

Why Should we Interpret Quantum Mechanics?

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Abstract

The development of quantum information theory has renewed interest in the idea that the state vector does not represent the state of a quantum system, but rather the knowledge or information that we may have on the system. I argue that this epistemic view of states appears to solve foundational problems of quantum mechanics only at the price of being essentially incomplete.

KEY WORDS: quantum mechanics; interpretation; information.

1 Introduction

The foundations and the interpretation of quantum mechanics, much discussed by the founders of the theory, have blossomed anew in the past few decades. It has been pointed out that every single year between 1972 and 2001 has witnessed at least one scientific meeting devoted to these issues [1].

Two problems in the foundations of quantum mechanics stand out prominently. The first one concerns the relationship between quantum mechanics and general relativity. Both theories are highly successful empirically, but they appear to be mutually inconsistent. Most investigators used to believe that the problem lies more with general relativity than with quantum mechanics, and that the solution would consist in coming up with a suitable quantum version of Einstein's gravitational theory. More recently, however, it has become likely that a correct quantum theory of gravity may involve leaps substantially bolder [2].

The second problem is more down-to-earth, and shows up starkly in ordinary nonrelativistic quantum mechanics. It consists in the reconciliation of the apparently indeterminate nature of quantum observables with the apparently determinate nature of classical observables, and it crystallizes in the so-called measurement problem. Broadly speaking, there are two ways to address it. The first one, elaborated by von Neumann [3], consists in denying the universal validity of the unitary evolution of quantum states, governed by the Schrödinger equation. State vector collapse, postulated by von Neumann but not worked out in detail by him, was made much more precise recently in spontaneous localization models [4]. The second road to reconciliation consists in stressing the universal validity of the Schrödinger equation, while assigning values to specific observables of which the state vector is not necessarily an eigenstate. Bohmian mechanics [5, 6, 7] and modal interpretations [8, 9], among others, fall in this category.

The past twenty years have also witnessed the inception and quick development of quantum information theory. This was not unrelated to foundational studies. Quantum cryptography [10] and quantum teleportation [11], for instance, are based on the Einstein-Podolsky-Rosen setup and algorithms for fast computation use entanglement in an essential way [12].

As foundational studies contributed to quantum information theory, a number of investigators feel that quantum information theory has much to contribute to the interpretation of quantum mechanics. This has to do with what has been called the *epistemic view* of state vectors, which goes back at least to Heisenberg [13] but has significantly evolved in the past few years [1, 14, 15, 16, 17, 18]. In the epistemic view, the state vector (or wave function, or density matrix) does not represent the objective state of a microscopic system (like an atom, an electron, a photon), but rather our knowledge of the probabilities of outcomes of macroscopic measurements. This, so the argument goes, considerably clarifies, or even completely dissolves, the EPR paradox and the measurement problem.

The purpose of this paper is to examine the status of the epistemic view. It is a minimal interpretation, and indeed was referred to as an “interpretation without interpretation” [16]. The question of the adequacy of the epistemic view is much the same as the one whether quantum mechanics needs being interpreted.

In Sect. 2, I shall review the main arguments in favor of the epistemic view of quantum states. They have to do with state vector collapse and the consistency of quantum mechanics with special relativity. It turns out

that the issue of interpretation can fruitfully be analyzed in the context of the *semantic view* of theories. As outlined in Sect. 3, this approach tries to answer the question, How can the world be the way the theory says it is? The next section will describe a world where the epistemic view would be adequate. This, it turns out, is not the world we live in, and Sects. 5 and 6 will argue that in the real world, the epistemic view in fact begs the question of interpretation.

2 Arguments for the epistemic view

Interpretations of quantum mechanics can be asserted with various degrees of illocutionary strength. The many-worlds interpretation [19], for instance, has sometimes been presented as following directly from the quantum-mechanical formalism. In a similar vein, Rovelli has proposed that the epistemic view follows from the observation that different observers may give different accounts of the same sequence of events [15].

Rovelli's argument goes as follows. A quantum system S with two-dimensional state space is initially described by the state vector $|\psi\rangle = \alpha|1\rangle + \beta|2\rangle$, where $|1\rangle$ and $|2\rangle$ are orthonormal eigenvectors of an observable Q . Sometime between t_i and t_f , an apparatus O (which may or may not include a human being) performs a measurement of Q on S , obtaining the value 1. Call this experiment \mathcal{E} . According to standard quantum mechanics, O describes \mathcal{E} as

$$\begin{aligned} & t_i \longrightarrow t_f \\ \alpha|1\rangle + \beta|2\rangle & \longrightarrow |1\rangle. \end{aligned} \tag{1}$$

Now let a second observer P describe the compound system made up of S and O . Let $|O_i\rangle$ be the state vector of O at t_i . The measurement interaction between O and S implies that their total state vector becomes entangled. Thus from the point of view of P , who performs no measurement between t_i and t_f , the experiment \mathcal{E} should be described as

$$\begin{aligned} & t_i \longrightarrow t_f \\ (\alpha|1\rangle + \beta|2\rangle) \otimes |O_i\rangle & \longrightarrow \alpha|1\rangle \otimes |O1\rangle + \beta|2\rangle \otimes |O2\rangle. \end{aligned} \tag{2}$$

Here $|O1\rangle$ and $|O2\rangle$ are pointer states of O showing results 1 and 2.

According to Rovelli, Eq. (1) is the conventional quantum-mechanical description of experiment \mathcal{E} from the point of view of O , whereas Eq. (2) is the description of \mathcal{E} from the point of view of P . From this he concludes that “[i]n quantum mechanics different observers may give different accounts of the same sequence of events.” Or, to borrow the title of his Sect. 2, “Quantum mechanics is a theory about information.”

The problem with this argument is that expressions like “standard quantum mechanics” or “conventional quantum-mechanical description” are fundamentally ambiguous. They can refer either (i) to strict unitary Schrödinger evolution, or (ii) in the manner of von Neumann, to Schrödinger evolution *and* collapse. Once a precise definition is agreed upon, either description (1) or description (2) (but not both) is correct. Strict Schrödinger evolution (i) is encapsulated in Eq. (2), whereas Schrödinger evolution with collapse (ii) is encapsulated in Eq. (1). The issue is not that the description depends on the observer, but that with any precise definition there is a specific problem. With definition (i), quantum mechanics seems to contradict experiment, while with definition (ii), one needs to provide an explicit collapse mechanism. Thus Rovelli’s discussion, rather than establishing the epistemic view, brings us back to the foundational problem outlined in Sect. 1.¹

The epistemic view can also be propounded not as a consequence of the quantum-mechanical formalism, but as a way to solve the foundational problems. It does so by denying that the (in this context utterly misnamed) state vector represents the state of a microscopic system. Rather, the state vector represents knowledge about the probabilities of results of measurements performed in a given context with a macroscopic apparatus, that is, information about “the potential consequences of our experimental interventions into nature” [1].

How does the epistemic view deal with the measurement problem? It does so by construing the collapse of the state vector not as a physical process, but as a change of knowledge [14]. Insofar as the state vector is interpreted as objectively describing the state of a physical system, its abrupt change in a measurement implies a similar change in the system, which calls for explanation. If, on the other hand, the state vector describes knowledge of conditional probabilities (i.e. probabilities of future macroscopic events conditional on past macroscopic events), then as long as what is condition-

¹My criticism of its starting point notwithstanding, much of the discussion in Ref. [15] is lucid and thought-provoking.

alized upon remains the same, the state vector evolves unitarily. It collapses when the knowledge base changes, thereby simply reflecting the change in the conditions being held fixed in the specification of probabilities.

The epistemic view also helps in removing the clash between collapse and Lorentz invariance [1, 20]. Take for instance the EPR setup with two spin $1/2$ particles, and let the state vector $|\chi\rangle$ of the compound system be an eigenstate of the total spin operator with eigenvalue zero. One can write

$$|\chi\rangle = \frac{1}{\sqrt{2}} \{ |+\rangle; \hat{n}\rangle \otimes |-\rangle; \hat{n}\rangle - |-\rangle; \hat{n}\rangle \otimes |+\rangle; \hat{n}\rangle \}, \quad (3)$$

where the first vector in a tensor product refers to particle A and the second vector to particle B . The vector $|+\rangle; \hat{n}\rangle$, for instance, stands for an eigenvector of the \hat{n} -component of the particle's spin operator, with eigenvalue $+1$ (in units of $\hbar/2$). The unit vector \hat{n} can point in any direction, a freedom which corresponds to the rotational symmetry of $|\chi\rangle$.

Suppose Alice measures the \hat{n} -component of A 's spin and obtains the value $+1$. If the state vector represents the objective state of a quantum system and if collapse is a physical mechanism, then B 's state immediately collapses to $|-\rangle; \hat{n}\rangle$. This explains why Bob's subsequent measurement of the \hat{n} -component of B 's spin yields the value -1 with certainty. Thus Alice's choice of axis at once determines the possible states into which B may collapse, and Alice's result immediately singles out one of these states.

If the two measurements are spacelike separated, there exist Lorentz frames where Bob's measurement is earlier than Alice's. In these frames the instantaneous collapse is triggered by Bob's measurement. This ambiguity, together with the fact that what is instantaneous in one frame is not in others, underscores the difficulty of reconciling relativistic covariance with physical collapse.

In the epistemic view, what changes when Alice performs a measurement is Alice's knowledge. Bob's knowledge will change either if he himself performs a measurement, or if Alice sends him the result of her measurement by conventional means. Hence there is no physical collapse on a spacelike hypersurface.

To the proponents of the epistemic view, the above arguments show that it considerably attenuates, or even completely solves, the problems associated with quantum measurements and collapse. I will argue, however, that this result is achieved only at the price of giving up the search for a spelled out

consistent view of nature.²

3 The semantic view of theories

Investigations on the structure of scientific theories and the way they relate to phenomena have kept philosophers of science busy for much of the twentieth century. In the past few decades, the semantic view has emerged as one of the leading approaches to these problems [8, 22, 23, 24]. Among other issues it helps clarifying, I believe it sheds considerable light on the question of the interpretation of quantum mechanics.

In the semantic view a scientific theory is a structure, defined primarily by models rather than by axioms or a specific linguistic formulation. A general theoretical hypothesis then asserts that a class of real systems, under suitable conditions of abstraction and idealization, belongs to the class of models entertained by the theory. If the theory is empirically adequate, the real systems behave (e.g. evolve in time) in a way predictable on the basis of the models. Yet the empirical agreement may leave considerable room on the way the world can be for the theory to be true. This is the question of interpretation.

This succinct characterization can best be understood by means of examples. Take classical particle mechanics. The (mathematical) structure consists of constants m_i , functions $\vec{r}_i(t)$ and vector fields \vec{F}_i (understood as masses, positions and forces), together with the system of second-order differential equations $\vec{F}_i = m_i \vec{a}_i$. A particular model is a system of ten point masses interacting through the $1/r^2$ gravitational force. A theoretical hypothesis then asserts that the solar system corresponds to this model, if the sun and nine planets are considered pointlike and all other objects neglected. Predictions made on the basis of the model correspond rather well with reality, especially if suitable correction factors are introduced in the process of abstraction. But obviously the model can be made much more sophisticated, taking into account for instance the shape of the sun and planets, the planets' satellites, interplanetary matter, and so on.

Now what does the theory have to say about how a world of interacting masses is really like? It turns out that such a world can be viewed in (at least) two empirically equivalent but conceptually very different ways. One

²The epistemic view was criticized from a different perspective by Zeh [21].

can assert that it is made only of small (or extended) masses that interact by instantaneous action at a distance. Or else, one can say that the masses produce everywhere in space a gravitational field, which then locally exerts forces on the masses. These are two different interpretations of the theory. Each one expresses a possible way of making the theory true (assuming empirical adequacy). Whether the world is such that masses instantaneously interact at a distance in a vacuum, or a genuine gravitational field is produced throughout space, the theory can be held as truly realized.

A similar discussion can be made with classical electromagnetism. The mathematical structure consists of source fields ρ and \vec{j} (understood as charge and current densities), and vector fields \vec{E} and \vec{B} (electric and magnetic fields) related to the former through Maxwell's equations. A function \vec{F} of the fields (the Lorentz force) governs the motion of charge and current carriers. A model of the theory might be a perfectly conducting rectangular guide with a cylindrical dielectric post, subject to an incoming TE_{10} wave.

Again, each specific model of interacting charges and currents can be viewed in empirically equivalent and conceptually different ways. One can allow only retarded fields, or both retarded and advanced fields [25]. If one assumes the existence of a complete absorber, one can get rid of the fields entirely, and view electrodynamics as a theory of moving charges acting on each other at a distance (though not instantaneously). Although the interpretation with genuine retarded fields is the one by far the more widely accepted, the other interpretations also provide a way by which Maxwell's theory can be true.

Let us now turn to quantum mechanics. The mathematical structure consists of state spaces \mathcal{H} , state vectors $|\psi\rangle$ and density operators ρ ; of Hermitian operators A , eigenvalues $|a\rangle$, and eigenvectors a ; of projectors P_a , etc. Defining quantum mechanics as covering strict unitary evolution, state vectors evolve according to the Schrödinger equation. The scope of the theory is specified (minimally) by associating eigenvalues a to results of possible measurements, and quantities like $\text{Tr}(\rho P_a)$ to corresponding probabilities.

One kind of real system that can be modelled on the basis of the structure is interference in a two-slit Young setup. Often the system can conveniently be restricted to the xy plane. In a specific model the source can be represented by a plane wave moving in the x direction, and the slits can be taken as modulating gaussian wave packets in the y direction. These packets then propagate according to the Schrödinger equation in free space and produce a

wave pattern on a screen. The absolute square of the wave amplitude is associated with the probability that a suitable detector will click, as a function of its position on the screen.

From the semantic point of view, the question of interpretation is the following: How can the world be so that quantum models representing Young setups (as well as other situations) are empirically adequate? The Copenhagen answer (or at least a variant of it) says that micro-objects responsible for the fringes don't have well-defined properties unless these are measured, but that large scale apparatus always have well-defined properties. I share the view of those who believe that this answer is complete only insofar as it precisely specifies the transition scale between the quantum and the classical. Bohm's answer to the above question is that all particles always have precise positions, and these positions are the ones that show up on screens [26]. The many-worlds view is that different detector outcomes simultaneously exist in different worlds or in different minds. I shall shortly attempt to assess the adequacy of the epistemic view, but first we should look at a world especially tailored to such an interpretation.

4 A world for the epistemic view

Consider a hypothetical world where large scale objects (meaning objects much larger than atomic sizes) behave, for all practical purposes, like large scale objects in the real world. The trajectories of javelins and footballs can be computed accurately by means of classical mechanics with the use of a uniform downward force and air resistance. Waveguides and voltmeters obey Maxwell's equations. Steam engines and air conditioners work according to the laws of classical thermodynamics. The motion of planets is well described by Newton's laws of gravitation and of motion, slightly corrected by the equations of general relativity.

Close to atomic scales, however, these laws may no longer hold. Except for one restriction soon to be spelled out, I shall not be specific about the changes that macroscopic laws may or may not undergo in the microscopic realm. Matter, for instance, could either be continuous down to the smallest scales, or made of a small number of constituent particles like our atoms. The laws of particles and fields could be the same at all scales, or else they could undergo significant changes as we probed smaller and smaller distances.

In the hypothetical world one can perform experiments with pieces of

equipment like Young's two-slit setup and Stern-Gerlach devices. The Young type experiment, for instance, uses two macroscopic devices E and D that both have on and off states and work in the following way. Whenever D is suitably oriented with respect to E (say, roughly along the x axis) and both are in the on state, D clicks in a more or less random way. The average time interval between clicks depends on the distance r between D and E , and falls roughly as $1/r^2$. The clicking stops if a shield of a suitable material is placed perpendicularly to the x axis, between D and E .

If holes are pierced through the shield, however, the clicking resumes. In particular, with two small holes of appropriate size and separation, differences in the clicking rate are observed for small transverse displacements of D behind the shield. A plot of the clicking rate against D 's transverse coordinate displays maxima and minima just as in a wave interference pattern. No such maxima and minima are observed, however, if just one hole is open or if both holes are open alternately.

At this stage everything happens as if E emitted some kind of particles and D detected them, and the particles behaved according to the rules of quantum mechanics. Nevertheless, we shall not commit ourselves to the existence or nonexistence of these particles, except on one count. Such particles, if they exist, are not in any way related to hypothetical constituents of the material making up D , E or the shield, or of any macroscopic object whatsoever. Whatever the microscopic structure of macroscopic objects, it has nothing to do with what is responsible for the correlations between D and E .³

In the hypothetical world one can also perform experiments with Stern-Gerlach setups. Again a macroscopic device D' clicks more or less randomly when suitably oriented with respect to another macroscopic device E' , both being in the on state. If a large magnet (producing a strongly inhomogeneous magnetic field) is placed along the x axis between E' and D' , clicks are no longer observed where D' used to be. Rather they are observed if D' is moved transversally to (say) two different positions, symmetrically oriented with respect to the x axis. Let ξ be the axis going from the first magnet to one of these positions. If a second magnet is put behind the first one along the ξ axis and D' is placed further behind, then D' clicks in two different

³Any objection to the hypothetical world on grounds that energy might not be conserved, action would not entail corresponding reaction, and so on, would miss the point, which is to clarify in what context the epistemic view can be held appropriately.

positions in the plane perpendicular to ξ . In the hypothetical world the average clicking rate depends on the magnet's orientation, and it follows the quantum-mechanical rules of spin 1/2 particles. Once again, however, we assume that the phenomenon responsible for the correlations between D' and E' has nothing to do with hypothetical constituents of macroscopic objects.

In the two experiments just described, quantum mechanics correctly predicts the correlations between D and E (or D' and E') when suitable macroscopic devices are interposed between them. In that situation, the theory can be interpreted in (at least) two broadly different ways. In one interpretation, the theory is understood as applying to genuine microscopic objects, emitted by E and detected by D . Perhaps these objects follow Bohmian like trajectories, or behave between emitter and detector in some other way compatible with quantum mechanics. In the other interpretation, there are no microscopic objects whatsoever going from E to D . There may be something like an action at a distance. At any rate the theory is in that case interpreted instrumentally, for the purpose of quantitatively accounting for correlations in the stochastic behavior of E and D .

In the hypothetical world being considered, I would maintain that both interpretations are logically consistent and adequate. Both clearly spell out how the world can possibly be the way the theory says it is. Of course, each particular investigator can find more satisfaction in one interpretation than in the other. The epistemic view corresponds here to the instrumentalist interpretation. It simply rejects the existence of microscopic objects that have no other use than the one of predicting observed correlations between macroscopic objects.

5 Insufficiency of the epistemic view

We shall assume that macroscopic objects exist and are always in definite states.⁴ Not everyone agrees with this. Idealistic thinkers believe there is nothing outside mind, and some fruitful interpretations of quantum mechanics (like the many-minds interpretation) claim we are mistaken in assuming the definiteness of macroscopic states.

⁴By this assumption, I mean that they are not in quantum superpositions of macroscopically distinct states. They may still be subject to the very tiny uncertainties required by Heisenberg's principle.

For the purpose of asserting the relevance of the epistemic view, however, these assumptions can be maintained. Indeed much of the appeal of the epistemic view is that it appears to reconcile them with the exact validity of quantum mechanics.

All scientists today believe that macroscopic objects are in some sense made of atoms and molecules or, more fundamentally, of electrons, protons, neutrons, photons, etc. The epistemic view claims that state vectors do not represent states of microscopic objects, but knowledge of probabilities of experimental results. I suggest that with respect to atoms, electrons and similar entities this can mean broadly either of three things:

1. Micro-objects do not exist [27].
2. Micro-objects may exist but they have no states.
3. Micro-objects may exist and may have states, but attempts at narrowing down their existence or specifying their states are useless, confusing or methodologically inappropriate.

In the first case, the question that immediately comes to mind is the following: How can something that exists (macroscopic objects) be made of something that does not exist (micro-objects)?⁵ And in the second case, we can ask similarly: How can something that has a state be made of something that does not have one?

Can we conclude from these interrogations that the epistemic view is logically inconsistent? Is the argument of the last paragraph a *reductio ad absurdum*? Not so. What the questions really ask is the following: How is it possible that the world be like that? How, for instance, can we have a well-defined macroscopic state starting from objects that do not have states? This, we have seen, is precisely the question of interpretation. Hence if the epistemic view is asserted as in cases (1) and (2), our discussion shows that it is incomplete and paradoxical, and that the process of completion and paradox resolution coincides with the one of interpretation.⁶

⁵I can find no answer to this question in Ref. [27] which, however, fits remarkably well with the hypothetical world of Sect. 4.

⁶Although a proponent of the epistemic view, Spekkens suggests looking for “the ontic states of which quantum states are states of knowledge” [17]. A specific way of making sense of quantum mechanics understood as a probability algorithm was recently proposed by Mohrhoff [28].

To address the third case, it will help focussing on a particular argument along this line, the one recently put forth by Bub [18]. Having in mind mechanical extensions of the quantum theory by means of nonclassical waves and particles, Bub appeals to the following methodological principle:

[I]f T' and T'' are empirically equivalent extensions of a theory T , and if T entails that, in principle, there *could not be* evidence favoring one of the rival extensions T' or T'' , then it is not rational to believe either T' or T'' .

Bub then contrasts the relationship between the quantum theory and its mechanical extensions like Bohmian mechanics, with the relationship between classical thermodynamics and its mechanical explanation through the kinetic-molecular theory. In the latter case there are empirical differences, as Einstein showed in 1905 in the context of Brownian motion, and as Perrin observed in 1909.

The realization that there may be empirical differences between thermodynamics and the kinetic theory of gases goes back to the 1860's [29], and is connected with the names of Loschmidt and Maxwell. But the kinetic theory is much older. Leaving aside the speculations of the Greek atomists, we find atomism well alive in the writings of Boyle and Newton in the seventeenth and early eighteenth centuries. D. Bernoulli explained the pressure of a gas in terms of atomic collisions in 1738, and Dalton used atoms to explain the law of multiple proportions around 1808. All this time though, there was little indication that the empirical content of the atomic models and the phenomenological theories might be different.

One may argue whether it was rational to believe in atoms before Loschmidt, but there is no question that it was very fruitful. As a matter of fact, one of the reasons for contemplating empirically equivalent extensions of theories is that they may open the way to nonequivalent theories. This was clearly one of Bohm's preoccupations in 1952 [5]. That this perspective may or may not bear fruits remains to be seen.

In the semantic view, the empirically equivalent mechanical extensions T' and T'' of T are rather called interpretations, emphasizing that each points to how the world can possibly be the way the theory says it is. Equivalently, each shows a way the theory can be true. In classical physics, finding ways that the theory can be true is usually nonproblematic, as was illustrated in Sect. 3. This, however, is not the case with the quantum theory. Every

logically consistent interpretation proposed should therefore be viewed as adding to the understanding of the theory.

Bub's methodological principle states that it is not rational to believe in empirically equivalent extensions T' or T'' of T , if there cannot in principle be evidence favoring the extensions. Presumably, however, it is rational to believe in T (assuming empirical adequacy). If T is singled out among its empirical equivalents, it must be so on the basis of criteria other than empirical, perhaps something like Ockham's razor. This comes as no surprise since even within the class of internally consistent theories, acceptance almost never depends on empirical criteria alone.

What criteria, other than empirical, make for theory acceptance has been the subject of lively debate, and the question may never be settled. But the problem of acceptance translates to interpretations. Assume that a theory is empirically adequate, and consider all the ways the world can be for the theory to be so. Each of these ways is an interpretation. Let an interpretation be true just in case the world is actually like it says it is. Necessarily then, an empirically adequate theory has one of its interpretations that is true.

Now assume that, among all available interpretations of a theory, no one is found acceptable on a given nonempirical criterion. Any proponent of the theory who believes that the criterion is important is then faced with the following choice. Either he hopes that an interpretation meeting the criterion will eventually be found and, whether or not he actually looks for it, he grants that the search is an important task; or he concludes that the theory, in spite of being empirically adequate, is not acceptable.

6 Conclusion

In attempting to solve the problems of measurement and instantaneous collapse, the epistemic view asserts that state vectors do not represent states of objects like electrons and photons, but rather the information we have on the potential consequences of our experimental interventions into nature. I have argued that this picture is adequate in a world where the theoretical structure used in the prediction of these consequences is independent of the one used in the description of fundamental material constituents.

In the world we live in, however, whatever is responsible for clicks in Geiger counters or cascades in photomultipliers also forms the basis of material structure. The epistemic view can be construed as denying that micro-

objects exist or have states, or as being agnostic about any logically coherent connection between them and macroscopic objects. In the first case, the solution it proposes to the foundational problems is simply paradoxical, and calls for an investigation of how it can be true. In the second case, it posits the existence of a link between quantum and macroscopic objects. Once this is realized, the urge to investigate the nature of this connection will not easily subside.

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