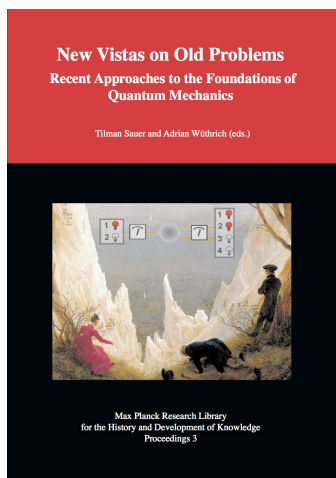


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Alexei Grinbaum:

Quantum Observer and Kolmogorov Complexity



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Quantum Observer and Kolmogorov Complexity

Alexei Grinbaum

Abstract. *Different observers do not have to agree on how they identify a quantum system. We explore a condition based on algorithmic complexity that allows a system to be described as an objective “element of reality.” We also suggest an experimental test of the hypothesis that any system, even much smaller than a human being, can be a quantum mechanical observer.*

1 Introduction

Quantum mechanical formalism has an orthodox interpretation that relies on the cut between the observer and the system observed (Dirac, 1930; von Neumann, 1932). This “shifty split” (Bell, 1990) of the world into two parts cannot be removed: the formalism only applies if the observer and the system are demarcated as two separate entities. Physical properties of the system, on one side of the split, do not exist independently of the observer, on the other side of the split, and can only be instantiated during the observation, or ‘measurement,’ of some dynamical variable of the system chosen by the observer.

The observer is essential for quantum mechanics, but precisely to whom or to what thing does this word refer? There is no consensus. What is extraordinarily difficult, Wheeler (1983) emphasized, is to state sharply and clearly where “the community of observer-participators” begins and where it ends. Quantum mechanics itself says nothing about the physical composition of the observer: whatever is meant by the word has no quantum mechanical description and lies outside physical theory. One cannot infer from a set of quantum mechanical measurements if the observer is a human being, a machine, a stone, a Martian, or the whole Universe.

It is remarkable that although nothing can be said about who the observer is, quantum mechanics gives unequivocal prescriptions for the content of the observer’s observation. Differently constituted observers, even if one is a butterfly

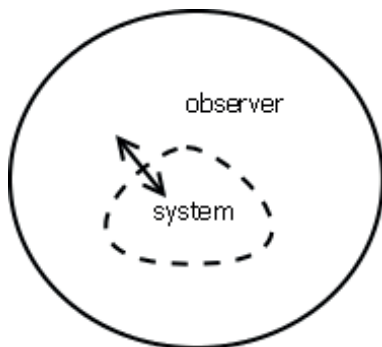


Figure 1: A “shifty split” between the observer and the quantum system.

on Earth and the other a drop of methane on Titan, will obtain the same probabilistic results provided that they manage to measure the same quantum system. How is this possible? Only because the mathematics of quantum mechanics is abstract: it deals with ‘systems’ and ‘observers,’ not with methane or butterflies.

The question of the observer’s exact physical constituency is not dealt with from within quantum mechanics; it is left for philosophy. Different interpretations of quantum mechanics provide different answers. Some say that only conscious human beings can be observers; others state that anything qualifies, even a single electron. Each answer to the question ‘what is an observer’ comes with a corresponding answer to the question ‘can observers disagree’ or ‘what makes them agree.’

As a part of his relative-state interpretation, Everett argued that observers are physical systems with memory, i.e., “parts... whose states are in correspondence with past experience of the observers” (Everett, 1957). We call this a *universal observer* hypothesis: any system with certain information-theoretic properties can serve as quantum mechanical observer, independently of its physical constituency, size, presence or absence of conscious awareness and so forth. In this vein, Rovelli claimed that observers are merely systems whose degrees of freedom are correlated with some property of the observed system: “Any system can play the role of observed system and the role of observing system. [...] The fact that observer O has information about system S (has measured S) is expressed by the existence of a correlation [...]” (Rovelli, 1996). However, the universal

observer hypothesis has remained a controversial statement to this day. For example, Peres claims in the way exactly opposite to Rovelli's, that "the two electrons in the ground state of the helium atom are correlated, but no one would say that each electron 'measures' its partner" (Peres, 1986). Our purpose is to clarify an information-theoretic definition of quantum mechanical observer and to propose a physical test of this hypothesis.

We start by a historical review in Section 2. In Section 3 we give a general definition of observer based on the intuitive feeling that a key component of observation is system identification. Then we apply to it the notion of Kolmogorov complexity, which is the main tool of ensuing analysis. In Section 4 this approach is developed to germinate a definition of quantum and classical systems. In Section 5 we consider a family of observers and require that a system be identified by them in the same way, thereby giving an information-theoretic criterion of an "element of reality." In Section 6 we show that observers can be allowed some disagreement while still maintaining an unambiguous identification of the observed element of reality. Finally, in Section 7 we suggest an experimental test of the universal observer hypothesis.

2 Observer as a Problem

2.1 Observer in the Copenhagen Orthodoxy

Bohr's lecture at Como in 1927 became the foundation of what later came to be known as the Copenhagen interpretation of quantum mechanics. Despite being a universal and orthodox reference in the debate on quantum mechanics, the Copenhagen interpretation has a variety of formulations none of which is the accepted dogma (Howard, 1994; Henderson, 2010). Its main point can be described by the following quote from Bohr: "Only with the help of classical ideas is it possible to ascribe an unambiguous meaning to the results of observation. [...] It lies in the nature of physical observation, that all experience must ultimately be expressed in terms of classical concepts." (Bohr, 1934, 94) Two different readings of Bohr's statement exist, related to what exactly is meant by "classical." The first is a straightforward inference that quantum mechanics requires classical mechanics:

It is in principle impossible to formulate the basic concepts of quantum mechanics without using classical mechanics. (Landau and Lifshitz, 1977, 2)

On the second reading, one maintains that quantum mechanical experiments can only be described by the classical language, which in turn leads us to classical mechanics, but it is the *language* that is a crucial ingredient:

Bohr went on to say that the terms of discussion of the experimental conditions and of the experimental results are *necessarily* those of ‘everyday language,’ suitably ‘refined’ where necessary, so as to take the form of classical dynamics. It was apparently Bohr’s belief that this was the only possible language for the *unambiguous communication* of the results of an experiment. (Bohm, 1971, 38)

The choice between classical mechanics and classical language is not always visible and many authors have failed to distinguish between the two formulations. A direct reference to classical mechanics means, for those who support this view, that the world consists of mechanical systems only, whether quantum or classical, and no external observer is necessary. On the contrary, an invocation of the classical language, concepts, or terms—and Bohr himself has always used these words—implies that the formulation of the problem includes somebody who is in command of classical concepts: the experimenter. This experimenter prepares the quantum system and then measures it acting as a quantum mechanical observer. Then observers possess a linguistic faculty because, according to Bohr’s dictum, they need to communicate between themselves unambiguously.

The mechanistic point of view and the linguistic point of view differ in the ways they account for the problem of agreement. Mechanistically, one assumes that the properties of classical systems exist objectively, i.e. independently of bringing other systems into consideration. Objectivity then guarantees that any further classical mechanical system will be able to interact with the initial system and acquire the same property, which encodes the measurement result. Mechanistic observers agree because disagreement is not classically observed.

The answer is less straightforward from the linguistic point of view. Observers agree on the results of quantum measurements because they agree on the use of classical concepts. But why do they agree on linguistic usage? How do they establish their agreement? How does it come about? It is a matter of pure convention usually left unanalyzed by the Copenhagen interpretation.

2.2 London and Bauer

John von Neumann's magisterial book on quantum mechanics first appeared in German in 1932 (von Neumann, 1932). It offered a theory of measurement that were to become a standard not only for the Copenhagen interpretation but for quantum mechanics as a physical theory in general. However, von Neumann's musings about the place of the observer were not entirely clear and satisfactory. The formalism worked perfectly, but what was exactly its meaning?

Writing as early as 1939, London and Bauer set the tone of one of the main branches of the post-von Neumann debate on the interpretation of quantum mechanics. They remark that quantum mechanics cannot ascribe properties to the quantum system in itself, only if there is a link to an observer. This observer is for London and Bauer a human person. An objective description of reality is therefore impossible and "it seems that the result of measurement is intimately linked to the consciousness of the person making it" (London and Bauer, 1939, 48).¹ Von Neumann's cut between the observer and the observed system is here pushed to the extreme position, leaving all physical systems on one side, including light photons, the eye and the nerves, and only leaving the observer's 'organ' of awareness, namely consciousness, on the other.

If this were true, why would objectivity be possible at all and why have physicists not yet become solipsists? Why do two physicists agree on what constitutes the object of their observation and on its properties? Because, according to London and Bauer (1939, 49), there exists something like a "community of scientific consciousness, an agreement on what constitutes the object of the investigation." The nature of this scientific consciousness remains however mysterious. London and Bauer only conclude that "it must yet be looked into."

2.3 Wigner

Remarks by London and Bauer were further developed by Eugene Wigner (1961). Consciousness of the observer "enters the theory unavoidably and unalterably" and corresponds to the impression produced by the measured system on the observer. Answering the question of realism, Wigner notes that the wave function "exists" only in the sense that "the information given by the wave function is communicable." Observers agree because they communicate measurement results to one another:

¹English translation in (Wheeler and Zurek, 1983, 218–259).

The communicability of information means that if someone else looks at time t and tells us whether he saw a flash, we can look at time $t + 1$ and observe a flash with the same probabilities as if we had seen or not seen the flash at time t ourselves.

The first observer tells us the result of his measurement: communication for Wigner is linguistic. The second observer, in this example of Wigner's, puts himself in the position of the first observer and acts just like him. This is only possible because the second observer has been told the measurement result by the first one.

Do observers actually have to communicate or is it enough to require that they simply *could* communicate the information about the measurement? Here Wigner's position is vague. On the one hand, he states, "If someone else somehow determines the wave function of a system, he can tell me about it [...]," which requires a mere possibility of communication but no sending of actual information. On the other hand, Wigner famously analyzes the following situation labeled 'Wigner's friend':

It is natural to inquire about the situation if one does not make the observation oneself but lets someone else carry it out. What is the wave function if my friend looked at the place where the flash might show at time t ? The answer is that the information available about the *object* cannot be described by a wave function. One could attribute a wave function to the joint system: friend plus object, and this joint system would have a wave function also after the interaction, that is, after my friend has looked. I can then enter into interaction with this joint system by asking my friend whether he saw a flash. [...] The typical change in the wave function occurred only when some information (the *yes* or *no* of my friend) entered *my* consciousness.

Although he calls this situation natural, Wigner is the only one among the founding fathers of quantum theory to have addressed it explicitly. Here Wigner's agreement with his friend is clearly possible thanks to the linguistic communication between them, but this communication itself is not a quantum measurement: whatever the situation, Wigner always knows the question he should put to his friend and fully trusts the answer, always *yes* or *no*. Communication from the friend must actually occur before the wave function could be known by Wigner; it is not enough that this communication be merely possible. As with the linguistic reading of the Copenhagen interpretation, Wigner's interpretation involving con-

sciousness of the observer leaves open the exact mechanism, whether a human convention or a physical given, of the agreement between observers.

Wigner also touches on the question of belief and trust in his discussion of the repeatability of experiments in physics. To explore the statistical nature of the predictions of quantum mechanics, it is necessary to be able to produce many quantum systems in the same state; subsequently these systems will be measured. One can never be absolutely sure, Wigner stipulates, that one has produced the same state of the system. We usually “believe that this is the case” and we are “fully convinced of all this” (Wigner, 1976, 267), even if we have not tried to establish experimentally the validity of the repeated preparation of the same state. What is at work here is again a convention shared by all physicists. How do they know that repeated preparations produce the same state if they do not measure each and every specimen in order to verify it? The answer is that they have common experience and a convention on what a ‘controlled experiment’ amounts to, and their respect of this commonly shared and empirically validated rules enables them to postulate the existence of repeated states even in the situations which had never been tested before. This is how physical theory with its laws and a precise methodology arises by way of abstraction (‘elevation,’ as Einstein or Poincaré would say (Friedman, 2001, 88)) from the physicist’s empirical findings and the heuristics of his work.

2.4 Everett

What is important about the observer? Only his function of an informational agent, not his physical constituency. The need to refer to consciousness exists, insofar as only consciousness can distinguish a mere physical correlation, e.g. of an external system with the observer’s eye, from the information actually available to the observer, i.e. such that he can act upon in the future. Other characteristics are irrelevant: say, the observer’s age plays no role (“there is little chance of making a big mistake if one does not know [the observer’s] age” (London and Bauer, 1939, 43)).

Treating the observer as an informational agent requires that we say precisely what makes different systems possessing information into observers. In other words, what is the nature of a convention shared by all observers, whose workings we notice when apparently unrelated measurements by different observers come out in a consistent way? Brillouin believes that information must be defined with the exclusion of all human element (George, 1953, 360), in which case the

convention between observers must necessarily have a physical, as opposed to linguistic or cultural, origin. Watanabe finds such a physical origin in the direction of time shared by all observers: “The past-to-future directions of all observers coincide. This statement has a well-defined physical meaning, for ‘positive time direction’ is a Lorentz-invariant concept” (George, 1953, 387). But both Brillouin’s and Watanabe’s ideas proved to be sterile in the history of physics. Time-directedness, for once, may be a necessary requirement, because, as we shall see later, observers are thermodynamical systems. But it is far from clear if Watanabe’s shared time direction is a sufficient or even a necessary condition.

Hugh Everett (1957) thought differently. Observers are for him systems that can be described in purely physical terms. These systems possess memory, defined as “parts [...] whose states are in correspondence with past experience of the observers.” Observers do not have to be human: they could be “automatically functioning machines, possessing sensory apparatus and coupled to recording devices.” Memory records are thus fundamental: it is memory that makes any physical system an observer. Everett continues, “if we are to be able to call the interaction an observation at all, the requirement that the observer’s state change in a manner which is different for each eigenfunction is necessary.” Repeatability relies on the necessary assumption that the eigenstates of the system be unchanged during measurement.

Everett was the first to explicitly consider the problem of several observers. The “interrelationship between several observers” is an act of communication between them, which Everett treats as establishing a correlation between their memory configurations. The consequences are described with remarkable clarity:

1. When several observers have separately observed the same quantity in the object system and then communicated the results to one another they find that they are in agreement. This agreement persists even when an observer performs his observation after the result has been communicated to him by another observer who has performed the observation.
2. Let one observer perform an observation of a quantity A in the object system, then let a second perform an observation of a quantity B in this object system which does not commute with A , and finally let the first observer repeat his observation of A . Then the memory system of the first observer will *not* in general show the same result for both observations. [...]

3. Consider the case when the states of two object systems are correlated, but where the two systems do not interact. Let one observer perform a specified observation on the first system, then let another observer perform an observation on the second system, and finally let the first observer repeat his observation. Then it is found that the first observer always gets the same result both times, and the observation by the second observer has no effect whatsoever on the outcome of the first's observations.

2.5 Rovelli

Rovelli (1996) proposed a relational interpretation of quantum mechanics. All physical systems have the capacity to act as observers, i.e., possess information about other physical systems. Information should be seen as an observer-dependent, rather than objective, notion. It is information in Shannon's sense indexed by two parameters: the first related to the observed system about which this information has been obtained, the second related to the observing system that has obtained information about the first system. Trying to remove the second index and to 'liberate' the notion of information from its relational sense is both impossible and meaningless. Objective information independent of the observing system does not exist.

However, the question of intersubjective agreement remains unclear. If each observer acts on his own and information is always defined relative to some observer, why do different observers agree on the measurement result and attribute the same state to the quantum system? For Rovelli, the answer lies in the interaction between observers, which is a quantum mechanical process like any other and, consequently, must be described in the same language of relative information. This information is encoded in the correlations between physical degrees of freedom of the observers. Now imagine three observers in a triangle (see Figure 2), with O_1 observing O_2 , O_2 observing O_3 , and O_3 observing O_1 .

Some of the degrees of freedom of O_1 are correlated with some degrees of freedom of O_2 . Similarly, some degrees of freedom of O_2 are correlated with the degrees of freedom of O_3 , and the degrees of freedom of O_3 are correlated with those of O_1 . These correlations must be self-consistent, i.e., no paradox must emerge from the circular correlation. How is this requirement realized physically? Perhaps it is always the case that when an observer is observed by another system, the degrees of freedom that the other system can 'see' are never the same as the

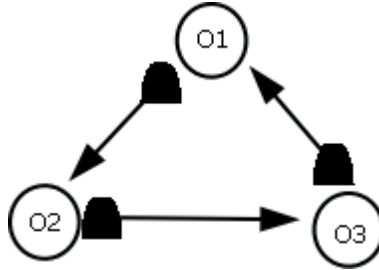


Figure 2: A triangle between three observers.

degrees of freedom in which the observer encodes his own measurement data. Or perhaps some other mechanism is at work, which precludes us from running into a contradiction. This issue is not explored by Rovelli and remains an open question.

3 Observer as a System Identification Algorithm

What characterizes an observer is that it (or he or she) has information about some physical system. This information fully or partially describes the state of the system. The observer then measures the system, obtains further information and updates his description accordingly. The physical processes of measuring the system, updating the information and ascribing a state to the system may happen in many different ways depending on the physical constitution of the observer. The memory of a computer acting as an observer, for instance, is not the same as human memory, and measurement devices vary in their design and functioning. Still one feature unites all observers: whatever they do, they do it to a *system*. In quantum mechanics, defining an observer goes hand in hand with defining a system under observation. An observer without a system is a meaningless nametag, a system without an observer who measures it is a mathematical abstraction. What remains constant throughout measurement is the identification, by the observer, of the quantum system.

Quantum systems aren't like sweets: they don't melt. Take a general thermodynamic system interacting with other systems. Such a system can dissipate, diffuse, or dissolve, and thus stop being a system. If at first a cube of ice gurgling into tepid water is definitely a thermodynamic system, it makes no sense

to speak about it being a system after it has dissolved. Quantum systems are not like this. Their states may evolve, but the observer knows how to tell the system he observes from the rest or the environment. An electron in a certain spin state remains an electron after measurement, i.e., it remains a system with a particular set of degrees of freedom. The observer maintains the identity of the system notwithstanding a change in the state of this system that may or may not occur. So, whatever else he might happen to be, the observer is primarily a system identification machine. Different observers having different features (clock hands, eyes, optical memory devices, internal cavities, etc.) all share this central characteristic.

Definition 3.1. An observer is a system identification algorithm (SIA).

Particular observers can be made of flesh or, perhaps, of silicon. ‘Hardware’ and ‘low-level programming’ are different for such observers, yet they all perform the task of system identification. This task can be defined as an algorithm on a universal computer, e.g. the Turing machine: take a tape containing the list of all degrees of freedom, send a Turing machine along this tape so that it puts a mark against the degrees of freedom that belong to the quantum system under consideration. Any concrete SIA may proceed in a very different manner, yet all can be modelled with the help of this abstract construction.

The SIAs whose physical realization may differ share one property that does not depend on the hardware: their algorithmic, or Kolmogorov, complexity. Any SIA can be reconstructed from a binary string of some minimal length (which is a function of this SIA) by a universal machine. As shown by Kolmogorov (1965), this minimal compression length defines the amount of information in the SIA and does not depend (up to a constant) on the realization of the SIA on this or that hardware. The common-lore view of a multitude of individual observers, one hastily printing, another yawning, a third one moving around his DNA strands, should in our opinion be superseded by a view of different SIAs, each with its algorithmic complexity defined via a universal machine.

4 Quantum and Classical Systems

Each quantum system has a certain number of degrees of freedom, which we think about as being independent parameters needed in order to characterize the state of the system. For example, a system with only two states (spin-up and spin-down)

has one degree of freedom and can be described by one parameter $\sigma = \pm 1$. If we write down these parameters as a binary string, the Kolmogorov complexity of that string is at least the number of the degrees of freedom of the system, i. e.,

$$K(s) \geq d_S, \quad (1)$$

where $K(s)$ is the Kolmogorov complexity of the binary string s representing the parameters of the system S , and d_S is the number of the degrees of freedom in S . In what follows the notation $K(s)$ and $K(S)$ will be used interchangeably.

When we say that an observer X observes a quantum system S , it is usually the case that $K(S) \ll K(X)$. In this case the observer will have no trouble keeping track of all the degrees of freedom of the system; in other words, the system will not ‘dissolve’ or ‘melt’ in the course of dynamics. However, it is also possible that X identifies a system with $K(S) > K(X)$. For such an observer, the identity of system S cannot be maintained and some degrees of freedom will fall out from the description that X makes of S .

Definition 4.1. System S is called quantum with respect to observer X if $K(S) < K(X)$, meaning that X will be able to maintain a complete list of all its degrees of freedom. Otherwise S is called classical with respect to X .

Suppose that X observes a quantum system S and another observer Y observes both S and X . If $K(Y)$ is greater than both $K(X)$ and $K(S)$, observer Y will identify both systems as quantum systems. In this case Y will typically treat the interaction between X and S as an interaction between two quantum systems. If, however, $K(X)$ and $K(Y)$ are close, $K(X) \gg K(S)$ and $K(Y) \gg K(S)$ but $K(X) \simeq K(Y)$, then Y will see S as a quantum system but the other observer, X , as a classical system. An interaction with a classical system, which we usually call ‘observation,’ is a process of decoherence that occurs when the Kolmogorov complexity of at least one of the systems involved approaches the Kolmogorov complexity of the external observer. In this case Y cannot maintain a complete description of X interacting with S and must discard some of the degrees of freedom. If we assume that all human observers acting in their SIA capacity have approximately the same Kolmogorov complexity, this situation may provide an explanation of the fact that we never see a human observer (or, say, a cat) as a quantum system.

One welcome consequence of Definitions 3.1 and 4.1 is that Kolmogorov complexity $K(X)$ is not computable. We as human observers do not seem to know the maximum number of the degrees of freedom in a system that we can still keep

track of. A photon is certainly a quantum system from our point of view, a simple atom too, a C_{60} perhaps as well, albeit seeing quantum effects with fullerenes is not easy. But we have never seen a quantum system having, say, 10^{23} degrees of freedom. So where does the border run? Is it a number like 6 or 20 or is it 10^n , $n > 2$? All we can say is that mathematics shows that human observers cannot compute their own $K(X)$.

5 Elements of Reality

Ever since the EPR paper (Einstein et al., 1935), the question of what is real in the quantum world has been at the forefront of all conceptual discussions about quantum theory. Einstein, Podolsky and Rosen formulated their question with regard to physical *properties*: e.g., is position or momentum real? This is, however, not the only problem of reality that appears when many observers enter the game. Imagine a sequence of observers X_i , $i = 1, 2, \dots$, each identifying systems S_n , $n = 1, 2, \dots$. System identifications of each S_n do not have to coincide as some observers may have their Kolmogorov complexity $K(X_i)$ below, or close to, $K(S_n)$, and others much bigger than $K(S_n)$. If there is disagreement, is it possible to say that the systems are real, or objects of quantum mechanical investigation, in some sense? We can encode the binary identification string produced by each observer in his SIA capacity as some random variable $\xi_i \in \Omega$, where Ω is the space of such binary identification strings, possibly of infinite length. Index i is the number of the observer, and the values taken by random variable ξ_i bear index n corresponding to “ i -th observer having identified system S_n .” Adding more observers, and in the limit $i \rightarrow \infty$ infinitely many observers, provides us with additional identification strings. Putting them together gives a stochastic process $\{\xi_i\}$, which is an observation process by many observers. If systems S_n are to have a meaning as “elements of reality,” it is reasonable to require that no uncertainty be added with the appearance of further observers, i.e., that this stochastic process have entropy rate equal to zero:

$$H(\{\xi_i\}) = 0. \quad (2)$$

We also take this process to be stationary and ergodic so as to justify the use of Shannon entropy.

Let us illustrate the significance of condition (2) on a simplified example. Suppose that $\theta_1, \theta_2, \dots$ is a sequence of independent identically distributed random

variables taking their values among binary strings of length r with probabilities q_k , $k \leq 2^r$. These θ_k can be seen as identifications, by different SIAs, of different physical systems, i.e., a special case of the ξ_i -type sequences having fixed length and identical distributions. For instance, we may imagine that θ_1 is a binary encoding of the first observer seeing an electron and θ_2 is a binary string corresponding to the second observer having identified a physical system such as an elephant; and so forth. Entropy becomes simply:

$$H = - \sum_k q_k \log q_k. \quad (3)$$

Condition (2) applied to entropy (3) means that all observers output one and the same identification string of length r , i.e., all SIAs are identical. This deterministic system identification, of course, obtains only under the assumption that the string length is fixed for all observers and their random variables are identically distributed, both of which are not plausible in the case of actual quantum mechanical observers. So rather than requiring identical strings we impose condition (2) as a criterion of the system being identified in the same way by all observers, i.e., it becomes a candidate quantum mechanical “object of investigation.”

6 Relativity of Observation

Let us explore the consequences of condition (2). Define a binary sequence α_n^i as a concatenation of the system identifications strings of systems S_n by different observers:

$$\alpha_n^i = \overline{(\xi_1)_n} \overline{(\xi_2)_n} \dots \overline{(\xi_i)_n}, \quad (4)$$

where index i numbers observers and the upper bar corresponds to “string concatenation” (a detailed definition can be found in Zvonkin and Levin (1970)). Of course, this concatenation is only a logical operation and not a physical process. A theorem by Brudno (1978, 1983) conjectured by (Zvonkin and Levin, 1970) affirms that the Kolmogorov complexities of strings α_n^i converge towards entropy:

$$\lim_{n \rightarrow \infty} \lim_{i \rightarrow \infty} \frac{K(\alpha_n^i)}{i} = H(\{\xi_i\}). \quad (5)$$

For a fixed i and the observer X_i who observes systems S_n that are quantum in the sense of Definition 4.1, variation of $K(\alpha_n^i)$ in n is bounded by the observer's own complexity in his SIA capacity:

$$K(\alpha_n^i) < K(X_i) \quad \forall n, \quad i \text{ fixed.} \quad (6)$$

Hence eqs. (2) and (5) require that

$$\lim_{i \rightarrow \infty} \frac{K(\alpha_n^i)}{i} = 0. \quad (7)$$

This entails that the growth of $K(\alpha_n^i)$ in i cannot be faster than logarithmical. Therefore, we have the following:

Proposition 6.1. *An element of reality that may become an object of quantum mechanical investigation can be defined only with respect to a class of not very different observers.*

To give an intuitive illustration, imagine adding a new observer X_{i+1} to a group of observers X_1, \dots, X_i who identify systems S_n . This adds a new identification string that we glue at the end of concatenated string α_n^i consisting of all X_i 's identifications of S_n , thus obtaining a new string α_n^{i+1} . The Kolmogorov complexity of α_n^{i+1} does not have to be the same as the Kolmogorov complexity of α_n^i ; it can grow, but not too fast, i.e., not faster than the logarithm. Adding a new observation may effectively add some new non-compressible bits, but not too many such bits. If this is so, then $H = 0$ still obtains. Although observers X_1, \dots, X_i, X_{i+1} produce slightly different identification strings, they agree, simply speaking, that an atom is an atom and not something that looks more like an elephant.

The above reasoning applies only to quantum systems S_n in the sense of Definition 4.1. This is because in the case of classical systems different observers may each operate their own coarse-graining, keeping only some degrees of freedom. System identification strings may then differ dramatically and one cannot expect $K(\alpha_n^i)$ to grow moderately.

7 Experimental Test

A previously suggested experimental connection between thermodynamics and theories based on Kolmogorov complexity is based on observing the conse-

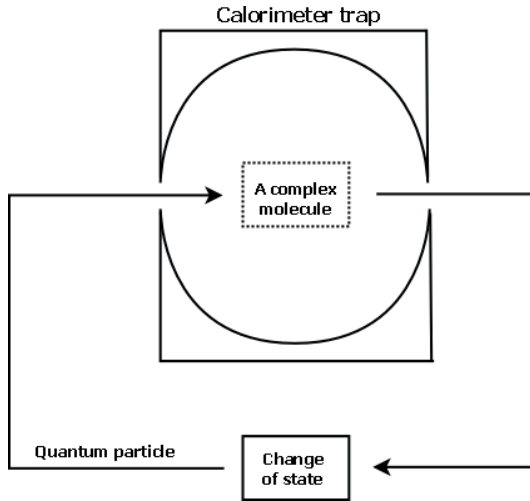


Figure 3: Experiment leading to heat production when physical entropy $\mathcal{S} = H + K$ changes.

quences of a change in the system's state (Zurek, 1989b,a, 1998; Erez et al., 2008). Zurek introduced the notion of physical entropy $\mathcal{S} = H + K$, where H is the thermodynamic entropy and K the Kolmogorov entropy. If the observer with a finite memory has to record the changing states of the quantum system, then there will be a change in \mathcal{S} , like the one depicted in Figure 3, and it will lead to heat production that can be observed experimentally.

What we propose here, based on a suggestion by Anton Zeilinger, is a simpler setting that can still serve as a test of the universal observer hypothesis. It does not rely on the measurement of particular states, but on the fact of measurement as such. If a measurement occurs, then the observer has identified the quantum system, and this fact in itself, if repeated, will eventually lead to heat production.

An individual fullerene molecule is placed in a highly sensitive calorimeter and bombarded with photons, which play the role of quantum systems with low $K(S)$ (Figure 4). According to the universal observer hypothesis, the fullerene is a quantum mechanical observer with $K(X) > K(S)$. Thus the absorption of the photon by the fullerene can be described as measurement: the fullerene identifies a quantum system, i.e. the photon, and observes it, obtaining new information.

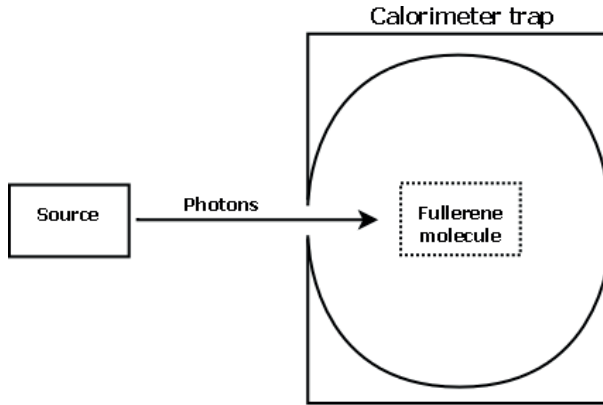


Figure 4: Experiment leading to heat production when observer’s memory becomes saturated.

Physically, this process amounts to establishing a correlation between the photon variables, i.e., its energy, and the degrees of freedom of the fullerene. The external observer knows that such a process has occurred but remains unaware of its exact content, so that he is aware that there has been measurement, but doesn’t know a precise state of the photon as measured by the fullerene, nor a precise state of the fullerene after measurement.

Informationally speaking, the same process can be described as storing information in the fullerene’s memory. If measurement is repeated on several photons, more such information is stored, so that at some point total Kolmogorov complexity will approach $K(X)$. When it reaches $K(X)$, the fullerene will stop identifying incoming photons as quantum systems. Any further physical process will lead to heat production due to the erasure of memory, as prescribed by the Landauer principle that creates information erasure and heat production (Landauer, 1961). Physically, this process will correspond to a change of state of the carbon atoms that make up the fullerene molecule: the calorimeter will register a sudden increase in heat when C_{60} cannot store more information, thereby ending its observer function.

Actual experiments with fullerenes show that this scenario is realistic. A fullerene molecule “contains so many degrees of freedom that conversion of electronic excitation to vibrational excitation is extremely rapid.” Thus, the fullerene

is a good candidate for a quantum mechanical observer, for “the molecule can store large amounts of excitation for extended periods of time before degradation of the molecule (ionization or fragmentation) is observed” (Lykke and Wurz, 1992). The experiments in which fullerenes are bombarded with photons demonstrate that “the energy of the electronic excitation as a result of absorption of a laser photon by a molecule is rapidly converted into the energy of molecular vibrations, which becomes distributed in a statistical manner between a large number of the degrees of freedom of the molecule [...] The fullerene may absorb up to 10 photons at $\lambda = 308$ nm wavelength before the dissociation of the molecule into smaller carbon compounds” (Eletskii and Smirnov, 1995). We read these results as a suggestion that there should be one order of magnitude difference between $K(S)$ and $K(X)$ and that this allows the fullerene to act as quantum mechanical observer for up to 10 photons at 308 nm wavelength. What needs to be tested experimentally in this setting is heat production: we conjecture that if the same process occurs inside a calorimeter, the latter will register a sudden increase in heat after the fullerene will have observed 10 photons. What we predict here isn’t new physics, but an explanation on a new level, i. e., the level of information, of a physical process, i. e., heat production, which plays a largely overlooked role in the dissociation of fullerenes. We suggest that heat production deserves special attention as a signature of the fullerene’s role as quantum mechanical observer.

As a side remark, imagine that the photon’s polarization state in some basis were fully mixed:

$$\frac{1}{2}(|0\rangle + |1\rangle).$$

While only the energy of the photon matters during absorption, the external observer records von Neumann entropy $H = \log 2$ corresponding to this mixture (the initial state of the fullerene is assumed fully known). After absorption, it is mandatory that this entropy be converted into Shannon entropy of the new fullerene state, corresponding nicely to the uncertainty of the external observer in describing the “statistical manner” of the distribution over a large number of the degrees of freedom. From the internal point of view, we may assume perfect ‘self-knowledge’ of the observer, which puts his Shannon entropy equal to zero. However, his Kolmogorov entropy will increase as a result of recording the measurement information (Zurek, 1989a). Heat produced during the erasure of measurement information is at least equal to Kolmogorov complexity of the

string that was stored in observer's memory; but according to quantum mechanics, this heat will not reveal to the external observer any information about the precise photon state observed by the fullerene.

8 Conclusion

The Copenhagen view of quantum mechanics traditionally described quantum systems and observers, epistemologically, as belonging to different categories. On the contrary, the view based on the relativity of observation, as proposed by Everett and later Rovelli, puts all systems on equal grounds and ascribes them only relative states. These two views are not as contradictory as they may seem. Relativity of observation has been understood by some proponents of the Copenhagen school (Hermann, 1935)², (Fock, 1971a,b). Information-theoretic treatment of the observer gives a chance to completely overcome the tension. On the one hand, the observer is an SIA and is characterized by its Kolmogorov complexity. On the other hand, quantum mechanics can be reconstructed from information-theoretic axioms and thus seen as a theory of information (Grinbaum, 2007). This puts all systems on equal grounds, in the spirit of Rovelli, while emphasizing the idea of relativity of observation, in the spirit of Fock.

Additionally, information-theoretic treatment of the observer provides a somewhat surprising result developing EPR's notion of "element of reality." One can make sense of a system existing independently of observation, with respect to a class of observers whose Kolmogorov complexities may differ, even if slightly. Equation (7) provides a mathematical criterion for this.

We have analyzed the observer as a system identification algorithm in the context of quantum mechanics. It remains an open question to apply this analysis to quantum field theory, where the task of system identification may look significantly different from the finite-dimensional situation. It also remains an open problem to realize experimentally the setup proposed in Section 7, which may lead to experimental confirmation of the universal observer hypothesis. Putting together this experimental test, which may show that a fullerene can act as an observer for up to 10 photons, and the remark on non-computability of $K(X)$ at the end of Section 4 begs yet another question: is it possible to say that, although $K(X)$ isn't computable in the mathematical sense, physical experiment effectively computes it?

²Quoted by Jammer (1974, 207–211).

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