Introduction

By analogy with the Industrial Revolution, at present many people talk about an Information Revolution that began in the mid-twentieth century and continues to this day. Although triggered by the advent of digital technologies and established by the proliferation of digital computers, the drastic changes rapidly exceeded the limits of technology to pervade all aspects of social life. Nowadays, information shapes all our everyday activities and thoughts.

Given this situation, it is not surprising that, during the past decades, philosophy has begun to focus its attention on the search of an elucidation of the notion of information. The many dimensions of information make this task particularly interesting from a philosophical viewpoint, but, at the same time, attempt against a unified answer to the problem. At present, different interpretations of the notion of information coexist, sometimes as the consequence of implicitly conflating its different meanings, but in many cases also as the result of the multiple facets of the concept.

At the same time, new interpretive problems have arisen with the advent of the research field called "quantum information theory." Those problems combine the difficulties in the understanding of the concept of information with the well-known foundational puzzles derived from quantum mechanics itself. Of course, interpretive issues were not an obstacle to the huge development of quantum information theory as a scientific area of research, where new formal results multiply rapidly. Nevertheless, the question "What is quantum information?" is still far from having an answer on which the whole quantum information community agrees.

It is in this context that the question about the nature of quantum information deserves to be considered from a conceptual viewpoint. The aim of this volume is, precisely, to address the issue from several and varied perspectives, which makes manifest its different aspects and its many implications. With this purpose, the chapters of this volume are organized in three parts. Part I, "The Concept of Information," groups the chapters mainly devoted to inquiring into the concept itself and its relationships with other notions, such as knowledge, representation, and manipulation. In Part II, "Information and Quantum Mechanics," the links between informational and quantum issues enter the stage. Finally, Part III, "Probability, Correlations, and Information," addresses the subject matter by considering how the notions of probability and correlation underlie the concept of information in different problem domains.

Part I opens with the chapter "About the Concept of Information," where Sebastian Fortin and Olimpia Lombardi begin by introducing some relevant distinctions that allow them to focus on mathematical information in the communicational context. In this context, after discussing the definition of some magnitudes involved in the Shannon formalism, the chapter deals entirely with interpretive matters. First, three interpretations of the concept of information are introduced, stressing their differences and specific difficulties. Then, the question about the existence of two qualitatively different kinds of information, classical and quantum, is addressed. On the basis of the previous discussion, the authors advocate for a theoretically neutral interpretation of information.

The main aim of the second chapter of this first part, "Representation, Interpretation, and Theories of Information," by Armond Duwell, is to stress the vital importance of representational and interpretive aspects for understanding the definition of information provided by Christopher Timpson. With this purpose, the chapter begins with discussing some basic features of representation and interpretation of theories. Then, two potential problems of Timpson's definition in Shannon information theory and in quantum information theory, respectively, are considered; the argumentation is directed to show that the resolution to those problems depends on recognizing how important users of the information theories are in determining what constitutes successful quantum information transfer. On this basis, the author concludes that Timpson's definition of information functions perfectly well and correctly elucidates what information is; moreover, specializations of this definition to various theories illustrate the differences in different types of information.

The third and final chapter of the opening part, "Information, Communication, and Manipulability," by Olimpia Lombardi and Cristian López, aims at supplying adequate criteria to identify information in a communicational context. For this purpose, the chapter begins by considering the different interpretations of Shannon's formalism that can be implicitly or explicitly found in the literature, and the additional challenges raised by the advent of entanglement-assisted communication. This analysis shows that the communication of information is a process that involves a certain idea of causation and the asymmetry implicit in it. On this basis, the authors claim that the manipulability accounts of causation supply the philosophical tools to characterize the transmission of information in a communicational context, and that many conundrums around the concept of information in this context are solved or simply vanish in the light of a manipulability view of information.

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Excerpt
More Information

Part II begins with Jeffrey Bub's chapter, "Quantum versus Classical Information." Bub opens his chapter by stressing that the question "What is quantum information?" has two parts: first, "what is information?" second, "what is the difference between quantum information and classical information?" and he proposes an answer to the second question. With this purpose, Bub begins by supplying a characterization of intrinsic randomness, and then shows that the nonlocal correlations of entangled quantum systems are only possible if the measurement outcomes on the separate systems are intrinsically random events. Then, intrinsic randomness increases the possibilities for information processing, essentially because new sorts of correlations are possible that cannot occur in a classic world. On this basis, the author concludes that intrinsic randomness marks the difference between quantum and classical information: quantum information is a type of information that is only possible in a world in which there are intrinsically random events.

In the following chapter of Part II, "Quantum Information and Locality," Dennis Dieks begins by recalling that the surprising aspects of quantum information are due to two distinctly non-classical features of the quantum world: first, different quantum states need not be orthogonal, and, second, quantum states may be entangled. He focuses on the concept of entanglement, since it leads, via non-locality, to those forms of communication that go beyond what is classically possible. In particular, he analyzes the significance of entanglement for the basic physical concepts of "particle" and of "localized physical system." According to the author, in general the structure of quantum mechanics is at odds with an interpretation in terms of particles, which may be localized. This leads him to the conclusion that quantum mechanics is best seen as not belonging to the category of space-time theories: the resulting picture of the quantum world is relevant for understanding in what sense quantum theory is non-local, and this in turn sheds light on the novel aspects of quantum information.

In his chapter, "Pragmatic Information in Quantum Mechanics," Juan Roederer argues that information is essentially a pragmatic notion. The chapter begins by distinguishing between two categories of interactions between bodies or systems: force-driven, which operates in the entire spatial-temporal domain, and information-driven, which leads to the definition of information as a pragmatic concept. Pragmatic information is defined as that which represents a physical, causal, and univocal correspondence between a pattern and a specific macroscopic change mediated by some complex interaction mechanism. On the basis of this definition, pragmatic information in itself does not operate in the quantum domain. According to the author, to the extent that information is pragmatic, talking about inaccessible or hidden information in quantum states makes no sense: quantum mechanics can only provide real – pragmatic – information by means of natural or deliberate macroscopic imprints left by a composite quantum system, which as a single whole interacts irreversibly with the surrounding macroscopic world.

In the last chapter of Part II, "Interpretations of Quantum Theory: A Map of Madness," Adán Cabello stresses the fact that, at present, physicists do not yet agree about what quantum theory is about, and argues that it is urgent to solve this problem. In order to contribute to the solution, he classifies the interpretations of quantum theory into two types, according to whether the probabilities of measurement outcomes are determined by intrinsic properties of the observed system or not. Cabello considers that these two types of interpretations are so radically different that there must be experiments that, when analyzed outside the framework of quantum theory, lead to different empirically testable predictions.

Part III, devoted to probabilities and correlations, begins with the chapter "On the Tension between Ontology and Epistemology in Quantum Probabilities," where Amit Hagar proposes a physical underpinning of quantum probabilities, which is dynamical, finitist, operational, and objective. According to this operationalist view, which dispels the metaphysics that surrounds the quantum state, finite-resolution measurement outcomes are taken as primitive and basic building blocks of the theory, and quantum probabilities are objective dynamical transition probabilities between finite-resolution measurement results. As a consequence, nonrelativistic quantum mechanics is seen as a phenomenological, "effective" theory, whose mathematical structure – the Hilbert space – rather than a fundamental structure that requires interpretation, is a tool for computing the probabilities of future states of an underlying deterministic and discrete process, from the inherently and objectively limited knowledge we have about it. According to the author, this view of probabilities can qualify as an objective alternative to the subjective view that the quantum information theoretic approach adheres to.

In his chapter, "Inferential versus Dynamical Conceptions of Physics," David Wallace addresses the issue of probabilities in physics by contrasting two possible attitudes towards a given branch of physics: inferential, as concerned with an agent's ability to make predictions given finite information, and dynamical, as concerned with the dynamical equations governing particular degrees of freedom. He contrasts these attitudes in classical statistical mechanics, in quantum mechanics, and in quantum statistical mechanics. In this last case, he argues that the quantum-mechanical and statistical-mechanical aspects of the question become inseparable. On this basis, the conclusion of the chapter is that the particular attitude adopted – whether to conceive of a given field in physics as a form of inference or as a study of dynamics – plays a central role in the foundations of quantum theory, and the exact same role in the foundations of statistical mechanics once it is understood quantum mechanically.

The chapter "Classical Models for Quantum Information," by Federico Holik and Gustavo Martín Bosyk, faces the question about the ontological status of quantum information. The first part of the chapter emphasizes the existence of probabilistic models that go beyond the classical and quantal realms, and the possibility of performing informational protocols in those models. On this basis, the authors argue that a generalized information theory can be conceived. In the second part, the question about the ontological reference of those probabilistic models is addressed. For this purpose, the authors recall the existence of many examples of physical systems built by means of an essentially classical ontology, but that are modeled by formal structures with quantum features. Their significance relies on the fact that they can be used to perform quantum information protocols. This fact points to the need of exploring the ontological implications of those simulations for the concept of quantum information.

The last chapter of Part III, "On the Relative Charecter of Quantum Corrlations," by Ángel Luis Plastino, Guido Bellomo, and Ángel Ricardo Plastino, revisits the concepts of entanglement and discord from a generalized perspective that focuses on the relational aspect of the term "correlation" with respect to the states and observables involved. From the fact that the concept of correlation is inherently relative to the non-unique partition of a system into subsystems, the authors favor a description-dependent view of the quantum correlations that provides what they call a second stage of relativity. On this basis, they propose generalized definitions for entanglement and discord. Moreover, the authors argue that the relative character of quantum correlations imposes restrictions on the classical appearance of the quantum. In particular, they prove that some types of quantum correlations may appear as classical correlations when certain relevant observables in a larger Hilbert space are measured. Therefore, the classical appearance of the quantum world is also relative to a given description.

As this brief overview shows, the question about what quantum information is can be addressed from many different perspectives, some of them complementary, others conflicting with each other. This plurality precisely reveals to what extent the community of quantum physicists and philosophers of physics is far from a consensus about the answer of that question. This volume is intended as a contribution to the discussion about the conceptual foundations of an exciting field like quantum information theory.

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Part I

The Concept of Information

1

About the Concept of Information

SEBASTIAN FORTIN AND OLIMPIA LOMBARDI

1 Introduction

As with other concepts that marked an era in the past, the clue of our time seems to lie in the concept of information. The appeal of the slogan "we live in the age of information" is strongly justified: we can perceive the pervasiveness of information in our lives as embodied in the explosion of highly advanced technologies devoted to computing and communication. But behind this materialization, at present, information has become an immaterial source of power, not only in the social domain, but also in the political and economic spheres. It is, then, not surprising that science has not been left out of this "information revolution": nowadays the concept of information has permeated almost all scientific disciplines, from physics and chemistry to biology and psychology.

In the face of this situation, since the past decades philosophy has begun to address the question of the content and the role of the concept of information in different domains. The present chapter is framed in this general trend: the aim here is to discuss the technical concept of information in the communicational context, whose classical locus is the paper where Claude Shannon (1948) introduces a precise formalism designed to solve certain specific technological problems in communication engineering. For this purpose, this chapter is organized as follows. Section 2 will introduce relevant distinctions that will allow us to focus on the concept of information in the context of interest. In Section 3, Shannon's formalism will be presented and some technical issues about the definition of the relevant magnitudes will be discussed. Section 4 will be devoted to interpretive matters: three interpretations of the concept of information will be introduced, stressing their differences and specific difficulties. Section 5 will contend with information in the quantum domain: the question about the existence of two qualitatively different kinds of information, classical and quantum, will be addressed. Finally, on the basis of the previous discussion, Section 6 will include some final remarks about the advantages of a theoretically neutral interpretation of information.

2 Finding the Way through Bifurcations

The philosophical analysis of the concept of information has resulted in a growing amount of literature devoted to this subject matter from very different perspectives. The purpose of this section is not to offer an exhaustive map of the land in the philosophical literature on information, a task that surely exceeds the capacity of a single chapter. The aim here is to introduce some relevant distinctions that will allow us to focus on the concept of information that will be the subject of interest in the subsequent sections.

2.1 'Information': Everyday Use versus Technical Use

The use of the term 'information' is not confined to the language of science or of philosophy. On the contrary, the term is strongly present in everyday language, with a general meaning that, as in all cases, resulted from a long and complex historical process. Related to the idea of knowing as apprehending the *form* of objects, prevailing in antiquity and the Middle Ages, in modern times, the term 'information' disappeared from the philosophical discourse, but gained popularity in everyday language, with the link to knowledge that has survived until today (see Adriaans 2013).

An author who stresses the difference between the everyday use and the technical use of the term 'information' is Christopher Timpson (2004, 2013), who takes the analogy between "truth" and "information" as a departing point to support his claim that 'information' is an abstract noun: "Austin's aim was to de-mystify the concept of truth, and make it amenable to discussion, by pointing to the fact that 'truth' is an abstract noun. So too is 'information'" (2013: 10). Timpson recalls that very often abstract nouns arise as nominalizations of various adjectival or verbal forms. On this basis, he extends the analogy between truth and information: "Austin leads us from the substantive 'truth' to the adjective 'true.' Similarly, 'information' is to be explained in terms of the verb 'inform'" (2013: 11). In turn, "[t]o inform someone is to bring them to know something (that they did not already know)" (2013: 11). In other words, the meaning of 'information' in everyday language is given by the operation of bringing knowledge and, therefore, the word is an abstract noun that does not refer to something concrete that exists in the world.

In this chapter, we will not analyze the use of the term 'information' in ordinary language, but we are interested in the technical use of the term, which is nevertheless far from being univocal.

2.2 The Technical Domain: Semantic and Mathematical Information

In the technical domain, the first distinction to be introduced is that between a semantic and a non-semantic view of information.

According to the first view, information is something that carries semantic content (Bar-Hillel and Carnap 1953; Bar-Hillel 1964; Floridi 2010, 2011); it is therefore strongly related to semantic notions such as reference, meaning, and representation. In general, semantic information is carried by propositions that intend to represent states of affairs; so, it has intentionality, "aboutness," that is, it is directed to other things. And although it remains controversial whether false factual content may qualify as information (see Graham 1999; Fetzer 2004; Floridi 2004, 2005; Scarantino and Piccinini 2010), semantic information maintains strong links with the notion of truth. At present there is a well-developed field of research in the philosophy of semantic information (see, e.g., Adriaans and Van Benthem 2008, and the Web site of the Society for the Philosophy of Information), in the context of which many strongly technical views of semantic information are proposed (just to mention some of them: Dretske 1981; Barwise and Seligman 1997; Floridi 2011; for a wide, updated source of references, see Floridi 2015; for an analysis of Dretske's proposal, see Lombardi 2005).

Non-semantic information, also called 'mathematical,' is concerned with many formal properties of different kinds of systems, among them the best known are the compressibility properties of sequences of states of a system and the correlations between the states of two systems, independently of the meanings of those states. We will focus on mathematical information; however, the mention of "mathematical information" does not specify yet what we are taking about.

2.3 The Many Faces of Mathematical Information

In the domain of mathematical information, different contexts can be distinguished, each one with its particular formal resources to deal with specific goals. The two traditional contexts are the computational and the communicational.

In the *computational context*, information is something that has to be computed and stored in an efficient way. In this framework, the algorithmic or Kolmogorov complexity measures the minimum resources needed to effectively reconstruct an individual message (Solomonoff 1964; Kolmogorov 1965, 1968; Chaitin 1966): it supplies a measure of information for individual objects taken in themselves, independently of the source that produces them. In the theory of algorithmic complexity, the basic question is the ultimate compression of individual messages. The main idea that underlies the theory is that the description of some messages can be compressed considerably if they exhibit enough regularity. The Kolmogorov complexity of a message is, then, defined as the length of the shortest possible program that produces it in a Turing machine. Many information theorists, especially computer scientists, regard algorithmic complexity as more fundamental than Shannon entropy as a measure of information (Cover and Thomas 1991: 3), to the extent that algorithmic complexity assigns an asymptotic complexity to an individual message without any recourse to the notion of probability (for a discussion of the relation between Shannon entropy and Kolmogorov complexity, see Cover and Thomas 1991: chapter 7; Lombardi, Holik, and Vanni 2016b).

In the *communicational context*, whose classical formalism was formulated by Claude Shannon (Shannon 1948; Shannon and Weaver 1949), information is primarily something to be transmitted between two points for communication purposes. The formalism Shannon proposed was designed to solve certain specific technological problems in communication engineering, in particular, to optimize the transmission of information by means of physical signals whose energy and bandwidth is constrained by technological and economic limitations. Shannon's theory is purely quantitative; it ignores any issue related to informational content: "[the] semantic aspects of communication are irrelevant to the engineering problem. The significant aspect is that the actual message is one selected from a set of possible messages" (1948: 379).

Although the best known, the computational and the communicational contexts are not the only mathematical contexts in which the concept of information is present. For instance, in an *inferential context*, the interest is to find a universally good prediction procedure on the basis of the possessed data, where "good" usually involves a version of Occam's Razor: "The simplest explanation is best." The *thermodynamic context* is devoted to relate information and entropy and to explain the entropy increase in terms of informational concepts and arguments. In a *gambling context*, the problem is to use informational resources to formalize a gambling game, by representing the wealth at the end of the game as a random variable and the gambler as a subject that tries to maximize that variable. These are only some of the non-classical contexts that show that, at present, information theory is a very wide body of formal knowledge with many different interests and applications (see Lombardi, Fortin, and Vanni 2015). In this chapter, we are interested in the communicational context, where the concept of information acquires a specific formal treatment, given by Shannon's theory.

3 The Formalism in the Communicational Context: Shannon's Theory

According to Shannon (1948; see also Shannon and Weaver 1949), a general communication system consists of five parts (see Figure 1.1):

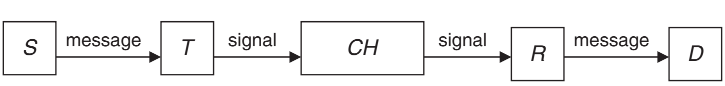

Figure 1.1. General communication system.