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What is quantum information?

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ABSTRACT

In the present article we address the question 'What is quantum information?' from a conceptual viewpoint. In particular, we argue that there seems to be no sufficiently good reasons to accept that quantum information is qualitatively different from classical information. The view that, in the communicational context, there is only one kind of information, physically neutral, which can be encoded by means of classical or quantum states has, in turn, interesting conceptual advantages. First, it dissolves the widely discussed puzzles of teleportation without the need to assume a particular interpretation of information. Second, and from a more general viewpoint, it frees the attempts to reconstruct quantum mechanics on the basis of informational constraints from any risk of circularity; furthermore, it endows them with a strong conceptual appealing and, derivatively, opens the way to the possibility of a non-reductive unification of physics. Finally, in the light of the idea of the physical neutrality of information, the wide field of research about classical models for quantum information acquires a particular conceptual and philosophical interest.

1. Introduction

The concept of information has proved to be one of the most difficult scientific concepts to interpret (Adriaans, 2013, Floridi, 2015). On the one hand, the word 'information' is used with many differing meanings; on the other hand, there are several different formalisms to treat the concept quantitatively. But even when a single formalism is considered, disagreements arise when the task at issue is the interpretation of the concept (Lombardi, Fortin & Vanni, 2015).

During the last decades, new interpretive problems have arisen with the advent of quantum information; those problems combine the difficulties in the understanding of the concept of information with the well-known foundational puzzles derived from quantum mechanics itself. This situation contrasts with the huge development of the research field named 'quantum information theory', where new formal results multiply rapidly. In this context, the question 'What is quantum information?' is still far from having an answer on which the whole quantum information community agrees. In fact, the positions about the matter range from those who seem to deny the existence of quantum information (Duwell, 2003), those who consider that it refers to information when it is encoded in quantum systems (Caves & Fuchs, 1996, Dieks, 2016), and those who conceive it as a new kind of information absolutely different from classical information (Jozsa, 1998, Brukner & Zeilinger, 2001).

In the present article we will address the question 'What is quantum information?' from a conceptual viewpoint. In particular, we will argue that there seems to be no sufficiently good reasons to accept that quantum information is qualitatively different from classical information. The view that, in the communicational context, there is only one kind of information, physically neutral, which can be encoded by means of classical or quantum states has, in turn, interesting conceptual advantages. First, it dissolves the widely discussed puzzles of teleportation without the need to assume a particular interpretation of information. Second, and from a more general viewpoint, it frees the attempts to reconstruct quantum mechanics on the basis of informational constraints from any risk of circularity; furthermore, it endows them with a strong conceptual appealing and, derivatively, opens the way to the possibility of a non-reductive unification of physics. Finally, in the light of the idea of the physical neutrality of information, the wide

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field of research about classical models for quantum information acquires a particular conceptual and philosophical interest.

For these purposes, the article is organized as follows. In Section 2 we begin by disentangling the different senses of the general notion of information in order to clarify the specific concept at issue in our discussion. In Section 3 Schumacher's formalism is introduced by contrast with Shannon's theory. Section 4 is devoted to critically asses the most common arguments for conceiving quantum information as qualitatively different from classical information. In Section 5 the relation between quantum information theory and quantum mechanics is considered, in order to make sense to the question about what peculiarities of quantum mechanics are really necessary to implement quantum protocols. Finally, in Section 6 we summarize our arguments and stress that calling into question the concept of quantum information does not imply, in any sense, downplaying the relevance of the widely developed field of quantum information theory.

2. Which notion of information?

Since information is a polysemantic concept that can be associated with different phenomena, 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 & Carnap, 1953; Bar-Hillel, 1964; Floridi, 2011); it is therefore strongly related with 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. Non-semantic information, also called 'mathematical', is concerned with the compressibility properties of sequences of states of a system and/or the correlations between the states of two systems, independently of the meanings of those states.

However, this distinction is not yet sufficiently specific, since in the domain of mathematical information there are at least two different contexts in which the concept of information is essential. In the *computational context*, information is something that has to be computed and stored in an efficient way; in this context, the algorithmic complexity measures the minimum resources needed to effectively reconstruct an individual message (Solomonoff, 1964, Kolmogorov, 1965, 1968, Chaitin, 1966). By contrast, in the traditional *communicational context*, whose classical *locus* is Claude Shannon's formalism (Shannon, 1948, Shannon & Weaver, 1949), information is primarily something that has to be transmitted between two points for communication purposes. 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.*" (Shannon, 1948, p. 379). In this paper we will focus on the concept of information in the communicational context.

In spite of the formal precision supplied by mathematics, the interpretation of the concept of information in a communicational context is still a matter of debate (see Lombardi, Holik & Vanni, 2016). Nevertheless, there are certain minimum elements that can be abstracted to characterize a communicational context. In fact, from a very abstract perspective, communication requires a source and a destination, both systems with a range of possible states: the sequences of the states of the source are the messages to be transmitted. As stressed above, Shannon (1948, p. 379) explicitly states that the only significant aspect of information is that a certain message is selected from a set of possible messages. Therefore, the goal of communication is to identify what message was produced at the source by means of the states occurred at the destination.

A view about information that has become very popular in the philosophical community is based on the traditional distinction between types and tokens. According to this view, given the sequence of states produced by the source, what it is intended to transmit is not the sequence of states itself, but another token of the same type. Therefore, the goal of communication is to reproduce at the destination another token of the same type as that produced at the source (Timpson, 2004, 2013, Duwell, 2008): this is the *type-information* (Duwell, 2008, p. 201) or *pieces* of information (Timpson, 2013, p. 24) to be transmitted, contrasted with the *quantity-information* or *bits* of information, that is, the measure of *how much* information the source produced (Timpson, 2008).

Although very convincing at first sight, that position is contradicted by the engineering practice in communication. Since the goal of communication consists in identifying at the destination the message produced at the source, the success criterion is given by a one-to-one or one-to-many (noisy channel, see next section) mapping from the set of states of the source to the set of states of the destination. Since this mapping is completely arbitrary, the states of the source and the states of the destination may be of a completely different nature: for instance, the source may be a dice and the destination a dash of lights; or the source may be a device that produces words in English and the destination a device that operates a machine. A face of a dice and a light in a dash are not tokens of a same type in any philosophically meaningful sense of the type-token distinction (see Wetzel, 2014). In other words, "*a type needs to have some content to be able to identify its tokens: the distinction between types and tokens is not merely formal or syntactic; being tokens or a same type is not an arbitrary relation.*" (Lombardi, Fortin & López, 2016, p. 222).

A possible move is the attempt to generalize the traditional Peircean difference between sentence-type and sentence-token in terms of *sameness of pattern or structure* (Timpson, 2013, p. 18): "*the success criterion is given by an arbitrary one-to-one mapping from the set of the letters of the source to the set of the letters of the destination*" (Duwell, 2008, p. 200). But this view faces two difficulties, one philosophical and the other technical (for a full development of these criticisms, see Lombardi, Fortin & López, 2016). On the philosophical side, admitting arbitrary one-to-one mappings as defining the relation "*x* is a token of the same type as the token *y*" leads to admit that any two things arbitrarily chosen can always be conceived as tokens of the same type. But this trivializes the distinction type-token and deprives it of conceptual usefulness. From a technical viewpoint, the appeal to the generalization of the type-token difference in terms of sameness of structure or one-to-one mappings forgets the possibility of noisy situations, in which one-to-many mappings link the states of the source and the states of the destination (see next section). Furthermore, these noisy situations are the cases of real interest in the practice of communication engineering. Summing up, despite of the wide dissemination of the ideas that link the transmission of information with the philosophical distinction between types and tokens, it is not necessary to reproduce at the destination what happened at the source for successful communication.

In general, the messages produced at the source are encoded before entering the channel that will transmit them, and decoded after leaving the channel and before being received at the destination. Shannon (1948) and Schumacher (1995) demonstrated theorems that supply the optimal coding in the so-called classical and quantum cases, respectively. The original articles of Shannon and Schumacher were followed by an immense amount of work, both theoretical and technological. Nevertheless, those foundational articles are always consulted to track the origin of the concepts and to discuss their content. For this reason, we will begin by recalling and comparing those formalisms.