Chapter

Introductory Chapter: Physics of Information and Quantum Mechanics - Some Remarks from a Historical Perspective

Sergio Curilef and Angel Ricardo Plastino

1. A bit of history

Ideas and techniques coming from information theory are nowadays gaining prominence in physics [1–6]. Quantum information, in particular, is one of the most active and rapidly advancing fields in the physical sciences [2, 6]. This state of affairs results from intricate historical developments that cannot be explained in a few pages. It is useful, however, in order to put quantum information science in a wider context, to try to summarize some of the main events that led to the present role of the concept of information in general physics and, in particular, in quantum physics. We shall briefly discuss and provide a short overview, within a historical perspective, of some basic features of the fields of the physics of information and quantum information. From the very inception of Shannon's information theory more than 70 years ago [7, 8], scientists found it intriguing that the engineering-motivated quantitative measure of information derived by Shannon is mathematically identical to the expression for entropy proposed several decades before by Boltzmann and by Gibbs. It is surprising that two conceptually different quantities, arising independently from completely different motivations in two unrelated fields, one belonging to pure science, and the other to engineering, share the same mathematical form. Various lines of thought developed in the subsequent years suggested that, rather than being just a superficial formal coincidence, the similarity indicates that there is a deep connection between information theory and physics. Physicists started paying serious attention to Shannon's information theory in the 1950s, thanks to a large extent to the pioneering efforts of Jaynes, who advanced a reformulation of statistical mechanics based on concepts from information theory [9, 10]. The basic idea behind Jaynes proposal is that the entropy associated with a macroscopic description of a physical system is actually a measure of the missing information about the system's precise microscopic state. Based on the connection between information and entropy Jaynes advanced the principle of maximum entropy (MaxEnt) as a guiding rule in statistical mechanics, for identifying the least biased statistical description of a physical system compatible with the available incomplete data. Later Jaynes promoted MaxEnt as a general principle of statistical inference. Some commentators do not include the works of Jaynes among the sources of the physics of information and of quantum information. Jaynes' works, however, were essential in propagating the notion that information theory is important for understanding fundamental aspects of physics. Ideas revolving around Jaynes' information-theoretical approach to statistical mechanics, and around the MaxEnt principle, found multiple successful applications in physics and

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elsewhere [11]. Many applications of MaxEnt are implemented in a classical setting. But there are also important applications to quantum problems. Starting with the works of Jaynes himself, the MaxEnt principle has been applied to quantum statistical mechanics in situations both at equilibrium and out of equilibrium. The MaxEnt principle has been applied even to the description of pure quantum states [12]. Generalizations of the MaxEnt principle, based on new information-entropic functionals [13], have also been explored and applied to a variety of problems, particularly in the field of complex systems [14]. Besides these information measures, there are other information-related quantities of physical relevance, such as Fisher's information measure [3]. Fisher's information was actually advanced before Shannon's [15], and represents a completely different concept [16]. It was introduced in the context of biology, but today constitutes an important tool in the study of diverse problems in physics (specially quantum physics) and other fields [3].

Another turning point in the story of scientists' gradual appreciation of the connection between physics and information was the formulation of Landauer's principle [17]. The principle says that there is a lower bound on the amount of energy that has to be dissipated each time that a bit of information is erased in a computing device. The minimum amount of energy that has to be dissipated is equal to $kT \ln 2$, where k is Boltzmann's constant and T is the absolute temperature at which the computer device works. Landauer's discovery established a direct and concrete connection between the concept of information and physical quantities such as energy and temperature. Landauer's principle constitutes a strong evidence that information has physical reality. This is nicely summarized in Landauer's famous motto "*information is physical*" [18]. Landauer principle has been the focus of intense research activity, and has been extended and generalized in diverse directions (see, for instance, [19] and references therein). Interest in the connections between physics and information increased substantially with the discovery that quantum mechanics allows for novel and highly counter-intuitive ways of transmitting and processing information. Some of the firsts steps in this direction were taken by Benioff [20], Feynman [21], and Deutsch [22], starting the field of quantum computation [6]. Around the same time, a striking feature of quantum information, encapsulated in Wootters and Zurek's quantum no-cloning theorem, was discovered [23]. These developments converged with other lines of inquiry going back to the works by Einstein, Podolsky and Rosen, and by Schroedinger, in the 1930s, on quantum nonlocality and entanglement, that together with later developments by von Neumann and by Bohm on hidden variables theories, led eventually to the discovery of Bell's inequalities (nice discussions on these developments can be found in [24]), and to the identification of quantum entanglement as one of the (if not *the*) most fundamental features distinguishing the quantum mechanical description of Nature from the classical one [25]. Afterwards, in the XXI century, the field of quantum information flourished and grew into myriad different directions [2], which are impossible to describe in this short note. Let us just mention that subjects central to the field of quantum information, such as quantum entanglement, are regarded by some researchers as key ingredients for understanding basic aspects of physics, such as the origin of gravity, Einstein's field equations, and the very structure of space–time [26].

2. Physics of information, quantum mechanics, and the future

The above are only a few highlights (corresponding particularly to the early steps) of the exploration of the connection between physics and information-related concepts. Even if summarized in a sketchy and incomplete fashion, they serve to illustrate a basic feature of these lines of inquiry. Research into the *physics of information*, which is here defined in a broad sense, as comprising all parts of physics, classical and quantum, where information-theoretical concepts play a central role, has two complementary facets. On the one hand, it investigates the capabilities allowed, and the limitations imposed, by the fundamental laws of Nature for the construction and operation of devices that transmit or process information [27–29]. A deep understanding of these issues may lead to revolutionary advances in information technologies, such as those expected from the fields of quantum communication and quantum computation. On the other hand, ideas and methods inspired in information theory help to achieve a deeper understanding of physics itself, as illustrated by Jaynes application of information theory to statistical mechanics [9, 10]. Rather than being in opposition, the two facets of the physics of information complement and stimulate each other. The friendly coexistence of the two facets reminds us of a famous quote by Poincare: "*I do not say: science is useful, because it teaches us to construct machines. I say: machines are useful because in working for us, they will some day leave us more time to make science. But finally it is worth remarking that between the two points of view there is no antagonism, and that man having pursued a disinterested aim, all else has been added unto him*" [30].

Research into the physics of information, including in particular the physics of quantum information, permitted the discovery of unexpected connections between apparently unrelated areas of science. New connections were established between different areas within physics, and also between physics and other sciences. As an illustration of the first kind of connections, we can mention that ideas related to Fisher's information suggested new connections between Schroedinger wave equation and Boltzmann transport equation [31]. With regards to the relationship between physics and other sciences, the physics of information is nowadays establishing profound relations between physics and biology [32]. The physics of information provides a set of theoretical and mathematical tools that constitutes a conceptual bridge between physics and biology. These developments, inextricably linked to the field of complex systems, include new theoretical ideas that affect all branches of biology. The study of consciousness constitutes perhaps the most remarkable example [33]. Until recently, the theory of consciousness was regarded as a subject that was outside the reach of scientific inquiry or, at least, outside the reach of a scientific treatment based on mathematically well-defined concepts, and amenable of quantitative experimental research. Although scientists, including physicists [34], have been interested in the phenomenon of consciousness for a long time, with psychologists and neuroscientists making a wealth of fascinating qualitative empirical discoveries, theoretical research into consciousness was largely regarded as a field of study for philosophers. The situation has changed dramatically in the last few years. Using ideas closely related to the physics of information, scientists are for the fists time attempting a mathematically-based theory of consciousness that might generate quantitative experimental predictions (see [33] and references therein). Most advances in the application to biology of methods or ideas related to the physics of information have been developed in a classical setting, but quantum mechanical aspects are starting to be explored in the new field of quantum biology [35]. There are even some intriguing hints suggesting that there might be connections between the phenomenon of consciousness and some basic aspects of quantum physics, such as the special and privileged role played in physics by the position observable [33].

The central role that the concept of information is gaining in physics raises some intriguing questions that deserve close scrutiny. The concept of information is, in a sense, a human-centered concept. After all, information theory was created to address engineering problems related to communication technology. We humans are the ones who care about information. Why should Nature care about information? Does nature care about information? These are perhaps naive questions. But we find it perplexing that a concept developed to address purely human needs turns out to be essential to understand the fabric of Nature at its deepest level. In this regard, one may also find intriguing that information-theoretical in physics reached their prominent role in physics precisely at a stage of human history, the "digital age", when information technology became the most prominent technological feature of human life. This is probably not a coincidence. The question is, do we nowadays tend to interpret the laws of Nature in information-theoretical terms, and adopt the computer as our technological metaphor for natural systems and processes [29], because we are all the time using computers (particularly iPhones, around which the life of many revolve)? In other periods of History, the most advanced or sophisticated technological devices were also adopted as metaphors for Nature. In early modern times the metaphor was the clock. Today it is the computer. Is it going to be replaced by another metaphor in the future? We cannot know. From history, however, we learn that some of the insights gained from the old clock metaphor are still valuable. They have been incorporated, in terms compatible with the computer metaphor, to the law of conservation of information [5, 36–38]. This law says that at the most basic level the time evolution of physical systems preserves information. The conservation of information is one of the most fundamental laws of physics [5]. It is more profound and rich than the concepts embodied in the clock-metaphor. It holds both at the classical and at the quantum-mechanical levels, and its implications are manyfold. For instance, the quantum no-cloning theorem is a consequence of the law of conservation of information. Some basic aspects of quantum mechanical measurements, that until recently were presented in textbooks as part of the postulates of quantum mechanics, can actually be derived from the conservation of information [37].

Coming back to the question of which will be the future technological metaphor for Nature, it may happen that no metaphor will ever replace the computer one. It is conceivable that the computer is the ultimate metaphor for Nature because, in a sense, it is a universal metaphor. A universal Turing machine can compute or simulate anything that can be computed or simulated by a mechanical device. Consequently, as technological metaphors go, there may be nothing beyond the computer. And, concomitantly, the deepest description of Nature may admit its most adequate formulation in terms of ideas and concepts from computer science and information theory. Time will tell.

The dominant role that the physics of information, and specially quantum information, plays today manifest itself in various ways. For instance, in the number and geographical spread of researchers working in quantum information. Towards the end of the XX century, most research on quantum information was concentrated in a few countries. In many countries, there was still no activity in the field, or the field was just starting. Even in some countries with large and highly-developed research communities, and with big economies, the researchers working in quantum information were still very few. Today the situation is completely different. In all corners of the world, there are research groups enthusiastically exploring the many facets of quantum information, and making valuable contributions. Quantum information is nowadays a well established research field. The heroic days of the pioneers are over. This does not mean that the days of discovery are over. On the contrary, each new development generates new questions: research opportunities seem to be better than ever. And it may be the case that the best is yet to come.

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Conflict of interest

The authors declare no conflict of interest.

Author details

Sergio Curilef[1*†] and Angel Ricardo Plastino[2†]

1 Departamento de Física, Universidad Católica del Norte, Antofagasta, Chile

2 CeBio y Departamento de Ciencias Básicas, Universidad Nacional del Noroeste de la Provincia de Buenos Aires, UNNOBA, Conicet, Junin, Argentina

*Address all correspondence to: scurilef@ucn.cl

† These authors contributed equally.

References

[1] P. Davies and N. H. Gregersen. Information and the Nature of Reality. Cambridge University Press; 2014.

[2] O. Lombardi, S. Fortin, F. Holik, and C. Lopez, editors. What Is Quantum Information? Cambridge University Press; 2017.

[3] B. R. Frieden. Science from Fisher Information: A Unification. Cambridge University Press; 2004.

[4] H. S. Leff and A. F. Rex, editors. Maxwellâ's Demons 2: Entropy, Classical and Quantum Information, Computing. Bristol, Philadelphia: Institute of Physics Publishing; 2003.

[5] L. Susskind and J. Lindesay. An Introduction to Black Holes, Information, and the String Theory Revolution: The Holographic Universe. World Scientific; 2004.

[6] M. A. Nielsen and I. L. Chuang. Quantum Computation and Quantum Information. Cambridge: Cambridge University Press; 2000.

[7] C. E. Shannon. A mathematical theory of communication. Bell Syst. Tech. J. 1948;27:379–423.

[8] C. E. Shannon and W. Weaver. The Mathematical Theory of Communication. Urbana, IL: University of Illinois Press; 1949.

[9] E. T. Jaynes. Information theory and statistical mechanics. Phys. Rev. 1957; 106:620.

[10] E. T. Jaynes. Information theory and statistical mechanics. II. Phys. Rev. 1957; 108:171.

[11] S. Pressé, K. Ghosh, J. Lee, and K. A. Dill. Principles of maximum entropy and maximum caliber in statistical physics. Rev. Mod. Phys. 2013;85:1115-1141.

[12] A. R. Plastino and A. Plastino. Maximum entropy and approximate descriptions of pure states. Phys. Lett. A 1993;181:446-449.

[13] C. Beck. Generalised information and entropy measures in physics. Contemp. Phys. 2009;50:495.

[14] C. Tsallis. Introduction to Nonextensive Statistical Mechanics – Approaching a Complex World. New York: Springer; 2009.

[15] R. A. Fisher. Theory of statistical estimation. Math. Proc. Cambridge Philos. Soc. 1925;22:700.

[16] A. R. Plastino and A. Plastino. What's the big idea? Cramer-Rao inequality and Rao distance. Significance 2020;17:39.

[17] R. Landauer. Irreversibility and heat generation in the computing process. IBM J. Res. Dev. 1961;5:183.

[18] R. Landauer. Information is physical. Phys. Today 1991;44:23.

[19] C. Zander, A. R. Plastino, A. Plastino, M. Casas, and S. Curilef. Landauer's principle and divergenceless dynamical systems. Entropy 2009;11: 586-597.

[20] P. Benioff. The computer as a physical system: A microscopic quantum mechanical Hamiltonian model of computers as represented by Turing machines. J. Stat. Phys. 1980;22: 563–591.

[21] R. P. Feynman. Simulating physics with computers. Int. J. Theor. Phys. 1982;21:467.

[22] D. Deutsch. Quantum theory, the Church-Turing principle and the universal quantum computer.

Proceedings of the Royal Society of London A 1985;400:97–117.

[23] W. K. Wootters and W. H. Zurek. A single quantum cannot be cloned. Nature 1982;299:802.

[24] J. S. Bell. Speakable and Unspeakable in Quantum Mechanics. 2nd ed. Cambridge University Press; 2004.

[25] I. Bengtsson and K. Zyczkowski. Geometry of Quantum States: An Introduction to Quantum Entanglement. Cambridge University Press; 2006.

[26] C. J. Cao and S. M. Carroll. Bulk entanglement gravity without a boundary: Towards finding Einstein's equation in Hilbert space. Phys. Rev. D 2018;97:086003.

[27] N. Margolus and L. B. Levitin. The maximum speed of dynamical evolution. Physica D 1998;120:188.

[28] S. Lloyd. Ultimate physical limits to computation. Nature 2000; 406:1047.

[29] S. Lloyd. Computational capacity of the universe. Phys. Rev. Lett. 2002;88: 237901.

[30] H. Poincare. The Value of Science. Dover; 1958.

[31] S. P. Flego, B. R. Frieden, A. Plastino, A. R. Plastino, and B. H. Soffer. Nonequilibrium thermodynamics and Fisher information: Sound wave propagation in a dilute gas. Phys. Rev. E 2003;68:016105.

[32] P. Davies. Does new physics lurk inside living matter? Physics Today 2020;73:34-40.

[33] M. Tegmark. Consciousness as a state of matter. Chaos, Solitons & Fractals 2015;76:238-270.

[34] E. Schroedinger. What Is Life? With Mind and Matter and Autobiographycal Sketches. Cambridge Universirty Press; 1996.

[35] Y. Kim, et al. Quantum biology: An update and perspective. Quantum Reports 2021;3:80-126.

[36] A. R. Plastino and A. Daffertshofer. Liouville dynamics and the conservation of classical information. Phys. Rev. Lett. 2004;93:138701.

[37] W. H. Zurek. Quantum origin of quantum jumps: Breaking of unitary symmetry induced by information transfer in the transition from quantum to classical. Phys. Rev. A 2007;76: 052110.

[38] C. Zander and A. R. Plastino. Fidelity measure and conservation of information in general probabilistic theories. EPL 2009;86:18004.