

Relational Quantum Mechanics

Carlo Rovelli

Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pa 15260, USA

(November 26, 2024)

I suggest that the common unease with taking quantum mechanics as a fundamental description of nature (the measurement problem) could derive from the use of an incorrect notion, as the unease with the Lorentz transformations before Einstein derived from the notion of observer-independent time. I suggest that this incorrect notion that generates the unease with quantum mechanics is the notion of observer-independent state of a system, or observer-independent values of physical quantities. I reformulate the problem of the interpretation of quantum mechanics as the problem of deriving the formalism from a set of simple physical postulates. I consider a reformulation of quantum mechanics in terms of information theory. All systems are assumed to be equivalent, there is no observer-observed distinction, and the theory describes only the information that systems have about each other; nevertheless, the theory is complete.

I. A REFORMULATION OF THE PROBLEM OF THE INTERPRETATION OF QUANTUM MECHANICS

In this paper, I discuss a novel view of quantum mechanics. This point of view is not antagonistic to current ones, as the Copenhagen [Heisenberg 1927, Bohr 1935], consistent histories [Griffiths 1984, Griffiths 1996, Omnes 1988, Gell-Mann and Hartle 1990], many-worlds [Everett 1957, Wheeler 1957, DeWitt 1970], quantum event [Huges 1989], many minds [Albert and Lower 1988, 1989, Lockwood 1986, Donald 1990] or modal [Shimony 1969, van Fraassen 1991, Fleming 1992] interpretations, but rather combines and complements aspects of them. This paper is based on a critique of a notion generally assumed uncritically. As such, it bears a vague resemblance with Einstein's discussion of special relativity, which is based on the critique of the notion of absolute simultaneity. The notion rejected here is the notion of absolute, or observer-independent, state of a system; equivalently, the notion of observer-independent values of physical quantities. The thesis of the present work is that by abandoning such a notion (in favor of the weaker notion of state –and values of physical quantities– *relative* to something), quantum mechanics makes much more sense. This conclusion derives from the observation that the experimental evidence at the basis of quantum mechanics forces us to accept that distinct observers give different descriptions of the same events. From this, I shall argue that the notion of observer-independent state of a system is inadequate to describe the physical world beyond the $\hbar \rightarrow 0$ limit, in the same way in which the notion of observer-independent time is inadequate to describe the physical world beyond the $c \rightarrow \infty$ limit. I then consider the possibility of replacing the notion of absolute state with a notion that refers to the relation between physical systems.

The motivation for the present work is the commonplace observation that in spite of the 70 years-lapse from the discovery of quantum mechanics, and in spite of the

variety of approaches developed with the aim of clarifying its content and improving the original formulation, quantum mechanics still maintains a remarkable level of obscurity. It is even accused of being unreasonable and unacceptable, even inconsistent, by world-class physicists (For example [Newman 1993]). My point of view in this regard is that quantum mechanics synthesizes most of what we have learned so far about the physical world: The issue is thus not to replace or fix it, but rather to understand *what* precisely it says about the world; or, equivalently: *what* precisely we have learned from experimental micro-physics.

It *is* difficult to overcome the sense of unease that quantum mechanics communicates. The troubling aspect of the theory assumes different faces within different interpretations, and a complete description of the problem can only be based on a survey of the solutions proposed. Here, I do not attempt such a survey; for a classical review see [d'Espagnat 1971], a more modern survey is in the first chapters of [Albert 1992], or, in compact form, see [Butterfield 1995]. The unease is expressed, for instance, in the objections the supporters of each interpretation raise against other interpretations. Some of these objections are perhaps naive or ill-posed, but the fact that that no interpretation has so far succeeded in convincing the majority of the physicists, indicates, I believe, that the problem of the interpretation of quantum mechanics has not been fully disentangled yet. This unease, and the variety of interpretations of quantum mechanics that it has generated is sometimes denoted as the measurement problem. In this paper, I address this problem and consider a way out.

The paper is based on two ideas:

- That the unease may derive from the use of a concept which is inappropriate to describe the physical world at the quantum level. I shall argue that this concept is the concept of observer-independent state of a system, or, equivalently, the concept of observer-independent values of physical quantities.

- That quantum mechanics will cease to look puzzling only when we will be able to *derive* the formalism of the theory from a set of simple physical assertions (“postulates”, “principles”) about the world. Therefore, we should not try to *append* a reasonable interpretation to the quantum mechanics *formalism*, but rather to *derive* the formalism from a set of experimentally motivated postulates.

The reasons for exploring such a strategy are illuminated by an obvious historical precedent: special relativity. I shall make use of this analogy for explanatory purposes, in spite of the evident limits of the simile.

Special relativity is a well understood physical theory, appropriately credited to Einstein’s 1905 celebrated paper. The formal content of special relativity, however, is coded into the Lorentz transformations, written by Lorentz, not by Einstein, and before 1905. So, what was Einstein’s contribution? It was to understand the physical meaning of the Lorentz transformations. (And more, but this is what is of interest here). We could say – admittedly in a provocative manner – that Einstein’s contribution to special relativity has been the interpretation of the theory, not its formalism: the formalism already existed.

Lorentz transformations were discussed at the beginning of the century, and their *interpretation* was debated. In spite of the recognized fact that they represent an extension of the Galilean group compatible with Maxwell theory, the Lorentz transformation were perceived as “unreasonable” and “unacceptable as a fundamental spacetime symmetry”, even “inconsistent”, before 1905; words that recall nowadays comments on quantum mechanics. The physical interpretation proposed by Lorentz himself (and defended by Lorentz long after 1905) was a physical contraction of moving bodies, caused by a complex and unknown electromagnetic interaction between the atoms of the bodies and the ether. It was quite an unattractive interpretation, remarkably similar to certain interpretations of the wave function collapse presently investigated! Einstein’s 1905 paper suddenly clarified the matter by pointing out the reason for the unease in taking Lorentz transformations “seriously”: the implicit use of a concept (observer-independent time) inappropriate to describe reality when velocities are high. Equivalently: a common deep assumption about reality (simultaneity is observer-independent) which is physically untenable. The unease with the Lorentz transformations derived from a conceptual scheme in which an incorrect notion –absolute simultaneity– was assumed, yielding any sort of paradoxical consequences. Once this notion was removed the physical interpretation of the Lorentz transformations stood clear, and special relativity is now considered rather uncontroversial.

Here I consider the hypothesis that all “paradoxical” situations associated with quantum mechanics –as the famous and unfortunate half-dead Schrödinger cat [Schrödinger 1935]– may derive from some analogous in-

correct notion that we use in thinking about quantum mechanics. (Not in *using* quantum mechanics, since we seem to have learned to use it in a remarkably effective way.) The aim of this paper is to hunt for this incorrect notion, with the hope that by exposing it clearly to public contempt, we could free ourselves from the present unease with our best present theory of motion, and fully understand what does the theory assert about the world.

Furthermore, Einstein was so persuasive with his interpretation of the Lorentz equations because he did not append an interpretation to them: rather, he re-derived them, starting from two postulates with terse physical content –equivalence of inertial observers and universality of the speed of light– taken as facts of experience. It was this re-derivation that unraveled the physical content of the Lorentz transformations and provided them a convincing interpretation. I would like to suggest here that in order to clarify the physical meaning of quantum mechanics, a similar result should be searched: Finding a small number of simple statements about nature –which may perhaps seem contradictory, as the two postulates of special relativity do– with clear physical content, from which the formalism of quantum mechanics could be derived. In other words, I have a methodological suggestion for the problem of the interpretation of quantum mechanics: Finding the set of physical facts from which the quantum mechanics’s formalism can be derived. To my knowledge, such a derivation has not been achieved yet. In this paper, I do not achieve such a result in a satisfactory manner, but I discuss a possible reconstruction scheme.

The program outlined is thus to do for the formalism of quantum mechanics what Einstein did for the Lorentz transformations: i. Find a set of simple assertions about the world, with clear physical meaning, that we know are experimentally true (postulates); ii. Analyze these postulates, and show that from their conjunction it follows that certain common assumptions about the world are incorrect; iii. Derive the full formalism of quantum mechanics from these postulates. I expect that if this program could be completed, we would at long last begin to agree that we have understood quantum mechanics.

In section 2, I analyze the measurement process as described by two distinct observers. This analysis leads to the main idea: the observer dependence of state and physical quantities, and to recognize a few key concepts in terms of which, I would like to suggest, the quantum mechanical description of reality “makes sense”. Prominent among these is the concept of information [Shannon 1949, Wheeler 1988, 1989, 1992]. In section 3, I switch from an inductive to a (very mildly) deductive mode, and put forward a set of notions, and a set of simple physical statements, from which the formalism of quantum mechanics can be reconstructed. I denote these statements as postulates, at the risk of misunderstanding: I do not claim any mathematical nor philosophical rigor, nor completeness –supplementary assumptions are made along the way. I am not interested here in a formaliza-

tion of the subject, but only in better grasping its physics. Ideas and techniques for the reconstruction are borrowed from quantum logic research, but motivations and spirit are different. Finally, in section 4, I discuss the picture of the physical world that has emerged, and attempt an evaluation. In particular, I compare the approach I have developed with some currently popular interpretations of quantum mechanics, and argue that the differences between these disappear, if the results presented here are taken into account.

In order to prevent the reader from channeling his/her thoughts in the wrong direction, let me anticipate a few terminological remarks. By using the word “observer” I do not make any reference to conscious, animate, or computing, or in any other manner special, system. I use the word “observer” in the sense in which it is conventionally used in Galilean relativity when we say that an object has a velocity “with respect to a certain observer”. The observer can be any physical object having a definite state of motion. For instance, I say that my hand moves at a velocity v with respect to the lamp on my table. Velocity is a relational notion (in Galilean as well as in special relativistic physics), and thus it is always (explicitly or implicitly) referred to something; it is traditional to denote this something as the observer, but it is important in the following discussion to keep in mind that the observer can be a table lamp. Also, I use information theory in its information-theory meaning (Shannon): information is a measure of the number of states in which a system can be –or in which several systems whose states are physically constrained (correlated) can be. Thus, a pen on my table has information because it points in this or that direction. We do not need a human being, a cat, or a computer, to make use of this notion of information.

II. QUANTUM MECHANICS IS A THEORY ABOUT INFORMATION

In this section, a preliminary analysis of the process of measurement is presented, and the main ideas are introduced. Throughout this section, standard quantum mechanics and standard interpretation –by which I mean for instance: formalism and interpretation in [Dirac 1930] or [Messiah 1958]– are assumed.

A. The third person problem

Consider an observer O (Observer) that makes a measurement on a system S (System). For the moment we may think of O as a classical macroscopic measuring apparatus, including or not including a human being. Assume that the quantity being measured, say q , takes two values, 1 and 2; and let the states of the system S be described by vectors (rays) in a two (complex) dimensional

Hilbert space H_S . Let the two eigenstates of the operator corresponding to the measurement of q be $|1\rangle$ and $|2\rangle$. As it is well known: if S is in a generic normalized state $|\psi\rangle = \alpha|1\rangle + \beta|2\rangle$, where α and β are complex numbers and $|\alpha|^2 + |\beta|^2 = 1$, then O can measure either one of the two values 1 and 2 – with respective probabilities $|\alpha|^2$ and $|\beta|^2$.

Assume that in a *given specific measurement* the outcome of the measurement is 1. From now on, we concentrate on describing this specific experiment, which we denote as \mathcal{E} . The system S is affected by the measurement, and at a time $t = t_2$ after the measurement, the state of the system is $|1\rangle$. In the physical sequence of events \mathcal{E} , the states of the system at t_1 and t_2 are thus

$$\begin{aligned} t_1 &\longrightarrow t_2 \\ \alpha|1\rangle + \beta|2\rangle &\longrightarrow |1\rangle \end{aligned} \quad (1)$$

Let us now consider this same sequence of events \mathcal{E} , as described by a second observer, which we refer to as P . I shall refer to O as “he” and to P as “she”. P describes the interacting system formed by S and O . Again, assume P uses conventional quantum mechanics. Also, assume that P does not perform any measurement on the $S - O$ system during the $t_1 - t_2$ interval, but that she knows the initial states of both S and O , and is thus able to give a quantum mechanical description of the set of events \mathcal{E} . She describes the system S by means of the Hilbert space H_S considered above, and O by means of a Hilbert space H_O . The $S - O$ system is then described by the tensor product $H_{SO} = H_S \otimes H_O$. As it has become conventional, let us denote the vector in H_O that describes the state of the observer O at $t = t_1$ (prior to the measurement) as $|init\rangle$. The physical process during which O measures the quantity q of the system S implies a physical interaction between O and S . In the process of this interaction, the state of O changes. If the initial state of S is $|1\rangle$ (resp $|2\rangle$) (and the initial state of O is $|init\rangle$), then $|init\rangle$ evolves to a state that we denote as $|O1\rangle$ (resp $|O2\rangle$). Think of $|O1\rangle$ (resp $|O2\rangle$) as a state in which “the position of the hand of a measuring apparatus points towards the mark ‘1’ (resp ‘2’)”. It is not difficult to construct model Hamiltonians that produce evolutions of this kind, and that can be taken as models for the physical interactions that produce a measurement. Let us consider the actual case of the experiment \mathcal{E} , in which the initial state of S is $|\psi\rangle = \alpha|1\rangle + \beta|2\rangle$. The initial full state of the $S - O$ system is then $|\psi\rangle \otimes |init\rangle = (\alpha|1\rangle + \beta|2\rangle) \otimes |init\rangle$. As well known, the linearity of quantum mechanics implies

$$\begin{aligned} t_1 &\longrightarrow t_2 \\ (\alpha|1\rangle + \beta|2\rangle) \otimes |init\rangle &\longrightarrow \alpha|1\rangle \otimes |O1\rangle + \beta|2\rangle \otimes |O2\rangle \end{aligned} \quad (2)$$

Thus, at $t = t_2$ the system $S - O$ is in the state $(\alpha|1\rangle \otimes |O1\rangle + \beta|2\rangle \otimes |O2\rangle)$. This is the conventional description of a measurement as a physical process [von Neumann 1932].

I have described an actual physical process \mathcal{E} taking place in a real laboratory. Standard quantum mechanics

requires us to distinguish system from observer, but it allows us freedom in drawing the line that distinguishes the two. In the above analysis this freedom has been exploited in order to describe the same sequence of physical events in terms of two different descriptions. In the first description, equation (1), the line that distinguishes system from observer is set between S and O . In the second, equation (2), between $S - O$ and P . Recall that we have assumed that P is not making a measurement on the $S - O$ system; there is no physical interaction between $S - O$ and P during the $t_1 - t_2$ interval. P may make measurements at a later time t_3 : if she measures the value of q on S and the position of the hand on O , she finds that the two agree, because the first measurement collapses the state into one of the two factors of (2), leaving the second measurement fully determined to be the consistent value. Thus, we have two descriptions of the physical sequence of events \mathcal{E} : The description (1) given by the observer O and the description (2) given by the observer P . These are two distinct *correct* descriptions of the same sequence of events \mathcal{E} . At time t_2 , in the O description, the system S is in the state $|1\rangle$ and the quantity q has value 1. According to the P description, S is not in the state $|1\rangle$ and the hand of the measuring apparatus does not indicate ‘1’.

Thus, I come to the observation on which the rest of the paper relies.

Main observation: In quantum mechanics different observers may give different accounts of the same sequence of events.

For a very similar conclusion, see [Zurek 1982] and [Kochen 1979]. In the rest of the work, I explore the consequences of taking this observation fully into account. Since this observation is crucial, I now pause to discuss and refute various objections to the main observation. The reader who finds the above observation plausible may skip this rather long list of objections and jump to section II.C.

B. Objections to the main observation

Objection 1. Whether the account (1) or the account (2) is correct depends on which kind of system O happens to be. There are systems that induce the collapse of the wave function. For instance, if O is macroscopic (1) is correct, if O is microscopic (2) is correct.

The derivation of (2) does not rely on any assumption on the systems, but only from the basics of quantum mechanics (linearity). Therefore a particular O system yielding (1) instead of (2) via Schrödinger evolution must behave in a way that contradicts the formalism of quantum mechanics as we know it. This implies that O cannot be described as a genuine quantum system. Namely that there are special systems that do not obey conventional quantum mechanics, but are intrinsically classical in that

they produce collapse of the wave functions –or the actualization of quantities’ values. This idea underlies a variety of old and recent attempts to unravel the quantum puzzle. The special systems being for instance gravity [Penrose 1989], or minds [Albert and Loewer 1988], or macroscopic systems [Bohr 1949]. If we accept this idea, we have to separate reality into two kinds of systems: quantum mechanical systems on the one hand, and special systems on the other. Bohr declares explicitly that we must renounce giving a quantum description of the classical world [Bohr 1949]. This is echoed in texts as [Landau and Lifschit 1977]. Wigner pushes this view to the extreme consequences and distinguishes material systems (observed) from consciousness (observer) [Wigner 1961]. Here, on the contrary, I wish to assume

Hypothesis 1: All systems are equivalent: Nothing distinguishes a priori macroscopic systems from quantum systems. If the observer O can give a quantum description of the system S , then it is also legitimate for an observer P to give a quantum description of the system formed by the observer O .

Of course, I have no proof of hypothesis 1, only plausibility arguments. I am suspicious toward attempts to introduce special non-quantum and not-yet-understood new physics, in order to alleviate the strangeness of quantum mechanics: they look to me very much like Lorentz’ attempt to postulate a mysterious interaction that Lorentz-contracts physical bodies “for real” – something that we now see was very much off of the point, in the light of Einstein’s clarity. Virtually all those views modify quantum mechanical predictions, in spite of statements of the contrary: if at t_2 , the state is as in (1), then P can never detect interference terms between the two branches in (2), contrary to quantum theory predictions. These discrepancies are likely to be minute, as shown by the beautiful discovery of the physical mechanism of decoherence [Zurek 1981, Joos and Zeh 1985], which “saves the phenomena”. But they are nevertheless different from zero, and thus observable (more on this later). I am inclined to trust that a sophisticated experiment able to detect those minute discrepancies will fully vindicate quantum mechanics against distortions due to postulated intrinsic classicality of specific systems. In any case, the question is experimentally decidable; and we shall see. Second, I do not like the idea that the present over-successful theory of motion can only be understood in terms of its failures yet-to-be-detected. Finally, I think it is reasonable to remain committed, up to compelling disproof, to the rule that all physical systems are equivalent with respect to mechanics: this rule has proven so successful, that I would not dismiss it as far as there is another way out.

Objection 2. What the discussion indicates is that the quantum state is different in the two accounts, but the

quantum state is a fictitious non-physical mental construction; the physical content of the theory is given by the outcomes of the measurements.

Indeed, one can take the view that outcomes of measurements are the physical content of the theory, and the quantum state is a secondary theoretical construction. This is the way I read [Heisenberg 1927] and [van Fraassen 1991]. According to this view, anything in between two measurement outcomes is like the “non-existing” trajectory of the electron, to use Heisenberg’s vivid expression, of which there is nothing to say. I am very sympathetic with this view, which plays an important role in section III. This view, however, does not circumvent the main observation for the following reason. The account (2) states that there is nothing to be said about the value of the quantity q of S at time t_2 : for P , at $t = t_2$ the quantity q does not have a determined value. On the other hand, for O , at $t = t_2$, q has value 1. From which the main observation follows again.

Objection 3. As before (only outcomes of measurements are physical), but the truth of the matter is that P is right and O is wrong.

This is indefensible. Since all physical experiments of which we know can be seen as instances of the $S - O$ measurement, this would imply that not a single outcome of measurement has ever been obtained yet. If so, how could have we learned quantum theory?

Objection 4. As before (only outcomes of measurements are physical), but the truth of the matter is that O is right and P is wrong.

If P is wrong, quantum mechanics cannot be applied to the $S - O$ system (because her account is a straightforward implementation of textbook quantum mechanics). Thus this objection predicts discrepancies, so far never observed, with quantum mechanical predictions, which include observable interference effects between the two terms of (2).

Objection 5. As before, but under the assumption that O is macroscopic. Then interference terms become extremely small because of decoherence effects. If they are small enough, they are unobservable, and thus $q = 1$ becomes an absolute property of S , which is true and absolutely determined, albeit unknown to P , who could measure it anytime, and would not see interference effects.

Strictly speaking this is wrong, because decoherence depends on which observation P will make. Therefore, the property $q = 1$ of S would become an absolute property at time t_2 , or not, according to which subsequent properties of S the observer P considers. This is the reason for which the idea of exploiting physical decoherence for the basic interpretation of quantum mechanics problem has evolved into the consistent histories interpretations, where probabilities are (consistently) assigned to histories, and not to single outcomes of measurements within a history. (See, however, the discussion on the no-histories slogan in [Butterfield 1995].)

Objection 6. There is no collapse. The description (1) is not correct, because “the wave function never really collapses”. The account (2) is the correct one. There are no values assigned to classical properties of system; there are only quantum states.

If so, then the observer P cannot measure the value of the property q either, since (by assumption) there are no values assigned to classical properties, but only quantum states; thus the quantity q doesn’t ever have a value. But we do describe the world in terms of “properties” that the systems have and values assumed by various quantities, not in terms of states in Hilbert space. In a description of the world purely in terms of quantum states, the systems never have definite properties and I do not see how to match such a description with *any* observation. For a detailed elaboration of this point, which is too often neglected, but I think is very strong, see [Albert 1992].

Objection 7. There is no collapse. The description (1) is not correct, because “the wave function never really collapses”. The account (2) is the correct one. The values assigned to classical properties are different from branch to branch.

This is a form of Everett’s view [Everett 1957], which entails the idea that when we measure the electron’s spin being up, the electron spin is also and simultaneously down “in some other branch” –or “world”, hence the many world denomination of this view. The property of the electron of having spin up is not absolutely true, but only true relative to “this” branch. We have a new “parameter” for expressing contingency: “which branch” is a new “dimension” of indexicality, in addition to the familiar ones “which time” and “which place”. Thus, the state of affairs of the example is that, at t_2 , q has value 1 in one branch and has value 2 in the other; the two branches being theoretically described by the two terms in (2). This is a fascinating idea that has recently been implemented in a variety of diverse incarnations. Traditionally, the idea has been discussed in the context of a notion of apparatus, namely a distinguished set of subsystems of the universe, and a distinguished quantity of such an apparatus –the preferred basis. Such a (collection of) preferred apparatus and preferred basis are needed in order to define branching, and thus in order to have assignment of values [Butterfield 1995]; the view has recently branched into the many mind interpretations, where the distinguished subsystems are related to various aspect of the human brain. (See [Butterfield 1995] for a recent discussion). These versions of Everett’s idea violate hypothesis 1, and thus I am not concerned with them. Alternatively, there are versions of Everett’s idea that reject the specification of preferred apparatus and preferred basis, and in which the branching itself is indexed by an arbitrarily chosen system playing the role of apparatus and an arbitrarily chosen basis. To my knowledge, the only elaborated versions of this view which avoids the difficulties mentioned in objection 5 have evolved into the histories formalisms considered below.

Objection 8. What is absolute and observer independent is the probability of a sequence A_1, \dots, A_n of property ascriptions (such that the interference terms mentioned above are extremely small - decoherence); this probability is independent from the existence of any observer measuring these properties.

This is certainly correct. In fact, this observation is at the root of the consistent histories (CH) interpretations of quantum mechanics [Griffiths 1984, 1996, Omnes 1988, Gell-Mann and Hartle 1990]. However, in my understanding, CH confirms the observation above that different observers give different accounts of the same sequence of events, for the following reason. The beauty of the histories interpretations is the fact that the probability of a sequence of events in a consistent family of sequences does not depends on the observer, precisely as it doesn't in classical mechanics. One can be content with this powerful result of the theory and stop here. However, probabilities depends on the choice of the consistent family of histories, which is chosen (to avoid misunderstanding: *whether or not* a physical occurrence can be assigned a probability depends on the family chosen). One (who?) makes a choice in picking up a family of alternative histories in terms of which he chooses to describe the system. Griffiths has introduced the vivid expression “framework” to indicate a consistent family of histories [Griffiths 1996]. There exist funny cases in which one framework is: “Is the value of the physical quantity Q equal to 1 at time t , or not?”, and a second framework is “Is the value of the physical quantity Q equal to 2 at time t , or not?”, and in each framework the answer is yes with probability 1! [Kent 1995, Kent and Dowker 1995, Griffiths 1996.] Therefore the description of what has happened at time t , that we can give on the basis of a fixed set of data, is: At t , Q was equal to 1, if we ask whether Q was 1 or not. Or: At t , Q was equal to 2, if we ask whether Q was 2 or not. There is no contradiction here (in Copenhagen terms, the same mathematics would indicate that the outcome depends on which apparatus is present), but it is difficult to deny that a large majority of physicists still want to understand more about this strangeness of quantum mechanics. In the Copenhagen view, the choice that corresponds to the choice between frameworks is determined by which classical apparatus is present. Namely, the framework is determined by the interaction of the quantum system with a classical object. In CH, one claims that property ascription does not need a classical interaction; the price to pay is that (probabilistic) predictions, rather than being uniquely determined, are framework dependent. In the example of the previous section, the observers O and P may choose two distinct frameworks, and the corresponding two descriptions are both valid: each one in its own framework. However, observer O does not have the choice of using the framework that the observer P uses, because he has “seen” $q = 1$. After having seen that $q = 1$, O has no option anymore of allowing a framework in which q is not 1. The fact that $q = 1$ has become one of his “data; and data de-

termine which frameworks are consistent. Therefore, the two observers O and P have different sets of frameworks at their disposal for describing the same events, because they have different data (for the same set of events). The framework in which (2) makes sense is available to P , but not to O , because O has data that include that fact that $Q = 1$ at t_2 . What is *data* for O is not data for P , who considers the full $S - O$ system: P is still allowed to choose a framework which does not include the value 1 of q at t_2 . Once the data are specified, all predictions are well defined in CH, but the characterization of what may count as data, and therefore which frameworks are available, is different for the two observers of the above example. Once more, we have that two different observers give different descriptions of the same set of events: what is data for O is only a possible choice of framework for P . I will return on this delicate point in the last section.

In conclusion, it seems to me that whatever view of quantum theory (consistent with hypothesis 1) one holds, the main observation is inescapable. I may thus proceed to the main point of this work.

C. Main discussion

If different observers give different accounts of the same sequence of events, then each quantum mechanical description has to be understood as relative to a particular observer. Thus, a quantum mechanical description of a certain system (state and/or values of physical quantities) cannot be taken as an “absolute” (observer independent) description of reality, but rather as a formalization, or codification, of properties of a system *relative* to a given observer. Quantum mechanics can therefore be viewed as a theory about the states of systems and values of physical quantities relative to other systems.

A quantum description of the state of a system S exists only if some system O (considered as an observer) is actually “describing” S , or, more precisely, has interacted with S . The quantum state of a system is always a state of that system with respect to a certain other system. More precisely: when we say that a physical quantity takes the value v , we should always (explicitly or implicitly) qualify this statement as: the physical quantity takes the value v with respect to the so and so observer. Thus, in the example considered in section 2.1, q has value 1 *with respect to* O , but not with respect to P .

Therefore, I suggest that in quantum mechanics “state” as well as “value of a variable” –or “outcome of a measurement–” are relational notions in the same sense in which velocity is relational in classical mechanics. We say “the object S has velocity v ” meaning “with respect to a reference object O ”. Similarly, I maintain that “the system is in such a quantum state” or “ $q = 1$ ” are always to be understood “with respect to the reference O .” In quantum mechanics *all* physical variables are relational, as is velocity.

If quantum mechanics describes relative information only, one could consider the possibility that there is a deeper underlying theory that describes what happens “in reality”. This is the thesis of the incompleteness of quantum mechanics (first suggested in [Born 1926]!). Examples of hypothetical underlying theories are hidden variables theories [Bohm 1951, Belfante 1973]. Alternatively, the “wave-function-collapse-producing” systems can be “special” because of some non-yet-understood physics, which becomes relevant due to large number of degrees of freedom [Ghirardi Rimini and Weber 1986, Bell 1987], complexity [Hughes 1989], quantum gravity [Penrose 1989] or other.

As is well known, there are no indications on *physical* grounds that quantum mechanics is incomplete. Indeed, the *practice* of quantum mechanics supports the view that quantum mechanics represents the best we can say about the world at the present state of experimentation, and suggests that the structure of the world grasped by quantum mechanics is deeper, and not shallower, than the scheme of description of the world of classical mechanics. On the other hand, one could consider motivations on *metaphysical* grounds, in support of the incompleteness of quantum mechanics. One could argue: “Since reality has to be real and universal, and the same for everybody, then a theory in which the description of reality is observer-dependent is certainly an incomplete theory”. If such a theory were complete, our concept of reality would be disturbed.

But the way I reformulated the problem of the interpretation of quantum mechanics in section I. should make us suspicious and attentive precisely to such kinds of arguments, I believe. Indeed, what we are looking for is precisely some “wrong general assumption” that we suspect to have, and that could be at the origin of the unease with quantum mechanics. Thus, I discard the thesis of the incompleteness of quantum mechanics and assume

Hypothesis 2 (Completeness): Quantum mechanics provides a complete and self-consistent scheme of description of the physical world, appropriate to our present level of experimental observations.

The conjunction of this hypothesis 2 with the main observation of section II.A and the discussion above leads to the following idea:

Quantum mechanics is a theory about the physical description of physical systems relative to other systems, and this is a complete description of the world.

The thesis of this paper is that this conclusion is not self-contradictory. If this conclusion is valid, then the incorrect notion at the source of our unease with quantum theory has been uncovered: it is the notion of true, universal, observer-independent description of the state of

the world. If the notion of observer-independent description of the world is unphysical, a complete description of the world is exhausted by the relevant information that systems have about each other. Namely, there is neither an absolute state of the system, nor absolute properties that the system has at a certain time. Physics is fully relational, not just as far as the notions of rest and motion are considered, but with respect to all physical quantities. Accounts (1) and (2) of the sequence of events \mathcal{E} are both correct, even if distinct: any time we talk about a state or property of a system, we have to refer these notions to a specific observing, or reference system. Thus, I propose the idea that quantum mechanics indicates that the notion of a universal description of the state of the world, shared by all observers, is a concept which is physically untenable, on experimental ground.*

Thus, the hypothesis on which I base this paper is that accounts (1) and (2) are both fully correct. They refer to different observers. I propose to reinterpret every contingent statement about nature (“the electron has spin up”, “the atom is in the so and so excited state”, the “spring is compressed”, “the chair is here and not there”) as elliptic expressions for relational assertions (“the electron has spin up *with respect to the Stern Gerlach apparatus*” ... “the chair is here and not there *with respect to my eyes*”, and so on). A general physical theory is a theory about the state that physical systems have, relative to each other. I explore and elaborate this possibility in this paper.

D. Relation between descriptions

The multiplication of points of view induced by the relational notion of state and physical quantities’ values considered above raises the problem of the relation between distinct descriptions of the same events. What is the relation between the value of a variable q relative to an observer O , and the value of the same variable relative to a different observer? This problem is subtle. Consider the example of section II.A. We expect some relation between the description of the world illustrated in (1) and in (2).

First of all, one may ask what is the “actual”, “absolute” relation between the description of the world relative to O and the one relative to P . This is a ques-

*To counter objections based on instinct alone, it is perhaps worthwhile recalling the great resistance that the idea of fully relational notions of “rest” and “motion” encountered at the beginning of the scientific revolution. I think that quantum mechanics (and general relativity) could well be in the course of triggering a –not yet developed– revision of world views as far reaching as the seventeenth century’s one (on this, see [Rovelli 1995]).

tion debated in the context of “perspectival” interpretations of quantum mechanics. I think that the question is ill-posed. The absolute state of affairs of the world is a meaningless notion; asking about the absolute relation between two descriptions is precisely asking about such an absolute state of affairs of the world. Therefore there is no meaning in the “absolute” relation between the views of different observers. In particular, there is no way of deducing the view of one from the view of the other.

Does this mean that there is no relation whatsoever between views of different observers? Certainly not; it means that the relation itself must be understood quantum mechanically rather than classically. Namely the issue of the relation between views must be addressed within the view of one of the two observers (or of a third one). In other words, we may investigate the view of the world of O , as seen by P . Still in other words: the fact that a certain quantity q has a value with respect to O is a physical fact; as a physical fact, its being true, or not true, must be understood as relative to an observer, say P . Thus, the relation between O ’s and P ’s views is not absolute either, but it can be described in the framework of, say, P ’s view.

There is an important physical reason behind this fact: It is possible to compare different views, but the process of comparison is always a physical interaction, and all physical interactions are quantum mechanical in nature. I think that this simple fact is forgotten in most discussions on quantum mechanics, yielding serious conceptual errors. Suppose a physical quantity q has value with respect to you, as well as with respect to me. Can we compare these values? Yes we can, by communicating among us. But communication is a physical interaction and therefore is quantum mechanical. In particular, it is intrinsically probabilistic. Therefore you can inquire about the value of q with respect to me, but this is (in principle) a quantum measurement as well.

Next, one must distinguish between two different questions: (i) Does P “know” that S “knows” the value of q ? (ii) Does P know what is the value of q relative to O ? (I know that you know the amount of your salary, but I do not know *what* you know about the amount of your salary).

(i) Can P “know” that O has made a measurement on S at time t_2 ? The answer is yes. P has a full account of the events \mathcal{E} . Description (2) expresses the fact that O has measured S . The key observation is that in the state at t_2 in (2), the variables q (with eigenstates $|1\rangle$ and $|2\rangle$) and the pointer variable (with eigenstates $|O1\rangle$ and $|O2\rangle$) are correlated. From this fact, P understands that the pointer variable in O has information about q . In fact, the state of $S - O$ is the quantum superposition of two states: in the first, $(|1\rangle \otimes |O1\rangle)$, S is in the $|1\rangle$ state and the hand of the observer is correctly on the ‘1’ mark. In the second, $(|2\rangle \otimes |O2\rangle)$, S is in the $|2\rangle$ state and the hand of the observer is, correctly again, on the ‘2’ mark. In both cases, the hand of O is on the mark

that correctly represents the state of the system. More formally, there is an operator M on the Hilbert space of the $S - O$ system whose physical interpretation is “Is the pointer correctly correlated to q ?” If P measures M , then the outcome of this measurement would be yes with certainty, when the state of the $S - O$ system is as in (2). The operator M is given by

$$\begin{aligned} M (|1\rangle \otimes |O1\rangle) &= |1\rangle \otimes |O1\rangle \\ M (|1\rangle \otimes |O2\rangle) &= 0 \\ M (|2\rangle \otimes |O2\rangle) &= |2\rangle \otimes |O2\rangle \\ M (|2\rangle \otimes |O1\rangle) &= 0 \end{aligned} \quad (3)$$

where the eigenvalue 1 means “yes, the hand of O indicates the correct state of S ” and the eigenvalue 0 means “no, the hand of O does not indicate the correct state of S ”. At time t_2 , the $S - O$ system is in an eigenstate of M with eigenvalue 1; therefore P can predict with certainty that O “knows” the value of q . Thus, it is meaningful to say that, according to the P description of the events \mathcal{E} , O “knows” the quantity q of S , or that he “has measured” the quantity q of S , and the pointer variable embodies the information.

A side remark is important. In general, the state of the $S - O$ system will not be an eigenvalue of M . In particular, the physical interaction between S and O which establishes the correlation will take time. Therefore the correlation between the q variable of S and the pointer variable of O will be established gradually. Does this mean that, in P views, the measurement is made “gradually”, namely that, according to P , q will have value with respect to O only partially? This is a much debated question: “Half the way through the measurement, has a measurement been done?”. By realizing that P ’s knowledge about O is also quantum mechanical, we find –I believe– the solution of the puzzle: If the state of the $S - O$ system is not an eigenstate of M , then, following standard quantum mechanics rule, this means that any eventual attempt of P to verify whether or not a measurement has happened will have outcome “yes” or “no” with a certain respective probability. In other words: there is no half-a-measurement; there is probability one-half that the measurement has been made! We never see quantum superpositions of physical values, we only see physical values, but we can predict which one we are going to see only probabilistically. Similarly, I can say only probabilistically whether or not a physical quantity has taken value for you; but I should not say that you “half-see” a physical quantity! Thus, by representing the fact that (for P) “the pointer variable of O has information about the q variable in S ” by means of the operator M resolves the well-known and formidable problem of defining the “precise moment” in which the measurement is performed, or the precise “amount of correlation” needed for a measurement to be established –see for instance [Bacciagaluppi and Hemmo 1995]. Such questions are not classical questions, but quantum mechanical questions, because whether or not O has measured S is not

an absolute property of the $S - O$ state, but a quantum property of the quantum $S - O$ system, that can be investigated by P , and whose yes/no answers are, in general, determined only probabilistically. In other words: *imperfect correlation does not imply no measurement performed, but only a smaller than 1 probability that the measurement has been completed.*

A second remark in this regard is that, due to the well-known bi-orthogonal decomposition theorem, there are always correlated variables in any coupled system (in a pure state). Therefore there is always “some” operator M for which the $S - O$ system is an eigenstate. Much emphasis has been given to this fact in the literature. I do not think this fact is very relevant. Imagine we have a quantum particle in a box, with a finite probability to tunnel out of it (say this models a nuclear decay). At some initial time we describe the state with a wave function concentrated in the box. At some later time a Geiger counter detects the particle outside the box, and we describe the particle as a position eigenstate at the Geiger counter position. During the time in between, we can describe the state of the particle by giving the wave form of its Schrödinger wave $\psi(x)$ as it leaks out of the box. Now, in principle, we know that there is an operator A in the Hilbert space of the particle such that $\psi(x)$ is an eigenstate of A . Therefore we know that “some” quantity is uniquely defined at any moment. But what is the interest of such observation? Very little, I would say. A will correspond to some totally uninteresting and practically non measurable quantity. Similarly, given an arbitrary state of the coupled $S - O$ system, there will always be a basis in each of the two Hilbert spaces which gives the bi-orthogonal decomposition, and therefore which defines an M for which the coupled system is an eigenstate. But this is of null practical nor theoretical significance. We are interested in *certain* self-adjoint operators only, representing observables that we know how to measure; for this same reason, we are only interested in correlations between *certain* quantities: the ones we know how to measure.

The second question P may ask is: (ii.) What is the outcome of the measurement performed by O ? It is important not to confuse the statement “ P knows that O knows the value of q ” with the statement “ P knows what O knows about q ”. In general, the observer P does not know “what is the value of the observable q that O has measured” (unless α or β in (2) vanish). An observer with sufficient initial information may predict which variable the other observer has measured, but not the outcome of the measurement. Communication of measurements results is however possible (and fairly common!). P can measure the outcome of the measurement performed by O . She can, indeed, measure whether O is in $|O1\rangle$, or in $|O2\rangle$.

Notice that there is a consistency condition to be fulfilled, which is the following: if P knows that O has measured q , then she measures q , and then she measures what O has obtained in measuring q (namely she measures the

pointer variable), then consistency requires that the results obtained by P on the q variable and on the pointer variable be correlated. Indeed, they are! as was first noticed by von Neumann, and as is clear from (2). Thus, there is a satisfied consistency requirement in the notion of relative description discussed. This can be expressed in terms of standard quantum mechanical language: From the point of view of the P description:

The fact that the pointer variable in O has information about S (has measured q) is expressed by the existence of a correlation between the q variable of S and the pointer variable of O . The existence of this correlation is a measurable property of the $S - O$ state.

E. Information

It is time to introduce the main concept in terms of which I propose to interpret quantum mechanics: information.

What is the precise nature of the relation between the variable q and the system O expressed in the statement “ $q = 1$ relative to O ”? Does this relation have a comprehensible physical meaning? Can we analyze it in physical terms? The answer has emerged in the previous subsection. Let me recapitulate the main idea: The statement “ q has a value relative to O ” refers to the contingent state of the $S - O$ system. But the contingent state of the $S - O$ system has no observer-independent meaning. We can make statements about the state of the $S - O$ system only provided that we interpret these statements as relative to a third physical system P . Therefore, it should be possible to understand what is the physical meaning of “ q has a value relative to O ” by considering the description that P gives (or could give) of the $S - O$ system. This description is not in terms of classical physics, but in quantum mechanical terms; it is the one given in detail above. The result is that “ q has value with respect to S means that there is a correlation between the variable q and the pointer variable in O , namely that P is able to predict that subsequent measurements she will make on q and on the pointer variable will produce correlated outcomes.

Correlation is “information” in the sense of information theory [Shannon 1949]. If the state of the $S - O$ system is in an eigenstate of M with eigenvalue 1, then the four possible configurations that the q variable and the pointer variable can take are reduced to two. Therefore (by definition) the pointer variable has information about q . Let me then take a lexical move. I will from now on express the fact that q has a certain value with respect to O by saying: O has the “information” that $q = 1$.

The notion of information I employ here should not be confused with other notions of information used in other contexts. I use here a notion of information that

does not require distinction between human and non-human observers, systems that understand meaning or don't, very-complicated or simple systems, and so on. As it is well known, the problem of defining such a notion was brilliantly solved by Shannon: in the technical sense of information-theory, the amount of information is the number of the elements of a set of alternatives out of which a configuration is chosen. Information expresses the fact that a system is in a certain configuration, which is correlated to the configuration of another system (information source). The relation between this notion of information and more elaborate notions of information is given by the fact that the information-theoretical information is a minimal condition for more elaborate notions. In a physical theory it is sufficient to deal with this basic information-theoretical notion of information. This is very weak; it does not require us to consider information storage, thermodynamics, complex systems, meaning, or anything of the sort. In particular: (i.) information can be lost dynamically (correlated state may become uncorrelated); (ii.) we do not distinguish between correlation obtained on purpose and accidental correlation; Most important: (iii.) any physical system may contain information about another physical system. For instance if we have two spin-1/2 particles that have the same value of the spin in the same direction, we say that one has information about the other one. Thus observer system in this paper is any possible physical system (with more than one state). If there is any hope of understanding how a system may behave as observer without renouncing the postulate that all systems are equivalent, then the same kind of processes –“collapse”– that happens between an electron and a CERN machine, may also happen between an electron and another electron. Observers are not “physically special systems” in any sense. The relevance of information theory for understanding quantum physics has been advocated by John Wheeler [Wheeler 1988, 1989, 1992].

Thus, the physical nature of the relation between S and O expressed in the fact that q has a value relative to O is captured by the fact that O has information (in the sense of information theory) about q . By “ q has a value relative to O ”, we mean “relative to P , there is a certain correlation in the S and O states”, or, equivalently, “ O has information about q ”.

Notice that this is, in a sense, only a partial answer to the question formulated at the beginning of this section. First, it is a quantum mechanical answer, because P 's information about the $S - O$ system is probabilistic. Second, it is an answer that only shifts the problem by one step, because the information possessed by O is explained in terms of the information possessed by P . Thus, the notion of information I use has a double valence. On the one hand, I want to weaken all physical statements that we make: not “the spin is up”, but “we have information that the spin is up” –which leaves the possibility open to the fact that somebody else has different information. Thus, *information* indicates the usual ascription of

values to quantities that founds physics, but emphasizes their relational aspect. On the other hand, this ascription can be described within the theory itself, as information-theoretical *information*, namely correlation. But such a description, in turn, is quantum mechanical and observer dependent, because a universal observer-independent description of the state of affairs of the world does not exist. Finally, there is a key irreducible distinction between P 's knowledge that O has information about q and O 's knowledge of q . Physics is the theory of the relative information that systems have about each other. This information exhausts everything we can say about the world.

At this point, the main ideas and concepts have been formulated. In the next section, I consider a certain number of postulates expressed in terms of these concepts, and derive quantum mechanics from these postulates.

III. ON THE RECONSTRUCTION OF QUANTUM MECHANICS

A. Basic concepts

Physics is concerned with relations between physical systems. In particular, it is concerned with the description that physical systems give of other physical systems. Following hypothesis 1, I reject any fundamental distinctions as: system/observer, quantum/ classical system, physical system/consciousness. Assume that the world can be decomposed (possibly in a variety of ways) in a collection of systems, each of which can be equivalently considered as an observing system or as an observed system. A system (observing system) may have information about another system (observed system). Information is exchanged via physical interactions. The actual process through which information is collected and perhaps stored is not of particular interest here, but can be physically described in any specific instance.

Information is a discrete quantity: there is a minimum amount of information exchangeable (a single bit, or the information that distinguishes between just two alternatives.) I will denote a process of acquisition of information (a measurement) as a “question” that a system (observing system) asks another system (observed system). Since information is discrete, any process of acquisition of information can be decomposed into acquisitions of elementary bits of information. I refer to an elementary question that collects a single bit of information as a “yes/no question”, and I denote these questions as Q_1, Q_2, \dots

Any system S , viewed as an observed system, is characterized by the family of yes/no questions that can be asked to it. These correspond to the physical variables of classical mechanics and to the observables of conventional quantum mechanics. I denote the set of these questions as $W(S) = \{Q_i, i \in I\}$, where the index i belongs to an

index set I characteristic of S . The general kinematical features of S are representable as relations between the questions Q_i in $W(S)$, that is, structures over $W(S)$. For instance, meaningful questions that can be asked to an electron are whether the particle is in a certain region of space, whether its spin along a certain direction is positive, and so on.

The result of a sequence of questions (Q_1, Q_2, Q_3, \dots) to S , from an observer system O , can be represented by a string

$$(e_1, e_2, e_3, \dots) \quad (4)$$

where each e_i is either 0 or 1 (no or yes) and represents the response of the system to the question Q_i . Thus the information that O has about S can be represented as a binary string. It is a basic fact about nature that knowledge of a portion (e_1, \dots, e_n) of this string provides indications about the subsequent outcomes $(e_{n+1}, e_{n+2}, \dots)$. It is in this sense that a string (4) contains the information that O has about S .

Trivially repeating the same question (experiment) and obtaining always the same outcome does not increase the information on S . The *relevant* information (from now on, simply information) that O has about S is defined as the non-trivial content of the (potentially infinite) string (4), that is the part of (4) relevant for predicting future answers of possible future questions. The relevant information is the subset of the string (4), obtained discarding the e_i 's that do not affect the outcomes of future questions.

The relation between the notions introduced and traditional notions used in quantum mechanics is transparent: A question is a version of a measurement. The idea that quantum measurements can be reduced to yes/no measurements is old. A yes/no measurement is represented by a projection operator onto a linear subset of the Hilbert space, or by the linear subset of the Hilbert space itself. Here this idea is not derived from the quantum mechanical formalism, but is justified in information-theoretical terms. The notions of observing system and observed system reflect the traditional notions of observer and system (but any system can play both roles here). $W(S)$ corresponds to the set of the observables. Recall that in algebraic approaches a system is characterized by the (algebraic) structure of the family of its observables.

A notion does not appear here: the state of the system. The absence of this notion is the prime feature of the interpretation considered here. In place of the notion of state, which refers solely to the system, the notion of the information that a system has about another system has been introduced. I view this notion very concretely: a piece of paper on which outcomes of measurements are written, hands of measuring apparatus, memory of scientists, or a two-value variable which is up or down after an interaction.

For simplicity, in the following I focus on systems that in conventional quantum mechanics are described by a

finite dimensional Hilbert space. This choice simplifies the mathematical treatment of the theory, avoiding continuum spectrum and other infinitary issues.

B. The two main postulates

Postulate 1 (Limited information). There is a maximum amount of relevant information that can be extracted from a system.

The physical meaning of postulate 1 is that it is possible to exhaust, or give a complete description of the system. In other words, any future prediction that can be inferred about the system out of an infinite string (4), can also be inferred from a finite subset

$$s = [e_1, \dots, e_N] \quad (5)$$

of (4), where N is a number that characterizes the system S . The finite string (5) represents the maximal knowledge that O has about S .[†] One may say that any system S has a maximal “information capacity” N , where N , an amount of information, is expressed in bits. This means that N bits of information exhaust everything we can say about S . Thus, each system is characterized by a number N . In terms of traditional notions, we can view N as the smallest integer such that $N \geq \log_2 k$, where k is the dimension of the Hilbert space of the system S . Recall that the outcomes of the measurement of a complete set of commuting observables, characterizes the state, and in a system described by a $k = 2^N$ dimensional Hilbert space such measurements distinguish one outcome out of 2^N alternative (the number of orthogonal basis vectors): this means that one gains information N on the system. Postulate 1 is confirmed by our experience about the world (within the assumption above, that we restrict to finite dimensional Hilbert space systems. Generalization to infinite systems should not be difficult.)

Notice that postulate 1 already adds the Planck’s constant to classical physics. Consider a classical system described by a variable q that takes bounded but continuous values; for instance, the position of a particle. Classically, the amount of information we can gather about it is infinite: we can locate its state in the system’s phase space with arbitrary precision. Quantum mechanically, this infinite localization is impossible because of postulate 1. Thus, maximum available information can localize the state only within a finite region of the phase space. Since

[†]The string (5) is essentially the state. The novelty here is not the fact that the state is defined as the response of the system to a set of yes/no experiments: this is the traditional reading of the state as a preparation procedure. The novelty is that this notion of state is relative to the observer that has asked the questions.

the dimensions of the classical phase space of any system are $(L^2 T^{-1} M)^n$, there must be a universal constant with dimension $L^2 T^{-1} M$, that determines the minimal localizability of objects in phase space. This constant is of course Planck's constant. Thus we can view Planck's constant just as the transformation coefficient between physical units (position \times momentum) and information theoretical units (bits).

What happens if, after having asked the N questions such that the maximal information about S has been gathered, the system O asks a further question Q_{N+1} ?

Postulate 2 (Unlimited information). It is always possible to acquire new information about a system.

If, after having gathered the maximal information about S , the system O asks a further question Q , to the observed system S , there are two extreme possibilities: either the question Q is fully determined by previous questions, or not. In the first case, no new information is gained. However, the second postulate asserts that there is always a way to acquire new information. This postulate implies therefore that the sequence of responses we obtain from observing a system cannot be fully deterministic.

The motivation for the second postulate is fully experimental. We know that all quantum systems (and all systems are quantum systems) have the property that even if we know their quantum state $|\psi\rangle$ exactly, we can still "learn" something new about them by performing a measurement of a quantity O such that $|\psi\rangle$ is not an eigenstate of O . This is an *experimental* result about the world, coded in quantum mechanics. Postulate 2 expresses this result.

Since the amount of information that O can have about S is limited by postulate 1, when new information is acquired, part of the old relevant-information becomes irrelevant. In particular, if a new question Q (not determined by the previous information gathered), is asked, then O loses (at least) one bit of the previous information. So that, after asking the question Q , new information is available, but the total amount of relevant information about the system does not exceed N bits.

Rather surprisingly, those two postulates are (almost) sufficient to reconstruct the full formalism of quantum mechanics. Namely, one may assert that the physical content of the general formalism of quantum mechanics is (almost) nothing but a sequence of consequences of two physical facts expressed in postulates 1 and 2. This is illustrated in the next section.

C. Reconstruction of the formalism, and the third postulate

In this section, I discuss the possibility of deriving the formalism of quantum mechanics from the physical as-

sertions contained in the postulates 1 and 2. This section is technical, and the uninterested reader may skip it and jump to section III.D. The technical machinery I employ has been developed (with different motivations) in quantum logic analyses. See for example [Beltrametti and Cassinelli 1981]. As I mentioned in the introduction, the reconstruction attempt is not fully successful. I will be forced to introduce a third postulate (besides various relative minor assumptions). I will speculate on the possibility of giving this postulate a simple physical meaning, but I do not have any clear result. This difficulty reflects parallel difficulties in the quantum logic reconstruction attempts.

Let me begin by analyzing the consequences of the first postulate. The number of questions in $W(S)$ can be much larger than N . Some of these questions may not be independent. In particular, one may find (experimentally) that they can be related by implication ($Q_1 \Rightarrow Q_2$), union ($Q_3 = Q_1 \vee Q_2$) and intersection ($Q_3 = Q_1 \wedge Q_2$). One can define an always false (Q_0) and an always true question (Q_∞), the negation of a question ($\neg Q$), and a notion of orthogonality as follows: if $Q_1 \Rightarrow \neg Q_2$, then Q_1 and Q_2 are orthogonal (we indicate this as $Q_1 \perp Q_2$). Equipped with these structures, and under the (non-trivial) additional assumption that \vee and \wedge are defined for every pair of questions, $W(S)$ is an orthomodular lattice [Beltrametti and Cassinelli 1981, Huges 1989].

If there is a maximal amount of information that can be extracted from the system, we may assume that one can select in $W(S)$ an ensemble of N questions Q_i , which we denote as $c = \{Q_i, i = 1, N\}$, that are independent from each other. There is nothing canonical in this choice, so there may be many distinct families c, b, d, \dots of N independent questions in $W(S)$. If a system O asks the N questions in the family c to a system S , then the answers obtained can be represented as a string that we denote as

$$s_c = [e_1, \dots, e_N]_c \quad (6)$$

The string s_c represents the information that O has about S , as a result of the interaction that allowed it to ask the questions in c . The string s_c can take $2^N = K$ values; we denote these values as $s_c^{(1)}, s_c^{(2)}, \dots, s_c^{(K)}$. So that

$$\begin{aligned} s_c^{(1)} &= [0, 0, \dots, 0]_c \\ s_c^{(2)} &= [0, 0, \dots, 1]_c \\ &\dots \\ s_c^{(K)} &= [1, 1, \dots, 1]_c \end{aligned} \quad (7)$$

Since the 2^N possible outcomes $s_c^{(1)}, s_c^{(2)}, \dots, s_c^{(K)}$ of the N yes/no questions are (by construction) mutually exclusive, we can define 2^N new questions $Q_c^{(1)} \dots Q_c^{(K)}$ such that the yes answer to $Q_c^{(i)}$ corresponds to the string of answers $s_c^{(i)}$:

$$Q_c^{(1)} = \neg Q_1 \wedge \neg Q_2 \wedge \dots \wedge \neg Q_N$$

$$\begin{aligned} Q_c^{(2)} &= \neg Q_1 \wedge \neg Q_2 \wedge \dots \wedge Q_N \\ &\dots \\ Q_c^{(k)} &= Q_1 \wedge Q_2 \wedge \dots \wedge Q_N \end{aligned} \quad (8)$$

We refer to questions of this kind as “complete questions”. By taking all possible unions of sets of complete questions $Q_c^{(i)}$ (of the same family c), we construct a Boolean algebra that has $Q_c^{(i)}$ as atoms.

Alternatively, the observer O could use a different family of N independent yes-no questions, in order to gather information about S . Denote an alternative set as b . Then, he will still have a maximal amount of relevant information about S formed by an N -bit string $s_b = [e_1, \dots, e_N]_b$. Thus, O can give different kinds of descriptions of S , by asking different questions. Correspondingly, denote as $s_b^{(1)} \dots s_b^{(K)}$ the 2^N values that s_b can take, and consider the corresponding complete questions $Q_b^{(1)} \dots Q_b^{(K)}$ and the Boolean algebra they generate. Thus, it follows from the first postulate that the set of the questions $W(S)$ that can be asked to a system S has a natural structure of an orthomodular lattice containing subsets that form Boolean algebras. This is precisely the algebraic structure formed by the family of the linear subsets of a Hilbert space, which represent the yes/no measurements in ordinary quantum mechanics! [Jauch 1968, Finkelstein 1969, Piron, 1972, Beltrametti and Cassinelli 1981.]

The next question is the extent to which the information (6) about the set of questions c determines the outcome of an additional question Q . There are two extreme possibilities: that Q is fully determined by (6), or that it is fully independent, namely that the probability of getting a yes answer is $1/2$. In addition, there is a range of intermediate possibilities: The outcome of Q may be determined probabilistically by s_c . The second postulate states explicitly that there are questions that are non-determined. Define, in general, as $p(Q, Q_c^{(i)})$ the probability that a yes answer to Q will follow the string $s_c^{(i)}$. Given two complete families of information s_c and s_b , we can then consider the probabilities[‡]

$$p^{ij} = p(Q_b^{(i)}, Q_c^{(j)}) \quad (9)$$

From the way it is defined, the $2^N \times 2^N$ matrix p^{ij} cannot be fully arbitrary. First, we must have

$$0 \geq p^{ij} \geq 1 \quad (10)$$

[‡]I do not wish to enter here the debate on the meaning of probability in quantum mechanics. I think that the shift of perspective I am suggesting is meaningful in the framework of an objective definition of probability, tied to the notion of repeated measurements, as well as in the context of subjective probability, or any variant of this, if one does not accept Jayne’s criticisms of the last.

Then, if the information $s_c^{(j)}$, is available about the system, one and only one of the outcomes $s_b^{(i)}$, may result. Therefore

$$\sum_i p^{ij} = 1 \quad (11)$$

We also assume that $p(Q_b^{(i)}, Q_c^{(j)}) = p(Q_c^{(j)}, Q_b^{(i)})$ (this is a new assumption! There is a relation with time reversal, but I leave it here as an unjustified assumption at this stage), from which we must have

$$\sum_j p^{ij} = 1 \quad (12)$$

The conditions (10-11-12) are strong constraints on the matrix p^{ij} . They are satisfied if

$$p^{ij} = |U^{ij}|^2 \quad (13)$$

where U is a unitary matrix, and p^{ij} can always be written in this form for some unitary matrix U (which, however, is not fully determined by p^{ij}).

Consider a question in the Boolean algebra generated by a family s_c , for instance

$$Q_c^{(jk)} = Q_c^{(j)} \vee Q_c^{(k)} \quad (14)$$

In order to take this question into account, we cannot consider probabilities of the form $p(Q_b^{(i)}, Q_c^{(jk)})$, because a yes answer to $Q_c^{(jk)}$ is less than the maximum amount of relevant information. But we may consider probabilities of the form, say,

$$p^{i(jk)i} = p(Q_b^{(i)}, Q_c^{(jk)} Q_b^{(i)}) \quad (15)$$

defined as the probability that a yes answer to $Q_b^{(i)}$ will follow a yes answer to $Q_b^{(i)}$ (N bits of information) and a subsequent yes answer to $Q_c^{(jk)}$ ($N - 1$ bits of information). As is well known, we have (experimentally!) that

$$\begin{aligned} p^{i(jk)i} &\neq p(Q_b^{(i)}, Q_c^{(j)}) p(Q_c^{(j)}, Q_b^{(i)}) \\ &\quad + p(Q_b^{(i)}, Q_c^{(k)}) p(Q_c^{(k)}, Q_b^{(i)}) \\ &= (p^{ij})^2 + (p^{ik})^2 \end{aligned} \quad (16)$$

Accordingly, we can determine the missing phases of U in (13) by means of the correct relation, which is

$$p^{i(jk)i} = |U^{ij} U^{ji} + U^{ik} U^{ki}|^2 \quad (17)$$

It would be extremely interesting to study the constraints that the probabilistic nature of all quantities p implies, and to investigate to which extent the structure of quantum mechanics can be derived in full from these constraints. One could conjecture that eqs.(13-17) could be

derived solely by the properties of conditional probabilities – or find exactly the weakest formulation of the superposition principle directly in terms of probabilities: this would be a strong result. Alternatively, it would be even more interesting to investigate the extent to which the noticed consistency between different observers’ descriptions, which I believe characterizes quantum mechanics so marvelously, could be taken as the missing input for reconstructing the full formalism. I have a suspicion this could work, but have no definite result. Here, I content myself with the more modest step of introducing a third postulate. For strictly related attempts to reconstruct the quantum mechanical formalism from the algebraic structure of the measurement outcomes, see [Mackey 1963, Maczinski 1967, Finkelstein 1969, Jauch 1968, Piron 1972].

Postulate 3 (Superposition principle). If c and b define two complete families of questions, then the unitary matrix U_{cb} in

$$p(Q_c^{(i)}, Q_b^{(j)}) = |U_{cb}^{ij}|^2 \quad (18)$$

can be chosen in such a way that for every c , b and d , we have $U_{cd} = U_{cb}U_{bd}$ and the effect of composite questions is given by eq.(17).

It follows that we may consider any question as a vector in a complex Hilbert space, fix a basis $|Q_c^{(i)}\rangle$ in this space and represent any other question $|Q_b^{(j)}\rangle$ as a linear combination of these:

$$|Q_b^{(j)}\rangle = \sum_i U_{bc}^{ji} |Q_c^{(i)}\rangle \quad (19)$$

The matrices U_{bc}^{ji} are then a unitary change of basis from the $|Q_c^{(i)}\rangle$ to the $|Q_b^{(j)}\rangle$ basis. Recall now the conventional quantum mechanical probability rule: if $|v^{(i)}\rangle$ are a set of basis vectors and $|w^{(j)}\rangle$ a second set of basis vectors related to the first ones by

$$|w^{(j)}\rangle = \sum_i U^{ji} |v^{(i)}\rangle \quad (20)$$

then the probability of measuring the state $|w^{(j)}\rangle$ if the system is in the state $|w^{(i)}\rangle$ is

$$p^{ij} = |\langle v^{(i)} | w^{(j)} \rangle|^2 \quad (21)$$

(20) and (21) yield $p^{ij} = |U^{ij}|^2$, which is equation (18). Therefore the conventional formalism of quantum mechanics as well as the standard probability rules follow completely from the three postulates. The set $W(S)$ has the structure of a set of linear subspaces in the Hilbert space. For any yes/no question Q_i , let L_i be the corresponding linear subset of H . The relations $\{\Rightarrow, \vee, \wedge, \neg, \perp\}$ between questions Q_i correspond to the relations {inclusion, orthogonal sum, intersection,

orthogonal-complement, orthogonality} between the corresponding linear subspaces L_i .

The inclusion of dynamics in the above scheme is straightforward. Two questions can be considered as distinct if defined by the same operations but performed at different times. Thus, any question can be labeled by the time variable t , indicating the time at which it is asked: denote as $t \rightarrow Q(t)$ the one-parameter family of questions defined by the same procedure performed at different times. In this way we have naturally the Heisenberg picture. As we have seen, the set $W(S)$ has the structure of a set of linear subspaces in the Hilbert space. Assuming that time evolution is a symmetry in the theory, the set of all the questions at time t_2 must be isomorphic to the set of all the questions at time t_1 . Therefore the corresponding family of linear subspaces must have the same structure; therefore there should be a unitary transformation $U(t_2 - t_1)$ such that

$$Q(t_2) = U(t_2 - t_1)Q(t_1)U^{-1}(t_2 - t_1) \quad (22)$$

By conventional arguments, these unitary matrices form an abelian group and $U(t_2 - t_1) = \exp\{-i(t_2 - t_1)H\}$, where H is a self-adjoint operator on the Hilbert space, the Hamiltonian. The Schrödinger equation follows immediately if we transform from the Heisenberg to the Schrödinger picture.

D. The observer observed

We now have the full formal machinery of quantum mechanics, with an interpretative novelty: the absence of the notion of state the system. I now return to the issue of the relation between information of distinct observers. How can a system P have information about the fact that O has information about S ? The information possessed by distinct observers cannot be compared directly. This is the key point of the construction. A statement *about* the information possessed by O is a statement about the physical state of O ; the observer O is a regular physical system. Since there is no absolute meaning to the state of a system, any statement regarding the state of O , including the information it possess, is to be referred to some other system observing O . A second observer P can have information about the fact that O has information about S , but any acquisition of information implies a physical interaction. P can get new information about the information that O has about S only by physically interacting with the $S - O$ system.

At the cost of repeating myself, let me stress again that I believe that the common mistake in analyzing measurement issues in quantum mechanics is to forget that two observers can compare their information (their measurement outcomes) only by physically interacting with each other. This means that there is no way to compare “the information possessed by O ” with “the information

possessed by P ", without considering a *quantum* physical interaction, or a quantum measurement, between the two.

The relation between the information possessed by distinct observers is thus given by the following: Viewed by O , information about S is the primary concept in terms of which one describes the world; viewed by P , the information that O has about S information is just a property of some degrees of freedom in O being correlated with some property of S . This can be taken as an additional ingredient to the structure defined by the three postulates; it ties the distinct observers to each other.

Again, the direct question "Do observers O and P have the same information on a system S ?" is meaningless, because it is a question about the absolute state of O and P . What is meaningful is to rephrase the question in terms of some observer. For instance, we could ask it in terms of the information possessed by a further observer, or by P herself. Consider this last case. At time t_1 , O gets information about S . P has information about the initial state, and therefore has the information that the measurement has been performed. The meaning of this is that she knows that the states of the $S - O$ systems are correlated, or more precisely she knows that if at a later time t_3 she asks a question to S concerning property A , and a question to O concerning his knowledge about A (or, equivalently, concerning the position of a pointer), she will get consistent results.

From the dynamical point of view, knowledge of the structure of the family of questions $W(S)$ implies the knowledge of the dynamics of S (because $W(S)$ includes all Heisenberg observables at all times). In Hilbert space terms, this means knowing the Hamiltonian of the evolution of the observed system. If P knows the dynamics of the $S - O$ system, she knows the two Hamiltonians of O and S and the interaction Hamiltonian. The interaction Hamiltonian cannot be vanishing because a measurement (O measuring S) implies an interaction: this is the only way in which a correlation can be dynamically established. From the point of view of P , the measurement is therefore a fully unitary evolution, determined by a peculiar interaction Hamiltonian between O and S . The interaction is a measurement if it brings the states (relative P) to a correlated configuration. On the other hand, O gives a dynamical description of S alone. Therefore he can only use the S Hamiltonian. Since between times t_1 and t_2 the evolution of S is affected by its interaction with O , the description of the unitary evolution of S given by O breaks down. The unitary evolution does not break down for mysterious physical quantum jumps, or due to unknown effects, but simply because O is not giving a full dynamical description of the interaction. O cannot have a full description of the interaction of S with himself (O), because his information is correlation, and there is no meaning in being correlated with oneself.

The reader may convince himself that even if we take into account several observers observing each other, there is no way in which contradiction may develop, provided

that one does not violate the two rules:

- (i) There is no meaning to the state of a system or the information that a system has, except within the information of a further observer.
- (ii) There is no way a system P may get information about a system O without physically interacting with it, and therefore without breaking down (at the time of the interaction) the unitary evolution description of O .

For instance, there is no way two observers P and O can get information about a system S independently from each other: one of two (say O) will have to obtain the information first. In doing so, he will interact with S at a certain time t . This interaction implies that there is a non vanishing interaction Hamiltonian between S and O . If P asks a question to O at a later time t' , she will either have to consider the interacting correlated $S - O$ system, or to realize that the unitary evolution of the O dynamics has broken down, due to the physical interaction she was not taking into account.

IV. CRITIQUE OF THE CONCEPT OF STATE

A. "Any observation requires an observer": summary of the ideas presented

Let me summarize the path covered. I started from the distinction between observer and observed-system. I assumed (hypothesis 1) that all systems are equivalent, so that any observer can be described by the same physics as any other system. In particular, I assumed that an observer that measures a system can be described by quantum mechanics. I have analyzed a fixed physical sequence of events \mathcal{E} , from two different points of observations, the one of the observer and the one of a third system, external to the measurement. I have concluded that two observers give different accounts of the same physical set of events (main observation).

Rather than backtracking in front of this observation, and giving up the commitment to the belief that all systems are equivalent, I have decided to take this experimental fact at its face value, and consider it as a starting point for understanding the world. *If different observers give different descriptions of the state of the same system, this means that the notion of state is observer dependent.* I have taken this deduction seriously, and have considered a conceptual scheme in which the notion of absolute observer-independent state of a system is replaced by the notion of information about a system that a physical system may possess.

I have considered three postulates that this information must satisfy, which summarize present experimental evidence about the world. The first limits the amount of relevant information that a system can have; the second summarizes the novelty revealed by the experiments

from which quantum mechanics derives, by asserting that whatever the information we have about a system we can always get new information. The third limits the structure of the set of questions; this third postulate can probably be sharpened. Out of these postulates the conventional Hilbert space formalism of quantum mechanics and the corresponding rules for calculating probabilities (and therefore any other equivalent formalism) can be rederived.

A physical system is characterized by the structure on the set $W(S)$ of questions that can be asked to the system. This set has the structure of the non-Boolean algebra of a family of linear subspaces of a complex k -dimensional Hilbert space. The information about S that any observer O can possess can be represented as a string s , containing an amount of information N .

I have investigated the meaning of this information out of which the theory is constructed. I have shown that the fact that a variable in a system O has information about a variable in a system S means that the variables of S and O are correlated, meaning that a third observer P has information about the coupled $S - O$ system that allows her to predict correlated outcomes between questions to S and questions to O . Thus correlation has no absolute meaning, because states have no absolute meaning, and must be interpreted as the content of the information that a third system has about the $S - O$ couple.

Finally, since we take quantum mechanics as a complete description of the world at the present level of experimental knowledge (hypothesis 2), we are forced to accept the result that there is no objective, or more precisely observer-independent meaning to the ascription of a property to a system. Thus, the properties of the systems are to be described by an interrelated net of observations and information collected from observations. Any complex situation can be described *in toto* by a further additional observer, and the interrelation is consistent. However, such *in toto* description is deficient in two directions: upward, because an even more general observer is needed to describe the global observer itself, and –more importantly– downward, because the *in toto* observer knows the content of the information that the single component systems possess about each other only probabilistically.

There is no way to “exit” from the observer-observed global system: “Any observation requires an observer” (The expression is freely taken from [Maturana and Varela 1920]). In other words, I suggest that it is a matter of natural science whether or not the descriptions that different observers give of the same ensemble of events is universal or not:

Quantum mechanics is the theoretical formalization of the experimental discovery that the descriptions that different observers give of the same events are not universal.

The concept that quantum mechanics forces us to give up is the concept of a description of a system independent

from the observer providing such a description; that is, the concept of absolute state of a system. The structure of the classical scientific description of the world in terms of *systems* that are in certain states is perhaps incorrect, and inappropriate to describe the world beyond the $\hbar \rightarrow 0$ limit.

B. Relation with other interpretations

I conclude with a brief discussion on the relation between the view presented here and some popular views of quantum mechanics. I follow [Butterfield 1995] to organize current strategies on the quantum puzzle. The first strategy (Dynamics) is to reject the quantum postulate that an isolated system evolves according to the linear Schrödinger equation, and consider additional mechanisms that modify this evolution –in a sense physically producing the wave function collapse. Examples are the interpretations in which the measurement process is replaced by some hypothetical process that violates the linear Schrödinger equation [Ghirardi Rimini and Weber 1986, Penrose 1989]. These interpretation are radically different from the present approach, since they violate hypothesis 2. My effort here is not to modify quantum mechanics to make it consistent with my view of the world, but to modify my view of the world to make it consistent with quantum mechanics.[§]

The second and third strategies maintain the idea that probabilistic expectations of values of any isolated physical system are given by the linear Schrödinger evolution. They must then face the problem of reconciling (in the example of section II.A) the probabilities expressed by the state at time t_2 in equation (2), $-q = 1$ with probability 1/2 and $q = 2$ with probability 1/2– with the assertion that the the observer O assigns the value $q = 1$ to the variable q at the same time t_2 . As Butterfield emphasizes, if this value assignment coexists with the probability distribution expressed by (2), then the eigenstate-eigenvalue link must be in some sense weakened, and the possibility of assigning values to variables in addition to the eigenstate case (extra values) allowed. The second and the third strategy in Butterfield’s classification differ on whether these extra values are “wholly a matter of physics” (Physics Values), or are “somehow mental or perspectival” (Perspectival Values). In the first case, the assignment is (in every sense) observer-independent. In the second case, it is (in some sense) observer-dependent.

[§]Note added. I have recently become aware of an idea to circumvent this problem by exploiting the infinite-number-of-degrees-of-freedom nature of the observing system. This could generate an apparently non-linear evolution from conventional Schrödinger evolution, via a symmetry-breaking instability generating effective superselection rules. See in particular [Jona-Lasinio *et. al.* 81, 86] and [Wightman 95].

A prime example of the second strategy (Physics Values) is Bohr's, or Copenhagen, interpretation –at least in one possible reading. Bohr assumes a classical world. In Bohr's view, this classical world is physically distinct from the microsystems described by quantum mechanics, and it is precisely the classical nature of the apparatus that gives measurement interactions a special status [Bohr 1949; for a clear discussion of this point, see Landau Lifshitz 1977].

Within the point of view developed in this paper, one can fix once and for all a privileged system S_o as “The Observer” (capitalized). This system S_o can be formed for instance by all the macroscopic objects around us. In this way we recover Bohr's view. The quantum mechanical “state” of a system S is then the information that the privileged system S_o has about S . Bohr's choice is simply the assumption of a set of systems (the classical systems) as privileged observers. This is consistent with the view presented here.** By taking Bohr's step, one becomes blind to the net of interrelations that are at the foundation of the theory, and puzzled about the fact that the theory treats one system, S_o , the classical world, in a way which is different from the other systems. The disturbing aspect of Bohr's view is the inapplicability of quantum theory to macrophysics. This disturbing aspect vanishes, I believe, at the light of the discussion in this paper.

Therefore, the considerations in this paper do not suggest any modification to the conventional *use* of quantum mechanics: there is nothing incorrect in fixing the preferred observer S_o once and for all. If we adopt the point of view suggested here, we continue to use quantum mechanics precisely as is it is currently used. On the other hand, this point of view (I hope) brings clarity about the physical significance of the strange theoretical procedure adopted in Bohr's quantum mechanics: treating a portion of the world in a different manner than the rest of it. This different treatment is, I believe, the origin of the unease with quantum mechanics.

The strident aspect of Bohr's quantum mechanics is cleanly characterized by von Neumann's introduction of the “projection postulate”, according to which systems have two different kinds of evolutions: the unitary and deterministic Schrödinger evolution, and the instanta-

neous, probabilistic measurement collapse [von Neumann 1932]. According to the point of view described here, the Schrödinger unitary evolution of the system S breaks down simply because the system interacts with something which is not taken into account by the evolution equations. Unitary evolution requires the system to be isolated, which is exactly what ceases to be true during the measurement, because of the interaction with the observer. If we include the observer into the system, then the evolution is still unitary, but we are now dealing with the description of a different observer. As suggested by Ashtekar, the point of view presented here can then be described as a fundamental assumption prohibiting an observer to be able to give a full description of “itself” [Ashtekar 1993]. In this respect, these ideas are related to earlier suggestions that quantum mechanics is a theory that necessarily excludes the observer [Peres and Zurek 1982, Roessler 1987, Finkelstein 1988, Primas 1990]. A recent result in this regard is a general theorem proven by Breuer [Breuer 1994], according to which no system (quantum nor classical) can perform a complete self-measurement. The relation between the point of view presented here and Breuer's result deserves to be explored.

Other views within Butterfield's second strategy (Physical Values) are Bohm's hidden variables theory, which violates hypothesis 2 (completeness), and modal interpretations, which deny the collapse but assume the existence of physical quantities' values. Of these, I am familiar with [van Fraassen 1991], or the idea of actualization of potentialities in [Shimony 1969, Fleming 1992]. The assumed values must be consistent with the standard theory's predictions, be probabilistically determined by a unitary evolving wave function, but they are not constrained by the eigenstate-eigenvalue link. One may doubt these acrobatics could work [See Bacciagaluppi 1995, Bacciagaluppi and Hemmo 1995]. I am very sympathetic with the idea that the object of quantum mechanics is a set of quantities' values and their distribution. Here, I have assumed value assignment as in these interpretations, but with two crucial differences. First, this value assignment is observer-dependent. Second, it need not be consistent with a unitary Schrödinger evolution, because the evolution is not unitary when the observed system interacts with the observer. Namely, there is collapse in each observer-dependent evolution of expected probabilities. These two differences allow values to be assigned to physical quantities without any of the consistency worries that plague modal interpretations. The point is that the break of the eigenstate-eigenvalue link is bypassed by that fact that the eigenvalue refers to one observer, and the state to a different observer. For a fixed observer, the eigenstate-eigenvalue link is maintained. Consistency should only be recovered between different observers, but consistency is only quantum mechanical as discussed in section III.D. Actuality is observer dependent. The fact that the values of physical quantities are relational and their consistency is only probabilisti-

**A separate problem is why the observing system chosen – S_o , or the macroscopic world– admits, in turn, a description in which expectations probabilities evolve classically, namely are virtually always concentrated on values 0 and 1, and interference terms are invisible. It is to this question that the physical decoherence mechanism [Joos Zeh 1985, Zurek 1981] provides an answer. Namely, *after* having an answer on what determines extra- values ascriptions (the observer-observed structure, in the view proposed here), the physical decoherence mechanism helps explaining why those ascriptions are consistent with classical physics in macroscopic systems.

cally required circumvents the potential difficulties of the modal interpretations.

A class of interpretations of quantum mechanics that Butterfield does not include in his classification, but which are presently very popular among physicists, is the consistent histories (CH) interpretations [Griffiths 1984, Omnes 1988, Gell-Mann and Hartle 1990]. These interpretations reduce the description of a system to the prediction of temporal sequences of values of physical variables. The key novelties are three: (i) probabilities are assigned to sequences of values, as opposed to single values; (ii) only certain sequences can be considered; (iii) probability is interpreted as probability of the given sequence of values within a chosen family of sequences, or framework. The restriction (ii) incorporates the quantum mechanical prohibition of giving value, say, to position and momentum at the same time. More precisely, in combination with (iii) it excludes all the instances in which observable interference effects would make probability assignments inconsistent. In a sense, CH represent a sophisticated implementation of the program of discovering a minimum consistent value attribution scheme. The price paid for consistency is that a single value attribution is meaningless: whether or not a variable has a value may very well depend on whether we are asking or not if at a later time another variable has a value.

There is a key subtlety in the CH scheme that has rarely been emphasized^{††}: this is the distinction between “properties that hold with probability one” and “data”. The interesting question to ask is: What is it that determines which frameworks are allowed? The standard answer in CH is that we have certain information on the system, call it *data*. In particular, we know that certain physical quantities of the system have certain values. The fact that certain quantities have certain values determines which framework are allowed to describe a phenomenon. Thus: *we rely on quantities having values (data) for selecting the allowed framework*. Then we derive probabilistic predictions about value attribution. These probabilistic predictions are framework dependent. It is often stated that in CH *all* value attributions are framework dependent; this is the way Nature is. *But if all value attributions are framework dependent, what are the data?* In CH there seem to be two distinct kind of value attributions: a weak value attribution: the framework dependent values, and a strong value attribution: the data, or facts. In CH the focus is totally on predictions about weak value attributions. But everyday life and scientific practice are about (possibly probabilistic) predictions of facts, namely facts that could be later used as data. To put it pictorially (and a bit imprecisely): I do not care about a science that tells me that my airplane will not crash “in one framework”; I want a science that

will tell me that my airplane will just not crash!

Consider the following situation (situation A): a set (D) of data on a system is given. From these data, it follows that there is a framework (call it F1) in which the question “Is Q equal to 1 at time t ?” can be asked, and the answer is yes with probability one. Then consider the following other situation (situation B): we have a set of data on the system, which consist in the set (D) *plus the data that $Q = 1$ at time t* . Is situation A physically the same as situation B in the consistent histories approach? The answer is no. In fact, situation A still allows for $Q = 2$ (strange but true) in a different framework, say F2, while situation B is incompatible with $Q = 2$, because F2 is not an admitted framework. *Therefore there should exist a physical way in which we pass from situation A to situation B*. Namely there should be way for a probability 1 prediction (in a framework) to become a data. The key question that, as far as I can see, the consistent histories approaches does not address is: how do we concretely pass (in a lab) from situation A to situation B? What is it that transforms a probability-one event (framework dependent) into something that we can use as data (framework independent)? If the transformation of a “probability-one-in-a-framework” situation into *data* is an actual occurrence in Nature, then I believe CH fails to tell me how this can happen (when does a framework becomes realized as data). If, on the other hand, what is data for me may fail to be data for somebody other, then one falls precisely into the scheme presented in this paper.

In the Copenhagen view, it is the interaction with a classical object that actualizes properties. A different solution has been suggested in this paper: interaction with any object, but then actualization of properties is only relative to that object. I do not see the solution of this problem within the history views. This is not to say that there is anything wrong in the CH approaches. To the opposite, I believe that the CH views are correct and precise. Still, there is a question that they leave open: the physical meaning of the framework dependence of the value assignments; more precisely, the understanding of how there can be facts, or data, if property ascriptions are only framework dependent. I think that the answer is simply that there are no (observer independent) data at all: the data that I have, and therefore the family of frameworks that I can use is different from your data, and therefore the family of framework that you can use. The histories interpretations are not inconsistent with the analysis developed here. What I try to add here is attention to the process through which the observer-independent, but framework-dependent probabilities attached to histories, may be related to actual observer-dependent descriptions of the facts of the world.

Finally, let me come to the third strategy (Perspectival Values), whose prime example is the many worlds interpretation [Everett 1957, Wheeler 1957, DeWitt 1970], and its variants. If the “branching” of the wave function in the many worlds interpretation is considered as a

^{††}The only discussion on this point I heard was by Isham.

physical process, it raises the very same sort of difficulties as the von Neumann “collapse” does. When does it happen? Which systems are measuring systems that make the world branch? These difficulties of the many-world interpretation have been discussed in the literature [See Earman 1986]. Alternatively, we may forget branching as a physical process, and keep evolving the wave function under unitary evolution. The problem is then to interpret the observation of the “internal” observers. As discussed in [Butterfield 1985] and [Albert 1992], this can be done by giving preferred status to special observers (apparatus) whose values determine a (perspectival) branching. See Objection 7 in section II.B. A variant is to take brains –“Minds”– as the preferred systems that determine this perspectival branching, and thus whose state determines the new “dimension” of indexicality. Preferred apparatus, or bringing Minds into the game, violates hypothesis 1.

There is a way of having (perspectival) branching keeping all systems on the same footing: the way followed in this paper, namely to assume that all values assignments are completely relational, not just relational with respect to apparatus or Minds. Notice, however, that from this perspective Everett’s wave function is a very misleading notion, not only because it represents the perspective of a non-existent observer, but because it even fails to contain any relevant information about the values observed by each single observer! There is no description of the universe *in-toto*, only a quantum-interrelated net of partial descriptions.

With respect to Butterfield’s classification, the interpretation proposed here is thus in the second, as well as in the third, group: the extra values assigned are “somehow perspectival” (but definitely not mental!), in that they are observer-dependent, but at the same time “wholly a matter of physics”, in the sense in which the “perspectival” aspect of simultaneity is “wholly a matter of physics” in relativity. In one word: value assignment in a measurement is not inconsistent with unitary evolution of the apparatus+system ensemble, because value assignment refers to the properties of the system with respect to the apparatus, while the unitary evolution refers to properties with respect to an external system.

From the point of view discussed here, Bohr’s interpretation, consistent histories interpretations, as well as the many worlds interpretation, are all correct. The point of view closest to the one presented here is perhaps Heisenberg’s. Heisenberg’s insistence on the fact that the lesson to be taken from the atomic experiments is that we should stop thinking of the “state of the system”, has been obscured by the subsequent terse definition of the theory in terms of states given by Dirac. Here, I have taken Heisenberg’s lesson to extreme consequences.^{††}

Crane is developing a point of view similar to the one discussed here and has attempted an ambitious extension of these ideas to the cosmological general-covariant gravitational case [Crane 1995]. It was recently brought to my attention that Zurek ends his paper [Zurek 1982] with conclusions that are identical to the ones developed here: “Properties of quantum systems have no absolute meaning. Rather, they must be always characterized with respect to other physical systems” and “correlations between the properties of quantum systems are more basic than the properties themselves” [Zurek 1982]. Finally, Rob Clifton has brought to my attention an unpublished preprint by Kochen [Kochen 1979], with ideas extremely similar to the ones presented here.

Acknowledgments

The ideas in this work emerged from: i. Conversations with Abhay Ashtekar, Julian Barbour, Alain Connes, Jürgen Ehlers, Brigitte Falkenburg, Gordon Fleming, Jonathan Halliwell, Jim Hartle, Chris Isham, Al Janis, Ted Newman, Roger Penrose, Lee Smolin, John Wheeler and HD Zeh; ii. A seminar run by Bob Griffiths at Carnegie Mellon University (1993); iii. A seminar run by John Earman at Pittsburgh University (1992); iv. Louis Crane’s ideas on quantum cosmology; v. The teachings of Paola Cesari on the importance of taking the observer

some version of naive realism, or some version of naive empiricism. I am aware of the “philosophical qualm” that the ideas presented here may then generate. The conventional reply, which I reiterate, is that Galileo’s relational notion of velocity used to produce analogous qualms, and that physics seems to have the remarkable capacity of challenging even its own conceptual premises, in the course of its evolution. Historically, the discovery of quantum mechanics has had a strong impact on the philosophical credo of many physicists, as well as on part of contemporary philosophy. It is possible that this process is not concluded. But I certainly do not want to venture into philosophical terrains, and I leave this aspect of the discussion to competent thinkers. Just a few observations: The relational aspect of knowledge is one of the themes around which large part of western philosophy has developed. In Kantian terms, only to mention a characteristic voice, any phenomenal substance which may be object of possible experience is “entirely made up of mere relations” [Kant 1787]. In recent years, the idea that the notion of observer-independent description of a system is meaningless has become almost a commonplace in disparate areas of the contemporary culture, from anthropology to certain biology and neuro-physiology, from the post-neopositivist tradition to (much more radically) continental philosophy [Gadamer 1989], all the way to theoretical physical education [Bragagnolo Cesari and Facci 1993]. I find the fact that quantum mechanics, which has directly contributed to inspire many of these views, has then remained unconnected to these conceptual development, quite curious.

^{††}With a large number of exceptions, most physicists hold

into account. It is a pleasure to thank them all. I also thank Gordon Belot, Jeremy Butterfield, Bob Clifton, John Earman, Simon Saunders and Euan Squires for discussions and comments on the first version of this work.

References

- Albert D, 1992, *Quantum Mechanics and Experience*, Cambridge Ma: Harvard University Press.
- Albert D and Loewer B, 1988, *Synthese* 77, 195-213; 1989, *Nous* 23, 169- 186
- Ashtekar 1993, personal communication
- Einstein A, Podolsky B, Rosen N 1935, *Phys Rev* 47
- Everet H 1957, *Rev of Mod Phys* 29, 454
- Bacciagaluppi G 1995, "A Kochen-Specker Theorem in the Modal Interpretation of Quantum Theory", *International Journal of Theoretical Physics*, to appear.
- Bacciagaluppi G and Hemmo M 1995, "Modal Interpretations of Imperfect Measurement", *Foundation of physics*, to appear.
- Belinfante FJ 1973, *A survey of Hidden variable theories*, Pergamon Press
- Bell J 1987, in *Schrödinger: centenary of a polymath*, Cambridge: Cambridge University Press
- Beltrametti EG, Cassinelli G 1981, *The Logic of Quantum Mechanics*, Addison Wesley
- Bohm D 1951, *Quantum Theory*, Englewood Cliffs, NJ
- Bohr N 1935, *Nature* 12, 65.
- Bohr N 1949, discussion with Einstein in *Albert Einstein: Philosopher-Scientist*, Open Court
- Born M 1926, *Zeitschrift für Physik* 38, 803.
- Bragagnolo W, Cesari P, Facci G 1993, *Teoria e metodo dell'apprendimento motorio*, Bologna: Societa' Stampa Sportiva
- Breuer 1994, "The impossibility of accurate state self-measurement", *Philosophy of Science*, to appear.
- Butterfield J 1995, *Words, Minds and Quanta*, in "Symposium on Quantum Theory and the Mind" Liverpool
- Crane L 1995, *Clock and Category: Is Quantum Gravity Algebraic?* *J Math Phys* 36
- D'Espagnat 1971, *Conceptual foundations of quantum mechanics*, Addison-Wesley
- DeWitt BS 1970, *Physics Today* 23, 30
- DeWitt BS, Graham N, 1973 *The Many World Interpretation of Quantum Mechanics*, Princeton University Press
- Dirac PMA 1930, *The principles of quantum mechanics*, Oxford: Clarendon Press
- Donald M 1990, *Proceedings of the Royal Society of London* A427, 43
- Earman J 1986, *A primer on determinism*, Dordrecht: Holland Reidel
- Everett H 1957, *Rev of Mod Phys* 29, 454
- Finkelstein D 1969, in *Boston Studies in the Philosophy of Science*, vol 5, eds Cohen RS and Wartofski MW, Dordrecht 1969
- Finkelstein D 1988, in *The universal Turing machine*, vol 5, eds R Herken, Oxford University Press
- Fleming NG 1992, *Journal of Speculative Philosophy*, VI, 4, 256.
- Gadamer HG 1989, *Truth and method*, New York: Crossroad.
- Gell-Mann M, Hartle J, 1990 in *Complexity, Entropy, and the Physics of Information, SFI Studies in the Sciences of Complexity*, vol III, ed W Zurek. Addison Wesley
- Ghirardi GC, Rimini A, Weber T 1986, *Phys Rev D*34, 470
- Greenberger, Horne and Zeilinger 1993, *Physics Today*
- Griffiths RB 1984, *J Stat Phys* 36, 219;
- Griffiths RB 1993, Seminar on foundations of quantum mechanics, Carnegie Mellon, Pittsburgh, October 1993
- Griffiths RB 1996 *Consistent Histories and Quantum Reasoning*; quant-ph/9606004. *Phys Rev A*, to appear 1996.
- Halliwel 1994, in *Stochastic Evolution of Quantum States in Open Systems and Measurement Process*, L Diosi ed., Budapest.
- Heisenberg W 1927, *Zeit fur Phys* 43,172; 1936 *Funf Wiener Vortage*, Deuticke, Leipzig and Vienna.
- Hughes RIG 1989, *The structure and interpretation of Quantum Mechanics*, Harvard University Press, Cambridge Ma

- Jauch J 1968, *Foundations of Quantum Mechanics*, Adison Wesley.
- Jona-Lasinio G, Martinelli F, Scoppola E 1981, Comm Math Phys 80, 223
- Jona-Lasinio G, Claverie P 1986, Progr Theor Phys Suppl 86, 54
- Joos E and Zee HD, Zeitschrift für Physik B59, 223
- Kant E 1787, *Critique of Pure Reason*, Modern Library New York 1958
- Kent A 1995, gr-qc/9512023, to appear in Phys Rev A; quant-ph/9511032; gr-qc/9604012; gr-qc/9607073.
- Kent A and Dowker F 1995, Phys Rev Lett 75, 3038, J Stat Phys 82, 1575
- Kochen S 1979, *The Interpretation of Quantum Mechanics*, unpublished.
- Landau LD, Lifshitz EM 1977, *Quantum Mechanics*, introduction, Pergamon Press
- Lockwood M 1989, *Mind brain and the Quantum*, Oxford, Blackwell
- Mackey GW 1963 *Mathematical Foundations of Quantum Mechanics* New York, Benjamin
- Maczinski H 1967, Bulletin de L'Academie Polonaise des Sciences 15, 583
- Maturana H, Varela F 1980, *Autopoiesis and Cognition. The Realization of the Living*, D. Reidel Publishing Company, Dordrecht, Holland
- Messiah A 1958, *Quantum Mechanics*, New York, John Wiley
- Newman ET 1993, Talk at the inaugural ceremony of the Center for Gravitational Physics, Penn State University, August 1993
- Omnes R 1988, J Stat Phys 57, 357
- Penrose R 1989, *The emperor's new mind*, Oxford University Press
- Peres A, Zurek WH 1982, American Journal of Physics 50, 807
- Piron C 1972, Foundations of Physics 2, 287
- Primas H 1990, in *Sixty-two years of uncertainty*, eds AI Miller, New York Plenum
- Roessler OE 1987, in *Real brains - Artificial minds*, eds JL Casti A Karlqvist, New York, North Holland
- Rovelli C 1995, "Half way through the woods", in *The Cosmos of Science*, J Earman and JD Norton editors, (University of Pittsburgh Press / Universitaets Verlag Konstanz, 1997), in print
- Shannon CE 1949, *The mathematical theory of communication*, University of Illinois Press
- Shimony A 1969, in *Quantum Concepts and spacetime*, eds R Penrose C Isham, Oxford: Clarendon Press.
- Schrödinger E 1935, Naturwissenschaften 22, 807
- Van Fraassen B 1991, *Quantum Mechanics: an Empiricist View*, Oxford University Press
- Von Neumann J 1932, *Mathematische Grundlagen der Quantenmechanik*, Springer, Berlin
- Wheeler JA 1957, Rev of Mod Phys 29, 463
- Wheeler JA 1988, *IBM Journal of Research and Development*, Vol 32, 1
- Wheeler JA 1989, *Proceedings of the 3rd International Symposium on the Foundations of Quantum Mechanics*, Tokyo
- Wheeler JA 1992, *It from Bit and Quantum Gravity*, Princeton University Report
- Wheeler J, Zurek W 1983, *Quantum Theory and Measurement* Princeton University Press
- Wightman AS 1995, in *Mesoscopic Physics and Fundamental Problems in Quantum Mechanics*, edited by E Di Castro, F Guerra, G Jona-Lasinio.
- Wigner EP 1961, in *The Scientist Speculates*, ed Good, New York: Basic Books.
- Zurek WH 1981, Phys Rev D24 1516
- Zurek WH 1982, Phys Rev D26 1862