“Bad Habits” in Quantum Mechanics

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Abstract

There are two common “bad habits” in the description, analysis, interpretation and teaching of fundamental aspects of quantum mechanics. One is the all too casual use of the term “information”, without making it explicitly clear which of the various types, Shannon, algorithmic or pragmatic, are meant. The other concerns the use of the term “knowledge”, without alluding to specific aspects of human brain function, for instance, when the observer selects the system under study, formulates simplified models, asks theoretical questions, plans an experiment, decides what to measure, prepares the system, chooses initial conditions, anticipates to obtain certain results and confirms a final state. I will show how an objective definition of information and recent results about information-processing in the brain help overcome the most common counter-intuitive aspects of quantum mechanics. In particular, I will discuss entanglement, teleportation, non-interaction measurements and decoherence in the light of the fact that the concept of pragmatic information, the one our brain handles, can only be defined in the macroscopic domain. Counter-intuitive aspects arise when we construct mental images of quantum systems in which the concept of pragmatic information is illegitimately forced into the quantum domain.

Introduction

It is understandable that words of such every-day usage as “information” and “knowledge” remain undefined in papers, books and lectures. Yet given some new ideas and experimental results about these two concepts, respectively, it is time to revisit some fundamental discussions of quantum mechanics, especially the role (or non-role) of the observer in quantum measurements and Gedanken-experiments. As a byproduct, this may also be of help in the re-examination of sometimes contentious concepts such as “objective existence”.

Physicists are accustomed to working with Shannon and algorithmic information. Traditional information theory, however, does not give a universal and objective definition of the concept of information applicable to all sciences—it is mainly concerned with the mathematical treatment of the quantity (and quality) of information, its transmission and its storage. In many situations, however, especially in genetics and brain science, the notion of quantity of information is of little importance: what counts is what information ultimately does, not how much it is, in what form it is expressed and how it subjectively appears to our senses or mental images.

Rather than attempting to define “information” ab initio, it is more appropriate to start with the concept of interaction between complex bodies as the primary concept (Roederer 1978, 2005). We can identify two distinct broad categories: 1) Interactions which can always be reduced to a linear superposition of physical interactions (i.e., forces) between the systems’ elementary constituents; 2) Interactions which cannot be expressed quantitatively as a linear superposition of elementary interactions, but in which patterns (in space and/or time) play the determining role on whether or not an interaction is to take place.

The simplest case of an interaction of the second category is an arrangement in which the presence of a specific pattern in a complex system A (the emitter) leads to a specific, unvocal change in complex system B (the recipient), a change that would not happen (or just occur by chance) in the absence of the pattern at the source. Information is then defined as “that which represents the univocal correspondence pattern → change”. This is called pragmatic information (Küppers 1990) and it is the reason why we call this second category “information-driven interactions”.

There are only three fundamental processes through which mechanisms of information-driven interactions can emerge (Roederer 2005): 1. Darwinian evolution; 2. adaptation or neural learning; 3. as the result of reasoning and long-term planning. In other words, they all involve living matter—indeed, information-driven interactions represent the defining property of life. Moreover, any information-driven interaction between inanimate complex systems must ultimately be life-generated or -designed, involving at one stage or another purposeful, goal-directed actions by a living system. For instance, an electromagnetic or sound wave emitted by a meteorological lightning discharge does not represent any information-driven interaction; on the other hand, the waves emitted by an electric discharge in the laboratory may be part of an overall information-driven interaction if they serve the purpose of causing a predesigned change somewhere on their way. Note that information-driven interactions affect the “normal” physical (non-biological) course of natural events. They all in-
olve irreversible processes in complex bodies of the classical macroscopic domain, with time-sequences which strictly obey the dictates of statistical thermodynamics and special relativity.

The concept of “information” does not appear as an active, controlling agent in purely physical interaction processes of category 1 above; it only appears there when an observer intervenes (Roederer 2005, Chapter 5). For instance, in thermodynamics the association between entropy and information arises not from nature per se, but from the way we the observers describe or manipulate nature (counting molecules in a pre-parceled phase space, coarse-graining, looking for regularities vs. disorder, predicting fluctuations, extracting mechanical work based on what we know about the system, etc). Similar arguments can be made when we describe black holes as “swallowing information”, or decoherence as “carrying away information on a quantum system” (see further below). In these examples, all physical interactions involved are “force-driven”; whenever we use the term information in their description we really mean “information for us, the observers”. And when we set the initial conditions of a classical mechanical system, we are converting it into an information-driven system with a given purpose (to achieve a change that would not happen naturally without our intervention).

Now we turn to the other issue, human brain function. Let us begin by pointing out that all mathematical quantities used in traditional information theory and probability are coupled to highly subjective concepts ultimately related to how the human brain reacts to certain sensory input. In most cases they relate to how the neural cognitive state changes from “not-knowing to knowing”. I like to describe this transition as the reduction of an initial brain state to one of possible “basis states”, where each basis state represents the mental image of one possible outcome of calculated or previously experienced alternatives at hand (positions of a “pointer in the head”).

Quite generally, pragmatic information involved in cognition is encoded in the brain as a determined spatio-temporal distribution of neural activity in specific regions of the cerebral cortex. In the study of a physical system, the pragmatic information involved represents the link between an external pattern (e.g., the initial positions of a system of mass points, the actual position of a dial in an instrument, the dots on cast dice) with a specific spatio-temporal neural activity pattern in the prefrontal lobes (e.g., Koch 2004 and references therein; Roederer 2005), corresponding to the knowledge “it’s this particular state and not any other possible one”. Modern neurobiology has an answer to the common question of “When does a specific distribution of neural firings actually become a mental image?” The neural activity distribution does not become anything—it is the image! In summary, the dynamic spatio-temporal distribution of neural impulses and the quasi-static spatial distribution of synapses and their efficiencies together are the physical realization of the global state of the functioning brain at any instant of time.

The human brain can recall at will stored information as images or representations, manipulate them, discover overlooked correlations, and re-store modified or amended versions thereof without any concurrent external or somatic input—it can go “off line” (Bickerton 1995). This is information generation par excellence and represents the human thinking process (Roederer 1978, Young 1987). Internally triggered human brain images as needed during scientific model-making and reasoning, however abstract, are snippets (expressed as different but distinct patterns of neural activity in specific regions of the cortex) derived from stored information acquired in earlier sensory or mental events, and pieced together under some central control (the “main program”) linked to human self-consciousness. The fact that the brain is an eminently classical information-processing device, trained through informational interactions with the classical macroscopic world, is very germane to how it participates in a quantum measurement and, in general, to how we can understand quantum mechanics. We already mentioned that similar situations already appear in classical physics per se, particularly in thermodynamics and its paradoxes.

Examples with single qubits

To discuss the implications for quantum mechanics, we turn to the quantum-to-classical transition and examine the measurement process as perhaps the most drastic “top-down” planned human intervention in a quantum system. Consider the measurement of a qubit; the measurement apparatus has a “quantum end”, with which the qubit interacts (e.g., the atoms to be ionized in a particle detector), and a “classical end” that after the measurement puts in evidence a consistent macroscopic change of form or pattern (e.g., voltage pulses, a luminescent screen, a pointer, a cat). It is the physical structure of the device enabling the occurrence of such macroscopic change that defines the observable in question. The observer per se is irrelevant during the measurement itself, except that we must not forget that it was a human being who designed the instrument (hence decided what observable to measure), who prepared the system to be measured, and whose brain ultimately expects to receive an image (the

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1In a gas there are unimaginable many possible dynamic con-

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2In animals, the time interval within which causal correlations can be established (trace conditioning) is of the order of tens of seconds and decreases rapidly if other stimuli are present (e.g., Han et al. 2003); in humans it extends over the long-term past and the long-term future (for a brief review of human vs. subhuman intelligence, see for instance Balter 2010).

3Quantum decoherence times in the brain would be ten or more orders of magnitude shorter than the minimum time required for any cognitive operation (e.g., Schlosshauer 2007).
neural correlate) of the change in the macroscopic state of the apparatus as a result of the measurement (knowledge of the value of the observable).

If \(|M\rangle\) represents the initial state of the entire apparatus, let call \(|M_0\rangle,|M_1\rangle\) the two possible alternative macroscopic states of the apparatus after the measurement. The instrument is deliberately built in such a way that when the qubit is in a basis state \(0\rangle\) before its interaction with the apparatus, the final state of the instrument after the measurement will be \(|M_0\rangle\), and if the state of the qubit is \(1\rangle\) the instrument will end up in state \(|M_1\rangle\). In either case, the state of the qubit will remain unchanged (all that this is possible is linked to a fundamental postulate of quantum mechanics, see Isham 1995.) Therefore, for the composite state qubit–apparatus we will have the following evolution in time, as determined by the Schrödinger equation:

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|0\rangle|M\rangle \rightarrow |0\rangle|M_0\rangle \quad \text{or} \quad |1\rangle|M\rangle \rightarrow |1\rangle|M_1\rangle
\]

Since the Schrödinger equation is linear in time, if the qubit is now in a superposed state, we will obtain an entangled state: \((\alpha|0\rangle + \beta|1\rangle)|M\rangle \rightarrow \alpha|0\rangle|M_0\rangle + \beta|1\rangle|M_1\rangle\), and the state of the composite system qubit–apparatus will, as long as it is kept isolated from other interactions, remain a linear superposition governed by the coefficients of the original qubit. However, one never has observed a macroscopic system with such peculiar properties as superposition and entanglement (the essence of the Schrödinger cat paradox): the end state of the composite system will always be either \(|0\rangle|M_0\rangle\) or \(|1\rangle|M_1\rangle\). Something must be happening physically after the first contact of the quantum system with the apparatus—the process of decoherence.

The most general composite system of two entangled qubits is described by the state \(\Psi = c_{00}|0\rangle_A|0\rangle_B + c_{01}|0\rangle_A|1\rangle_B + c_{10}|1\rangle_A|0\rangle_B + c_{11}|1\rangle_A|1\rangle_B\) with the normalization condition \(\sum c_{ik}^2 = 1\). Unless \(c_{00}c_{11} = c_{01}c_{10}\) (which means that the expression is factorable), neither qubit is in a definite state—only the composite system is. Measuring qubit A and having it end up in, say, the eigenstate \(|0\rangle_A\), would leave the other qubit B in the superposed state \(c_{00}|0\rangle_B + c_{01}|1\rangle_B\), which is different from the state \(c_{10}|0\rangle_B + c_{11}|1\rangle_B\), had the measurement resulted in \(|1\rangle_A\)—regardless of how far away from each other the qubits are located.

It is important to have a clear idea of the time relationships involved. Take two qubits A and B that have become maximally entangled in the antisymmetric Bell state \(\Psi^- = 1/\sqrt{2}(|0\rangle_A|1\rangle_B - |1\rangle_A|0\rangle_B)\) at time \(t_0\). We may imagine qubit B now being taken to the Moon. If nothing else is done to either, we can bring B back to Earth, and with some suitable experiment (e.g., interference) demonstrate that the total state of the system had remained entangled all the time. Now, if instead at time \(t_A > t_0\) a measurement is made on qubit A leaving the composite system reduced to either state \(|0\rangle_A|1\rangle_B\) or \(|1\rangle_A|0\rangle_B\), the qubit on the Moon will be reduced to either basis state \(|1\rangle_B\) or \(|0\rangle_B\), respectively, a fact that can be verified by a measurement. The puzzling thing is that it does not matter when that measurement on B is made—even if made before \(t_A\). Of course, we cannot predict which of the two alternatives will result. All we can affirm is that in a maximally entangled pair of qubits, the measurement results on each one will be correlated, no matter the temporal order in which they were made.

One might argue that in the case of a measurement on B at an earlier time \(t_B < t_A\), it was this measurement that caused the reduction (also called collapse) of the qubits' composite state but the concepts of “earlier” and “later” are not relativistically invariant properties. The result of all this is that if viewed as a physical process, the reduction of the quantum state of an entangled system is non-local in space and time. Yet nothing strange happens at the macroscopic level: the state reduction cannot be used to transmit any real information from A to B. In terms of our definition of pragmatic information, there is no “spooky” action-at-a-distance: an experimenter manipulating A has no control over exactly which macroscopic change shall occur in the apparatus at B, and vice versa.

The previous discussion also says something about how we think intuitively of time at the quantum level: *Time is a macroscopic concept*, to be measured on the basis of macroscopic changes in a clock (or the position of a star—even an atomic clock must have classical components to serve as a timepiece). We can assign time marks to a quantum system only when it interacts locally with (or is prepared by) a macroscopic system. The time variable in the wave function \(\Psi(x,t)\) indeed refers to the time, defined by a macroscopic clock external to the quantum system, at which \(|\Psi|^2\) represents the probability density of actually observing the quantum system at the position \(x\) in configuration space. Because of this, it is unlikely to be able to find a modified form of the Schrödinger equation that can describe quantitatively a quantum system during the process of state reduction.

Yet another insight into questions of non-locality can be gleaned from the re-examination of the so-called *quantum teleportation* of a qubit. An entangled pair of qubits in, again, the antisymmetric Bell state \(\Psi^- = 1/\sqrt{2}(|0\rangle_A|1\rangle_B - |1\rangle_A|0\rangle_B)\) is produced at time \(t_0\) and taken far away from each other. At time \(t_A > t_0\) an unknown qubit in superposed state \(|\alpha\rangle_C + \beta|1\rangle_C\) is brought in and put in interaction with qubit A. The total, composite, state of the three-qubit system is now \(1/\sqrt{2}(|\alpha\rangle_A|\alpha\rangle_B + \beta|1\rangle_B|1\rangle_A - |1\rangle_A|0\rangle_B)\), which can be shown algebraically to be equal to a linear superposition of four Bell states in the \(A-C\) subspace, with coefficients that are specific transforms of the type \((-\alpha|0\rangle_B - \beta|1\rangle_B), (+\alpha|1\rangle_B - \beta|0\rangle_B)\), and so on. Therefore, if now a measurement is made on the pair \(A-C\) of any observable whose eigenstates are the four Bell states, the state of the entire system will collapse into just one of the four terms (with 25% probability each), with the qubit at B left in a superposed state with coefficients given by the parameters \(\alpha, \beta\) of the now vanished unknown qubit \(C\). If

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4Regarding non-locality, it is interesting that today there is as much abhorrence of this concept as there was, centuries ago, concerning a Sun-centered planetary system, or Newton’s First Law. Yet, as an example, the entire framework of electromagnetism can, in entirely logical and fact-compatible terms, be formulated in an action-at-a-distance fashion by means of non-local interactions between mutually distant electric charges and currents (e.g., Wheeler and Feynman 1949).
the observer at point A informs B (through classical, macroscopic means) which basis Bell state has resulted in the measurement—only two bits are needed to label each possible basis state—observer B can apply the appropriate inverse unitary transformation to his qubit, and thus be in possession of the teleported qubit C (defined by the unknown coefficients \( \alpha \) and \( \beta \)).

The puzzling aspect of this procedure is that it looks as if the infinite amount of information on two real numbers (those defining the normalized pair of complex numbers \( \alpha \) and \( \beta \)) was transported from A to B by means of only two classical bits. Even worse: there is a whopping 25% chance that the observer at B was in possession of the unknown qubit even before receiving those two key bits!

The answer is that, according to our definition, the parameters \((\alpha, \beta)\) do not represent pragmatic information. There is no way to verify the teleportation of a specific, single qubit; the only way verification could be accomplished is through a statistical process, repeating the whole procedure \( N \) times, from the identical preparation of each one of the three qubits to the actual measurement of the teleported qubit. If we determine the frequencies of occurrence \( N_0 \) and \( N_1\mathrm{=}N-N_0\) of the \(|0\rangle \mathrm{B} \) and \(|1\rangle \mathrm{B} \) states, and express the teleported qubit state in its polar (Bloch sphere) form \( |\Psi\rangle = \cos(\theta/2)|0\rangle + \exp(i\phi) \sin(\theta/2)|1\rangle \), it can be shown that the number of statistically significant figures of \( \theta \) and \( \phi \) (in base 2) to be obtained is equal to the total number \( 2N \) of bits transmitted classically (i.e., macroscopically) from A to B, so, from the statistical point of view, there is no paradox! This indeed brings out clearly the fact that classical information about a quantum state can only be extracted statistically from a mixture of equally prepared qubits. It also shows that there is no way of teleporting true pragmatic information and, as a consequence, a macroscopic object!

The process of decoherence

Let us address now the question of what, if any, physical processes are responsible for decoherence in the transition from the quantum domain to the macroscopic, classical, part of a measurement apparatus. We shall assume that the measuring apparatus consists entirely of mutually interacting qubits—lots of them, perhaps \( 10^{22} \) or \( 10^{23} \)—with one of which the external qubit to be measured enters into interaction at time \( t_0 \). We also assume that the binary observable is of the “which-path” type (see below). In our model, the apparatus particles represent a stochastic web, coarse-grained in such a way that, as the interaction process propagates, only two distinct macroscopic end states \( M_0 \) and \( M_1 \) are possible, realized as two topologically or temporally different forms or patterns (the so-called pointer states, represented in orthogonal Hilbert subspaces of enormous dimensions). The final macroscopic state actually achieved will depend on the actual basis state of the measured qubit (see discussion above).

Now, what will happen if the qubit to be measured is in a superposed state? The first physical interaction at time \( t_0 \) would create an entangled state of the system “qubit—first apparatus particle” which through further inter-component interactions would then expand to the entire composite system “qubit—apparatus” in a cascade of interactions and further entanglements throughout the apparatus. Accordingly, the classical end of the apparatus also should end up in a superposed state—a fact that is never observed (think of the Schrödinger cat!). Obviously, somewhere in the time-cascade of interactions from the initial contact at time \( t_0 \) to the formation of the final macroscopic state, there is a breakdown of the entanglement between the original qubit and the instrument, both of which will be left in separate but correlated states, either \(|0\rangle \) and \( M_0 \), or \(|1\rangle \) and \( M_1 \), respectively.

Notice the “back-propagation of causation” in this picture. The physical interaction processes causing the breakdown of entanglement are non-local in space and time: something that happens physically and locally inside the apparatus (and in the environment—see below) has a retro-effect on the original qubit “out there”? (See our earlier discussion of timing).

An even more striking illustration of non-locality is that of a “non-interaction” measurement. Thus far we have implicitly considered only intrinsic binary variables of the particle to be measured, like spin, polarization, energy levels, etc. Let us turn now to an external variable like the two possible paths of a photon in a Mach-Zehnder interferometer or of an electron in a Stern-Gerlach experiment. In either case we have two possible basis states, say the trajectories \( |\text{left}\rangle \) and \( |\text{right}\rangle \). A superposed “which-path” state of the particle will be \( \alpha|\text{left}\rangle + \beta|\text{right}\rangle \).

We now interpose a non-destructive measurement device in the left path that can be turned on during a very brief interval of time after the superposed state was created. The device has the property that (i) when the particle is in the eigenstate \( |\text{right}\rangle \) and the counter was turned on during the exact time when the particle would be passing were it to travel on the left path, it will show the state \( M_0 \) (no count); and (ii) when the particle is in the eigenstate \( |\text{left}\rangle \), the instrument will exhibit a macroscopic change into state \( M_1 \) (e.g., emit a blip or click).

If the particle is now in a maximally superposed which-path state such as \( 1/\sqrt{2}(|\text{left}\rangle + |\text{right}\rangle) \), it will get entangled with the quantum end of the apparatus, in principle leading to the composite state \( 1/\sqrt{2}(|\text{left}\rangle M_1 + |\text{right}\rangle M_0) \) of the particle-apparatus system. However, decoherence will occur further up in the entanglement cascade, and, with 50/50 probability the state of the composite system will end up reduced to either of one or the other independent states “left-path and count” or “right-path and no-count”.

We now ask: What actually has caused the collapse when the final state \( |\text{right}\rangle M_0 \) arises, which our classical mind wants to interpret as a particle “sailing through unscathed” along the right path without, apparently, ever having touched the measurement apparatus in the left branch? Since in this non-interaction measurement a state reduction obviously did take place, a decoherence process must have occurred in the “untouched” and turned-on detector—but we will never be able to find out, i.e., be able to extract pragmatic information about it by “looking into the innards” of the apparatus while decoherence is occurring (if we do, we would be interfering with yet another apparatus with which the participating elements will get entangled and then decohere). Also, as we...
shall mention below, in a (non-demolition) interaction, decoherence does not involve any energy transfer from qubit to apparatus, whether it leads to a macroscopic change or not in the latter (the energy required for such change is always provided by a local reservoir in the instrument). If the detector was not turned on at exactly the time the particle would be going through its interaction point, no reduction would take place, and the particle would remain in a superposed which-path state.

There has been considerable discussion during the last decades about the possible physical causes of decoherence. Opinions are converging to “its the environment” (e.g., Zurek 2007). It is physically impossible to shield the composite system qubit–apparatus completely from outside influences (gravity, long-wave electromagnetic radiation, thermal and vacuum fluctuations, etc.). Since by definition a measurement apparatus must be able to respond macroscopically with a change in form or pattern in order to yield extractable pragmatic information (usable by a human observer), at some stage the apparatus will have to be sufficiently complex, and so will be the cascade of interactions; thus, the more vulnerable the combined system will be to stochastic perturbations. Times of decoherence have been calculated for specific highly simplified cases, and they usually turn out to be extraordinarily short (order of $10^{-14}$ s to much, much less). Schlosshauer (2007) gives examples; he also shows examples in which there is no exchange of energy with the environment (non-dissipative decoherence). For a different view, more along the so-called “many-worlds approach”, see Griffith (2003).

Measurement processes and their apparatuses are artifices—human-planned and designed for a specific purpose (to determine correlations and make predictions). However, note that the preceding discussion can be applied to the case in which we replace the artificial measurement apparatus with the natural environment per se. Just replace the word “apparatus” with “the environment” with which a given quantum system willy-nilly interacts and gets entangled, according to the previous discussion. As long as this entanglement persists, the given quantum system will have lost its original state, and only the composite quantum system–environment will have a defined state, however complicated and dislocated. Now, if the interaction with the environment leads to a macroscopic change somewhere (potentially verifiable through information-extraction by an observer), the state of the quantum system will be reduced to some specific eigenstate, correlated with the change in question. The cascade of entanglements in a quantum measurement also involves a stochastic ensemble of environmental components with which the instrument’s components are in subtle but unavoidable interaction.

A collateral consequence of natural decoherence is that any peculiar quantum property like superposition will have little chance of spreading over a major part of a macroscopic object, which indeed will behave classically whenever observed. Quantum behavior of a macroscopic system is not forbidden (a Schrödinger cat could be in a superposed state of dead and alive at the same time!), but its probability and duration would be ridiculously small. This also explains the fact that many artificial quantum systems are very unstable in a superposed state, and thus very difficult to handle in the laboratory—a fact that represents one of the biggest challenges to quantum computing.

Concluding Remarks

From the previous discussion it seems advisable to refrain from using the classical concept of pragmatic information indiscriminately in the quantum domain—even in Gedanken-experiments! Yet quite commonly we do, especially when we teach—but then we should not be surprised that by forcing the concept of information (and for that matter, the concept of macroscopic time) into the quantum do-

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1. Even some classical measurement processes require participation of the environment. When you measure the size of an object with a caliper, you can do that in total darkness, because the caliper interacts directly (elastically) with the object, but if you measure it with a ruler, you need to submerge everything in a “bath of photons” whose scattering or reflection is what your optical system uses to extract the wanted information on object–apparatus interaction.

2. With the decay times depending on the original wave functions of the individual nuclei before decoherence, as well as on unavoidable interactions of the latter with the environment leading to possible fluctuations in the exponential decay.

3. Organic macromolecules deserve special consideration, but are outside the scope of this article. They behave classically and are capable of encoding pragmatic information in the form of stable patterns. Decoherence within a molecule? Somewhere in this lies hidden the transition from non-life to life (Roederer 2005).
main, we are triggering mental images of “weird” behavior that is contradictory to our every-day macroscopic experience.

To me, the problem of the interpretation of quantum mechanics is more of a pedagogical nature than a philosophical one. For instance, how should one answer correctly the often-asked question: Why is it not possible, even in principle, to extract information on the actual state of a single qubit? Because by the definition of information, to make that possible there would have to be some specific process by means of which a change is produced somewhere in the macroscopic classical domain that is in one-to-one correspondence with the qubit’s parameters immediately prior to that process. Only for eigenstates (basis states) can this happen—decoherence prevents the formation of any macroscopic trace of superposed states. And because of the non-local character of entanglement, in the case of an initially superposed state, the end state of the qubit will always appear correlated with the end state of the macroscopic system, i.e., will emerge reduced to a correlated basis state. In somewhat trivial summary terms, quantum mechanics can only provide real information on natural or deliberate macroscopic imprints left by a given quantum system that has undergone a given preparation and then interacts with the surrounding macroscopic world8.

So what are the coefficients in a qubit state like $\alpha|0\rangle + \beta|1\rangle$? They are parameters in a mathematical model representation of the system, which within an appropriate framework enables us to make quantitative, albeit only probabilistic, predictions about the system’s possible macroscopic imprints on the classical domain. We may call $\alpha$ and $\beta$ information, and we do—the common usage of the terms “quantum bit” and “quantum information” testifies to this. Yet in doing so we are repeatedly obliged to point out its “hidden nature”!

In the present article I tried to show that what we normally call quantum information is just not the type of pragmatic information which our brains are designed to handle in the first place. Indeed, using John Wheeler’s terminology (e.g., Zeh 2002) what we have here is “bit from it” (where the “it” is any classically-behaving decohered micro or macro quantum system and the “bit” an algorithmic measure of the amount of possible neural correlates it may evoke). So where and how does “real information” appear in quantum computing?

The preparation of an ensemble of quantum systems with respect to some specific observables (some specific Hilbert sub-space) necessarily will involve, like any measurement, an artificial macroscopic setup that leaves at least some elements of the ensemble in given known basis states (of those observables). This set of eigenstates (or the corresponding eigenvalues) can be viewed as an initial classical “pattern” (remember that basis states behave classically in a measurement). The art of quantum computing consists of subjecting this quantum ensemble to appropriate unitary transformations in such a way that a final state can be reached in which at least some of its elements end up in a (usually different) set of predefined basis states. The final set of corresponding eigenvalues represents a classical pattern that will be in univocal correspondence with the classical pattern of the initially prepared basis states. This correspondence, by definition, does indeed represent legitimate pragmatic information.

Obviously, during the time interval between the initial and final states, any extraneous non-unitary intervention, whether artificial (a measurement) or natural (decoherence), will destroy the macroscopic input-output correlation. Indeed, in this interim interval, the proverbial mandate of “don’t ask, don’t tell” applies (Roederer 2005)—not because we don’t know how to extract relevant information to answer our questions, but because pragmatic information per se does not operate in the quantum domain.

References


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8 After all, Heisenberg stated already in 1927: “A particle trajectory is created only by the act of observing it”!