The information interpretation of quantum mechanics

Karl Svozil

Institut für Theoretische Physik, Technische Universität Wien
Wiedner Hauptstraße 8-10/136 A-1040 Vienna, Austria
e-mail: svozil@tuwien.ac.at

Abstract

In the information interpretation of quantum mechanics, information is the most fundamental, basic entity. Every quantized system is associated with a definite discrete amount of information \[1\]. This information content remains constant at all times and is permuted one-to-one throughout the system evolution. What is interpreted as measurement is a particular type of information transfer over a fictitious interface. The concept of a many-to-one state reduction is not a fundamental one but results from the practical impossibility to reconstruct the original state after the measurement.

Information and the quantum

In the following we take the position that information is the most fundamental concept in understanding the quantum. This approach has been recently investigated by Zeilinger and Brukner \[1, 2, 3\] and Summhammer \[4\]. It can be traced back to Schrödinger’s “catalogue of expectation values” \[4\], many coffee-house conversations here in Vienna \[3, 7\] as well as to the writings of Brillouin \[8\], Gabor \[9\] and the late Landauer \[10\], among others (e.g., \[11\]).

In standard treatments, the quantum evolution is presented in a twofold manner. (i) Inbetween measurements, there is a unitary and thus reversible
one-to-one evolution. (ii) The measurement itself is modeled irreversibly, many-to-one, which is associated with the “wave function collapse” or “reduction of the state vector.”

In what follows we suggest to extend the unitary evolution also to the measurement process. Thereby, we assume a uniform reversible one-to-one quantum evolution which is not interrupted by measurements causing many-to-one reductions.

This amounts to suggesting that the concept of irreversible measurement (ii) is no deep principle but originates in the practical inability to reconstruct a particular quantum state. Reconstruction may widely vary with technological capabilities which often boil down to financial commitments.

Information, in particular information encoded into a quantum system, is conserved, irrespective of whether or not a “measurement” has taken place.

Measurement apparatus as interface

In what follows, the measurement apparatus is modeled by an interface between the observer and the observed subsystem. An interface is introduced as a theoretical entity forming the common boundary between two parts of a system, as well as a means of information exchange between those parts. By convention, one part of the of the system is called “observer” and the other part “object.” Both the observer and the object are embedded into one and the same system. The interface should be thought of as merely an intermediate construction, a “scaffolding,” capable of providing the necessary conceptual means.

One could quite justifiably ask (and this question has indeed been asked by Professor Bryce deWitt), “where exactly is the interface in a concrete experiment, such as a spin state measurement in a Stern-Gerlach apparatus?”

We take the position here that the location of the interface very much depends on the physical proposition which is tested and on the conventions assumed. Let us consider, for example, a statement like “the electron spin in the z-direction is up.”

In the case of a Stern-Gerlach device, one could locate the interface at the apparatus itself. Then, the information passing through the interface is identified with the way the particle took.

One could also locate the interface at two detectors at the end of the beam paths. In this case, the “meaningful” information (with respect to the
question asked) penetrating through the interface corresponds to which one of the two detectors (assumed lossless) clicks (cf. Fig. [1]).

The interface could also be situated at the computer interface card registering this click, or at an experimenter who presumably monitors the event (cf. Wigner’s friend [12]), or at the persons of the research group to whom the experimenter reports, to their scientific peers, and so on.

It should be kept in mind that the proposition considered may be only a (minor) part of the information communicated via the interface, and that in a uniform one-to-one environment, all information would be needed for reconstruction. As a consequence, it is certainly not sufficient to reconstruct the state of the electron.

The object may also not be prepared to accept the question asked. In such a case, one may speculate that the interface acts as a “translator” between the observer and the object. This may indeed be the reason of an intrinsic irreducible randomness of certain outcomes. The quantum system as a whole behaves deterministically; i.e., according to the unitary evolution of the quantum state.

Since there is no material or real substrate which could be uniquely identified with the interface, in principle it could be associated with or located at anything which is affected by the state of the object. The only difference is the reconstructibility of the object’s previous state (cf. below): the “more macroscopic” (i.e., many-to-one) the interface is, the more difficult it becomes to reconstruct the original state of the object.
Reconstruction and information flow density

A direct consequence of the conservation of information is the possibility to define continuity equations. In analogy to magnetostatics or thermodynamics we may represent the information flow by a vector which gives the amount of information passing per unit area and per unit time through a surface element at right angles to the flow. We call this the information flow density $j$. The amount of information flowing across a small area $\Delta A$ in a unit time is

$$j \cdot n \Delta A,$$

where $n$ is the unit vector normal to $\Delta A$. The information flow density is related to the average flow velocity $v$ of information. In particular, the information flow density associated with an elementary object of velocity $v$ per unit time is given by $j = \rho v$ bits per second, where $\rho$ stands for the information density (measured in bits/m$^3$). For $N$ elementary objects per unit volume carrying one bit each,

$$j = Nvi.$$

Here, $i$ denotes the elementary quantity of information measured in bit units. The information flow $I$ is the total amount of information passing per unit time through any surface $A$; i.e.,

$$I = \int_A j \cdot n \, dA.$$

We have assumed that the cut is on a closed surface $\mathcal{A}_c$ surrounding the object. The conservation law of information requires the following continuity equation to be valid:

$$\int_{\mathcal{A}_c} j \cdot n \, dA = -\frac{d}{dt} \text{(Information inside)}$$

or, by defining an information density $\rho$ and applying Gauss’ law,

$$\nabla \cdot j = -\frac{d\rho}{dt}.$$

To give a quantitative account of the present ability to reconstruct the quantum wave function of single photons, we analyze the “quantum eraser”
paper by Herzog, Kwiat, Weinfurter and Zeilinger [13]. The authors report an extension of their apparatus of $x = 0.13$ m, which amounts to an information passing through a sphere of radius $x$ of

$$I_{qe} = 4\pi x^2 c \rho = 6 \times 10^7 \text{bits/second}.$$ 

Here, $j = c \rho$ ($c$ stands for the velocity of light in vacuum) with $\rho = 1 \text{bit/m}^3$ has been assumed. At this rate the reconstruction of the photon wave function has been conceivable.

We propose to consider $I$ as a measure for wave function reconstruction. In general, $I$ will be astronomically high because of the astronomical numbers of elementary objects involved. Yet, the associated diffusion velocity $v$ may be considerably lower than $c$.

**Effective many-to-one-ness**

In this final part of the communication we mention reasons why most measurements appear to be irreversible. In such cases, we claim, that either (i) information flows off too fast, i.e., $I$ is too large, or (ii) the interface is not total such that information “leaks” to regions outside of the observer’s control; or (iii) the macroscopic level of description effectively maps many different microscopic states onto a single macroscopic state.

The question of why on the macroscopic scale systems tend to behave irreversibly while the microphysical laws are reversible is not entirely new and has, in the context of statistical mechanics, already been discussed intensively by Boltzmann [14, 11]. In the case (iii), the interface effectively introduces “classicality” in the following sense. The observer seeks an answer to a particular question or proposition. This proposition is often only a part of the information the object is communicating. In disregarding these other aspects, the experimenter induces irreversibility into the particular description level.

In summary we have put forward here the suggestion that irreversibility in quantum measurements is no primary concept. It is postulated that, at least in principle, every quantum measurement could be “undone.”

**References**

[1] Anton Zeilinger. A foundational principle for quantum mechanics. *Foundations of Physics*, 29(4):631–643, 1999.
[2] Časlav Brukner and Anton Zeilinger. Malus’ law and quantum information. *Acta Physica Slovaca*, 49(4):647–652, 1999.

[3] Časlav Brukner and Anton Zeilinger. Operationally invariant information in quantum mechanics. *Physical Review Letters*, 83(17):3354–3357, 1999.

[4] Johann Summhammer. Invariance of elementary observations. preprint, 2000.

[5] Erwin Schrödinger. Die gegenwärtige Situation in der Quantenmechanik. *Naturwissenschaften*, 23:807–812, 823–828, 844–849, 1935. English translation in [15] and [16, pp. 152-167].

[6] Daniel M. Greenberger. Private communication.

[7] Johann Summhammer. Private communication.

[8] L. Brillouin. *Science and Information Theory*. Academic Press, New York, second edition edition, 1962.

[9] Denis Gabor. Light and information. *Progress in Optics*, 1:111–153, 1961.

[10] R. Landauer. Computation, measurement, communication and energy dissipation. In S. Haykin, editor, *Selected Topics in Signal Processing*, page 18. Prentice Hall, Englewood Cliffs, NJ, 1989.

[11] H. S. Leff and A. F. Rex. *Maxwell’s Demon*. Princeton University Press, Princeton, 1990.

[12] Eugene P. Wigner. Remarks on the mind-body question. In I. J. Good, editor, *The Scientist Speculates*, pages 284–302. Heinemann and Basic Books, London and New York, 1961. Reprinted in [16, pp. 168-181].

[13] Thomas J. Herzog, Paul G. Kwiat, Harald Weinfurter, and Anton Zeilinger. Complementarity and the quantum eraser. *Physical Review Letters*, 75(17):3034–3037, 1995.
[14] Jean Bricmont. Science of chaos or chaos in science? *Annals of the New York Academy of Sciences*, 775:131–176, 1996. also reprinted in [17] and as e-print [http://xxx.lanl.gov/abs/chao-dyn/9603009].

[15] J. D. Trimmer. The present situation in quantum mechanics: a translation of Schrödinger’s “cat paradox”. *Proc. Am. Phil. Soc.*, 124:323–338, 1980. Reprinted in [16, pp. 152-167].

[16] John Archibald Wheeler and Wojciech Hubert Zurek. *Quantum Theory and Measurement*. Princeton University Press, Princeton, 1983.

[17] Jean Bricmont. Science of chaos or chaos in science? In Paur R. Gross, Norman Levitt, and Martin W. Lewis, editors, *Flight from Science and Reason*. John Hopkins University Press, 1997.