Dialogue on the Fundamental Quantum Nature of the World

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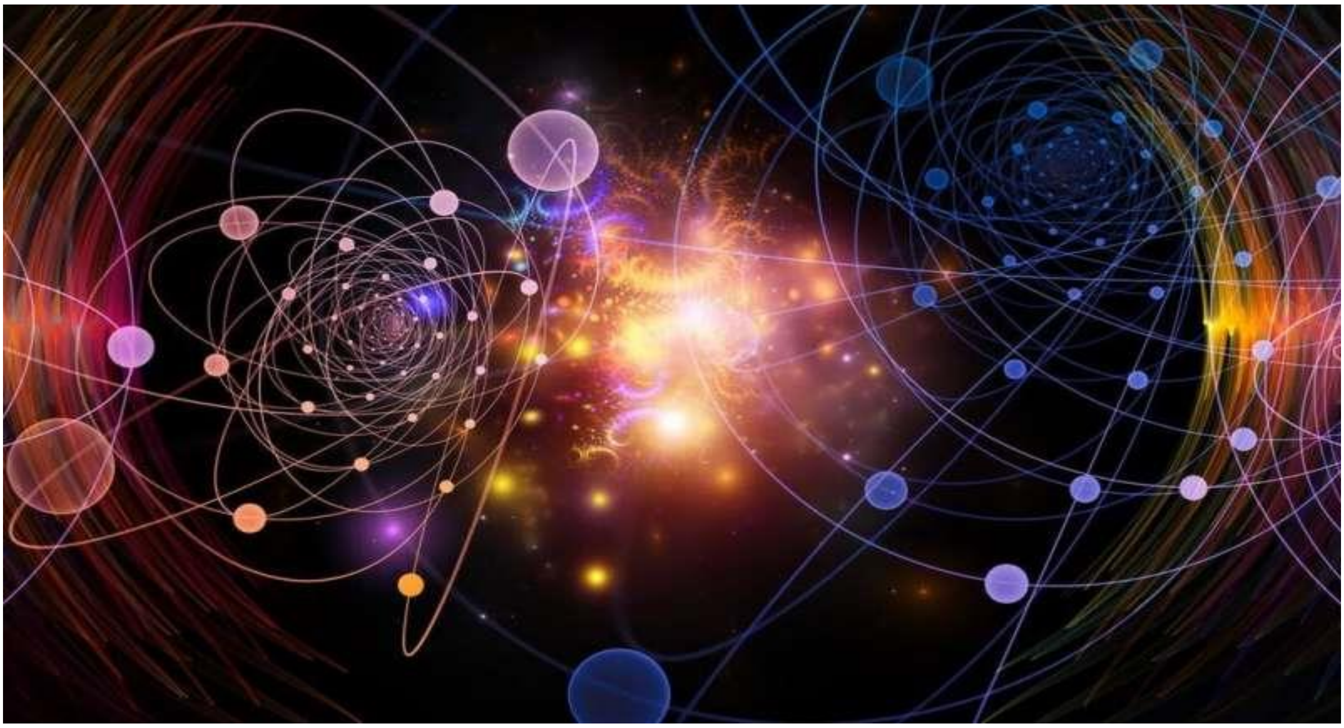

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0. Introduction

It was 1900 when the concept of quanta was first introduced by Max Planck [1], and 1932 when the Nobel Committee honoured Werner Heisenberg with the Nobel Prize “for the creation of quantum mechanics”. Since then, many great minds, have contributed to the improvement of quantum mechanics (QM), which now counts an enormous number of applications, from electronics to microscopy and biology, from cryptography to computing, from chemistry to optics, and more.

If on the one hand great consensus has been achieved on the mathematics of QM, much poorer is the consensus on the fundamental meaning of its laws, ultimately on the fundamental nature of the universe. Here, different interpretations of quantum mechanics will be discussed and compared: these are the Copenhagen, the ensemble, the many worlds, the hidden variables (in particular De Broglie-Bohm), the informational and the objective collapse interpretations. To do so, the major exponents of each interpretation have been invited to the discussion, while Albert Einstein will serve as moderator. Now I shall leave him the word.

I. Preliminary Information

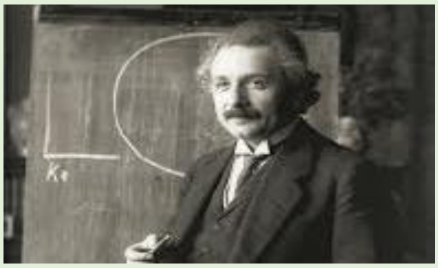
***Einstein**:* Welcome to the discussion. Before the meeting begins, let me make a concise but precise introduction to QM. In particular, the reader should have in their mind some of the principles *all* the interpretations of QM must rely upon:

- A system is described by a wavefunction $|\psi\rangle$. The wavefunction is the linear superposition of all the states (eigenstates) $|\phi_n\rangle$ the system can be found in:

$$|\psi\rangle = \sum a_n |\phi_n\rangle.$$

- A dynamical variable (observable) is represented by an operator, which returns a certain real value (eigenvalue) for each eigenstate. Those values are the possible outcomes of a measurement.
- When a measurement is performed, the probability of the wavefunction being in the n^{th} eigenstate, hence the result being the n^{th} eigenvalue is $|a_n|^2$ (Born's rule).

Know the Scientist: **Albert Einstein**

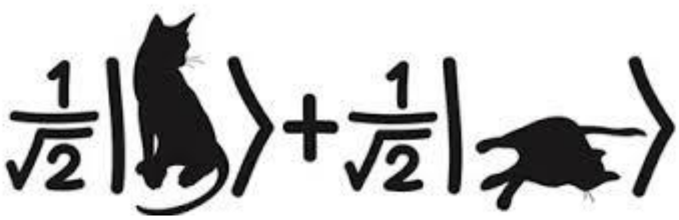


Einstein (1879-1955) is mainly known for Relativity, undoubtedly, one of the greatest intellectual achievements in human history. He also made fundamental contributions to physics as the "always criticizing father" of QM (Nobel 1921) and many other fields.
Notable facts: His name and face became synonyms of science and genius.
In 1999 he was appointed by Time magazine "Person of the Century".

- The evolution in time of the wavefunction of an isolated system is deterministic, and it is described by the time dependent Schrodinger Equation (TDSE):

$$i\hbar\frac{\partial}{\partial t}|\psi\rangle = \hat{H}|\psi\rangle = -\frac{\hbar^2}{2m}\nabla^2|\psi\rangle + \hat{V}|\psi\rangle$$

where the RHS is the Hamiltonian operator applied on the wavefunction: the energy of the system.



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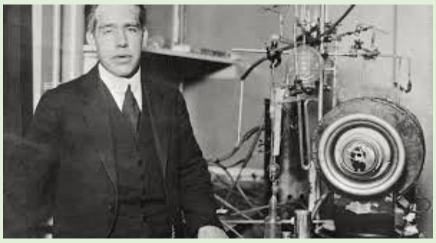
It will be appreciated that these laws leave room to some questions with uncertain answer. Regarding the wavefunction I may want to ask, off the top of my head:

- What is the ontological nature of the wavefunction?
- Ergo, is it an existing object or just a theoretical concept?
- Is the description provided by the wavefunction complete?

Or, about the concept of measurement:

- What mechanism governs the measuring process?
- How is it possible the results of a measurement are coherent with the others if the wavefunction has a probabilistic nature?
- What is a measuring observer?
- How does a system evolve in time when not isolated, hence when interacting with an observing external system?

Know the Scientist: **Niels Bohr**



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Bohr (1885-1962) was a Danish physicist. First known for the eponymous model of the atom (Nobel 1922), he immensely contributed to laying the foundations of QM, and further expanding it.

Notable facts: like his brother, Bohr was a passionate footballer (goalkeeper) [4].

After he won the Nobel, Carlsberg donated him free beer [5]. His son Aage won the Nobel as well, in 1975, but received no free beer.

II. The Copenhagen Interpretation (CI)

Einstein*:* The first of the interpretations which will be assessed is the Copenhagen Interpretation (CI), being it, perhaps, the most diffused and accepted. Being developed in the 20s, let me leave the word to one of its founders, my old friend Niels Bohr.

Bohr*:* Thank you. I will proceed by assessing your legitimate questions. First, I would like to point out I believe the wavefunction offers a *complete* description of the system it refers to [2]. There is no room for hidden entities.

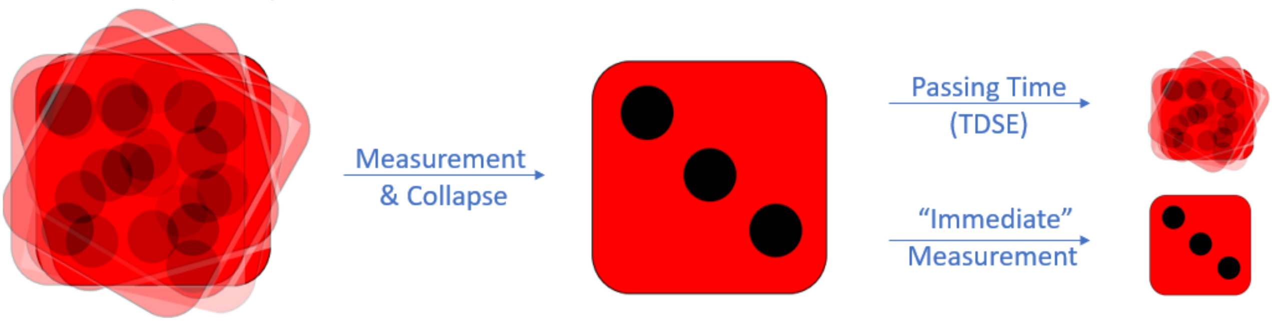
However, the reader should not fall into the misleading conception the wavefunction coincides with the object: the object is real, the wavefunction is just a theoretical computational tool [3]. If we want to say it in a formal way, it has an epistemic nature, not ontic [*Bruises in the room*].

Regarding the measurement problem, we know the wavefunction of an isolated system exists as a superposition of different eigenstates: I believe the same holds for the system itself. Consider a hypothetical "quantum dice": before being observed, it exists as a superposition of 6 possible states. Once observation occurs, both the wavefunction and the system itself collapse [*Other bruises in the room*] onto one of the eigenstates. Mathematically, if the m^{th} eigenvalue is measured, the wavefunction has collapsed onto the m^{th} eigenstate:

$$|\psi\rangle = |\phi_m\rangle.$$

Once the value of the dice is observed being, say, 3, the dice uniquely exists in the 3-state. Then, if no measurement is performed, it will evolve according to TDSE and again tend to be in a superposition of states, otherwise, if it is observed immediately after, it will still be in the 3-state.

The Copenhagen's "Quantum" Dice



A quantum dice would live in a superposition of all its states, each associated to a certain probability, generally evolving in time. A measurement would force the dice to collapse into one of the states, say 3. Performing immediately after that same measurement would give the same result. Passing time would instead "shuffle" the states again.

Now, what do we mean for observer? In CI, an observer behaves classically [3], and probably there's no better definition than my [*hesitates*] … colleague's, Heisenberg:

"The observer has, rather, only the function of registering decisions, i.e., processes in space and time, and it does not matter whether the observer is an apparatus or a human being; but the registration, i.e., the transition from the "possible" to the "actual," is absolutely necessary here and cannot be omitted from the interpretation of quantum theory." [6]

III. The Ensemble Interpretation (EI)

Einstein*:* Thank you Niels, your treatise was clear and complete. Now my friend Max Born will speak about the ensemble (or statistical) interpretation (EI).

Born: Thanks. The EI is among all, I believe, the most minimalist interpretation, as fewest assumptions are made [7]. I believe the wavefunction naturally characterizes not a single system, but an ensemble of equally prepared systems [7], in other words not *one* roll of dice, but *multiple*. Follows that no mysterious collapse needs to be postulated.

Einstein*:* Many unnatural theoretical interpretations of QM become immediately unnecessary assuming the description refers to ensembles [8], but how does EI then deal with single systems?

Know the Scientist: **Max Born**

Churchill Archives Center

Born (1882-1970) was a German physicist, who importantly contributed to the foundation and definition of the principles of QM (Nobel 1954) but whose contributions to physics also extend to other fields.
Notable fact: Many great scientists of the last century figure among his students or assistants. [9]

Born: In the same way probability deals with a single roll of dice: it predicts the *probability* of the outcome, not the outcome itself. Predicting the outcome only becomes possible when dealing with multiple trials.

Bohr: And how big should *n* be so that a group of objects is an appropriate ensemble, if I may ask?

Born*:* I'm worried that depends on the experiment being performed. In general, the bigger, the better.

Know the Scientist: **Hugh Everett III**

[11]

Everett III (1930-1982) was an American physicist. After the development of MWI, he dedicated to military research.
Notable fact: "He ate, smoked and drank as he pleased", but "he lived good life and was satisfied". [12]

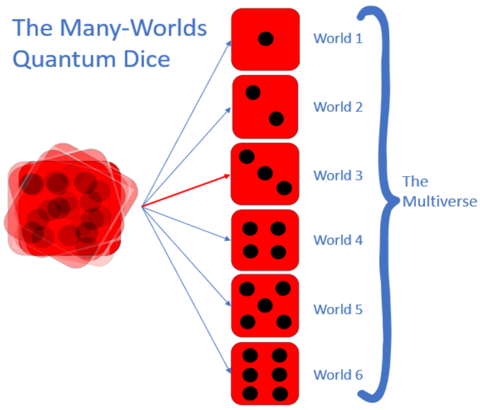
IV. The Many-Worlds Interpretation (MWI)

Einstein: Thanks, now let me introduce you the many-worlds interpretation, one of the most controversial but "attractive" physical theories. When introduced by Hugh Everett in 1957 [10] it was met with criticism or indifferency, now it's widely renowned. Let me leave the word to his founder.

Everett: I will be direct: I disagree with everything Bohr said [*Utter silence and stunned expressions all over*]. The idea of the collapse is weird and unmotivated, an *ad hoc* mechanism. The figure of the observer in his theory is ambiguous. The idea the wavefunction isn't real, quite controversial.

The wavefunction describes everything we can know about the object, right? Then why should they not coincide? This is my first assumption: the wavefunction is real, coinciding with the object itself. [10] Ultimately, the totality of the existence coincides with a universal wavefunction [*Bohr mutters*]. Secondly, as QM is assumed being complete, both the measurand system S and the measuring apparatus M have a quantum wave-like behaviour. [10]

Then, when a measurement is performed, M and S interact with each other and entangle to themselves defining a composite system MS. Additionally, MS is entangled with the whole rest of the universe (or perhaps I should say multiverse) [*smiles*] in the terms of the universal wavefunction. MS exists in multiple states, one for each possible outcome of the measurement. Therefore, due to their entanglement, the universal wavefunction as well, hence the whole existence too, exists as a superposition of multiple states, one for each outcome. Every time an observation-like event occurs, the universe splits into multiple branches, also called "histories", each one existing *independently* of the others: they cannot interact with each other. [10]

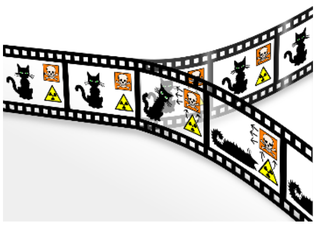


For each outcome, a world. If we observed the 3-state, for Copenhagen's all other histories are "cancelled"; for MWI the other histories exist and are observed in other worlds.

If I can reprise the previous example, when the quantum dice is rolled and consequently observed, 6 different and non-interacting worlds will arise, one for each outcome.

Since the worlds cannot interfere, any thinking individual will only have memory of its own world and history, and, for that reason, nature will appear probabilistic and characterised by a wavefunction collapse sort of thing. However, from a God-eye point of view, there is no such thing as collapse, the evolution of the multiverse is deterministic, uniquely determined by the initial state of the universal wavefunction and TDSE, and everything (literally everything) that could physically happen, has happened, in multiple worlds. This may appear as the weirdest idea, instead it's the more logical of them all.

Oh… one last thing … quantum suicide [13]. It's the idea of investigating QM interpretations by putting yourself in Schrodinger's cat box multiple times: if MWI is true, there will be one universe arising from the experiment where you survive an extraordinarily huge number of times (but you die earlier in all the others). If MWI is false, your only "copy" almost surely eventually dies. I recommend you not trying it but assisted suicide clinics may consider this.



Christian Schirm (Chrischi on Wikipedia)

V. The Hidden Variables and De Broglie-Bohm Interpretations (BBI)

Einstein*:* Thanks, your point of view was certainly unusual… but clear, and well defined. Now I would like to briefly treat hidden variables theories (HVT), which assume QM is incomplete as some unobservable entities guide the evolution of the system. Then, the non-deterministic behaviour of QM would just reflect our lack of knowledge [14].

In 1927, I attempted to create a deterministic theory myself [16], but it involved some "spooky action at a distance" [17][18] that deeply concerned me. Similarly, De Broglie presented a HVT at the 5th Solvay Conference, but "discouraged by criticisms" [19], abandoned it shortly after. His theory was expanded by David Bohm in 1952 [20]. Professor…

Know the Scientist: **David Bohm**

[15]

Bohm (1917-1922) was an American physicist. Beyond physics, his work is notable for his philosophical and neuropsychological theories and unorthodox ideas.

Notable fact: his younger communist ideals made him leave USA In the 50s.

Bohm: Briefly, this theory postulates the existence of a pilot wave, corresponding to a guiding equation, which, based on the wavefunction, determines the evolution of the configuration of the system (made of particles). Such configuration is *always* well defined, but due to our lack of knowledge, it appears blurred. The guide equation results hidden to us. [21]

When I proposed it, it received mostly bad reviews: Heisenberg defined it "superfluous ideological structure" [22] and W Pauli "artificial" [23]. I shared the idea it was contrived [24] …

Everett*:* I must say I share those critics: if the wavefunction is real, then the associated particle is superfluous: the pure wave theory is itself satisfactory" [25].

Bohm*:* I don't think simplicity or superficiality are the correct grounds of scientific enquiry. We cannot tell God to play with Ockham Razor [*Einstein and Bohr smile*].

Know the Scientist: **John A Wheeler**

Institute for Advanced Studies

Wheeler (1911-1992) was an American physicist. Awarded many prizes (but never the Nobel) his work extended from QM to General Relativity.

Notable fact: he gave prime importance to teaching and many great scientists figure among his students. [27]

VI. The Informational Interpretations (II)

Einstein: Yes, presumably we cannot tell God how to play… after all, it's the reason we are here, isn't it? Now let's consider a totally different perspective: the informational interpretation. I leave the word to John Wheeler.

Wheeler: Yes, informational theories ask us to radically shift the perspective we look at things.

In general, they assume, as CI, that the wavefunction is a computational tool. However, it is not considered as directly describing the system itself, but rather the *knowledge* we have of it. It's not a property of the object, but it is that information required to make predictions of it [26].

Then, the collapse is not a real physical process: it only occurs in the observer simply because it's *all* a construct of the observer itself. [28]

Everett: Don't you think, professor, there should be something more? Something real underneath?

Wheeler: Well, why can't information be the real thing underneath?

You see, in my "it from bit" theory, I assume the "it" (the particles, waves and fields) follows from the "bit" (the information), which is itself the core of existence [29]. Thus, the observer is participatory in the creation of the universe.

Adapted from depositphotos.com

VII. Objective Collapse Interpretations (OCI)

Einstein: Now, the very last theory we will be treating is objective collapse interpretations (OCI). Professor Penrose…

Penrose: Very briefly, they assume the standard TDSE is an approximation which should be supplemented with additional (nonlinear stochastic) terms which would incorporate and physically explain the collapse behaviour of reality.

These terms become negligible for standard quantum isolated systems, whereas dominate in the case of classically behaving systems, thus matching our experience. [29] Among these there are GRW, CSL and (my) DL models. In particular, in my model it would be quantum gravity the origin of the additional terms, hence the collapse.

They have the advantage they could be tested, provided our testing equipment is precise enough. Two last notes: work is in progress to make them match relativity, and … they would violate energy conservation [*Murmurs all over*].

Know the Scientist: **Roger Penrose**

Photograph: Anthony Howarth/Science Photo Library

Penrose (1931) is a British physicist. His work mainly concerns the fields of Cosmology, gravity and blackholes (Nobel in 2020).

Notable fact: he also has a great passion for mathematical games and tiling theory.

VIII. Conclusions

***Einstein**:* Perfect … now, before I objectively collapse [*chuckles*]… I'm sorry… [*chuckles even more*] we can conclude our meeting. As predicted, the interpretations diverge on multiple issues, majorly the fundamental nature of the wavefunction and of the observer, and the idea of collapse. Hopefully, the table I prepared will provide a clear summation of the main points and differences between those interpretations.

THE INTERPREATIONS' MAIN FEATURES

Theory	Ontic Wavefunction	Collapse	Deterministic Behaviour	Observer's Role	Supplement Entities/Terms
Copenhagen	NO	YES	NO	YES	NO
Ensemble	NO	NO	Agnostic	NO	Agnostic
Many-Worlds	YES	NO	YES	NO	NO
De Broglie-Bohm	YES	NO	YES	NO	YES
Informational	NO	YES	Agnostic	YES	NO
Objective Collapse	YES	YES	NO	NO	YES

It must also be noted other interpretations have been formulated. All the interpretations are designed to meet the empirical observations, and unfortunately no practical experiment has been designed (yet) able of proving or disproving any of them.

Whether are we doomed to only being able of "shutting up and calculating" [30] or not, the future will tell us. Thank you for your participation.

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