The Info-Computation Turn in Physics

Israel Belfer
Bar Ilan University, Israel

Abstract

Modern Computation and Information theories have had significant impact on science in the 20th century - in theory and application. This influence is tracked (through a generalized, *Information-laden* scientific Style of Reasoning denoting the Information-theoretical and Computational turn in science), with a focus on the information processing and transfer metaphors and descriptive tools prevalent in current physics. Implementation of Information-Theoretical concepts produces such mathematical physical developments as Black-Hole Thermodynamics (BHTD) and the Black-Hole War. The treatment of physical systems as information processing systems drives such branches of physics as Quantum Information Theory (QIT). The common Informational basis of computation and communication brings about a foundational shift in scientific reasoning with deep – potentially problematic as well as intriguing – philosophical ramifications. Models of computation and of physics

1 Scientific Revolutions through a New Style of Reasoning

Conceptions (Rolf Landauer, 1991) of physical reality as an Information[1] -processing system permeate current science -- from rigorous statistical analysis (thermodynamics of black holes), through semantic aspirations to world-views such as Extreme Digital Ontology. Information processing ontologies are heralded as new Galilean world-systems of Info-Computationalism.[2] As pervasive (Gleick, 2011) and perhaps overused a concept as it is – Information is heralded by some as 'the new language of science' (Baeyer, 2004). Even if accepted, this role requires a finer tuned description, offered by Hacking's Styles of Reasoning. This brand of metaconcepts (Hacking, 1992, 2004) enables a description of a science imbued with information processing and transmission terminology. Hacking's Styles (adopted from Crombie[3]) come about through scientific revolutions, quieter than paradigm-shifts or the great scientific revolutions of the 20th century, but with deep impact on science and society.

---

1 The term "Information" will – unless explicitly defined otherwise – refer to the leanest technical definition in binary digits that constitute the units of digitized information in modern computation and computation theories (C.E. Shannon, 1948).

2 Cf. (Dodig-Crnkovic and Burgin 2011, 149–184): "A Dialogue Concerning Two World Systems: Info-Computational vs. Mechanistic", for an outline of internal conceptual differences between different modes of scientific modelling – those infused with Information and the classical world system of energy and matter. The emphasis here is more on the confluence of Information's various uses and the way they change physical modelling – and reciprocally redefining elements of computation.

3 (Hacking, 1982), p.161 – the list includes: *simple mathematical postulations; experimentation; modeling; taxonomy; statistical reasoning; and historical-genetic development*. Styles are discursive ('reasoning' - rather than Crombie's conceptual 'thinking') meta-concepts in science, describing motifs of epistemic sense-making (for the scientific, epistemic and social spheres); broad cross-disciplinary motifs in scientific and institutional spheres. Styles permeate many aspects of scientific research and their respective sociological, political and cultural setting. Unlike other meta-concepts that organize the scientific weltanschauung , different styles can co-exist with previously established ones. The criteria for a new Style, and its associated 'revolution' (Schweber and Watcher, 2000; Hacking, 1993) include a new scientific vocabulary as well as a wider social and conceptual context – an impact on multiple disciplines and new institutions relying on the standards for rationality given by the meta-conceptual frame of the style.

Hacking's Styles of Reasoning as listed by Hacking (Hacking, 1982) (following the historical outline laid out by Crombie (1995)) are meta-concepts that arrange the scheme of ideas and practices in science and society. Not precisely paradigm-shifts - closer to Foucalts *epistemes* - They are the conceptual schemes in which (In Hacking's words) researchers:

" ...researchers look actively for problems to formulate and solve, rather than for an accepted consensus without argument. The varieties of scientific method so brought into play may be distinguished as:

(a) the simple postulation established in the mathematical sciences,

(b) the experimental exploration and measurement of more complex observable relations,

(c) the hypothetical construction of analogical models,

(d) the ordering of variety by comparison and taxonomy,

(e) the statistical analysis of regularities of populations and the calculus of probabilities, and

(f) the historical derivation of genetic development.

The first three of these methods concern essentially the science of individual regularities, and the second three the science of the regularities of populations ordered in space and time."

The rise of a Style of Reasoning manifests in a *Hacking-Type Revolution* (Coined by Schweber (2000, p. 583)), which is the process of the new Style's asserting itself. I posit that the computation-communication turn marks the rise of a new Style of Reasoning, involving its own revolution, a process with distinct features of scientific agendas, new semantic fields, institutions and social influence. In a nutshell, it is an *emplacement* rather than *replacement* revolution (Humphreys, 2011, p. 132). The latter is the more prominent kind, where the old system is abandoned in concept, theory or practice. The former is a change in the way science is done that does not forgo the existing methods and ideas. The existing disciplines are not replaced but rather slide into the new world-system, driven by a new terminology like a Munchousian wolf substituting the horse from within in midstride, pulling the carriage all the way to St. Petersburg. There is no incommensurable gap between the two world-systems, and yet a new language takes over.[4] According to Hacking (1992, pp. 130–157), a new Style boasts new sentences, new objects of research, and criteria for law-like regularities. Reasoning – unlike Crombie's thinking – relates to multiple levels of scientific discourse: the conceptual, experimental, sociological.

Schweber & Watcher (2000, p. 585) recognized in the computational (Information-processing) revolution the rise of a new Style:

"We are witnessing another Hacking type revolution, which for lack of a better name we call the 'complex systems modeling and simulation' revolution, for complexity is one of its buzzwords and ***mathematical modeling and simulation on computers constitute*** *its Style of Reasoning".*

I propose that this Style and its associated Hacking-type revolution be incorporated into the ubiquity of Information-Theoretical and Information-Processing terminology in science (Baeyer, 2004), creating a generalized form of the shift based on Information concepts: That is, a Hacking-Type revolution of Information-laden science, with *digitized Information* as its Style. Digitized Information relates to the entire gamut of modern communication and computation. This revolution is subtle but pervasive; at its core - the concept of Information in science and society, from the practice

---

4 Hacking's criteria for such subtle revolutions are (Hacking, 1982, 1992), used by Schweber & Watcher (2000, p. 583): *i) They transform a wide range of scientific practices and they are multi-disciplinary. In a Hacking-type revolution something happens in more than one discipline; a multiplicity of scientific disciplines are transformed. ii) New institutions are formed that epitomize the new directions. iii) They are linked with substantial social change. After a Hacking-type revolution there is a different feel to the world, there is a marked change in the texture of the world. iv) Because they are "big" there can be no complete, all-encompassing history of a Hacking type revolution.*

of e-science[5] to the revamped Platonist and Pythagorean ontologies identifying physical reality with number and word.

By expanding on the same theme of an Information-processing Hacking type revolution to include Information transmission – such as theories communication and cryptography – one achieves more than a parceling together of a theoretical basis for these fields, or even of their accumulative technological impact, since communication and computation – Information transfer and processing – are inextricably linked theoretically and practically. The celebrated father of Information theory Claude Shannon (1948), also devised the electronic representation of Boolean logic in his Master's thesis. The common thread connecting all of these theoretical approaches and applied technologies is the modern concept of quantified Information.

2 Elements of Information-Laden Physics

2.1 Information Processing

Scientific laws are now being viewed as algorithms. Many of them are studied in computer experiments. Physical systems are viewed as computational systems, processing information much the way computers do. New aspects of natural phenomena have been made accessible to investigation. A new paradigm has been born.[6]

The computational aspect of the shift in science has been described as a new Style of Reasoning (Schweber & Watcher, 2000). Using computers and programing changes the way we perceive logical reasoning and rationality. Older metaphors of the clockwork universe (or the older paragon of technology – the waterwheel and camshaft) are supplanted in favor of a new one, be it an abstract Turing Machine or an actualized physical computer. The discussions surrounding the Church-Turing thesis often revolve around the point of weak vs. strong computation-physics analogies.[7] In a new Informational Style, this is transcended by the physical giving way in the hierarchical order of explanatory modeling. Computational modeling and problems such as N-P completeness - usually not at the top of the list of worries for a physicist who sees natural systems evolve easily through NP-hard configurations (Yao, 2003) - are in this context just as close to the heart of physical ontology as the classical realist and mathematical modeling issues (Wolfram, 1985).

In order to identify the Informational core of the Hacking type revolution brought on by computation and simulation, it is important to recognize the close relationship between computation and communication theories from their wartime crucible[8], to their joint influence on physics through

5 The term used to describe scientific research that is highly intensive in its use of computation (simulation, numeric analysis) and communication (networks of machines, institutes, research groups and individuals) technologies. Powerful processing and storage capacities are applied to extremely large of experimental data-sets. The term was coined by John Taylor, Director General of the United Kingdom's Office of Science and Technology <http://www.nesc.ac.uk/nesc/define.html>. Such projects as the LHC depend as much on IT as on the science, and are inherently collaborative efforts in a networked scientific community that is an intrinsic part of the Information-Age.

6 (Wolfram, 1984). The ontological version of this statement should not be taken as an expression of mainstream physics but as a digital-physics application of it, *cf.* Steven Weinberg's (Weinberg, 2002) remark on the cellular automata of Wolfram's pan-computationalism, dismissing it as the computer-centricity of "a lapsed particle physicist" that finds the inspiration for laws of nature in the tools of his craft (albeit he does not dispute the possibility of this direction to be fruitful, only the sources of Wolframs convictions).

7 Penrose (1989, p. 49, 1994, pp. 20–21) is a classic example of delving into the issue of the Church-Turing Thesis with classical terminology (dividing the algorithmic, the physicality and the computation into separate philosophical questions), but dealing with the question of its significance as a physical problem (not accepting the full weight as such).

8 It is not difficult to see the way communication and computation as inextricable from each other in the hindsight of the current state of telecommunication and the internet. What should be appreciated is their association at the source, with Shannon, Weaver (Claude Elwood Shannon & Weaver, 1949), and Wiener's cybernetics (Wiener, 1948). Shannon is not only the formulator of Information Theory (1948), but he wrote his Master's Thesis at MIT (Claude E. Shannon, 1938; Claude Elwood

the common denominator as used by Bennett (1973) in the analysis of reversible computing and its inextricable relation to entropy of Information. In the intense cauldron of the technological and scientific efforts in World War II, the new brand of mathematical logic that evolved into computation theory and application, joined with the efforts in cryptography, data analysis and communication. The new Style is the result of those efforts, expressed in the highly interconnected Cybernetics[9], Computation and Information Theories and their social and scientific ramifications. Information is shaped conceptually by the attempts to manage the boundary between order and disorder – by calculation and algorithmic definitions of complexity[10], ultimately describing physical reality through it – by numerically solving equations or simulating the dynamics of state-evolution.

The end result of the 20th century's development of Information technology and dealing with subtle connections between physics and information, culminate for the digital physicists in a research project on the scale of science itself (Wright, 1988, p. 4):

Here [at the interface of computer science and physics] two concepts that traditionally have ranked among science's most fundamental — matter and energy — keep bumping into a third: information. The exact relationship among the three is a question without a clear answer, a question vague enough, and basic enough, to have inspired a wide variety of opinions. Some scientists have settled for modest and sober answers. Information, they will tell you, is just one of many forms of matter and energy; it is embodied in things like a computer's electrons and a brain's neural firings, things like newsprint and radio waves, and that is that. Others talk in grander terms, suggesting that information deserves full equality with matter and energy, that it should join them in some sort of scientific trinity, that these three things are the main ingredients of reality.

The connection of computation and physical reality requires more than an abstract relation. The scientific mode of reasoning needs to be piqued by the limits of Information processing and its analogy to natural processes. Feynman's wonderment in the face of space-time's ability to maintain a process that would take an enormous amount of computing power makes him (as in other cases) the prophet of modern digital physics and quantum computation (Feynman, 1994, p. 51):

It always bothers me that, according to the laws as we understand them today, it takes a computing machine an infinite number of logical operations to figure out what goes on in no matter how tiny a region of space, and no matter how tiny a region of time. How can all that be going on in that tiny space? Why should it take an infinite amount of logic to figure out what one tiny piece of space/time is going to do? So I have often made the hypotheses that ultimately physics will not require a mathematical statement, that in the end the machinery will be revealed, and the laws will turn out to be simple, like the chequer board with all its apparent complexities. [11]

This observation echoes the later styles of Wolfram's New Kind of Science (Wolfram, 2002) and the role of cellular automata in the digital physics espoused by Fredkin (Fredkin, 1992), but these

---

Shannon, 1940) -- A Symbolic Analysis of Relay and Switching Circuits – electric switching implementing electrically the algebra of logic. This is the modern computer, the electric manifestation of Turing's machine (Shannon and Turing and during the war, and they could only talk about what they were not working at the time – machines that could think. *Cf.* (Gleick, 2011, p. 3).

9 Brillouin, a major contributer to the Information-physics connection, was first inspired to expand on IT's potential in physics by the confluence of communication and computation in the new science of Cybernetics. He read Norbert Wiener's Cybernetics in which he posits that "Information means negative entropy" (and somewhat patronizingly reminds the readers of Shannon & Weaver, (1949) in his review in in Physics Today, September 1950). Brillouin started thinking about the way Information is measured in relation to entropy in physics and published some of his initial analysis of the book and its subject (Leon Brillouin, 1956; 1962). His concept of Negentropy as a measure of lack of Information was published in his book on physics and IT and was part of the Information-context that enabled Jacob Bekenstein to develop an entropy function for black holes (Jacob D. Bekenstein, 1973)

10 Algorithmic Information measures and Kolmogorov complexity (1977; Gregory J. Chaitin, 1966) tie computer theory and Information Theory back together, by defining the Information content of a system/string as the shortest length of code necessary to create it (or simulate it).

11 Originally this was a lecture in 1957, part of the Character of Physical Law lecture series.

directions are inherently non-continuous, aiming at digitizing physical ontology, a project Feynman did not endorse in this observation.

The common basic unit of Information lies at the root of Information and Computation theories.[12] There is a strong genealogical connection as well: The historical wartime efforts that combined communication, cryptography and computation; the technological and theoretical digitization basis of both, and the later rise of a networked world of computers and communication lines; the conceptual confluence of communication and computation, Information and control in cybernetics[13](Müller & Müller, 2007). It was through the analysis of reversible computation that the relation between erasure and entropy gain was recognized by Landauer[14] – and capitalized on by Bekenstein.

Schweber and Watcher identified computation and its applications as a Hacking-type scientific revolution, and followed some of its key features in chemistry and physics. As computation and communication are the woof and warp of the same Information-oriented cloth of 20th century technology, society and science, the character of the Hacking-type revolution they identified as computation-simulation, can be understood fully through the impact of IT on science. Thus the basic element in both – Information - becomes unmistakably evident.

Going beyond the traditional connection of computation and physical reality, uing draws an analogy that is closer to the way a discipline is practiced and the key problems it deals with (Turing & Copeland, 2004, p. 421):

There is a remarkably close parallel between the problems of the physicist and those of the cryptographer. The system on which a message is enciphered corresponds to the laws of the universe, the intercepted messages to the evidence available, the keys for a day or a message to important constants which have to be determined. The correspondence is very close, but the subject matter of cryptography is very easily dealt with by discrete machinery, physics not so easily.

The 20th century saw the development of "hard" mathematical-physics branches imbued with IT, *Information-laden* in that they owe their existence and intelligibility to Information processing neo-Pythagorean (Steiner, 1998) metaphors and technically defined tools:

2.2 Information Transfer

Following the earlier Informational context of thermodynamics – from Maxwell's demon to Brillouin's Negentropy - Jakob Bekenstein's seminal work on Black Hole Thermodynamics (BHTD) (J. D Bekenstein, 2006; Jacob D. Bekenstein, 1973) made use of the IT *quantification of unknown Information* in describing gravitational singularities as Thermodynamic entities. The Information-content of this physical state and its upper bound, were later applied to the mundane matter, propelling Fields of research such as Quantum Information Theory, and String Theory(Susskind, 2008). BHTD and later M-Theory produced the Holographic Principle (Hooft, 1993; Susskind, 1995) according to which the physical system is encoded onto its surface area (N-1 dimensionality).

QIT is where Information processing and transmitting are the ruling conceptual scheme, with inherent constraints and possibilities – cloning, transporting, quantum encoding – defining the contours of classical quantum mechanics in an information-processing mode. Seth Lloyd's depiction (Lloyd, 2006) of the world-as-a-quantum-computer ("it's all bit-flipping!" as he puts it) is a paragon of Information-laden physics, in the digital ontology but even more importantly in the semantic

---

12 This statement does not replace the existing picture of computation's relation to logic, or Information theory to statistics. The notion of a binary digit is, however, responsible for the actualized success of these disciplines separately and together.

13 The close personal and professional relationship between Shannon and Weaver resulted in the second addition of the Mathematical Theory of Communication (Claude Elwood Shannon & Weaver, 1949) with Weaver's introduction.

14 This analysis of computer science plays a crucial role in moving the IT-physics connection to the next stage. Landauer connected the loss of Information to energy investment, in what came to be known as "Landauer's principle" (R. Landauer, 1961; 1991)– "Information is Physical". The principle is that Information erasure is the fundamental irreversible aspect of the generalized Carnot cycle involving a Maxwell's demon.

condensing of the complexity of physical dynamics into the language of Information processing: "It's all bit-flipping"; but perhaps more than pan-computationalism, it is an opportunity to revisit foundational quantum issues in a new light, as in the work of Quantum-Bayesians (Fuchs, 2010).

Wheeler adopts Information even closer to the heart of physics (Wheeler, 1990), asserting that every physical object is essentially Informational in his famous aphorism "It from Bit", in a way that combines information-processing and Information-transfer. Through the foundational 'observer problem' in quantum mechanics, the informational aspect turned into a basic element of physical reality by John Archibald Wheeler (1990, p. 5):

It from bit. Otherwise put, every 'it' – every particle, every field of force, even the space-time continuum itself – derives its function, its meaning, its very existence entirely – even if in some contexts indirectly – from the apparatus-elicited answers to yes-or-no questions, binary choices, bits. 'It from bit' symbolizes the idea that every item of the physical world has at bottom – a very deep bottom, in most instances – an immaterial source and explanation; that which we call reality arises in the last analysis from the posing of yes–no questions and the registering of equipment-evoked responses; in short, that all things physical are Information-theoretic in origin and that this is a participatory universe. [15]

This participatory universe combines the quantum mechanical problem of the observer, with the Information theoretical concepts developed by Wheeler's student, Bekenstein, and his own concept of a computationally driven physical reality.

A Style-of-Reasoning helps in situating such a radical claim – not necessarily on the map of philosophy or physics (though it certainly stands there), but rather as a scientific- epistemic approach to identifying what the tough questions are, the character of nature. Wheeler saw it as an inauguration of a discipline in science, a research program that he actively encouraged young researchers to take up.

2.3 Examples from physics

Information-laden physics owes much to Maxwell's demon, especially to the work by Bennett and Landauer regarding information erasure and reversible computing, connecting Information processing, storage, transfer – with basic physics of thermodynamics. From there, the informational context was expanded to the confluence of quantum mechanics and general relativity by Jakob Bekenstein who studied gravitational singularities (as well as quantum mechanical objects) in Information-theoretical terms. His approach was expanded on in M-theoretical Holographic principle according to which physical reality is encoded on the hypersurface of the N-dimensional system (loop-quantum gravity also relates to his work on the entropic bound and spectra from black holes, relying on informational bounds).

Lloyd (Lloyd, 2006) explains that physical reality computes itself, regarding the operations of quantum mechanical systems as computations – whether tracked or not. This goes much further than the explicit aims of finding out the behavior of Information in quantum systems (Quantum Information – teleportation, no cloning, etc.) or devising specific factorization algorithms that run faster than classical computers (Quantum Computation – Holevo bound, Shor factorization), but it is a growingly pervasive conception of physical systems in the QIT community.

15 First Presented as: "It From Bit", *3rd International Symposium on Foundations of Quantum Mechanics*, Tokyo 1989.

3 Conceptual Impact

Let us examine some claims made by physicists over the past few decades: Black Holes have entropy; this entropy is a measure of Information (Bekenstein, 1972; 1973). It is also tied in with the surface area of the singularity. Information that falls into a black hole is encoded on its surface area. According to the Holographic Principle (Maldacena & Susskind, 1996), the entire physical system of the universe is in fact encoded on the surface area circumscribing it. The world is thus made safe for quantum mechanics and for physical science as a whole requiring Information-conservation as a fundamental aspect of physical reality (Susskind, 2008, pp. 9, 179).

The previous paragraph is made up entirely of sentences that are distinctly Information-laden in that they could carry no meaning at the time before Information saturated the physical description of the world, and are therefore Hacking's *new sentences*. The objects described in it are *new objects* in the same sense. Their identity relies on scientific conjectures and theoretical analysis. This new jargon is not just a set of freshly minted words and newly formalized definitions for scientific analysis and experimental strategy. It is what the emergence of "the normal" was to the statistical style at the turn of the 19th century – a new way to make sense of the world that makes the new Jargon seem completely natural.[16]

New linguistic and technical objects in Hacking's Styles of Reasoning are new semantic fields, truth-carrying niches in which sentences can be formed with regard to denizens of these spaces. Being so well-accepted into the scientific and colloquial language, the new jargon makes it almost impossible to describe situations in a time before the rise of this style without historical over-extension, using its terms anachronistically. Such sentences refer to an age when they would simply make no sense[17] if uttered (example: Information-conservation as an indispensible foundation in science).[18] Also, earlier suggestions that did not receive much attention early on garner renewed attention and development - digital physics as a case in point.

From the new names to the law-like regularities governing them and the status of their investigation as a scientific practice, the new topics in physics are the woof and warp of a bona-fide Hacking-type revolution. Schweber and Watcher offer computation and simulation as a style, relating to new branches of complexity and chaos and dealing with the conceptual issue of emergence reductionism. Adding the measures of Information and their role in science generalizes this to an Information-laden Hacking-type revolution.

3.1 Philosophical Implications

The philosophical standing of a digitized physical ontology leaves much to be desired, as pointed out by Floridi's analysis of Ontological vs. Structural Information (Floridi, 2011, chap. 14, 15). That being said, one should take stock of where Informational concepts have taken science – albeit without perfect philosophical grounding: a new quazi-substance; descriptive tool; a new dynamic of processing and state evolution; element of structure. Even more importantly, Information analysis changed the goals of scientific endeavor: new problems of Information conservation, analysis of Information processing, capacity and transfer in physical systems, are bona-fide physical interests. In the history of ideas, this is a significant phase in the course of scientific trajectory.

There are philosophical issues unique to the new Style of Information-laden Science:

16* When reduced to terms that existed in the scientific past (information in terms of statistics or dynamic processes), the language becomes unmanageable. But it is not just a matter of shorthand and scientific slang. The new sentences make claims that are incoherent without the centrality of Information and its network of application to support them. The texture of theory and reality slides into a new language game.

17 Hacking uses the Statistical Style of Reasoning (Hacking, 1990, pp. 160–169, 180–188) to illustrate this point.

18* Unlike a Kuhnian paradigm shift, this retroactive application of name and identity to a research question or thought-experiment is not necessarily an over-extension of the vocabulary (unless attempted by a historian). Once a style is functional it is not a fallacy to apply it to subjects that have not had its benefit before.

The first is *the advent of a new principle- theoretical physical reasoning*, based on Information conservation or similar notions.

The principle approach to constructing theories is an assumption of pre-established guidelines for Natural law. The most famous example is Einstein's work on relativity.[19] Principles regarding Information - such as conservation principles or bounded[20]. What marks most scientific principles is their *boundedness* - they pertain to a set of variables or objects that are constrained so that laws derivable from them take on a specific shape, sometimes with far-reaching results, but with a predefined purview.

What happens with Information in science is more general: for example, an assumption about the conservation of Information (Susskind, 2008; Hawking, 2004)[21] pertains to the scientific enterprise as a whole, the very possibility of discerning any regularities and law-like behavior of nature.[22]. As far as principles in science go – this one is not an emergent phenomena or a constraint on the behavior of possible theories, but a predefined setting for any and all scientific descriptions. This absoluteness is extreme but also very simple: going out of bounds with Information in physical systems means that there is no way for a system to 'keep track' of its own development. In classical systems – it is the requirement of reversibility, in quantum mechanics, the unitarity of operators. This fundamental *necessary* principle has also been suggested[23] - albeit not widely accepted - as *sufficient* for deriving the laws of nature under investigation in modern science.

The second philosophical point regarding IT in science, especially physics, is its core as the quantification of unknowns. Its formulation into the statistical function of entropy, was named *negentropy* by Brillouin (Leon Brillouin, 1956) for this reason. This is the same element that Bekenstein made use of when coming up with the GSL for black holes, describing what is unknown about matter falling into a singularity, and utilizing that description's mathematical homology with entropy. It is also what insures that "Information is Physical" (Rolf Landauer, 1991) – the entropy cost in the operation of Maxwell's demon coming into play specifically through the *erasure* of its memory in the generalized Carnot cycle (Kanter & Shental, 2009). It partly inherits this trait from the Bayesian strand of statistical theory, and some of the earliest proponents of IT's incorporation into science saw it as a true application of Bayesianism into physics (Jaynes, 1957a, 1957b)

3.2 Pan-Computationalism

Another topic of philosophical concern is the ontological significance of questions from the realm of computer-science such as computational complexity (Aaronson, 2005; Aaronson & Wigderson,

---

19 In thermodynamics, the principle of equivalence of heat and work set the stage for the laws developed by Clausius, Karnot and Gibbs (Needham, 2011, pp. 3–6).

20 "…a principle of information invariance or information preservation. It seems reasonable to compare this principle, in a metaphoric way, with the principle of energy preservation in physics." (Klir, 2006, p. 388).

21 In an Information-laden Style, these early scientific issues become an inherent part of the new canon in the retrospective view of the discipline's memory. Physics that places Information-conservation as a "the most basic law of science" upon which all of science (sic!) for the past 300 years stands (Susskind, 2008, p. 9).

22 Assuming that Information is conserved is described by Susskind as the basis for all of science since Newton, that is – it is the prerequisite for developing any stable dynamic description of physical systems, since information is defined by him to be that which is needed for the system to progress in time from one state to another. The subjectivity of knowledge, or the separation between information and its carriers, are not the issue, as it would be detrimental in his view for the scientific enterprise to have within nature the possibility of irrevocably lost Information. Whether Information is an objective or subjective construct is not the issue (though Susskind himself holds a conservative point of view on this issue).

23 The description of mathematical operations essential to the manipulation of information (encoding, decoding and transmission) became prominent metaphor and practical tool for scientific work, and the myriad of information measures (Arndt, 2004) and the physical instruments dedicated to Information measurement (Gershenfeld, 2000) are at the crux of some central branches of physics today (Bais & Farmer, 2007; Karnani, Pääkkönen, & Annila, 2009), and according to some Information-enthusiasts are basic generating principles for the entirety of physics (Frieden, 1998) and science (Frieden, 2004) in what is known as Extreme Digital Information.

2009)[24]. A philosophical issue that is a staple of Information-laden science is that of computability and physical reality. This is a cluster of topics – discussions of the Church-Turing thesis and their applications in explicit Quantum-Information research (Deutsch, 1985)[25]; The Zuse (1970, 1982) technical-computational universe; The redefinition of N-P complete problems in the realm of computational complexity or an Informationally bound Holographic Universe. The Turing thesis is at the core of all these various discussions, taking on acute physical relevance in the context of a world quantified and described in term. Its shortcomings and potential explanatory power are both magnified in Information-laden science.

References

Aaronson, S. (2005). Guest Column: NP-complete problems and physical reality. *SIGACT News*, *36*(1), 30–52. doi:10.1145/1052796.1052804

Aaronson, S., & Wigderson, A. (2009). Algebrization: A new barrier in complexity theory. *ACM Transactions on Computation Theory TOCT*, *1*(1), 1–54. doi:10.1145/1490270.1490272.

Arndt, C. (2004). *Information Measures: Information and Its Description in Science and Engineering*. Springer.

Baeyer, H. C. V. (2004). *Information: The New Language of Science*. Harvard University Press.

Bais, F. A., & Farmer, J. D. (2007). *The Physics of Information*. Retrieved from http://www.citebase.org/abstract?id=oai:arXiv.org:0708.2837

Bekenstein, J. D. (2006). *Of Gravity, Black Holes and Information*. Di Renzo Editore.

Bekenstein, Jacob D. (1973). Black Holes and Entropy. *Physical Review D*, *7*(8), 2333–2346. doi:10.1103/PhysRevD.7.2333

Bennett, C. H. (1973). Logical reversibility of computation. *IBM J. Res. Dev.*, *17*(6), 525–532. doi:10.1147/rd.176.0525

24 Also discussed by Widgersen in his lecture - “Computational Complexity and Modeling Physical Reality”, Lecture on June 6th, 2010, at the Hebrew University, Jerusalem, “Symmetry in Physics” Research Workshop, Centenary of Giulio Racah (Israel Science Foundation event).

25 Deutsch asserts that “It is argued that underlying the Church-Turing hypothesis there is an implicit physical assertion. Here, this assertion is presented explicitly as a physical principle: **'every finitely realizable physical system can be perfectly simulated by a universal model computing machines operating by finite means'**. Classical physics and the universal Turing machine . . . do not obey the principle…” – along with the formative quantum-computation analysis, Deutsch shows the separation of attitude between classical physics and C-T and the underlying simulation principle. From the Information-laden point of view, the separation here is not between the physical and the conceptual, but between how classical physics is hypothesized and how the underlying assumption regards reality. The key feature in this distinction is Information as representation vs. Information as the subject matter.

Brillouin, Leon. (1956). *Science and Information Theory* (1st ed.). Academic Press.

Brillouin, Léon. (1962). *Science and information theory.* (2d ed.). New York: Academic Press.

Chaitin, G. J. (1977). Algorithmic information theory. *IBM JOURNAL OF RESEARCH AND DEVELOPMENT*, *21*, 350–359.

Chaitin, Gregory J. (1966). On the Length of Programs for Computing Finite Binary Sequences. *Journal of the ACM*, *13*, 547–569.

Crombie, A. C. (1995). *Styles of Scientific Thinking in the European Tradition: The History of Argument and Explanation Especially in the Mathematical and Biomedical Sciences and Arts*. Duckworth Pub.

Deutsch, D. (1985). Quantum Theory, the Church-Turing Principle and the Universal Quantum Computer. *Proceedings of the Royal Society of London. A. Mathematical and Physical Sciences*, *400*(1818), 97–117. doi:10.1098/rspa.1985.0070

Feynman, R. P. (1994). *The character of physical law*. Modern Library.

Floridi, L. (2011). *The Philosophy of Information*. Oxford University Press, USA.

Fredkin, E. (1992). Finite nature. *Progress in Atomic Physics, Neutrinos and Gravitation* (Vol. -1, p. 345). Presented at the Progress in Atomic Physics, Neutrinos and Gravitation. Retrieved from http://adsabs.harvard.edu/abs/1992pnap.conf..345F

Frieden, B. R. (1998). *Physics from Fisher Information: A Unification*. Cambridge University Press.

Frieden, B. R. (2004). *Science from Fisher Information: A Unification*. Cambridge University Press.

Fuchs, C. A. (2010). QBism, the Perimeter of Quantum Bayesianism. *arXiv:1003.5209*. Retrieved from http://arxiv.org/abs/1003.5209

Gershenfeld, N. A. (2000). *The Physics of Information Technology*. Cambridge University Press.

Gleick, J. (2011). *The Information: A History, a Theory, a Flood*. Pantheon.

Hacking, I. (1982). Language, Truth and Reason (pp. 48–66).

Hacking, I. (1990). *The Taming of Chance* (1st ed.). Cambridge University Press.

Hacking, I. (1992). “Style” for Historians and Philosophers. *Historical Ontology*, *23*(1), 1–20. doi:10.1016/0039-3681(92)90024-Z

Hacking, I. (2004). *Historical Ontology*. Harvard University Press.

Hooft, G. ’t. (1993). Dimensional Reduction in Quantum Gravity. *Salamfestschrift, A Collection of Talks from the Conference on Highlights of Particle and Condensed Matter Physics*, Bookmark and Share World Scientific Series in 20th Century Physics (Vol. 4). World Scientific Publishing Company. Retrieved from http://arxiv.org/abs/gr-qc/9310026

Humphreys, P. (2011). Computational Science and Its Effects. In M. Carrier, A. Nordmann, R. S. Cohen, J. Renn, & K. Gavroglu (Eds.), *Science in the Context of Application*, Boston Studies in the Philosophy of Science (Vol. 274, pp. 131–142). Springer Netherlands. Retrieved from http://www.springerlink.com/content/nq6q2721w4318174/abstract/

Jaynes, E. T. (1957a). Information Theory and Statistical Mechanics. *[[Physical Review]] Series II*, *106*(4), 620–630. doi:10.1103/PhysRev.106.620

Jaynes, E. T. (1957b). Information Theory and Statistical Mechanics. II. *Physical Review*, *108*(2), 171–190. doi:10.1103/PhysRev.108.171

Kanter, I., & Shental, O. (2009). Shannon meets Carnot: Generalized second thermodynamic law. *EPL (Europhysics Letters)*, *85*(1), 10006. doi:10.1209/0295-5075/85/10006

Karnani, M., Pääkkönen, K., & Annila, A. (2009). The Physical Character of Information. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Science*, *465*(2107), 2155–2175. doi:10.1098/rspa.2009.0063

Klir, G. J. (2006). *Uncertainty And Information: Foundations of Generalized Information Theory*. John Wiley & Sons.

Landauer, R. (1961). Irreversibility and heat generation in the computing process. *IBM J. Res. Dev.*, *5*(3), 183–191. doi:10.1147/rd.53.0183

Landauer, Rolf. (1991). Information is Physical. *Physics Today*, *44*(5), 23–29. doi:10.1063/1.881299

Lloyd, S. (2006). *Programming the Universe: A Quantum Computer Scientist Takes On the Cosmos* (First ed.). Knopf.

Maldacena, J. M., & Susskind, L. (1996). D-branes and Fat Black Holes. *Nuclear Physics B*, *475*, 679.

McMullin, E. (Ed.). (Notre Dame, Ind. : University of Notre Dame Press, c1992.). *The Social dimensions of science*. Studies in science and the humanities from the Reilly Center for Science, Technology, and Values ; v. 3. Notre Dame, Ind. :: University of Notre Dame Press.

Müller, A., & Müller, K. H. (2007). *An Unfinished Revolution?: Heinz Von Foerster and the Biological Computer Laboratory, BCL, 1958-1976*. Edition Echoraum.

Needham, P. (2011). *Commentary on the Principles of Thermodynamics by Pierre Duhem*. Springer.

Penrose, R. (1989). *The Emperor's New Mind: Concerning Computers, Minds, and the Laws of Physics*. Oxford ; New York: Oxford University Press.

Penrose, R. (1994). *Shadows of the Mind: A Search for the Missing Science of Consciousness*. Oxford ; New York: Oxford University Press.

Schweber, silvan, & Watcher, M. (2000). Complex Systems, Modelling and Simulation. *Studies In History and Philosophy of Science Part B: Studies In History and Philosophy of Modern Physics*, *31*(4), 583–609.

Shannon, C.E. (1948). *A mathematical theory of communication* (No. 27 :379). Bell System technical journal.

Shannon, Claude E. (1938). A Symbolic Analysis of Relay and Switching Circuits. *American Institute of Electrical Engineers, Transactions of the*, *57*(12), 713 –723. doi:10.1109/T-AIEE.1938.5057767

Shannon, Claude Elwood. (1940). *A symbolic analysis of relay and switching circuits* (Thesis). Massachusetts Institute of Technology. Retrieved from http://dspace.mit.edu/handle/1721.1/11173

Shannon, Claude Elwood, & Weaver, W. (1949). *The Mathematical Theory of Communication*. University of Illinois Press.

Steiner, M. (1998). *The Applicability of Mathematics As a Philosophical Problem*. Harvard University Press.

Susskind, L. (1995). The world as a hologram. *Journal of Mathematical Physics*, *36*(11), 6377–6396. doi:doi:10.1063/1.531249

Susskind, L. (2008). *The Black Hole War: My Battle with Stephen Hawking to Make the World Safe for Quantum Mechanics* (First ed.). Little, Brown and Company.

Turing, A. M., & Copeland, B. J. (2004). *The Essential Turing: Seminal Writings in Computing, Logic, Philosophy, Artificial Intelligence, and Artificial Life Plus The Secrets of Enigma*. Clarendon Press.

Weinberg, S. (2002, October 24). Is the Universe a Computer? *The New York Review of Books*. Retrieved from http://www.nybooks.com/articles/archives/2002/oct/24/is-the-universe-a-computer/

Wheeler, J. A. (1990). *Information, physics, quantum: The search for links*. Physics Dept., University of Texas.

Wiener, N. (1948). *Cybernetics: or, Control and communications in the animal and the machine*. Hermann.

Wolfram, S. (1984). Computer Software in Science and Mathematics. *Scientific American*, *251*(3), 188–92,194,196–200,203.

Wolfram, S. (1985). Undecidability and intractability in theoretical physics. *Physical Review Letters*, *54*(8), 735–738. doi:10.1103/PhysRevLett.54.735

Wolfram, S. (2002). *A New Kind of Science* (1st ed.). Wolfram Media.

Wright, R. (1988). *Three Scientist and Their Gods* (Third Printing.). Crown.

Yao, A. C.-C. (2003). Classical physics and the Church–Turing Thesis. *J. ACM*, *50*(1), 100–105. doi:10.1145/602382.602411

Zuse, K. (1970). *Calculating Space*. Massachusetts Institute of Technology, Project MAC.

Zuse, K. (1982). The computing universe. *International Journal of Theoretical Physics*, *21*(6), 589–600.