What is quantum information?

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1.- Introduction

The word 'information' refers to a polysemantic concept associated with very different phenomena, such as communication, knowledge, reference and meaning (Floridi 2010, 2011). In the discussions about this matter, the first distinction to be introduced is that between a semantic view, according to which information carries semantic content and, thus, is related to notions as reference and meaning, and a statistical view, concerned with the statistical properties of a system and/or the correlations between the states of two systems. Although the *locus classicus* of the statistical concept is the famous article by Claude Shannon (1948), there are many other formal concepts of information, such as the Fisher information (see Fisher 1925), or the algorithmic information (Chaitin 1987). However, the problems of interpretation do not disappear even when the attention is restricted to a single formal concept (see Lombardi, Holik and Vanni 2014).

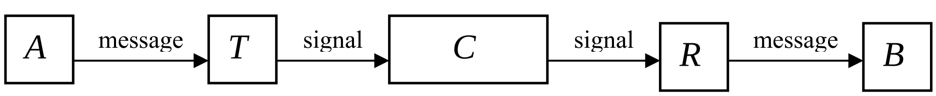
During the last decades, new interpretive problems have arisen with the advent of quantum information, which combine the difficulties in the understanding of the concept of information with the well-known foundational puzzles derived from quantum mechanics itself. This situation contrasts with the huge development of the research field named 'quantum information', 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 and Fuchs 1996), and those who conceive it as a new kind of information absolutely different than Shannon information (Jozsa 1998; Brukner and Zeilinger 2001).

In the present article we will address the question 'What is quantum information?' from a conceptual viewpoint. For this purpose, in Section 2 Schumacher's formalism is introduced by contrast with Shannon's theory. In Section 3 the definition of quantum information in terms of a quantum source is discussed. Section 4 is devoted to analyze the definition of information in terms of coding theorems. These tasks lead us to focus on the relationship between Shannon entropy and von Neumann entropy in Section 5, and to discuss the differences between the concepts of bit and qubit in Section 6. In the light of these arguments, in Section 7 we will endow the phenomenon of teleportation with a reading different than usual. The traditional assumption that quantum information is inextricably linked to quantum mechanics is considered in Section 8. The previous discussions will allow us, in Section 9 to analyze the different interpretations of the concept information, in the search of a characterization adequate to Shannon's and to Schumacher's formalism. Finally, in Section 10 we will draw our conclusions, whose core is the idea that there is not a quantum information as qualitatively different than Shannon information.

2.- Shannon and Schumacher

Shannon's theory is presented in the already classical paper "The Mathematical Theory of Communication" (1948, see also Shannon and Weaver 1949), where a general communication system consists of five parts:

- A *message source A*, which generates the message to be received at the destination.
- A *transmitter T*, which turns the message generated at the source into a signal to be transmitted. In the cases in which the information is encoded, coding is also implemented by this system.
- A *channel C*, that is, the medium used to transmit the signal from the transmitter to the receiver.
- A *receiver R*, which reconstructs the message from the signal.
- A *message destination B*, which receives the message.



The message source A is a system of n states a_i, which can be thought as the *letters* of an alphabet $A_A = \{a_1, ..., a_n\}$, each with its own probability $p(a_i)$; the sequences of N states-letters are called *messages*. Analogously, the message destination B is a system of m states b_j, *letters* of an alphabet $A_B = \{b_1, ..., b_m\}$, each with its own probability. On the basis of these elements, the entropies of the source $H(A)$ and of the destination $H(B)$ can be computed as:

$$H(A) = -\sum_{i=1}^{n} p(a_i) \log p(a_i) \qquad\qquad H(B) = -\sum_{j=1}^{m} p(b_j) \log p(b_j) \qquad (1)$$

and are measured in *bits* when the logarithm to base 2 is used. When $H_i = -\log p(a_i)$ is defined as the individual entropy corresponding to individual state a_i of the message source, the entropy

$H(A)$ turns out to be "*the average of these* H_i *weighted in accordance with the probability of occurrence of the states in question*" (Shannon 1948, p. 396). On this basis, it is natural to interpret H_i as a measure of the information generated at the source *A* by the occurrence of a_i, and $H(A)$ as the average amount of information produced at *A*. The aim of communication is to identify the message produced at the source by means of the message received at the destination.

The entropies $H(A)$ and $H(B)$ are related through the *mutual information* $H(A;B)$, that is, the information generated at *A* and received at *B*, which can be computed as:

$$H(A;B) = -\sum_{i=1}^{n}\sum_{j=1}^{m} p(a_i,b_j)\log\frac{p(a_i)\,p(b_j)}{p(a_i,b_j)} = H(A) - E = H(B) - N \tag{2}$$

where the *equivocation E* is the information generated at *A* but not received at *B*, and the *noise N* is the information received at *B* but not generated at *A*. In turn, the channel *C* is defined by the matrix $\left[\,p(b_j/a_i)\,\right]$, where $p(b_j/a_i)$ is the conditional probability of the occurrence of b_j at *B* given that a_i occurred at *A*, and the elements in any row add up to 1. The largest amount of information that can be *transmitted* over *C* is measured by the *channel capacity CC*, defined as:

$$CC = \max_{p(a_i)} H(A;B) \tag{3}$$

where the maximum is taken over all the possible distributions $p(a_i)$ at *A*.

The transmitter *T* encodes the messages produced by the message source: coding is a mapping from the source alphabet $A_A = \{a_1,\ldots,a_n\}$ to the set of finite length strings of *symbols* from the code alphabet $A_C = \{c_1,\ldots,c_q\}$, also called *code-words*. Whereas the number *n* of the letters of A_A is usually any number, the code alphabet A_C is more often binary: $q = 2$. In this case, the symbols are *binary digits* (binary alphabet symbols). On the other hand, the code alphabet A_C can be physically implemented by means of systems of *q* states.

The code-words do not have the same length: the code word w_i, corresponding to the letter a_i, has a length l_i. Therefore, coding is a fixed- to variable-length mapping. The *average code-word length* can be defined as:

$$\langle l\rangle = \sum_{i=1}^{n} p(a_i)\, l_i \tag{4}$$

$\langle l\rangle$ indicates the compactness of the code: the lower the value of $\langle l\rangle$, the greater the efficiency of the coding, that is, fewer resources $L = N\langle l\rangle$ are needed to encode the messages of length *N*. The *Noiseless-Channel Coding Theorem* (First Shannon Theorem) proves that, for sufficiently long messages ($N\to\infty$), there is an optimal coding process such that the average length *L* of the coded message is as close as desired to a lower bound $L_{\min}$ computed as

$$L_{\min} = \frac{NH(A)}{\log q} \tag{5}$$

When the code alphabet has two symbols, then $L_{\min} = NH(A)$. The proof of the theorem is based on the fact that the messages of *N* letters produced by the message source *A* fall into two classes: one of them consisting of $2^{NH(A)}$ typical messages, and the other composed of the atypical messages. When $N \to \infty$, the probability of an atypical message becomes negligible; so, the source can be conceived as producing only $2^{NH(A)}$ possible messages. This suggests a natural strategy for coding: each typical message is coded by a binary sequence of length $NH(A)$, in general shorter than the length N of the original message.

This formalism has received and still receives different interpretations. Some authors conceive Shannon information as a physical magnitude, whereas others consider that the primary meaning of the concept of information is always linked with the notion of knowledge (we will come back to this point in Section 9). In this section we do not dwell on this issue, but will only focus on the similarities and the differences between Shannon information and quantum information.

Although there were many works on the matter before the article of Benjamin Schumacher (1995) "Quantum Coding", it is usually considered the first precise formalization of the quantum information theory. The main aim of the article is to prove a theorem for quantum coding analogous to the noiseless coding theorem of Shannon's theory. With this purpose, Schumacher considers a message source *A* is a system of *n* states-letters a_i, each with its own probability $p(a_i)$; then, *A* has a Shannon entropy $H(A)$ computed as in eq.(1). In turn, the transmitter *T* maps the set of the states-letters a_i of the source *A* onto a set of *n* states $|a_i\rangle$ of a system *M*. The states $|a_i\rangle$ belong to a Hilbert space $\mathcal{H}_M$ of dimension $\dim(\mathcal{H}_M) = d$ and may be non-orthogonal. The mixture of states of the signal source *M* can be represented by a density operator:

$$\rho = \sum_{i=1}^{n} p(a_i)|a_i\rangle\langle a_i| \in \mathcal{H}_M \otimes \mathcal{H}_M \tag{6}$$

whose von Neumann entropy is:

$$S(\rho) = Tr(\rho \log \rho) \tag{7}$$

In the case that the $|a_i\rangle$ are mutually orthogonal, then the von Neumann entropy is equal to the Shannon entropy: $S(\rho) = H(A)$. In the general case, $S(\rho) \leq H(A)$.

Given the above mapping, the messages $(a_{i1}, a_{i2}, ..., a_{iN})$ of *N* letters produced by the message source *A* are encoded by means of sequences of *N* states $(|a_{i1}\rangle, |a_{i2}\rangle, ..., |a_{iN}\rangle)$, with $i \in \{1, 2, ..., n\}$. This sequence can be represented by the state $|\alpha\rangle = |a_{i1}, a_{i2}, ..., a_{iN}\rangle$ of a system M^N, belonging to a Hilbert space $\mathcal{H}_{M^N} = \mathcal{H}_M \otimes \mathcal{H}_M \otimes ... \otimes \mathcal{H}_M$ $(N \text{ times})$, of dimension d^N. This state is transmitted through a channel C composed of L two-state systems Q called *qubits*, each represented in a Hilbert space $\mathcal{H}_Q$ of dimension 2. Therefore, the Hilbert space of the channel will be $\mathcal{H}_C = \mathcal{H}_Q \otimes \mathcal{H}_Q \otimes ... \otimes \mathcal{H}_Q$ (L times), of dimension 2^L. Analogously to the Shannon case, L indicates the compactness of the code: the lower the value of L, the greater the efficiency of the coding, that is, fewer qubits are needed to encode the messages. The *Quantum Noiseless-Channel Coding Theorem* proves that, for sufficiently long messages, the optimal number $L_{\min}$ of qubits necessary to transmit the messages generated by the source with vanishing error is given by $NS(\rho)$.

Schumacher designs the proof of the theorem by close analogy with the corresponding Shannon's theorem. Again, the idea is that all the possible states $|\alpha\rangle$ (representing the messages of N letters produced by the message source A), belonging to $\mathcal{H}_{M^N}$ of dimension $d^N = 2^{N\log d}$, fall into to classes: one of typical states belonging to a subspace of $\mathcal{H}_{M^N}$ of dimension $2^{NS(\rho)}$, and the other of atypical messages. When $N \to \infty$, the probability of an atypical state becomes negligible; so, the source can be conceived as producing only messages represented by states belonging to a subspace of $2^{NS(\rho)}$. Therefore, the channel can be designed to be represented in a Hilbert space $\mathcal{H}_C$ such that $\dim(\mathcal{H}_C) = 2^L = 2^{NS(\rho)}$, and this means that the minimum number $L_{\min}$ of qubits necessary to transmit the messages of the source is $L_{\min} = NS(\rho)$.

Schumacher's formalism is elegant and clear; nevertheless, disagreements begin when it is endowed with different readings.

3.- Two kinds of source, two kinds of information?

Christopher Timpson characterizes information as classical or quantum depending on the kind of source that produces it: "*If classical information$_t$* [information in its technical sense] *is what is produced by a classical information$_t$ source –the Shannon prototype– then quantum information$_t$ is what is produced by a* quantum *information$_t$ source*" (Timpson 2008, p. 24, emphasis in the original; see also Timpson 2004, 2013). According to Timpson, this is part of the analogical strategy followed by Schumacher: "*Schumacher followed Shannon's lead: consider a device —a quantum source—which, rather than outputting systems corresponding to elements of a classical alphabet, produces systems in particular quantum states ρ_{x_i} with probabilities $p(x_i)$.*" (Timpson 2006, p. 593).

Of course, this characterization preserves an elegant symmetry between Shannon's and Schumacher's proposals. However, when Schumacher's article is read with care, one can see that this is not what the author says. On the contrary, Schumacher begins by defining the *message source A* that produces each a_i with probability $p(a_i)$, and only in the stage of coding he introduces the *quantum signal source*, which "*is a device that codes each message a_M from the source A into a "signal state" $|a_M\rangle$ of a quantum system M*." (Schumacher 1995, p. 2738). This means that the quantum states involved in the process described by Schumacher do not come from a message source, but from a quantum system *M* that is part of the device that encodes the *messages* produced by the message source and turns them into *signals* to be transmitted through the channel. In other words, the quantum system *M* is part of what Shannon called 'transmitter'. This remark is in agreement with what is suggested by the title itself of Schumacher's article: "Quantum Coding" and not "Quantum Information".

Against those who conceive quantum information as something radically different than Shannon information (see, for example, Jozsa 1998, Brukner and Zeilinger 2001), the above considerations tend to support the position according to which, strictly speaking, there are not two kinds of information: 'quantum information' is only a confusing way of talking about information encoded by quantum means. This is the position adopted by Caves and Fuchs when stating that "*Quantum information refers to the distinctive information-processing properties of quantum systems, which arise when information is stored in or retrieved from nonorthogonal quantum states*" (Caves and Fuchs 1996, p. 226).

Somebody could reject the above position by quoting Schumacher who, after stressing the difference between copying and transposition, says that "*We can therefore imagine a communication scheme based upon transposition. At the coding end, the signal of a source system M is transposed via the unitary evolution U into the coding system X. The system X is conveyed from the transmitter to the receiver. At the decoding end, the unitary evolution U' is employed to recover the signal state from X into M', an identical copy of system M* " (Schumacher 1995, p. 2741). A light reading of this fragment may interpret it as talking about the information generated by *M* and arriving at *M'*; a kind of information that is quantum because generated by the quantum source *M*. However, this is not the proper reading. As it is clear in the above quote, the system *X* "*is conveyed from the transmitter to the receiver*", not from the message source *A* and the message destination *B*. Moreover, the system *M* is at the *coding end* and the system *M'* is at the *decoding end*; so, *M* is not the message source *A*. Again, as the title of the paper expresses, here the focus is on the stages of coding in the transmitter, transmitting through the channel, and decoding at the receiver: there is no quantum source of quantum information that produces quantum states as messages: the quantum state $|\alpha\rangle$ is not the message but the signal.

The assumption that the system *M* is the quantum source of information, as if the quantum states produced by it were the letters of the messages, leads to suppose that the aim of communication is to the transposition of the state generated at *M* into *M'*. On this basis, Timpson states that what we want to transmit is not the sequence of states itself, but another *token* of the same type: "*one should distinguish between the concrete systems that the source outputs and the type that this output instantiates*." (Timpson 2004, p. 22; see also Timpson 2008). Then, the goal of communication, both classical and quantum, is to reproduce at the destination another token of the same type: "*What will be required at the end of the communication protocol is either that another token of this type actually be reproduced at a distant point*" (Timpson 2008, p. 25).

Against these claims, it must be noticed that the goal of any communication is not to reproduce at the destination a token of the same type as that produced at the source. As stressed by Shannon, in communication "[t]*he significant aspect is that the actual message is one* selected from a set *of possible messages*." (1948, p. 379, emphasis in the original). Any communication engineer knows that the states b_j of the destination system *B* can be states of any kind, completely different than the states a_i of the source system *A*: the goal of communication is to identify at the destination which sequence of states a_i was produced by the message source *A*. For instance, the message source may be a dice and the message destination a dash of lights; or the message source may be a device that produces words in English and the message destination a device that operates a machine. A face of a dice and a light in a dash cannot be conceived as tokens of a same type without depriving the distinction type-token of any philosophical content and conceptual usefulness (for a detailed criticism, see Lombardi, Fortin and López 2014). The idea that successful communication needs to reproduce at the destination the same type-state as that produced at the source seems to be the result of focusing on the quantum case, and confusing the message source with the system *M*, which is not the message source but a part of the signal source belonging to the transmitter.

In the same sense, it is important not to confuse the success of communication with the *fidelity* of the process of transposition, defined as (Schumacher 1995, p. 2742):

$$F = \sum_{i=1}^{n} p(a_i) \left| a_i \right\rangle \left\langle a_i \right| \omega_i \qquad (8)$$

where the $\left| a_i \right\rangle \left\langle a_i \right|$ correspond to the signal states produced at *M*, and the ω_i represent the signal states obtained at *M'* as the result of the transposition, which do not need to be pure. Fidelity measures the effectiveness of the stage of transmission through the channel, and it is a property of the channel: the fidelity of a transmission is less than unity when the channel is limited in the sense that $\dim\left(\mathcal{H}_C\right) < \dim\left(\mathcal{H}_{M^N}\right)$ (although indefinitely close to unity when $\dim\left(\mathcal{H}_C\right) = 2^{NS(\rho)}$, as proved by the quantum coding theorem). The success of communication, on the contrary, is defined by a one-to-one (or even a one-to-many) mapping from the set of states-letters of the *message source* and the set of states-letters of the *message destination*, which makes possible to identify at the destination the state-letter occurred at the message source. This mapping is completely conventional and depends on the particular application at task. Of course, how successful a certain situation of communication based on quantum transposition is will be function of the fidelity of the transposition, but also of the reliability of the operations of coding and decoding, which correlate the states a_i of the message source *A* with the quantum states $|a_i\rangle$ of *M*, and the quantum states w_i of *M'* and the states b_i of the destination *B*, respectively. In other words, the approximation to success in a particular situation of communication depends on the whole communication arrangement, and not only on the transmission stage. The identification of the success of communication with the fidelity of transposition (see Duwell 2008 for discussion) runs parallel with the identification of the message source with the signal source, and both lead to conclude that quantum information is a different kind of information than "classical" Shannon information.

But the defender of the qualitative peculiarity of quantum information might insist: What prevents us to consider *M* as a quantum source and to define quantum information as what is produced by the quantum source? In this case, the goal of communication would be to reproduce at the destination *M'* the same type-state as that produced at the source *M*. Of course, definitions are conventional, and we can assign names at will. But, this view distorts the very idea of communication, which consists in identifying what happens at the message source (what message is produced) by means of what happens at the message destination, with no need that the source state and the destination state be tokens of the same type. Moreover, if quantum information were what is produced by the quantum source –which produces quantum states–, sending information would turn out to be transposing quantum states. In fact, when it is forgotten that transposing is only a part of a communication situation and it is disregarded the role played by the message source and the message destination, nothing would change in the discourse about quantum information if one replaced the term 'quantum information' by the term 'quantum state'. As Armond Duwell clearly states, although it can be argued that there are specific properties that motivate a new concept of information, different than Shannon's, when those properties are revised, "[i]*t is obvious that there is already a concept that covers all of these properties: the quantum state. The term 'quantum information' is then just a synonym for an old concept*" (Duwell 2003, p. 498). Therefore, 'quantum information' turns out to mean quantum state, but the whole meaningful reference to communication gets lost.

In summary, up to this point there seems to be no reasons to consider that there exists a quantum information as qualitatively different than Shannon information. However, as we will see in the next section, a further argument has been raised to support the peculiarity of quantum information.

4.- Two kinds of coding, two kinds of information?

Another strategy of those who see quantum information as a different and peculiar type of information is to link the very meaning of the concept of information with the coding theorems: if the theorems are different in the classical and the quantum case, the corresponding concepts of information are also different. For instance, Timpson *defines* the concept of information in terms of the noiseless coding theorems: "*the coding theorems that introduced the classical (Shannon, 1948) and quantum (Schumacher, 1995) concepts of information$_t$* [the technical concept of information] *do not* merely *define measures of these quantities. They also introduce the concept of* what it is *that is transmitted,* what it is *that is measured*." (Timpson 2008, p. 23, emphasis in the original). In other words, information measures "*the minimal amount of channel resources required to encode the output of the source in such a way that any message produced may be accurately reproduced at the destination. That is, to ask how much information$_t$ a source produces is ask to what degree is the output of the source* compressible*?*" (Timpson 2008, p. 27, emphasis in the original).

The first thing to notice here is that the strategy of defining Shannon information via the noiseless coding theorem turns the theorem into a definition. In fact, now the Shannon entropy $H(A)$ of the message source A is not defined by eq. (1) as the average amount of information per letter generated by A, but it is defined as the average number of bits necessary to code a letter of the message source A using an ideal code, and eq. (1) becomes a theorem resulting from a mathematical proof. In the quantum coding case, the strategy of defining the von Neumann entropy $S(\rho)$ in terms of Schumacher's quantum coding theorem is more reasonable because, as argued above, $S(\rho)$ plays a role in the stage of coding and is a property of the signal source, and not of the message source. However, this does not amount to suppose that, in this case, the information generated at the message source and to be transmitted to the message destination is measured by $S(\rho)$: once again, this is a conclusion derived from improperly identifying the message source with the signal source.

As explained in Section 2, the coding theorems are proved for the case of very long messages, strictly speaking, for messages of length $N \to \infty$. Thus, it says nothing about the relation between the information generated at the message source by the occurrence of a single state and the resources needed to encode it. Therefore, if the noiseless coding theorems embody the very nature of classical and quantum information, it makes no sense to talk about the individual amount of information conveyed by a single state. Not only that, but one wonders whether short messages can be conceived as embodying information to the extent that they are not covered by the noiseless coding theorems.

When explaining the elements of the general communication system, Shannon (1948, p. 381) characterizes the transmitter as a system that operates on the message coming from the source in some way to produce a signal suitable for transmission over the channel. In many cases, as telegraphy, the transmitter is also responsible for encoding the source messages. However, in certain cases the message is not encoded. For instance, in traditional telephony the transmitter operates as a mere transducer, by changing sound pressure into a proportional electrical current. If one insists on defining information in terms of the noiseless coding theorems, how to talk about information in these situations that do not involve coding?

Summing up, the strategy of defining information via the noiseless coding theorems conflates two aspects of communication that the traditional textbooks urged us not to conceptually confuse: the information generated at the message source, which depends on its states and the probability distribution over them, and is independent of coding –even independent of the very fact that the messages are coded or not–, and the resources necessary to encode the occurrence of those states, which also depends on the particular coding selected (for a more detailed argument, see Lombardi, Fortin and López 2014). Given a message source A, the information $H(A)$ generated by it can be coded in many different ways. Shannon's noiseless coding theorem says that $H(A)$ also measures the optimal length of the coded messages when coded by means of classical systems of, say, two states; Schumacher's noiseless coding theorem says that, if quantum systems are used for coding instead of classical systems, the optimal coding is measured by $S(\rho)$. And this raises the question about the relationship between Shannon entropy and von Neumann entropy.

5.- The relationship between Shannon entropy and von Neumann entropy

The first point that is usually stressed is that the von Neumann entropy is, in general, lower than the Shannon entropy:

$$S(\rho) \leq H(A) \qquad (9)$$

In turn, the so-called Holevo bound (Holevo 1973) establishes an upper bound for the mutual information in the case of quantum coding. When the signal states are pure states $|a_i\rangle$, the bound is given by:

$$H(A;B) \leq S(\rho) \qquad (10)$$

From a perspective that establishes a clear difference between classical and quantum information, Timpson distinguishes between *specification* information and *accessible* information. Specification information is the amount of information required to specify the sequence of states of N two-state systems. Accessible information is the amount of information that can be acquired or read from the sequence by measurement. If the states are non-orthogonal, it is not possible to distinguish among them perfectly; therefore, "*in the classical case, the two quantities will coincide, as classical states are perfectly distinguishable*." (Timpson 2008, p. 4). According to Timpson, this distinction can be made only in the case of communication of classical information by means of quantum systems, where the specification information is $H(A)$, and the accessible information is $H(A;B)$, whose upper bound is given by $S(\rho)$. But in the strictly quantum case, the distinction cannot be made because there is no classical source of information: there is only a quantum source producing quantum information measured in qubits: "*Thus when talking about the amount of information that is associated with a given system, or has been encoded into it, we need to clarify whether we are talking about transmitting* classical *information* using *quantum systems, or whether we are talking about encoding and transmitting quantum information properly so-called. In the former context, the notions of specification and accessible information apply: how much classical information is required to specify a sequence, or how much classical information one can gain from it, respectively; and we know that at most one classical bit can be encoded into a qubit. In the latter context, we apply the appropriate measure of the amount of quantum information*." (Timpson 2008, p. 5, emphasis in the original).

This interpretation must face the problem that this is not what Schumacher says in his article. As the author clearly explains, $H(A)$ is the Shannon entropy of the *message source*, and the von Neumann entropy $S(\rho)$ is a property of the *signal source* in the case of coding by means of quantum states. When the signal states $|a_i\rangle$ are mutually orthogonal, they turn out to be the eigenstates of ρ and the $p(a_i)$ become its eigenvalues; therefore, $S(\rho) = H(A)$. When the signal states $|a_i\rangle$ are not mutually orthogonal, in general the $|a_i\rangle$ have no simple relation with the eigenstates of ρ; then $S(\rho) < H(A)$. And the Holevo bound establishes the maximum amount of information $H(A;B)$ produced at the message source *A* and received at the message destination *B*. There are not two possible cases here, one classical with quantum coding, where the Holevo bound applies, and another strictly quantum, where the bound does not apply and that is the subject matter of quantum information theory. Schumacher's paper always speaks about a communication situation where the outputs of a message source *A* are coded by means of quantum systems, and there is not another situation under consideration by contrast with this one.

In turn, if the signal states $|a_i\rangle$ are not orthogonal, it is not possible to distinguish among them perfectly by means of measurement. This means that, even if they are transposed with perfect fidelity between *M* and *M'*, no measure on *M'* will be sufficient to recover the states produced in *M*. The process of measuring on *M'* consists in the decoding process at the receiver, which aims at reconstructing the original message from the signal; then, when the signals states are non-orthogonal, such a reconstruction cannot be perfect, and the amount of information produced at the message source *A* and received at the destination *B*, $H(A;B)$, is less than the amount of information $H(A)$ produced at the message source. When the whole situation is addressed with the conceptual tools of abstract communication theory, the conclusion is not surprising: if messages are encoded by means of non-orthogonal –and then non perfectly distinguishable– states, there is a loss of information between the message source and the message destination measured by an equivocation $E \neq 0$; therefore, $H(A;B) = H(A) - E < H(A)$. And the Holevo bound gives the bound of this information loss, which is not due to a non-perfect fidelity in the transposition of the state through the channel, but is the result of an imperfect decoding at the receiver. In this explanation, there is still no quantum information as different than classical information and with a conceptual content that differs from the meaning of the quantum state itself in some substantial sense.

6.- Bits and qubits

In the definition of the Shannon entropy, the choice of a logarithmic base amounts to a choice of a unit for measuring information. If the base 2 is used, the resulting unit is called '*bit*'. But the natural logarithm can also be used, and in this case the unit of measurement is the *nat,* contraction of *natural unit*. And when the logarithm to the base 10 is used, the unit is the *Hartley*. The possibility of using different units to quantify information shows the difference between the amount of information associated with an event and the value obtained by using a particular unit of measurement.

For a long time it was quite clear in the field of communication engineering that "bit" was a unit of measurement, and that the fact that a different unit can be used did not affect the very nature of information. However, with the advent of quantum information, the new concept of *qubit* entered the field: a qubit is primarily conceived not as a unit of measurement of quantum information, but as a quantum system of two-states used to encode the information of a source. This way of talking about qubits has gradually seeped into Shannon's theory and its talk about bits. This process led to a progressive reification of the concept of bit, which now is also –and many times primarily– conceived as referring to a classical system of two states. Some authors still distinguish between the two meanings of the concept: "*I would like to distinguish two uses of the word "bit." First, "bit" refers to a unit of information that quantifies the uncertainty of two equiprobable choices. Second, "bit" also refers to a system that can be in one of two discrete states.*" (Duwell 2003, p. 486). But nowadays the conflation between the two meanings is much more frequent: "*The Shannon information* $H(X)$ *measures in bits (classical two-state systems) the resources required to transmit all the messages that the source produces*." (Timpson 2006, p. 592). The same confusion appears in the quantum case, where the qubit, besides referring two-state quantum systems, is now also conceived as the unit of measurement of the quantum information, quantified by the von Neumann entropy: "*just as Shannon's noiseless coding theorem introduces the concept of the bit as a measure of information, the quantum noiseless coding theorem introduces the concept of the qubit as a measure of quantum information, characterising the quantum source*." (Timpson 2004, p. 26).

Although very widespread, this undifferentiated use of the term 'bit' sounds odd to the ears of an old communication engineer, who has the difference between a system and a unit of measurement deeply internalized. For him, conflating a bit with a two-state system is like confusing a meter with the Prototype Meter bar, an object made of an alloy of platinum and iridium and stored in the *Bureau International des Poids et Mesures* in Sèvres. And asserting that the Shannon information $H(X)$ gives a measure "in bits (classical two-state systems)" amounts to saying that the length L gives a measure "in meters (platinum-iridium bars)". In order to avoid this kind of confusions about the concept of bit, it might be appropriate to follow the suggestion of Carlton Caves and Christopher Fuchs (1996), who propose to adopt the term '*cbit*' to name a two-state classical system when used to encode information, by analogy with the term 'qubit' that names a two-state quantum system involved in quantum coding. This terminology keeps explicit the distinction between the quantity of information produced at the message source, which is usually measured in bits (but may also be measured in other units), and the systems of q states (usually $q = 2$) used to physically implement coding.

From this viewpoint, information is always measured in bits, and it is generated by a message source A of Shannon entropy $H(A)$. In turn, this information can be coded by means of cbits (classical two-state systems) or of qubits (quantum two-state systems). The optimal resources needed to encode the information (the number of systems required, in average) are given in the first case by the Shannon entropy $H(A)$ (Shannon's noiseless coding theorem), and in the second case by the von Neumann entropy $S(\rho)$ (Schumacher's noiseless coding theorem). Therefore, all the peculiarities with which quantum information is usually endowed are features of the quantum coding: "*the properties* [supposedly specific of quantum information] *depend on the type of physical system used to store information, not on new properties of information*" (Duwell 2003, p. 481).

The arguments of the last four sections lead us to the following remark. It is clear that, in his famous article, Schumacher exploits the analogy between Shannon's theory and his new proposal. But the analogy is focused on the coding-transmitting-decoding stage: the transmitter-channel-receiver part of the communication arrangement in Shannon's general characterization. Schumacher's purpose is to formulate a quantum coding theorem whose demonstration runs parallel to that of Shannon's noiseless coding theorem. However, this analogy is usually extended beyond its original scope. This extension introduces the concept of quantum source as the parallel of the supposedly classical source (the message source), and conceives the von Neumann entropy $S(\rho)$ as the quantum equivalent of the Shannon entropy $H(S)$: $S(\rho)$ would measure in qubits the quantum information generated by the quantum source, as $H(S)$ measures in bits the classical information generated by the classical source; and the quantum coding theorem would show that $S(\rho)$ establishes the optimal resources needed to code quantum information as the classical coding theorem shows that $H(S)$ establishes the resources needed to code classical information. This close parallelism is certainly very appealing, but does not agree with the content of the article that supposedly laid the foundations of quantum information theory. And if, pace Schumacher, one tries to defend the extended analogy, the concept of quantum information becomes indistinguishable from that of quantum state and loses its connection with the general idea of communication that should support it.

7.- What is transferred in teleportation?

Teleportation is one of the most discussed issues in the field of quantum information. Although a direct result of quantum mechanics, it appears as a weird phenomenon when described as a process of transmission of information. Broadly speaking, an unknown quantum state $|\chi\rangle$ is transferred from Alice to Bob with the assistance of a shared pair of particles prepared in an entangled state and of two classical bits sent from Alice to Bob (the description of the protocol can be found in any textbook on the matter; see, e.g., Nielsen and Chuang 2010). In general, the idea is that a very large (strictly infinite) amount of information is transferred from Alice to Bob by sending only two bits through a classical channel.

In his detailed analysis of teleportation, Timpson (2006) poses the two central questions of the debate: "*First, how is so much information transported? And second, most pressingly, just how does the information get from Alice to Bob?*" (Timpson 2006, p. 596). We will consider the two questions from the viewpoint developed in the previous sections.

Regarding to the first question, it is usually said that the amount of information generated at the source is, in principle, infinite, because two real numbers are necessary to specify the state $|\chi\rangle$ among the infinite states of the Hilbert space. Even in the case that a coarse-graining is introduced in the Hilbert space, the amount of information is immensely greater than the two bits sent through the classical channel. This great amount of information cannot be transported by the two classical bits that Alice sends to Bob. So, how is so much information transported? Timpson's answer to this first problem is based on the supposed difference between classical information encoded in quantum systems and quantum information. In the classical case, he relies on the distinction between specification information and accessible information: although the specification information –the information necessary to specify the state– is very large, or even infinite, the accessible information –the information that Bob can retrieve by measurement– is always limited by the Holevo bound, which "*restricts the amount of information that Bob may acquire to a maximum of one bit of information per qubit, that is, to a maximum of one bit of information per successful run of the teleportation protocol*." (Timpson 2006, p. 595).

However, this answer leaves us with many conceptual questions. If the qualitative difference between classical and quantum information is accepted, it seems that only the *classical* information needed to specify the state is infinite, and it is this classical information that is inaccessible at Bob's end. But, what about *quantum* information? How much quantum information is transferred? The answer seems to be: one qubit per successful run of the teleportation protocol. But if the term 'qubit' refers to a two-state quantum system, we cannot say that a qubit was transferred: there is no quantum system that Alice sends to Bob (Figure 1 in Timpson 2006 shows the contrary: it is Bob who sends one of the subsystems of the maximally entangled state to Alice). Perhaps 'qubit' has to be understood in its other meaning, that is, as the unit of measurement of the quantum information carried by $|\chi\rangle$, quantified by the von Neumann entropy $S(\rho)$. But this does not dispel our perplexity, since the von Neumann entropy $S(\rho)$ corresponding to the state $|\chi\rangle$ is zero, because $|\chi\rangle$ is a pure state. On the other hand, what is the amount of the classical information generated at the source, and quantified by the Shannon entropy $H(A)$? In order to compute it, it is necessary to count with the distribution of probability over the possible states of the source, since $H(A)$ depends essentially on that distribution: a source might have infinite states such that only one of them has non-zero probability; in this case, $H(A)$ would be zero. These remarks show that it makes no sense to describe a phenomenon as teleportation in informational terms if the message source, with its possible states and their probabilities, is not clearly characterized. Only on the basis of such characterization one can talk meaningfully about the amount of information $H(A)$ –measured in bits– of the message source, and about the entropy $S(\rho)$ –measured in qubits– of the signal source that produces the quantum states to be teleported in the successive runs of the protocol.

Let us now consider the second question: how does the information get from Alice to Bob? In traditional communication, the information is always transferred from the transmitter to the receiver by some physical carrier. But it is usually assumed that in teleportation there is no physical carrier between Alice and Bob other than that represented by the two classical bits that Alice sends to Bob. This has lead many physicists to search for the physical link that can play the role of the carrier of information. For Richard Jozsa (1998, 2004), quantum information is a new kind of information, which has an amazing non-classical property: it may flow backwards in time. In teleportation, the information travels backwards in time to the event at which the entangled pair was produced and then travels forwards to the future (see also Penrose 1998). According to David Deutsch and Patrick Hayden (2000), the quantum information travels hidden in the classical bits. In order to avoid these views, Timpson cuts the Gordian knot of teleportation by adopting a deflationary view of information, according to which "*there is not a question of information being a substance or entity that is transported, nor of 'the information' being a referring term*." (2006, p. 599); therefore, the only meaningful issue in teleportation is about the physical processes involved in the protocol.

Perhaps the exotic explanations of teleportation can be avoided without depriving the concept of information of any content, if the full communication situation is considered. In fact, communication requires a message source A that produces letters, which are coded by means of quantum states at the signal source M, which, in turn, produces the signal to be transferred to the receiver. In this communication framework, it can be seen that teleportation is a phenomenon that corresponds to the stage of transmission. In particular, it is a case of what Schumacher called 'transposition': "*"quantum teleportation"* […] *is a rather exotic example of a transposition process*" (Schumacher 1995, p. 2741). But, as explained in Section 3, transposition is not the transmission of the information generated at the message source A to the destination end B; it is the transference of the signal from the transmitter to the receiver. In this case, the signal is the quantum state $|\chi\rangle$, which cannot be copied into the receiver M', but can be transposed with a fidelity F. In other words, teleportation is a physical process that allows a quantum state to be transferred between two quantum systems without leaving a copy behind, and this process does not need to be conceptualized in informational terms to be understood. In other words, teleportation could be explained with absolutely no reference to information. Therefore, if there is a puzzle in teleportation, it is the old quantum puzzle embodied in non-locality, and not a new mystery about a new kind of information. Again, when the discourse about quantum information is properly debugged, the concept of 'quantum information' has no different content than that of the concept of quantum state.

8.- Quantum states or non-orthogonal states?

According to several authors (Timpson 2003; Duwell 2003; Lombardi 2004; Lombardi, Fortin and Vanni 2014), the information appearing in Shannon's theory and measured by the Shannon entropy is not classical, but is neutral with respect to the physical theory that describes the systems used for its implementation. Armond Duwell expresses very clearly this idea: "*The Shannon theory is a theory about the statistical properties of a communication system. Once the statistical properties of* *a communication system are specified, all information-theoretic properties of the communication system are fixed.* […] *Hence, the Shannon theory can be applied to any communication system regardless whether its parts are best described by classical mechanics, classical electrodynamics, quantum theory, or any other physical theory*." (Duwell 2003, p. 480). By contrast, quantum information is usually presented as inextricably linked to quantum mechanics. For instance, on the basis of identifying the success of communication with the fidelity of transposition (recall our criticism to that identification in Section 3), Duwell claims that "[t]*he distance between Shannon information theory and quantum information theory concerns the nature of success criteria for the two theories. Quantum information theory, with its standard correspondence rules (that states describe states of quantum systems), has a very natural success criterion.*" (Duwell 2008, p. 213). The idea that quantum mechanics dictates the need of a new kind of information is very common in the physicist community: "*One of the most fascinating aspects of recent work in fundamental quantum theory is the emergence of a new notion, the concept of quantum information, which is quite distinct from its classical counterpart*" (Jozsa 1998, p. 49). In other words, even for those who admit that Shannon information is theoretically neutral, quantum information seems to be essentially tied to quantum mechanics.

This view about quantum information finds the specificity of this kind of information in a well-known property of quantum states: their indistinguishability. Non-orthogonal quantum states are not distinguishable by measurement: "*in contrast to classical systems, quantum measurement theory places severe restrictions on the amount of information we can obtain about the identity of a given quantum state by performing any conceivable measurement on it.*" (Jozsa 1998, p. 50). For Timpson, whether the states produced by the respective sources are distinguishable or not is what discriminates between the two types of information, classical and quantum: "*a distinguishing characteristic of classical information$_t$* [the technical concept of information] *when compared with quantum information$_t$ is that the varying outputs of a classical information source are distinguishable one from another*" (Timpson 2008, p. 24). These are only two examples of the widespread way of sorting the concepts involved to the field of information into two groups: classical-orthogonal-distinguishable and quantum-non-orthogonal-indistinguishable.

Once this difference between "classical" Shannon information and quantum information is accepted, the following step is to compare and relate them to each other. An idea that pervades the bibliography on the subject is that, since for a mixture of orthogonal states $S(\rho) = H(A)$, Shannon information is a particular case of quantum information: it is the case in which the states are distinguishable. Jeffrey Bub expresses this view: "[c]*lassical information is that sort of information represented in a set of distinguishable states –states of classical systems, or orthogonal quantum* *states – and so can be regarded as a subcategory of quantum information, where the states may or may not be distinguishable.*" (Bub 2007, p. 576). Or, the other way around, von Neumann entropy is conceived "*as a generalization of the notion of Shannon entropy*." (Bub 2007, p. 576).

These claims, although seemingly clear when considered individually, lead us to some perplexities when taken together: if classical information is a subcategory of quantum information, classical information is also quantum? So, why "classical" information is classical? Do we need to assume that classical physics arises as the classical limit of quantum mechanics? On the other hand, if classical information is a particular case of quantum information, then, pace Duwell (2003), strictly speaking what really exist is quantum information and not classical information. In turn, if quantum information turns out to be the most general concept of information and, at the same time, it is really essentially tied to quantum mechanics, any attempt to reconstruct quantum mechanics in informational terms runs the risk of becoming circular. A way of avoiding circularity is to use a concept of information more general than that involved in Shannon and Schumacher formalisms, as in the case of the CBH characterization of quantum theory (Clifton, Bub and Halvorson 2003). This confusing picture shows the need of a conceptual and terminological "cleaning" in the field of quantum information.

A starting point for this task is to break the threatening circularity by reconsidering the usually acritically accepted link between quantum information and quantum mechanics. Let us suppose for a moment that quantum information is information represented in non-orthogonal states, does it make quantum information quantum? Certainly, in general quantum states are non-orthogonal, but the opposite is not true: non-orthogonal states can be also defined in a classical framework. In fact, as Wayne Myrvold (2010) stresses, some features traditionally considered as peculiarly quantum can be recovered in a formalism that deals with classical mixed states defined as probability measures over a classical phase space (or in the Hilbert space formalism of classical statistical mechanics, see Koopman 1931). In particular, two classical mixtures can be defined as orthogonal if and only if their supports are disjoint. Furthermore, even the no-cloning theorem, originally obtained in the quantum context (Dieks 1982, Wootters and Zurek 1982; see the extension to mixtures in Barnum *et al*. 1996), can be proved in the classical statistical domain by taking overlapping probability distributions with non-trivial supports as dynamical variables (Daffertshofer, Plastino and Plastino 2002; see discussion in Teh 2012).

These results suggest that, at the end of the day, quantum information is not as quantum as originally supposed. In fact, Schumacher formalism could be repeated without using the term 'quantum', by talking only about states belonging to a Hilbert space (such as it was introduced in Section 2), with no reference to a specific physical theory. Once this is acknowledged, it is not difficult to conceptually imagine that, in a counterfactual history, “quantum” information could be developed in the nineteenth century, in terms of, say, Gaussian functions with disjoint supports on a phase space.

Somebody might retort, following Schrödinger (1936), that the essential difference between the classical and the quantum is located in entanglement. However, in the first place it has to be recalled that there are “classical” simulations of quantum mechanics that recover the main features of the theory (see, e.g. Aerts 1988), even regarding entanglement (Collins and Popescu 2002). However, this is not the most important point of the argument. The main issue here is the role played by entanglement in Schumacher’s proposal. As argued in the previous section, in this case communication takes advantage of entanglement to implement transposition, and transposition is a physical process that allows the signal to be transferred between two systems without leaving a copy behind. However, this does not mean that any transposition process needs to be implemented by entanglement. Schumacher is explicit about this point: “*The system X is conveyed from the transmitter to the receiver*. […] *The system X is the quantum channel in this communication scheme, and supports the transposition of the state of M into M’*.” (Schumacher 1995, p. 2741). As it is quite clear, transposition needs the signal to be conveyed from the transmitted to the receiver, but such a goal can be met by sending a physical system *X* from the two ends by “standard” ways, without resorting to entanglement. Therefore, even accepting that entanglement is the hallmark of the quantum, it is not essential to Schumacher theory, which can be implemented on the basis of a traditional channel.

The conclusion drawn from this argument is that there is no difference between “classical” information and “quantum” information regarding the physical substrata that implement them. Analogously to the case of Shannon’s theory, which is not classical but theoretically neutral, the same can be said about Schumacher’s theory: it is not quantum, but neutral with respect to the physical theory that describes the systems used for its implementation. When this conclusion is combined with our previous claim that there is no quantum information as different than classical information, information theory acquires a much simpler and clearer presentation, where the terms ‘classical’ and ‘quantum’ disappear. A message source A produce messages that carry information –neither classical nor quantum–, whose average amount is measured by the Shannon entropy $H(A)$. The messages so produced enter the transmitter, which –in general– encodes them by means of a signal source M that produces signals. Coding can be performed by means of orthogonal or non-orthogonal states. In the orthogonal case, Shannon’s coding theorem relates the Shannon entropy $H(A)$ with the optimal coding. In the non-orthogonal case, Schumacher’s coding theorem introduces the von Neumann entropy $S(\rho)$ of the mixture of states of the signal source M as the relevant magnitude that gives the optimal coding. The signals are then transmitted between transmitter and receiver through the communication channel, which can be implemented in different ways. Fidelity measures the effectiveness of the signal transmission through the channel, between the signal source *M* and the system *M'* at the receiver end. The system *M'* performs a decoding process that turns the signals into messages, which finally arrive to the message destination *B*. The success of communication, defined by a one-to-one –or a one-to-many– mapping from the set of states-letters of the message source *A* and the set of states-letters of the message destination *B*, can be quantified in terms of the mutual information $H(A;B)$.

In this completely abstract characterization, it makes sense to say that the theoretical tools used in non-orthogonal coding are the most general, since they can represent the orthogonal coding situation as a particular case, when $S(\rho)=H(A)$. On the other hand, when information theory is understood independently of the physical systems that materialize communication, then the attempts to reconstruct quantum mechanics on the basis of informational constraints (Fuchs 2002; Clifton, Bub and Halvorson 2003) acquire a strong conceptual appealing. In fact, if information is a concept that can be formally defined and theoretically treated independently of any particular theory of physics, then the reconstruction of quantum mechanics in terms of that concept presents the theory in a completely new light. Moreover, the reconstruction of different physical theories on the same neutral informational basis, if possible, would allow them to be meaningfully compared without reductionist prejudices.

In summary, conceiving the concept of information as independent from physical theories contributes to the understanding of the subject matter and to dispel confusions. Nevertheless, this position does not answer yet the question about the nature of information.

9.- What is information?

Once it is accepted that there are not two kinds of information, classical and quantum, the problem of interpretation is simpler: now the question about the nature of information is only one. However, as we will see, the answer is not just one.

The notion most usually connected with the concept of information is that of knowledge: information provides knowledge, modifies the state of knowledge of those who receive it. For instance, Fred Dretske adopts an epistemic interpretation when he states that: "*information is a commodity that, given the right recipient, is capable of yielding knowledge.*" (1981, p. 47); in a similar trend, Jon Dunn defines information as "*what is left of knowledge when one takes away belief, justification and truth*" (2001, p. 423). Some authors believe that the link between information and knowledge is a feature of the everyday notion of information and not of the technical concept (see Timpson 2004, 2013). However, the literature shows that this is not the case: physicists frequently speak about what we know or may know when dealing with information. For instance, Zeilinger equates information and knowledge when he says that "[w]*e have knowledge, i.e., information, of an object only through observation*" (1999, p. 633) or, with Bruckner, "[f]*or convenience we will use here not a measure of information or knowledge, but rather its opposite, a measure of uncertainty or entropy.*" (2009, pp. 681-682). In the quantum context, Christopher Fuchs adheres to Bayesianism regarding probabilities and, as a consequence, advocates for an epistemic interpretation of information (see, e.g., Caves, Fuchs and Schack 2002).

Although seemingly safe, the epistemic view leads to perplexities in certain simple situations. Let us consider a source S that transmits information to two physically isolated radio receivers R_A and R_B via a physical link (electromagnetic waves). In this case, although there is no physical interaction between the two receivers, the correlations between their states are not accidental, but they result from the physical dependence of those states on the states of S. Therefore, strictly from the epistemic interpretation of information it must be admitted the existence of an *informational* link between the two receivers: it is possible to learn something about R_B by looking at R_A and vice versa. And this holds even in the case that R_B is farther from the source S than R_A, so that the events at R_B occur later than those at R_A: from the epistemic view, R_A carries information about what will happen at R_B.

The traditional physical interpretation of information blocks this possibility by conceiving information as a physical magnitude (see, *e.g.*, Rovelli 1996). This is the common view of communication engineers, for whom the essential feature of information consists in its capacity to be generated at one point of the physical space and transmitted to another point; it can also be accumulated, stored and converted from one form to another. From this perspective, the link with knowledge is not a central issue, since the transmission of information can be used only for control purposes, such as operating a device at the destination end by modifying the state of the source. For some physicists, information is a physical entity with the same ontological status as energy. It has also been claimed that its essential property is the power to manifest itself as structure when added to matter (Stonier 1990, 1996).

In general, the physical interpretation of information appears strongly linked with the idea expressed by the well-known *dictum* 'no information without representation': the transmission of information between two points of the physical space necessarily requires an information-bearing signal, that is, a physical process propagating from one point to the other. Rolf Landauer is an explicit defender of this position when he claims that "*information is physical*" (1991, p. 23):

"[i]*nformation is not a disembodied abstract entity; it is always tied to a physical representation. It is represented by engraving on a stone tablet, a spin, a charge, a hole in a punched card, a mark on a paper, or some other equivalent*." (Landauer 1996, p. 188). The need of a carrier signal sounds natural in the light of the generic idea that physical influences can only be transferred through interactions. On this basis it is clear that, in the situation of the two radio receivers, there is no information transmission to the extent that there is no physical signal propagating between them.

Although the physical interpretation of the concept of information prevailed among physicists and communication engineers involved in the traditional applications of Shannon theory, the situation began to change with the advent of "quantum information". In fact, entanglement assisted communication shows that, although the mere correlation is not sufficient for communication of information, asking for a physical signal acting as a carrier of information from source to destination is a too strong requirement. The traditional physical view leads to artificial solutions as those of backwards flowing information or of classically hidden information. It is in this sense that the possibility of transposition of states via entanglement has philosophical implications: not because introduces quantum information as a different kind of information with its own peculiarities, but because it shows that the traditional requirement of a carrier signal flowing through space is not necessary for transmission of information.

A defender of the physical view might retort that the difference between information that requires a carrier signal through space, which takes a finite amount of time, and information that can be transmitted without such a signal is radical enough to be the basis for distinguishing two kinds of information: classical information (which requires a carrier signal for transmission) and quantum information (which does not) (possibility suggested by Jeffrey Bub, personal communication). Again, since names are conventional, there is no contradiction in this proposal. However it would lead us to the uncomfortable consequence that a given source would generate different kinds of information with no change in its own nature: the fact that a source generates classical or quantum information would depend not on itself but on the fact of how the messages will be encoded later. In other words, we could not decide whether a source generates classical or quantum information by only considering it; moreover, if the kind of coding to be used at the coding stage were not decided yet, the nature, classical or quantum, of the information generated by the source would be indeterminate. If these conclusions are to be avoided, conceiving a single kind of information, which can be encoded and transmitted in different ways, seems to be a more reasonable alternative.

When the idea of two kinds of information is left aside, the physical interpretation of the concept of information faces a new challenge: to retain the idea of information as a physical magnitude, but without requiring a physical carrier and without falling into a mere epistemic view. What is needed, therefore, is to give support to the idea that what happens at the source causes what happens at the destination, but with a concept of causality that does not rely on physical interactions or space-time lines connections. In particular, causality cannot be conceived in terms of energy flow (Fair 1979, Castañeda 1984), physical processes (Russell 1948, Dowe 1992), or property transference (Ehring 1997, Kistler 1998). Perhaps good candidates for conceptualizing the informational links from a non-epistemic stance are the manipulability theories of causation, according to which causes are to be regarded as devices for manipulating effects (Price 1991, Menzies and Price 1993, Woodward 2003). The rough idea is that, if C is genuinely a cause of E, then if one can manipulate C in the right way, this should be a way of manipulating or changing E (for an introduction, and also criticisms, see Woodward 2013). The view of causation as manipulability is widespread among statisticians, theorists of experimental design and many social and natural scientists, as well as in causal modeling. In the present context we are not interested in discussing whether this is the correct or the best theory of causation in general, or whether it can account for all the possible situations usually conceived as causation. Here it suffices to notice that the manipulability view may be particularly useful to elucidate the concept of information, given that "[t]*he fundamental problem of communication is that of reproducing at one point either exactly or approximately a message selected at another point.*" (Shannon 1948, p. 379). This view blocks situations like those of the two correlated receivers as cases of information transmission; but, at the same time, it admits cases in which there is a certain control of what happens in the destination end by means of actions at the source end, in spite of the absence of any physical signal between the two extremes of the communication arrangement.

10.- Concluding remarks

In the present paper we have developed different arguments to show that there are no reasons to consider that there exists quantum information as qualitatively different than Shannon information. There is only one kind of information, which can be coded by means of orthogonal or non-orthogonal states. The analogy between Shannon's theory and Schumacher's theory is confined to coding theorems. The attempt to extend the analogy beyond this original scope leads to a concept of quantum information that becomes indistinguishable from that of quantum state. But information is essentially linked with communication, as it is clear in both Shannon's and Schumacher's proposals. If we detach information from this link, we are not talking about information but about quantum mechanics.

This conclusion stands in the same line as that of Duwell, when he audaciously claimed that "[q]*uantum information does not exist*" (2003, p. 479). Regrettably, later he changes his mind under the influence of Timpson's works (Duwell 2008). In this new trend, he introduces a questionable distinction between the success of communication and the goal of communication in order to preserve the relevance of the distinction type-token in the discussion about the nature of information (see criticisms in Lombardi, Fortin and López 2014).

Here we have also stressed the neutrality of information with respect to the physical theories that describe the systems used for its implementation. This view opens the way towards a non-reductive unification of physics: if different physical theories can be reconstructed on the same neutral informational basis, they could be meaningfully compared with no need of searching for reductive links among them.

Finally, we have argued that, although not by introducing a new kind of information, the irruption of quantum mechanics in the theoretical domain of information has deep consequences regarding the concept itself. In fact, the possibility of transmission of information without signal carrier in the transposition stage represents a strong challenge for the physical interpretation of information. The physical view is forced to find new explanations for information transmission, which gives up the need of a physical carrier between transmitter and receiver without falling in mere correlation. We have suggested that a manipulability theory of causation could serve to this conceptual purpose; but this will be the subject of a future research.

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