doi.org/10.1007/978-3-319-96448-5.

Dodig Crnkovic, G. and Marcin Schroeder (2018) Contemporary Natural Philosophy and Philosophies, *Philosophies* Vol. 3 Issue 42 p. 1-4.

Holstein, T.* Dodig-Crnkovic G. and Pelliccione P. *Ethical and Social Aspects of Self-Driving Cars,* http://arxiv.org/abs/1802.04103.

Holstein, T.* Dodig-Crnkovic G. Avoiding the Intrinsic Unfairness of the Trolley Problem. Avoiding the Intrinsic Unfairness of the Trolley Problem, *IEEE/ACM International Workshop on Software Fairness* (FairWare), Gothenburg, 2018, pp. 32-37. doi: 10.23919/FAIRWARE.2018.8452918

Mikkilineni, R. et al. (2018) SE4COG '18: Proceedings of the 1st International Workshop on Software Engineering for Cognitive Services. Proceedings (editor), 2018 ICSE 2018 Gothenburg, Sweden, 2018-05-27. https://dblp.org/db/conf/icse/fairware2018.

2017

Burgin M. and Dodig-Crnkovic G., Prolegomena to Information Taxonomy. *Proceedings 2017*, 1(3), 210; doi: 10.3390/IS4SI-2017-04035.

Dodig-Crnkovic G. and Cicchetti A. Computational Aspects of Model-Based Reasoning, Invited chapter in the SPRINGER HANDBOOK OF MODEL-BASED SCIENCE, 2017, pp. 695-718. https://link.springer.com/chapter/10.1007%2F978-3-319-30526-4_32.

Dodig-Crnkovic G. and Giovagnoli R. (Eds) *Representation and Reality in Humans, Other Living Organisms and Intelligent Machines*, Springer, Sapere book series, 2017.

Dodig-Crnkovic G. and Giovagnoli R. Introduction to the Proceedings of the Workshop “Habits and Rituals” at IS4SI-2017 Gothenburg, Sweden, 15 June 2017 *Proceedings 2017*, 1(3), 235; doi: 10.3390/Proceedings1030235.

Dodig-Crnkovic G. and Giovagnoli R. *Preface. Representation and Reality in Humans,* Other Living Organisms and Intelligent Machines, Springer, Sapere book series, 2017.

Dodig-Crnkovic G. and Lowe R., Morphological Computing and Cognitive Agency. *Proceedings 2017,* 1(3), 185; doi: 10.3390/Proceedings1030185.

Dodig-Crnkovic G. and von Haugwitz, R*. Reality Construction in Cognitive Agents through Processes of Info-Computation. In: Dodig-Crnkovic G. and Giovagnoli R. (Eds) *Representation and Reality in Humans, Other Living Organisms and Intelligent Machines*, Springer, Sapere book series, 2017.

Dodig-Crnkovic G. Introduction to the Proceedings of the is4si-2017 Summit of the International Society for the Study of Information on Digitalization for a Sustainable Society: Embodied, Embedded, Networked, Empowered through Information, Computation & Cognition! Gothenburg, Sweden, 12–16 June 2017. Proceedings 2017, 1(3), 275; doi: 10.3390/Proceedings1030275.

Dodig-Crnkovic G., Kade D.*, Wallmyr M.*, Holstein T.* and Almér A. Transdisciplinarity seen through Information, Communication, Computation, (Inter-) Action and Cognition. Chapter in the book: *Burgin and Hofkirchner*, eds.

Dodig-Crnkovic, G., Nature as a Network of Morphological Infocomputational Processes for Cognitive Agents, *The European Physical Journal Special Topics,* DOI: 10.1140/epjst/e2016-60362-9 Eur. Phys. J. 2017, 226, 181–195.

INFORMATION STUDIES AND THE QUEST FOR TRANSDISCIPLINARITY - vol. 9 of the World Scientific Series in Information Studies, 2017, *World Scientific.* pp. 217-261 http://arxiv.org/abs/1604.04711.

Johnsen A.*, Dodig-Crnkovic G., Lundqvist K., Hänninen K., Pettersson P. Risk-based Decision-making Fallacies: Why Present Functional Safety

Standards Are Not Enough. MARCH2017 International Workshop on Decision Making in Software Architecture @ ICSA 2017 Gothenburg, Sweden. 04.04.2017. Published in: Software Architecture Workshops (ICSAW), 2017 *IEEE International Conference*. doi: 10.1109/ICSAW.2017.50.

Lowe R., Dodig-Crnkovic G., Almér A. Predictive Regulation in Affective and Adaptive Behaviour: An Allostatic-Cybernetics Perspective; In: Vallverdú J., Mazzara M., Talanov M., Distefano S., Lowe, R. (Eds) Advanced Research on Biologically Inspired Cognitive Architectures. A volume in the Advances in Computational Intelligence and Robotics (ACIR) Book Series. IGI Global. 2017. pp. 148-177.

Schroeder M. J., Marijuán P. C. and Dodig-Crnkovic G. Seventh International Conference on the Foundations of Information Science (FIS 2017): Structure, Dynamics, Complexity in the Informational Nature. *Proceedings 201*7, 1(3), 69; doi: 10.3390/proceedings1030069.

2016

Crnkovic I., Dodig-Crnkovic G. Digitalisation as a Strategic Choice at University – Challenges in Research and Education ECSS 2016 Budapest. Informatics Europe. *European Computer Science Summit*. (Conference position statement) 23.10.2016.

Dodig-Crnkovic, G. and Sapienza, G.*, *Ethical Aspects of Technology in the Multi-Criteria Decision Analysis.* IACAP conference, Ferrara, June 14-17, 2016.

Dodig-Crnkovic, G., Information, Computation, Cognition. Agency-Based Hierarchies of Levels. (Author's draft). *FUNDAMENTAL ISSUES OF ARTIFICIAL INTELLIGENCE*, Müller V. C. (ed.), Synthese Library 377, pp 139-159.

Dodig-Crnkovic, G., Morphological computing as reality construction for a cognizing agent, In: Almér A., Lowe, R., Billing E., *Proc. SWECOG 2016 conference*, Gothenburg Oct. 6-7 2016.

Dodig-Crnkovic, G., Morphological computing as self-organization of a cognizing intelligent agent, First International Conference on

Intelligence Science (ICIS2016), Chengdu University of Technology, Chengdu, China, 2016/11/01.

Sapienza, G.*, Dodig-Crnkovic, G. and Crnkovic, I. Inclusion of Ethical Aspects in Multi-Criteria Decision Analysis. Proc. WICSA and CompArch conference. Decision Making in Software Architecture (MARCH), *2016 1st International Workshop*. Venice April 5-8 2016. DOI: 10.1109/MARCH.2016.5, ISBN: 978-1-5090-2573-2. *IEEE.*

Springer International Publishing Switzerland 2016, DOI 10.1007/978-3-319-26485-1_10. http://arxiv.org/abs/1311.0413 http://arxiv.org/abs/1311.0413.