Quantum mechanics: measurement problem

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The puzzle of measurement

Feynman, R. P., 'Simulating physics with computers', *International Journal of Theoretical Physics* 21 (1982): 467-88.

> *"[We] always have had (secret, secret, close the doors!) we always have had a great deal of difficulty in understanding the world view that quantum mechanics represents. At least I do, because I'm an old enough man that I haven't got to the point that this stuff is obvious to me. Okay, I still get nervous with it... you know how it always is, every new idea, it takes a generation or two until it becomes obvious that there is no real problem. It has not yet become obvious to me that there's no real problem. I cannot define the real problem, therefore I suspect there's no real problem, but I'm not sure there's no real problem." (471)*

The 'standard' view: Copenhagen interpretation

The Copenhagen interpretation consists in something like the following assertions:

1. reduction of the wave function, dynamical collapse (Principle E)
2. Born's statistical interpretation of the wave function (Principle D)
3. indeterminism (as a result of these two)
4. Bohr's correspondence principle
5. Bohr's complementarity

Bohr: the correspondence principle

Bohr, Niels (1949). Discussion with Einstein on epistemological problems in atomic physics. In P.A. Schilpp (ed.), *Albert Einstein: Philosopher-Scientist*. Open Court, pp. 199-241.

Principle (Correspondence (CP))

Classical physics and quantum physics must give the same predictions for 'large systems'. More precisely, quantum and classical physics agree in the so-called classical limit, i.e. when the quantum numbers characterizing the system are large.

- CP constrains construction of QT by quantization recipes in that it gives special status to those operators corresponding to classical magnitudes and identifies incompatible pairs of them
- The CP as understood by Bohr implies that there are two realms, the classical and the quantum.

Como 1927: complementarity

International Physics Congress, Como (Italy), September 1927

> *"...it is decisive to recognize that, however far the phenomena transcend the scope of classical physical explanation, the account of all evidence must be expressed in classical terms...*
>
> *"This crucial point... implies the impossibility of any sharp separation between the behaviour of atomic objects and the interaction with the measuring instruments which serve to define the conditions under which the phenomena appear. In fact, the individuality of the typical quantum effects finds its proper expression in the circumstance that any attempt of subdividing the phenomena will demand a change in the experimental arrangement introducing new possibilities of interaction between objects and measuring instruments which in principle cannot be controlled.*

"Consequently, evidence obtained under different experimental conditions cannot be comprehended within a single picture, but must be regarded as complementary in the sense that only the totality of the phenomena exhausts the possible information about the objects.

"Under these circumstances an essential element of ambiguity is involved in ascribing conventional physical attributes to atomic objects, as is at once evident in the dilemma regarding the corpuscular and wave properties of electrons and photons, where we have to do with contrasting pictures, each referring to an essential aspect of empirical evidence." (op. cit., 209f)

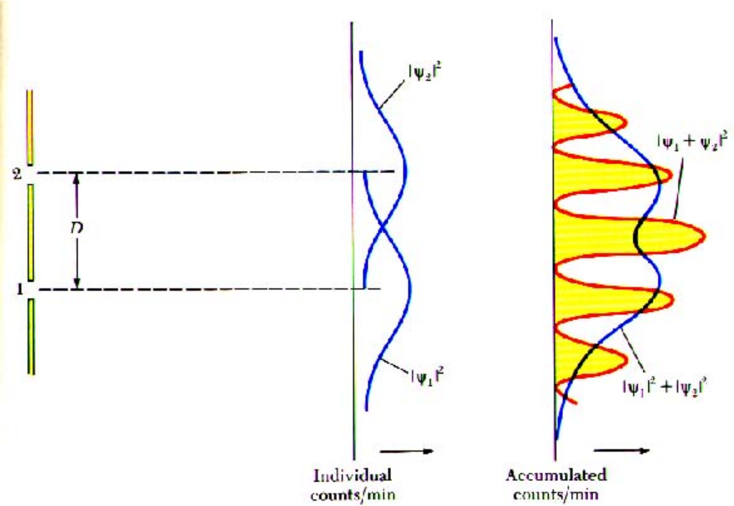
Principle (Complementarity)

A quantum mechanical object can have seemingly contradictory properties, exhibiting different ones in different experiment settings. For example, depending on the experimental set-up, a single quantum-mechanical object can either behave in a particle-like or a wave-like manner, but not simultaneously as both. The particle-like and the wave-like behaviour, for which the particle has a real propensity or disposition, are mutually exclusive in the sense that they can never be observed simultaneously.

Comments:

- Complementarity does not merely restrict what we can know about the properties of a physical entity, but it imposes limits to that entity's very manifestation of the property in the physical world.
- All properties of a quantum-mechanical system come in complementary pairs, corresponding to pairs of incompatible properties as declared by the uncertainty relation.

Illustration: double slit experiment



The problem with the standard view of QM

In a nutshell

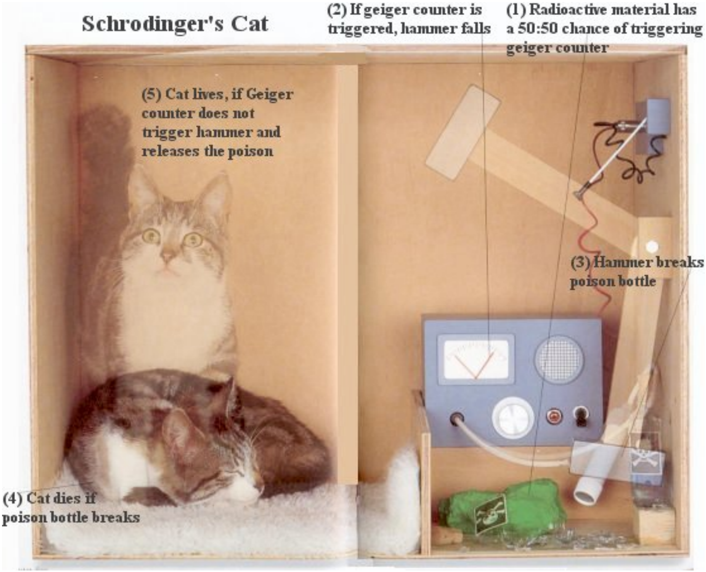
Principle C asserts that the dynamics of any quantum system is described by the Schrödinger equation, which is a linear and deterministic equation. Principle E asserts that whenever a measurement is made upon a quantum system, its state collapses into an eigenstate of the measured observable. This collapse is non-linear and indeterministic. As stated, the two Principles are thus incompatible. They could be made compatible if we gave a precise and complete dynamical prescription for all quantum systems in all circumstance, e.g., by giving necessary and sufficient conditions for what is a 'measurement' and what the precise collapse dynamics is.

Schrödinger's cat

📄 Schrödinger, E., 'Die gegenwärtige Situation in der Quantenmechanik' ('The present situation in quantum mechanics'), *Naturwissenschaften* 23 (1935): 807-812; 823-828; 844-849.

"One can even set up quite ridiculous cases. A cat is penned up in a steel chamber, along with the following device (which must be secured against direct interference by the cat): in a Geiger counter there is a tiny bit of radioactive substance, so small, that perhaps in the course of the hour one of the atoms decays, but also, with equal probability, perhaps none; if it happens, the counter tube discharges and through a relay releases a hammer which shatters a small flask of hydrocyanic acid. If one has left this entire system to itself for an hour, one would say that the cat still lives if meanwhile no atom has decayed. The psi-function of the entire system would express this by having in it the living and dead cat (pardon the expression) mixed or smeared out in equal parts.

"It is typical of these cases that an indeterminacy originally restricted to the atomic domain becomes transformed into macroscopic indeterminacy, which can then be resolved by direct observation. That prevents us from so naively accepting as valid a 'blurred model' for representing reality. In itself it would not embody anything unclear or contradictory. There is a difference between a shaky or out-of-focus photograph and a snapshot of clouds and fog banks."


Schrodinger's Cat
(2) If geiger counter is triggered, hammer falls
(1) Radioactive material has a 50:50 chance of triggering geiger counter
(5) Cat lives, if Geiger counter does not trigger hammer and releases the poison
(3) Hammer breaks poison bottle
(4) Cat dies if poison bottle breaks

Barrett, J., *The Quantum Mechanics of Minds and Worlds*, Sec. 2.5, particularly pp. 43f.

- After exactly one hour, the cat is in the superposition state

$$\frac{1}{\sqrt{2}}|\text{alive}\rangle + \frac{1}{\sqrt{2}}|\text{dead}\rangle, \tag{1}$$

  but to have a macroscopic object like a cat in a superposition state like this seems bizarre...
- So, we could insist on definite measurement outcomes (and linear dynamics), but that would mean that the quantum state (the wave function) of the cat is not complete (there is a fact of the matter whether the cat is dead or alive).
- Copenhagen orthodoxy: Our act of observation collapses the superposition to one of its terms, making the cat definitely dead or alive.
- It is somehow our lifting of the lid of the box that causes the collapse.
- OK, but it gets weirder...

Eugene Wigner (1902-1995) and his friend

- Hungarian physicist and mathematician, fled to the US
- Nobel 1963 "for his contributions to the theory of the atomic nucleus and the elementary particles, particularly through the discovery and application of fundamental symmetry principles"
- What causes the collapse of the wave function?
- Answer: the consciousness of the observer

⇒ Wigner's 'idealism'

- Illustration: the paradox of Wigner's friend

Wigner's friend

Barrett, J., *The Quantum Mechanics of Minds and Worlds*, Sec. 2.6. (great source for this material).

- Suppose you put one of Wigner's friends in the box with the cat. Measurement: ask the friend whether the cat is alive or dead.
- If we consider your friend as part of the experimental setup, quantum mechanics predicts that before you ask Wigner's friend whether the cat is dead or alive, he is in a superposition of definitely believing the cat is dead and definitely believing that the cat is alive.

⇒ absurd consequence of Bohr's view

- Wigner's solution: there is a natural division between what constitutes a measurement and what does not—the presence of a conscious observer, and of course the friend is conscious.

- Not popular because it raises many conundrums: does the cat have consciousness?
- More seriously, Wigner's view requires a division of the world into two realms, one occupied by conscious beings who are not subject to the laws of physics but who can somehow miraculously disrupt the ordinary deterministic evolution of the physical systems, and the other by the physical systems themselves, which evolve deterministically until a conscious being takes a look at what's going on.
- Problem: Copenhagen requires such a division between system and the classical world of observation reports...

Albert's formulation of the measurement problem

Albert, Ch. 4.

- Suppose that everything evolves according to the Schrödinger equation.
- Suppose we have a hardness measuring device: device with dial with three settings ('ready', 'hard', 'soft').
- Set the device such that it reads 'ready' and then feed e^- into it, and they get their hardnesses measured. These measurements are recorded by final position of dial ('hard' or 'soft').
- Assumptions entail that it must act such that:

$$\begin{aligned} |\text{ready}\rangle_m |\text{hard}\rangle_e &\longrightarrow |\text{`hard'}\rangle_m |\text{hard}\rangle_e \\ |\text{ready}\rangle_m |\text{soft}\rangle_e &\longrightarrow |\text{`soft'}\rangle_m |\text{soft}\rangle_e \end{aligned} \tag{2}$$

where the subscripts *m* and *e* designate the states of the measuring device and the electron, respectively.

⇒ from (1) and (2) and the linearity of the Schrödinger equation, it follows that a black state evolves, with certainty, into

$$\frac{1}{\sqrt{2}}|\text{'hard'}\rangle_m|\text{hard}\rangle_e + \frac{1}{\sqrt{2}}|\text{'soft'}\rangle_m|\text{soft}\rangle_e \tag{3}$$

- (Verify for yourself that this is the case.)
- But if we assume that measurements have definite outcomes, then by the postulate of collapse (Postulate E), and by Born's rule (Postulate D) for the probabilities, we get

$$\begin{array}{lll} \textit{either} & |\text{'hard'}\rangle_m|\text{hard}\rangle_e & \text{(with probability 0.5)} \\ \textit{or} & |\text{'soft'}\rangle_m|\text{soft}\rangle_e & \text{(with probability 0.5)} \end{array} \tag{4}$$

- But this is measurably different from (3)!
- (4) has definite outcomes but violates the Schrödinger equation, while (3) is a state in which there is no matter of fact about where the pointer is pointing...

A "somewhat sharper" formulation

- Introducing Martha who is a competent observer, i.e. the Schrödinger equation entails that Martha (= physical system, whose state is indicated by subscript o) behaves like this:

$$\begin{aligned}
|\text{ready}\rangle_o|\text{ready}\rangle_m &\longrightarrow |\text{`ready'}\rangle_o|\text{ready}\rangle_m \\
|\text{ready}\rangle_o|\text{`hard'}\rangle_m &\longrightarrow |\text{`hard'}\rangle_o|\text{`hard'}\rangle_m \\
|\text{ready}\rangle_o|\text{`soft'}\rangle_m &\longrightarrow |\text{`soft'}\rangle_o|\text{`soft'}\rangle_m
\end{aligned}$$

  where $|\text{ready}\rangle_o$ is the physical state of Martha when she is alert and intent on reading off the pointer setting, $|\text{`xyz'}\rangle_o$ is her physical state in which she believes that the pointer is pointing to 'xyz'.

- From the competence of the observer, and the linearity of Schrödinger's equation, it follows that when Martha has read off the pointer reading for state (3), the overall state will be, with certainty,

$$\frac{1}{\sqrt{2}}|\text{`hard'}\rangle_o|\text{`hard'}\rangle_m|\text{hard}\rangle_e + \frac{1}{\sqrt{2}}|\text{`soft'}\rangle_o|\text{`soft'}\rangle_m|\text{soft}\rangle_e \qquad (5)$$

- But again, the requirement for definite measurement outcomes (essentially Postulates D and E), entails that when Martha is done, then

$$\begin{array}{lll} \textit{either} & |\text{`hard'}\rangle_o|\text{`hard'}\rangle_m|\text{hard}\rangle_e & \text{(with probability 0.5)} \quad (6) \\ \textit{or} & |\text{`soft'}\rangle_o|\text{`soft'}\rangle_m|\text{soft}\rangle_e & \text{(with probability 0.5)} \end{array}$$

- But again: (5) and (6) are empirically different, only (6) is empirically correct; (5) is "unspeakably strange": "it's a state in which there is no matter of fact about whether or not Martha thinks the pointer is pointing in any particular direction." (79)
- And (5) is really strange: "This is a state wherein... it isn't right to say that Martha believes that the pointer is pointing to 'hard,' and it isn't right to say that Martha believes that the pointer is pointing to 'soft,' and it isn't right to say that she has both of those beliefs (whatever that might mean), and it isn't right to say that she has neither of those beliefs." (79fn)

⇒ The Postulate of Dynamics (Postulate C) and the Postulate of Collapse (Postulate E) are in flat contradiction.

Maudlin's first problem: the problem of outcomes

Maudlin, *Topoi* 14 (1995): 7-15.

Theorem (Measurement Problem 1 (MP1))

"The following three claims are mutually inconsistent.

1.A *"The wave-function of a system is complete, i.e. the wave-function specifies (directly or indirectly) all of the physical properties of a system.*

1.B *"The wave-function always evolves in accord with a linear dynamical equation (e.g. the Schrödinger equation).*

1.C *"Measurements of, e.g., the spin of an electron always (or at least usually) have determinate outcomes, i.e., at the end of the measurement the measuring device is either in a state which indicates spin up (and not down) or spin down (and not up)." (7)*

'Proof.' Essentially along the lines of Albert's chapter 4, e.g. if 1.A is true, and thus the wave function must specify every physical fact about the measuring device, and 1.B is true, then 1.C must be false, etc. □

Taxonomize the solutions to MP1

1. Hidden-variable theories deny 1.A, since they postulate more reality than is represented in $|\psi\rangle$
    - Examples: Bohm's theory, modal interpretations such as van Fraassen's (1991)
    - less tendentious: additional variables (AV) theories
2. Collapse theories abandon 1.B, since they assert that dynamics is, at least sometimes, non-linear
    - Examples: Copenhagen, Spontaneous Localization theory of Ghirardi, Rimini, Weber (1986) (GRW); Continuous Spontaneous Localization theory of Perle (1990)
    - less tendentious: non-linear theories
3. Multiverse theories reject 1.C, since they maintain that measuring devices indicate both (or all) outcomes
    - Examples: many-world theories, Everett's Relative State interpretation (1957)
    - logically possible: 'nulliverse' theory

New physics

- A solution to MP1 must thus by necessity either be a AV theory, a non-linear theory, or a multiverse theory (or some combination thereof).

⇒ each option involves the postulation of new physics:

1. AV theories must specify what additional variables there are and what dynamical laws govern them
2. Non-linear theories must provide the non-linear dynamical equations and specify under when exactly they apply (something the Copenhagen interpretation did not do)
3. Multiverse theories must explain why it seems as if there are definite outcomes; in other words, they must answer why Schrödinger's cat seems either definitely alive or definitely dead

Maudlin's second problem: the problem of statistics

- Strictly speaking, the three claims in MP1 are not logically inconsistent:
- We could say that for any superposition state the detector outcome is 'UP'.
- A bit less crude: the detector outcome is determined by the term with largest coefficient (in all cases), 50-50 superposition states are of measure zero
- But any such brute force solution of MP1 seems to run afoul a new problem...

Theorem (Measurement Problem 2 (MP2))

"Formally, the following three claims are mutually inconsistent:

2.A *"The wave-function of a system is complete, i.e. the wave-function specifies (directly or indirectly) all of the physical properties of a system.*

2.B *"The wave-function always evolves in accord with a deterministic dynamical equation (e.g. the Schrödinger equation).*

2.C *"Measurement situations which are described by identical initial wave-functions sometimes have different outcomes, and the probability of each possible outcome is given (at least approximately) by Born's rule." (11)*

'Proof.' If the wave-function always evolves deterministically (2.A), then two systems with identical initial wave functions will have identical final wave functions. Since wave functions are complete (2.A), this identity would be total. Particularly, they cannot contain detectors indicating different outcomes, contra 2.C. □

1. An AV theory solves MP2 by denying 2.A: systems with identical wave functions may still be physically different, and thus lend themselves to different outcomes
    - But the additional variables would have to be manifest, i.e. having an observable effect on the pointer of the measurement device.
2. Non-linear theories solve the problem by assuming an indeterministic evolution (by denying 2.B).
    - In the standard interpretation and in GRW theory, collapses are postulated to be irreducibly stochastic.
3. But multiverse theories face a difficulty: they cannot make sense of Born's rule and thus cannot reproduce actual quantum-mechanical measurements.

The difficulty of multiverse theories with probabilities

- How can a multiverse theory mark a difference between a 50-50 superposition and a 75-25 superposition?
- Maudlin: they can't, and that's the deep reason why they fail.
- Problem: in 75-25 case, it can't mean that the two worlds corresponding to the different outcomes are unequally likely, since they both exist.
- Typical answer: somehow, those branches in which the observed long-time frequencies of very long (infinite?) sequences of measurements match those predicted by Born rule get assigned a probability that approaches 1.
- Maudlin: this constitutes a petitio principii (i.e. it begs the question): every one of the branches is equally likely to occur (with probability 1)

"There is, in the Many Worlds picture, simply nothing for the numbers generated by Born's rule to be probabilities of, and this problem is not ameliorated if those numbers approach 1 or 0. The denial of 2.C... cannot be reconciled with the quantum theory as it is used to make predictions. Without also employing either additional variables or a non-linear, stochastic evolution of the wave-function, the multiverse (or nulliverse) views cannot solve our problems, and if they do invoke either of these, then the postulation of the many worlds is sheer extravagance." (12)

Concentrating on the first two option, we thus find that

> *"[a]s J. S. Bell succinctly put it, 'either the wave-function, as given by the Schrödinger equation, is not everything, or it is not right'... Putting together the two problems, we can say that whatever new physics we invent to solve the measurement problem, it must be so constructed that (a) measurements typically have outcomes and (b) probabilities are assigned to those outcomes which at least approximate the probabilities derived by use of Born's rule. These conditions supply the standard by which one can evaluate new theories." (12)*

Maudlin's third problem: the problem of effect

- Some interpretations, such as van Fraassen's modal interpretation and Richard Healey's interpretation, manage to solve MP1 and MP2, but not MP3:

Theorem (Measurement Problem 3 (MP3))

The result of a measurement therefore has predictive power for the future: after the first measurement is completed we are in a position to know more about the outcome of the second than we could before the first measurement was made. Any theory which seeks to replicate the empirical content of the traditional theory should have this feature. Let us call this the problem of effect, to indicate the effect of the first measurement on the particle (or at least our knowledge of the particle).

- Bohm's theory and GRW, and perhaps others, can also solve this problem and thus survive the test...

Schrödinger on the collapse of the wave function

"If one has to stick to this damned quantum jumping, then I regret having ever been involving in this thing." (Jammer 1974: 344, ref.4, Pais 1988: 261)

The idea of a collapse

Albert, Ch. 5.

- Principle E ("collapse") suggests that there must be a collapse of the wave function.
- Important early work: John von Neumann, *Die mathematischen Grundlagen der Quantenmechanik* (1932)
- Neumann argued that there must two dynamical regimes:
    1. no measurements: dynamical laws of motion, Schrödinger equation
    2. when there are measurements occurring: dynamical evolution according to collapse postulate, not in accordance with dynamical laws
- Problem: what this really amounts to depends on exact meaning of term 'measurement'...

- Suppose we have a quantum state in an eigenstate of operator $\hat{A}$ and we make a measurement of $\hat{B}$ which doesn't commute with $\hat{A}$.
- We know: by the time the measurement is done (a sentient observer has formed a belief about what the measurement device indicates), there must have been a violation of dynamical law, i.e. a collapse
- Precisely when does the collapse occur?
- First attempt (by Wigner): always happens precisely at the level of consciousness
- Note that this proposal implies (substance) dualism.
- Problem: what precisely is conscious and what isn't?

- Second attempt: microscopicness (i.e. collapse occurs at the last ‘reasonable’ moment)
- Idea: whenever two macroscopically distinct states get superposed, the state collapses
- This proposal implies that there are two sorts of physical systems: (1) purely microscopic systems (those which don't contain macroscopic subsystems) that always evolve in accordance with the dynamical laws so long as there is no interaction with macroscopic systems; and (2) macroscopic systems that evolve according to more complicated laws of motion
- Problem: what precisely is ‘macroscopic’?

Couldn't we settle the issue empirically?

- Couldn't we observe precisely where and when the collapse (a physical event!) occurs?
- Albert consider the standard measurement setup (a black e^- is measured by a hardness box) to distinguish between two theories: one, T_1, entails that the collapse occurs when the measuring device becomes correlated with the e^-, the other, T_2, that collapse occurs at some later moment in time, e.g. when the light from the pointer reaches the retina of the observer
- He then shows that although there exists in principle a measurement that could distinguish between T_1 and T_2, it turns out to be extremely difficult to perform...

Conditions on a theory of collapse

Condition (i: Measurements have outcomes)

"We want [a theory of collapse] to guarantee that measurements... always have outcomes; we want it to guarantee... that there can never be any such thing in the world as a superposition of 'measuring that A is true' and 'measuring that B is true.' " (92)

Condition (ii: Statistical connection)

"We want it to preserve the familiar statistical connections between the outcomes of those measurements and the wave functions of the measured systems just before those measurements. That is, we want it to entail, or we want it at least to be consistent with, principle D." (93)

Condition (iii: Empirically correct dynamics)

"We want it to be consistent with everything which is experimentally known to be true of the dynamics of physical systems. We want it, for example, to be consistent with the fact that isolated microscopic physical systems have never yet been observed not to behave in accordance with the linear dynamical equations of motion, the fact that such systems, in other words, have never yet been observed to undergo collapses." (ibid.)

Ghirardi-Rimini-Weber (1986): the GRW theory

- search for physical mechanism of collapse
- outcomes are typically recorded in the position of something (e.g. tips of pointers, drops of ink on paper, etc.)

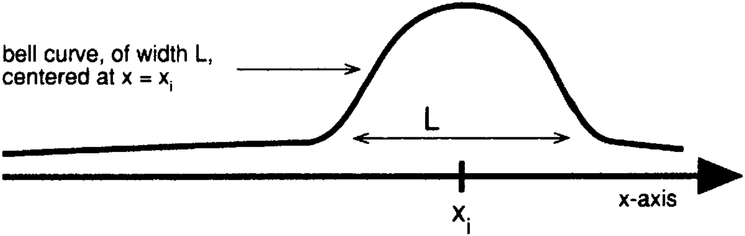
⇒ Can we construct a theory which entails that every macroscopic object always has some particular position?

- The GRW theory supposes that there exists, by natural law, a small, fixed probability for each quantum system independently that it will collapse during a unit time interval s.t. the position onto which it collapses is probabilistically determined by postulate D.
- In between collapses, a quantum system will evolve according to the Schrödinger equation.

The GRW theory

- The GRW theory thus entails that collapses almost never happen to isolated microscopic systems, but that states consisting of many, many particles, collapse almost certainly and almost immediately with the standard quantum mechanical probabilities.
- But what about uncertainty? If the position is precise, the momentum is maximally uncertain...
- But the GRW theory adds a slight modification that takes care of this:

"Stipulate that when a particle undergoes a collapse, what its wave function gets multiplied by isn't an eigenstate of the position operator but is rather a bell-shaped function like the one in figure 5.3...



"What we want from [collapses...] is to insure that macroscopic objects... almost invariably have almost determinate locations. And it turns out that this revised prescription can deliver that; it turns out that the bell curves can be made narrow enough so that whatever uncertainties there are in the positions of macroscopic things are almost invariably microscopic ones. And it turns out... that these curves can nonetheless be made wide enough... so that the violations of the conservation of energy and or momentum which the multiplication by these curves will produce will be too small to be observed." (97f)

Problems for the GRW theory

- So is everything fine? Not quite...
- Trouble: bell-curved functions are nonzero everywhere (although very small)

⇒ Strictly speaking: particles are still in superposition states of being all over the place and thus don't put anything even in approximately determinate locations.

⇒ The revised prescription cannot insure that measuring devices with pointers ever have definite outcomes...

- What needs to be explained is why putting the state vectors of pointers close to those with definite outcomes suffices for all relevant purposes.
- Also: GRW gives position an unjustified role as determining property.

David Bohm (1917-1992)

- Berkeley PhD 1943
- Princeton, U of Sao Paolo, Technion Haifa, U Bristol, Birkbeck College London
- In 1949, the House Un-American Activities Committee called upon Bohm to testify before it, but he pleaded the 5th amendment (right to decline to testify) because he didn't want to give evidence against any of his colleagues.
- was arrested in 1950 for non-cooperation with the Committee, but was acquitted in 1951
- Princeton refused to re-instate him, despite the pleads by Einstein

Bohm's theory in a nutshell

Albert, Ch. 7.

- (almost) exactly the same empirical content as standard QM
- much the same mathematical apparatus
- different metaphysics: "every material particle in the world invariably has a perfectly determinate position." (Albert, 134)
- deterministic dynamics
- dynamics only appear to be probabilistic, because of our epistemic limitations

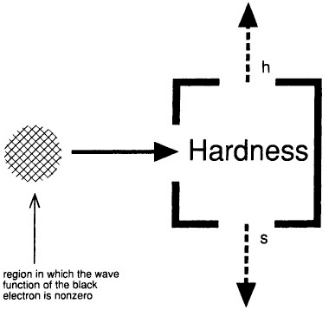
⇒ gives probabilities the same role as in classical physics

- wave functions are thought to be physical entities (although distinct from particles)—and not like a mathematical representation of a system's state

- wave functions are physical entities whose properties are their amplitudes at every given point in space
- dynamical evolution is completely governed by the linear Schrödinger equation, without nonlinear episodes of collapse
- wave functions 'push the particles around'
- additional laws in theory how this pushing, this 'guidance' happens

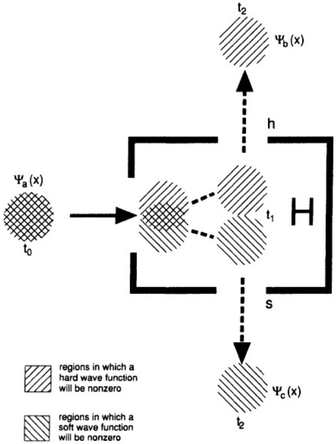
Application to concrete measurement situations

- look at measurements with spin boxes
- Main point: "all of the future positions of this electron... can in principle be determined, with certainty, from its present position" (145) (including the aperture from which the e$^-$ exits the spin box)



$$|\text{black}\rangle|\psi_a(x)\rangle \longrightarrow \frac{1}{\sqrt{2}}\left(|\text{hard}\rangle|\psi_b(x)\rangle + |\text{soft}\rangle|\psi_c(x)\rangle\right) \tag{7}$$

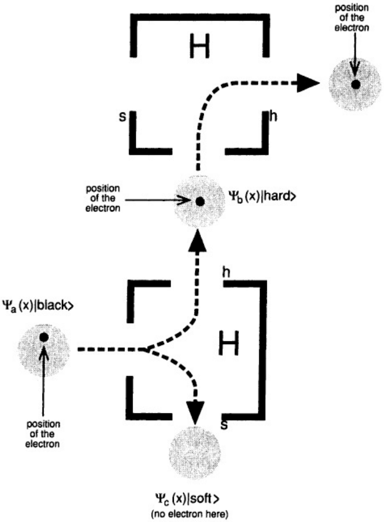
(indices to wave functions indicate the region where they are nonzero)



Wherever the particle exactly happens to be, it'll be carried along by the 'local currents' of the quantum-mechanical probability amplitudes. This entail that

> *"in the event that the electron starts out in the upper half of the region where $\psi_a(x)$ is nonzero, then it will ultimately emerge from the hard aperture of the box; and in the event that the electron starts out in the lower half of that initial region, then it will ultimately emerge from the soft aperture of the box." (147)*

If the e^- emerges from the hard (soft) aperture, and is subsequently fed into another hardness box (without permitting the hard and soft branches of the wave function to be reunited), it will, with certainty, emerge from the hard (soft) aperture of the second box because in between boxes, it moves through regions of space in which the amplitude of the soft (hard) part of the wave function is zero: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position of the electron
s
h
position of the electron
$\Psi_b(x)|\mathrm{hard}\rangle$
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$\Psi_a(x)|\mathrm{black}\rangle$
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position of the electron
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$\Psi_c(x)|\mathrm{soft}\rangle$
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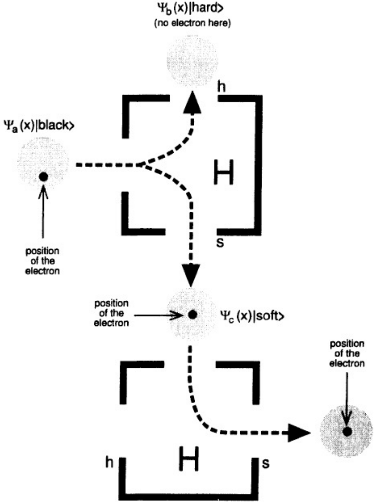
$\Psi_b(x)|\mathrm{hard}\rangle$
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$\Psi_c(x)|\mathrm{soft}\rangle$
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Central features of Bohmian mechanics (BM)

1. BM is contextual, i.e., measurement outcomes will depend not just on the particle's exact location and its wave function, but also on the detail of the measurement set-up (flipping the orientation of a hardness box may change the outcome!).

⇒ Properties other than position, such as hardness, colour, etc., are not intrinsic to particle/quantum system.

2. BM is non-local, i.e., the dynamical evolution of any particle will in general depend on the position of other particles in the universe.

⇒ BM stands in tension with special relativity, leading Albert to conclude that "taking Bohm's theory seriously will entail being instrumentalist about special relativity." (161)

Bohmian mechanics: in conclusion

"This is the kind of theory whereby you can tell an absolutely low-brow story about the world... in which the whole universe always evolves deterministically and which recounts the unfolding of a perverse and gigantic conspiracy to make the world appear to be quantum-mechanical.

"And that conspiracy works... like this: Bohm's theory entails everything that quantum mechanics entails... about the outcomes of measurements of the positions of particles in isolated microscopic physical systems; and moreover it entails that whenever we carry out a measurement of any quantum-mechanical observable whatever, then... the measured system... will subsequently evolve just as if that system's wave function has been collapsed, by the measurement, onto an eigenfunction... of the measured observable, even though as a matter of fact is hasn't been; and it also entails that the probabilities of those 'collapses' will be precisely the familiar quantum-mechanical ones." (169f)

Hugh Everett III (1930-1982)

- entered graduate school at Princeton in 1953
- One night in 1954, "after a slosh or two of sherry," he had a conversation with fellow grad student Charles Misner and Aage Petersen (long-time assistant to Bohr) during which he had the basic idea behind the many-worlds theory
- began to work these ideas into a dissertation under the supervision of J.A. Wheeler
- Spring 1956: Wheeler takes draft to Copenhagen to discuss it with the Master, Pedersen, and Alexander Stern

Princeton, 1955: Everett (second from right) with Niels Bohr and Charles Misner (first from left).

The drama of the dissertation

- After these deliberations, Wheeler wrote back to Everett: "Your beautiful wave function formalism of course remains unshaken; but all of us feel that the real issue is the words that are to be attached to the quantities of the formalism."
- Here's a taste of the "words": "From the viewpoint of the theory, all elements of a superposition (all 'branches') are 'actual,' none any more 'real' than the rest." (In a footnote of the dissertation draft)
- In a letter to Stern, Wheeler excused Everett's theory as an extension, not a refutation of the received Copenhagen wisdom...

Wheeler to Stern

"I think I may say that this very fine and able and independently thinking young man had gradually come to accept the present approach to the measurement problem as correct and self-consistent, despite a few traces that remain in the present thesis of a past dubious attitude. So, to avoid any possible misunderstanding, let me say that Everett's thesis is not meant to question the present approach, but to accept it and generalize it."

From many worlds to Mutually Assured Destruction

- Of course, Everett would have completely disagreed!
- In 1957, Wheeler made Everett delete all unorthodox passages from his draft, cut it to one quarter of the original length, and submit the tamed version.
- In April 1957, the committee accepted the abridged version.
- Discouraged, he left academia to work on military and industrial mathematics and computation.
- In 1959-60, he helped to draft classified report WSEG No. 50 which overthrew prevailing nuclear military strategy by establishing the result of a nuclear conflict with the Soviet Union as Mutually Assured Destruction.

The original relative-state formulation

- Everett: what if the dynamical evolution of a quantum system is always in accordance with the Schrödinger equation?

⇒ no collapse, solves the measurement problem by rejection of claim that there must be definite measurement results

⇒ doesn't rely on problematic distinction between micro- and macroworld or between object and observer or between conscious and non-conscious objects

- Instead: universal wave function, observer is inside the total system

⇒ Puzzle for Everett: how can we explain that the total system's (particle-apparatus-observer) being in a post-measurement state of entangled superposition of mutually incompatible records is in agreement with the empirical predictions made by standard QM?

- To this end, Everett presented a principle...

Principle (Fundamental Relativity of Quantum Mechanical States)

In the post-measurement superposition state, the observer records 'x-spin up' relative to the particle being in a state of x-spin up and 'x-spin down' relative to the particle being in a state of x-spin down.

- But this principle does not by itself provide the determinate measurement records predicted by standard QM.

⇒ gap between what Everett sets out to explain and what he delivers: "He set out to explain why observers get precisely the same sort of measurement records in his no-collapse formulation of quantum mechanics as predicted by the standard collapse formulation of quantum mechanics, but ends up describing a post-measurement observer who apparently does not have any particular measurement record." (Barrett 2014, SEP article on Everett, §3)

Three problems for the original relative-state theory

Barrett, Jeff (2014). Everett's relative-state formulation of quantum mechanics. *Stanford Encyclopedia of Philosophy*. `http://plato.stanford.edu/entries/qm-everett/`.

According to Barrett (2014), Everett's original relative-state theory suffers from three basic problems:

1. It offers no explanation of the sense in which the observer has, or appears to have, a determinate measurement record.
2. It fails to account for the standard probabilistic predictions of standard QM.
3. It is not empirically coherent, i.e. it doesn't explain how empirical justification for accepting it can be had when the world would in fact be faithfully described by it.

Various developments of Everett's original theory try to answer these three challenges, albeit in different contexts.

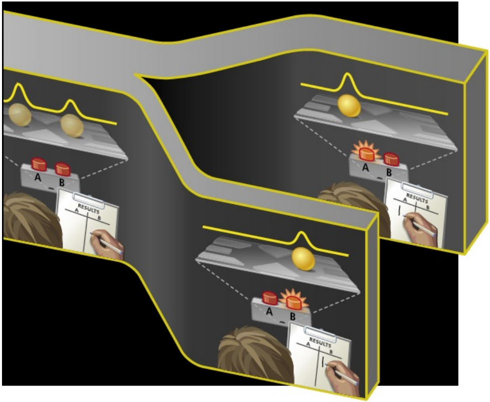
Developments of the bare theory

So given that the bare theory is, in Barrett's words, not empirically coherent, just like Everett's original formulation, let's look for ways to develop Everett's rejection of the collapse postulate and see where that leads us. Options:

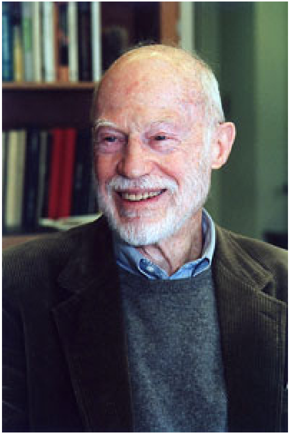
1. canonical many-worlds interpretation of DeWitt
2. many minds (Albert, Loewer)
3. many histories

(1) Many worlds (Bryce DeWitt)

DeWitt 1970, 1971, 1973.



- wave function describing system bifurcates at each interaction of observer with superposed object
- no interaction between branches (which each contains complete copy of system)
- today's explanation of how branches become independent: decoherence theory



Bryce DeWitt (1923-2004)

Of course, DeWitt's splitting of worlds whenever the states of systems become correlated is counterintuitive, as he freely admits:

> *"I still recall vividly the shock I experienced on first encountering this multiworld concept. The idea of* 10^{100} *slightly imperfect copies of oneself all constantly splitting into further copies, which ultimately become unrecognizable, is not easy to reconcile with common sense. Here is schizophrenia with a vengeance." (1973, 161)*

Problems of the many-worlds view

1. interpretational: very likely not how Everett conceived of his proposal, since Everett's original suggestion did not involve physical splitting of observers or other physical systems
2. ontological extravaganza
3. preferred-basis problem: this was already addressed as one of Albert's points of critique; it is a serious problem, and it's unclear as of yet whether there are completely satisfactory answers to it; most people in this camp use decoherence theory to solve this problem, i.e. tell a story about how the interaction of the system with the environment (settings on apparatus, etc) determines the basis along which splitting occurs.

4. getting the statistics right: also already discussed; there exist various proposals to resolve this issue, and it's debated whether they solve the problem; what is clear, though, is that Everett's own proposal of conceiving of these probabilities in the same way as in classical thermodynamics doesn't work without further assumptions.
5. potential incompatibility with special relativity: particularly those who maintain that the splittings are physical have great trouble reconciling it with SR; this is a deep and completely unresolved issue.