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Research Article

Notes on the Essential System to Acquire Information

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This paper introduces a short survey on recent information theories and reviews some critical notes expressed on quantum information. The severe difficulties emerging from the literature lead us to argue about the way to follow, and in a preliminary stage, we consider how to proceed in order to provide a reasonable contribution to the conceptualization of information in classical and quantum physics. We conclude that we should go toward the essential elements of the system that acquire information and should define the common components of the measurement processes. In this way we should be able to establish fundamental properties and to circumvent tricky difficulties arisen by the concept of the observer and the variety of interferences that disturb the acquisition of information. Universal experience shows how *sharpness* is the indispensable feature of detected signals and we calculate the discernability of observables using various mathematical formalisms. The present logical frame brings evidence on how information is not an absolute quantity, and we close with a few notes on the *information relativism* which modern literature tackles from the operational stance and the philosophical stance.

1. Introduction

In 1982, Richard Feymann put forward the early concept of quantum computing and inaugurated *quantum information science* (QIS) which is a mixture of physics, computing and engineering. Basically, QIS is grounded upon Shannon's seminal work [1], and Von Neumann introduced the analog of the information entropy in the quantum context

$$N = -\operatorname{Tr} \rho \log \rho, \tag{1.1}$$

where ρ is the density operator. If p_i is eigenvalue of ρ with associate eigenvector $|i\rangle$, we have

$$\rho = \sum_i p_i |i\rangle\langle i|, \tag{1.2}$$

where $|i\rangle$'s are orthonormal. The density operator in (1.2) corresponds to a set of quantum states $|i\rangle$ with probability p_i. Later the quantum analogue of Shannon's noiseless coding theorem was developed by Schumacher [2].

Ample debate arose about the limits of this conceptual framework. In fact, the everyday concept of information is closely associated with the concepts of knowledge and meaning, and it is reliant on the prior concept of the observer: all of them cause pressing and endemic problems.

Shannon's deliberate exclusion of semantic aspects from his theory fired criticism [3] and led a number of authors to elaborate alternative information theories. The following partial list of proposed theories can give an idea of the strong opposition to Shannon interpretation as universal interpretation of information:

(i) *semantic* theory of information by Carnap [4],

(ii) *logical* theory of information by Tarski [5],

(iii) *cybernetic* information theory by Nauta jr. [6],

(iv) *qualitative* theory of information by Mazur [7],

(v) *autopoietic* theory of information by Maturana and Varela [8],

(vi) *systemic* theory of information by Luhmann [9],

(vii) *general* information theory by Klir [10],

(viii) *organizational* information theory by Stonier [11],

(ix) *social* theory of information by Goguen [12],

(x) *hierarchical* theory of information by Losee [13],

(xi) *philosophy* of information by Floridi [14],

(xii) *biological* information theory by Jablonka [15],

(xiii) *physical* theory of information by Levitin [16],

(xiv) *general* theory of information by Burgin [17].

Apart from authors who make their own attempts at a definition, there are also those who consider Shannon's theory good but insufficient and refine it or enrich it with alternative interpretations. I append four studies in the areas of economy, software programming, and biology:

(xv) *economic* theory of information by Marschak [18],

(xvi) *algorithmic* theory of information by Kolmogorov [19],

(xvii) *hierarchical* information theory by Brookes [20],

(xviii) *living system* information theory by Miller [21].

Some writers, aware of the limited boundaries of the Shannon-Neumann theory, attempt to narrow the area of concern. They tend to see the entropy as a parameter useful to calculate channel rates and signals, and indirectly recognize the circumscribed view on communication and environment [22].

Zeilinger [23] claimed that the Shannon information is not appropriate as a measure of information in the quantum context. Their argument takes two forms: firstly, the Shannon information is too intimately tied to classical notions of measurement to be applicable in quantum mechanics (QM); secondly, it cannot be used to define an appropriate notion of "total information content" for quantum systems.

Zeilinger's Foundational Principle raised criticism instead the characterization theorem by Clifton [24] was assessed more favorably. However, the implications of the theorem for the traditional foundational problems in quantum mechanics remain rather obscure.

Entropy (1.1) is zero for a pure state and is positive for a mixed state; Stotland and others note how a state that is pure to one observer can simultaneously be mixed to another observer. In addition, we suppose to prepare two spins in a pure singlet state. In such a case, the von Neumann entropy of a single spin is

$$N = \ln(2), \tag{1.3}$$

while the system as a whole has

$$N = 0. \tag{1.4}$$

It implies that the amount of information related to a subsystem is larger than the amount of information required to determine the outcome of a measurement of the whole system. Thus Stotland et al. introduced a new definition of entropy that reflects the inherent uncertainty of quantum mechanical states. This definition allows distinguishing between the minimum uncertainty entropy of pure states and the excess statistical entropy of mixtures [25].

Griffiths highlights how quantum information, in contrast to classical information, allows for different incompatible types (or species) of information which cannot be combined with each other. He discusses how to get around these problems and allows a fully consistent formulation of the microscopic statistical correlations needed to properly begin the "quantization" of classical information [26].

Devetak et al. holds the adequacy of Shannon's ideas only for macroscopic systems or asymptotically large number of signals [27]. He objects there are no consistent ways of applying the basic ideas of classical information theory to small numbers of microscopic quantum systems.

Jozsa concludes "Over the past decade quantum information theory has developed into a vigorous field of research despite the fact that *quantum information, as a precise concept, is undefined* [28]." The foregoing brief and incomplete survey should be enough to agree that the concept of information is a question which has not yet received a definitive answer in classical and quantum physics alike. Not only did authors miss universal consensus but even more the various theoretical proposals clash one another. Poster makes an interesting review of the present confusing scenario and concludes that the classification of those theories is challenging too [29].

2. In Search of a General Principle

In our opinion, the general definition of information is so much on acute and pressing problem that one should not attack the concept of information in a direct manner, but should discuss the way to follow in the preliminary step.

2.1. Methodological Notes

Remark 2.1. We believe that a study upon information should be grounded upon solid tenets which embrace both the classical and quantum environments. We fear that a specialized theory that covers a small area of interest—for example, a theory confined in QM—could lead to trivial, wrong or even bizarre conclusions. A contribution to QIS could be considerably useful as long as this contribution endeavors to provide a broad interpretation of facts.

Remark 2.2. The vast majority of authors agree that information has a certain physical basis; notably each sign has a body. In the literature, *the body of information is called* "*signifier*" while "*signified*" is the represented object [30, 31]. For example a +3.4 volt impulse is the signifier and the symbolic bit "1" is signified by that voltage impulse.

Remark 2.3. The researches upon the abstract interpretation of information go on and nobody can see its end. Instead of investigating the idea of information which lies beyond the horizon, we could make one move at a time and could work around the concept of signifier that has universal consensus. In addition, the concept of signifier is consistent with physicists' and engineers' concern who handle material elements.

Remark 2.4. Common literature accepts *that measurement is the method to acquire information* from the physical reality. Measurement lies at the crossway between physics and the information science. Remark 2.2 yields that *measurement is the rigorous way to detect a signifier from a defined event*. In other words, the measurement process S perceives the spontaneous signifier E emerging from Nature and translates E into the *artificial signifier F* which scientists manipulate in a manner easier than the original item E. The system S substitutes E for the more practical signifier F.

Remark 2.5. Horodecki writes "Quantum information, though not precisely defined, is a fundamental concept of quantum information theory which $(\cdots)$ provides new physical resources. *A basic problem is to recognize the features of quantum systems responsible for those phenomena*." [32]. We agree that it should be useful to analyze how a signifier is detected; in this way we could make clearer some basic properties of information and measures. In detail, the present paper means to analyze the anatomy of the measurement process. We are oriented to dissect the particulars of the system that acquires information, namely, the essential components of S.

Remark 2.6. Because of the central importance of measurement in quantum mechanics, some authors conclude that QIS can help in solving the foundational and interpretative problems of QM. Proponents are inclined to believe that a general information theory can considerably attenuate or even completely solve the problems of quantum measurement. Some researchers on QIS have argued for an information theoretic interpretation of the entire QM. Steane makes radical suggestions. He proposes a wide-ranging theoretical task to arrive at a set of principles like energy and momentum conservation, but which apply to information and from which much of quantum mechanics could be derived [33]. Remarks from 2.1 to 2.5 are congruent with this position in the sense that *the study of signifiers could lead toward the essentials of measurement* and in turn could contribute to answer fundamental questions in physics.

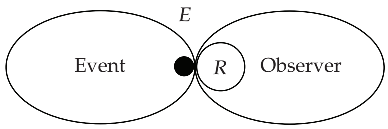

Figure 1

2.2. Essential Components to Acquire Information

No information completely independent from life is known, and S is necessarily equipped with the observer and the gauged event.

(i) The observer constitutes a very intricate agent who affects measurement in obscure manner because of his culture, knowledge, consciousness, and so forth. Problems are so tricky that some author, such as Popper [34], is inclined to exclude the observer from the model of experiment. Others suggest the division between the epistemic and the ontological views of quantum experiments [35]; namely, they resort to philosophy in order to tackle the problem of the observer.

We search for the basic elements of the measurement process; hence we pay attention to the objective and physical component of the observer that is a receptor or a sense organ or an instrument and put aside the mind operations—that is, recognition, assignment of significance, and interpretation—which are fuzzy and subjected to personal feeling. We reduce the right side of Figure 1 to the sensory unit R that universal experience shows as the mandatory element of measurement.

(ii) The signifier E emerges from the event under consideration but the phenomena typical of that event can put on a false show of E. For example, statistical fluctuations of molecules affect a thermodynamical measure. Decoherence and entanglement deform a quantum measure. An ample assortment of phenomena, which cannot be treated through a general conceptualization, characterizes events. We keep E as the compulsory element of the event to measure and put aside the heterogeneous and particular phenomena that disturb the perception of a signal.

In conclusion, S_E determines the birth of information and is equipped with the signifier E and the detector R. In particular, R sees E in contrast with E^* [36] and translates E into the readout F which is a better manageable signal. One can conclude that the set E, E^*, F, and R is responsible for the basic informational phenomena observed in classical and quantum physics alike.

Definition 2.7. The *essential measurement system* is the following quadruplet:

$$S_E = (E, E^*, F; R). \tag{2.1}$$

2.3. The Principle of Sharpness

Technical literature shows how R is capable of assuming a precise state on condition that E is not fuzzy, notably, the signifier E has to contrast with an adjacent entity E^*. The generic stuff E, whether an artifact (i.e. writings, pixels) or natural element (i.e., a quantum particle),

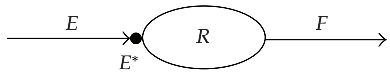

Figure 2

is capable of informing on condition it is distinguishable [36]. Discriminability is the special feature of all the signifiers which may be summarized into the following *principle of sharpness.*

Definition 2.8. The entity E is a signifier if E is distinct from an adjacent entity E^* with respect to the reference R

$$E\ \text{NOT}{=}_{\text{R}} E^*, \tag{2.2}$$

where E andE^* are elements of the algebraic space $\mathcal{E}_a$.

We mean to derive the equations that describe the acquisition of information from (2.2). We use a variety of formalisms, and in this way we bring evidence about the generality of the present framework. We subdivide the calculus of signifiers into two sections: the first deals with *single signifiers* and the second with *multiple signifiers*.

2.4. Single Signifier

2.4.1.

Let E and E^* be Subsets in the set space $\mathcal{E}_s$. From the principle of sharpness, one concludes that the signifier E is distinct from E^* if *the intersection subset* is void

$$I = \{E \cap E^*\} = \emptyset. \tag{2.3}$$

Instead the signifier becomes a blur when I is not empty

$$I \neq \emptyset. \tag{2.4}$$

Results (2.3) and (2.4) are normally adopted in photography, printing technology, and so forth.

2.4.2.

Let $\overrightarrow{E}$ and $\overrightarrow{E^*}$ be Applied Vectors in the vector space $\mathcal{E}_v$.

When $\overrightarrow{E}$ and $\overrightarrow{E^*}$ apply *the application points,* P_E and P_{E^*} coincide, and the vectors produce the resultant vector $\overrightarrow{G}$. The original vectors $\overrightarrow{E}$ and $\overrightarrow{E^*}$ cannot be individually detected because $\overrightarrow{G}$ takes their place. The resultant vector $\overrightarrow{G}$ may be subdivided into two or more vectors at will, but there is no general rule to go back to the original vectors once $\overrightarrow{E}$ and $\overrightarrow{E^*}$ have been summed up and fused.

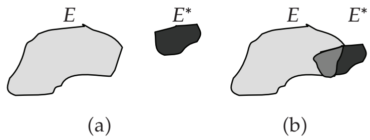

Figure 3

The signifier $\overrightarrow{E}$ is distinct from $\overrightarrow{E^*}$ when the application points P_E and P_{E^*} lie apart; namely, the module of the distance-vector is greater than zero

$$\left|\overrightarrow{P_E P_{E^*}}\right| \neq 0. \tag{2.5}$$

2.4.3.

Suppose E and E^* are Points in the metric continuous space $\mathcal{E}_m$. The signifier E is distinct from E^* if these points do not occupy the same place. The following inequality derives directly from (2.2)

$$E \neq E^*, \tag{2.6}$$

and leads to *the separation s* presently used in the digital technologies

$$s = |E - E^*| \neq 0. \tag{2.7}$$

2.4.4.

Suppose E is a Subset in the Metric Continuous Space $\mathcal{E}_m$. If one does not specify any term of comparison, necessarily E^* must include all the points of the space. The signifier is distinct from E^* if *the range of the intersection* between E and E^* is zero

$$\Delta I_E = 0. \tag{2.8}$$

Namely, E includes only one point. This definition consists with the margin of precision in modern methods of measure.

2.4.5.

Suppose E and E^* are one-dimension matrices with binary values, and the number of corresponding odd bits d_{EE^*} is said to be the *distance* between the matrices. The signifier E is distinct from E^* if d_{EE^*} is not null,

$$d_{EE^*} \neq 0. \tag{2.9}$$

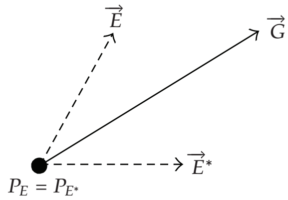

Figure 4

When the distance is null, the matrices are equals. Definition (2.9) is consistent with Hamming's distance used in binary technology.

2.5. Multiple Signifiers

Sometimes the receiver does not detect a unique signifier, instead R perceives a set that is the population of signifiers. We assume that (2.8) is true for each single signifier E. In order to verify (2.2), it is necessary to locate $\overline{E}$: the relevant information for the statistical application. The most popular measures of locations are the *mean*, the *median*, and the *mode*. In a second stage one calculates the overall quality of $\overline{E}$. In accordance to (2.2), the fuzziness is given by the spread of the data: the larger the diffusion the lower the quality of $\overline{E}$. The *variance* and the *standard deviation* are the best known measures for the spread.

2.5.1.

Suppose that the N discrete values belong to the metric space $\mathcal{E}_m$; the mean $\overline{E}$ is defined as

$$\overline{E} = \frac{\Sigma E}{N}, \tag{2.10}$$

and the variance is

$$\operatorname{Var}(E) = \frac{\Sigma\left(E - \overline{E}\right)^2}{N}. \tag{2.11}$$

2.5.2.

When signifiers are given by a continuous distribution with probability density function $p(E)$, the mean is obtained by the definite integral taken for E ranging over its field of observation

$$\overline{E} = \int E \cdot p(E)dE, \tag{2.12}$$

and the variance is calculated in the ensuing manner

$$\operatorname{Var}(E) = \int \left(E - \overline{E}\right)^2 p(E)dE. \tag{2.13}$$

Principle (2.2) yields that the calculated signifier $\overline{E}$ is valuable information when the variance is small. Conversely, the more $\mathrm{Var}(E)$ is ample, the more $\overline{E}$ becomes dim. The signifier does not make any sense at the upper limit of the variance.

In conclusion, the principle of sharpness justifies and unifies the foregoing equations obtained through an assortment of methods so far. Symbolic formula (2.2) gives *the condition of existence of information* in absolute terms namely, yes/no, while the mathematical equations in Sections 2.4 and 2.5 quantify the *degrees of quality* of various signifiers.

3. Information Relativism

The right side of (2.2) proves that the existence of information relies on the confrontation term and presumes the intervention of R that accomplishes the detection process. One is obliged to conclude that information is not an absolute quantity in the present framework; E^* and R cause double relativism. We call *couple relativity* the impact of E^* on the existence of E, and *reference relativity* the influence caused by the receiver R.

3.1. Operational and Metaphysical Perspectives

The information relativity brings about knotty problems. Experimental acquisition of information can fail even in straightforward phenomena due to R and/or $E^*.I$ quote a pair of noticeable relativistic effects occurring in classical and quantum physics:

(1) One remarks "Information disappears whenever we close our eyes or forget about it." It is enough the blink of an eye, namely, it is enough to switch of R, to destroy whatsoever signifier.

(2) The Schrödinger equation tells the possible positions of a quantum particle and this probabilistic distribution keeps true until a measurement is made. The particle collapses due to the intervention of R.

The above effects seem to lead to the following ensuing conclusions.

(i) The conservation of matter and energy constitutes a basic principle in classical physics, and the cancellation of information yields that the material origins of information have no foundation. A sign should not disappear if a sign has a concrete body. Thus information relativity seems to deny the same concept of signifier.

(ii) The receptor R can subvert a signifier which instead should remain genuine. The measurement process proves to be unreliable and this shakes classical and quantum physics at its foundations.

We attempt to go deep into the severe questions (1.1) and (1.2) by exploring (2.2).

Equation (2.2) could be catalogued as a *tautology* in point of abstract logic. The inequality may be placed close to $A \neq B$ that holds universal unconditioned truth. The inequality sounds always valid and rather trivial when one assumes the abstract viewpoint; instead (2.2) has different meanings from the experimental perspective. Equation (2.2) particularizes the conditions for the factual determination of a signifier and holds that any object is a potential piece of information but its capability becomes effective provided that R intervenes. This agent allows a signifier to pass from the potential state to the real informational state. An object goes on living as a sign when R keeps it alive and E disappears as long as that object is no longer available to an observer. In conclusion, inequality (2.2) illustrates the properties of the informational status of E and does not fix the physical essence of E.

This highlights the difference between the operational approach and the philosophical approach to the measurement problem.

The interference of the receptor denies the physical and special nature of information when one argues from the abstract stance. Inevitably, one infers radical conclusions and finds out irreconcilable statements if he/she reasons on the metaphysical plane [37]. The measurement problem raises broader philosophical discussion in QM between, on one hand, Cartesian and Lockean accounts of observation as the creation of "inner reflections" and, on the other hand, neo-Kantean conceptions of observation as a quasi-externalized physiological process. Under the influence of philosophical debates, David Bohm proposed ontological interpretations of QM [38].

Instead (2.2) holds that the information relativity is universal but does not constitute a metaphysical phenomenon. Inequality (2.2) suggests the operational approach to interpret detection and experimental evidences sustain this approach. Technicians are capable of stepping in and surmounting a number of down-to-earth obstacles using appropriate countermeasures. Experimentalists are capable of circumventing or minimizing the influence of the information relativism due to the operational significance of (2.2). For example, the human senses are incompatible with E in a number of circumstances, the subsidiary probe R_U is sandwiched, and the receptor R controls the readout of R_U. The impossibility of direct perception does not constitute a metaphysical question since technicians amend through *indirect perception*.

The present framework puts forward a novel answer to the questions arising in classical and quantum physics, since the information relativity constitutes a broad, universal effect, and justifies phenomena that appear rather paradoxical.

The present study does not explain the special phenomena that embody the information relativity in each event because those phenomena have differing origins. In fact the present study restricts itself to the indispensable elements E, E^*, and R. We have openly put aside the discussion on each event that brings into effects relativistic phenomena since thermodynamics, optics, mechanics, quantum physics, and other sectors exhibit a variety of topics that cannot be treated in a unified theory. We have examined the essential system of measurement S_E that is universal and not each complete system S that varies according to the application field.

4. Conclusions

The present paper starts with the unsatisfactory state of modern theories on information. In particular, we focus on the abstract concept of information which has not reached universal consensus so far instead the concept of signifier is amply shared and could offer a basis for theoretical advances.

As second, we find that the idea of observer turns out to be all-including in the literature, and the measured event affects the measurement process through a variety of mechanisms in various fields. The essential system S_E includes the receptor R and the signal E and we talk over the way S_E works.

The receptor and the signifier are regulated by the so-called *principle of sharpness*. We have developed this principle with a variety of mathematical formalisms that consist with the results obtained so far.

Finally we argue on the information relativity that derives from the sharpness principle. The present logical frame sustains the operational approach to the severe effects resulted in the information relativism and disproves the philosophical interpretations of the measurement problem.

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References

[1] M. Keyl, "Fundamentals of quantum information theory," *Physics Report*, vol. 369, no. 5, pp. 431–548, 2002.

[2] B. Schumacher, "Quantum coding," *Physical Review A*, vol. 51, no. 4, pp. 2738–2747, 1995.

[3] Y. Bar-Hillel, *Language and Information, Selected Essays on Their Theory and Application*, Addison-Wesley, Reading, Mass, USA, 1964.

[4] R. Carnap and Y. Bar-Hillel, "An outline of a theory of semantic information," in *Language and Information: Selected Essays on Their Theory and Application*, Y. Bar-Hillel, Ed., pp. 221–274, Addison-Wesley, Reading, Mass, USA, 1964.

[5] A. Tarski, *Logic, Semantics, Metamathematics*, edited by J. Corcoran, Hackett, Indianapolis, Ind, USA, 1983.

[6] D. Nauta Jr., *The Meaning of Information*, Mouton, The Hague, The Netherlands, 1970.

[7] M. Mazur, *Qualitative Theory of Information*, Mir, Moscow, Russia, 1974.

[8] H. R. Maturana and F. Varela, *Autopoiesis and Cognition: The Realization of the Living*, Reidel, Dordrecht, The Netherlands, 1980.

[9] N. Luhmann, *Essays on Self-Reference*, Columbia University Press, New York, NY, USA, 1990.

[10] G. Klir, *Facets of System Science*, Oxford Pergamon Press, New York, NY, USA, 1991.

[11] T. Stonier, *Information and the Internal Structure of the Universe: An Exploration into Information Physics*, Springer, New York, NY, USA, 1994.

[12] J. Goguen, "Towards a social, ethical theory of information," in *Social Science, Technical Systems and Cooperative Work: Beyond the Great Divide*, G. C. Bowker, L. Gasser, S. L. Star, and W. Turner, Eds., pp. 27–56, Erlbaum, Philadelphia, Pa, USA, 1997.

[13] R. M. Losee, "A discipline independent definition of information," *Journal of the American Society for Information Science*, vol. 48, no. 3, pp. 254–269, 1997.

[14] L. Floridi, *Philosophy and Computing: An Introduction*, Routledge, New York, NY, USA, 1999.

[15] E. Jablonka, "Information: its interpretation, its inheritance, and its sharing," *Philosophy of Science*, vol. 69, no. 4, pp. 578–605, 2002.

[16] L.B. Levitin, "Physical information theory. Part I," in *Proceedings of Workshop on Physics and Computation*, pp. 210–214, 1991.

[17] M. Burgin, *Theory of Information: Fundamentality, Diversity and Unification*, World Scientific, Singapore, 2009.

[18] J. Marschak, "Towards an economic theory of organization and information," in *Decision Processes*, R. M. Thrall, C. H. Coombs, and R. L. Davis, Eds., John Wiley & Sons, New York, NY, USA, 1954.

[19] A. N. Kolmogorov, "Three approaches to the definition of the quantity of information," *Problems of Information Transmission*, vol. 1, pp. 3–11, 1965.

[20] B. C. Brookes, "The foundations of information science—part I: philosophical aspects," *Journal of Information Science*, vol. 2, no. 3-4, pp. 125–133, 1980.

[21] J. G. Miller, *Living Systems*, McGraw-Hill, New York, NY, USA, 1978.

[22] C. G. Timpson, "Philosophical aspects of quantum information theory," in *The Ashgate Companion to Contemporary Philosophy of Physics*, D. Rickles, Ed., pp. 197–261, Ashgate, Surrey, UK, 2008.

[23] A. Zeilinger, “A foundational principle for quantum mechanics,” *Foundations of Physics*, vol. 29, no. 4, pp. 631–643, 1999.
[24] R. Clifton, J. Bub, and H. Halvorson, “Characterizing quantum theory in terms of information-theoretic constraints,” *Foundations of Physics*, vol. 33, no. 11, pp. 1561–1591, 2003.
[25] A. Stotland, A. A. Pomeransky, E. Bachmat, and D. Cohen, “The information entropy of quantum-mechanical states,” *Europhysics Letters*, vol. 67, no. 5, pp. 700–706, 2004.
[26] R. B. Griffiths, “Types of quantum information,” *Physical Review A*, vol. 76, no. 6, Article ID 062320, 11 pages, 2007.
[27] I. Devetak, A. W. Harrow, and A. J. Winter, “A resource framework for quantum Shannon theory,” *IEEE Transactions on Information Theory*, vol. 54, no. 10, pp. 4587–4618, 2008.
[28] R. Jozsa, “Illustrating the concept of quantum information,” *IBM Journal of Research and Development*, vol. 48, no. 1, pp. 79–85, 2004.
[29] M. Poster, *The Mode of Information*, University of Chicago Press, Chicago, Ill, USA, 1990.
[30] D. Chandler, *Semiotics*, Routledge, New York, NY, USA, 2001.
[31] P. Cobley, *Introducing Semiotics*, Icon Books, London, UK, 2004.
[32] M. Horodecki, P. Horodecki, R. Horodecki, and M. Piani, “Quantumness of ensemble from no-broadcasting principle,” *International Journal of Quantum Information*, vol. 4, no. 1, pp. 105–118, 2006.
[33] A. Steane, “Quantum computing,” *Reports on Progress in Physics*, vol. 61, no. 2, pp. 117–173, 1998.
[34] K. R. Popper, “Quantum mechanics without “the observer”,” in *Quantum Theory and Reality*, M. Bunge, Ed., Springer, New York, NY, USA, 1967.
[35] H. P. Stapp, *The Mindful Universe: Quantum Mechanics and the Participating Observer*, Springer, New York, NY, USA, 2007.
[36] P. Rocchi and L. Gianfagna, “An introduction to the problem of the existence of classical and quantum information,” in *Proceedings of the Quantum Theory, Reconsideration of Foundations (QTRF-3 ’05)*, pp. 248–258, June 2005.
[37] A. Petersen, *Quantum Physics and the Philosophical Tradition*, MIT Press, Cambridge, Mass, USA, 1968.
[38] D. Bohm and B. J. Hiley, *The Undivided Universe: An Ontological Interpretation of Quantum Theory*, Routledge, New York, NY, USA, 1993.