Foundational problems of quantum mechanics and a possible solution: Collapse Theories

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Sketch of the talk

- Linear character of the theory and objective properties of individual systems.

- Entanglement and the measurement (macro-objectification) problem.

- Entanglement, Nonlocality and the "spooky action-at-a-distance". QM vs SR.

- Various proposals to overcome the measurement Problem. In particular: "Collapse Models".

- Open problems and Perspectives.

An important premise

- I will deal essentially with nonrelativistic quantum theory. However, most of the difficulties affect also QFT and other recent approaches.

On the occasion of ICTP's 25° anniversary Bell recalled that Dirac divided the difficuties of quantum mechanics in First and Second Class Difficulties (my talk is devoted to those of the first class).

Dirac: … *when this new development occurs, people will find rather futile to have had so much of a discussion on the role of observation …*

Bell: *That's his opinion on the first class difficulties. He gives much comfort to those people who are worried about them. He sees that they exist and are difficult. Many of the founding fathers would not have admitted that.*

Bell then goes on reviewing the important steps in overcoming the Second Class and adds a comment concerning the First Class difficulties.

Bell: *There have also been developments on the first class side. Again they do not fulfil Dirac's expectations in this sense. He thought that technical developments in quantum theory would eventually illuminate the first class difficulties. And they haven't. The developments that I have just told you on the second class side have not touched at all on the first class side, and the first class developments are separate.*

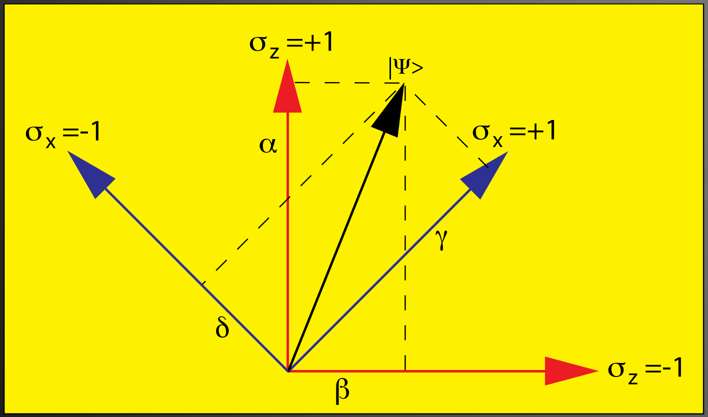
Linearity and objective properties.

a). $|\phi\rangle$ and $|\chi\rangle$: possible states $\Rightarrow$ $\alpha|\phi\rangle + \beta|\chi\rangle$ is a possible state.

b). The evolution preserves the superpositions.

c). Probabilities of outcomes related to projections (of the statevector on the eigenstates).

d). The observables (s.a. operators) do not commute $\Longrightarrow$ they do not share complete sets of eigenvectors. Making sharp one quantity makes nonepistemically undefined other quantities (conditional predictions).



How to attribute objective properties? The EPR criterion: when the theory attaches probability 1 to the outcome.

First Q-lesson: do not attribute too many properties to a system, some are possessed some have the ontological status of potentialities.

However, an isolated system considered as a whole and in a pure state has always a complete set of properties.

Entanglement: It occurs when one considers composite systems. In fact, in such a case two types of states are possible:

Factorized states: $|\Psi(1,2)\rangle = |\phi^{(1)}\rangle \otimes |\chi^{(2)}\rangle$ in which, obviously, both constituents have objective properties

Entangled states: $|\Psi(1,2)\rangle = \sum_i c_i |\phi_i^{(1)}\rangle \otimes |\chi_i^{(2)}\rangle$

may even have no property (sharp or unsharp) at all.

Schmidt bi-ortho-normal decomposition. It is always possible and the c_i are real and positive.

For instance: *if the* $\{\phi_i^{(1)}\}$ *are a c.o.n.s*, *and the* c_i *are all different from zero,*

S_1 is totally entangled with S_2: there is no observable of this subsystem for which one can claim that its value belongs to a proper subset of its spectrum. Think, e.g. of the energy; you are not allowed to claim that the energy of the systems lies, let us say, between 1MeV and 1 GeV or similar. Moreover, this holds for

ALL CONCEIVABLE PHYSICAL QUANTITIES!

The best known case is the one of the maximally entangled singlet state

$$|\Psi(1,2)\rangle = \frac{1}{\sqrt{2}}[|z,\uparrow\rangle_1 \otimes |z,\downarrow\rangle_2 - |z,\downarrow\rangle_1 \otimes |z,\uparrow\rangle_2]$$

For which one has:

$$P(\sigma^{(1)} \cdot a = +1) = P(\sigma^{(2)} \cdot b = +1) = 1/2, \forall a, b$$

The paradigmatic case of an embarrassing whole: the macro-objectification or measurement problem of Q.M.

The sketchy ideal von Neumann measurement scheme for $S = s_{micro} + App$

1. Eigenvalues and eigenvectors for s_{micro}: $\Omega|\phi_i\rangle = \omega_i|\phi_i\rangle$

2. Microstates are "measurable": $|\phi_i\rangle \otimes |A_0\rangle \rightarrow |\phi_i\rangle \otimes |A_i\rangle$

3. The orthogonal macrostates $|A_i\rangle$ correspond to mutually exclusive perceptions of the conscious observer,

4. Equation 2 implies: $[\sum c_i|\phi_i\rangle] \otimes |A_0\rangle \rightarrow \sum c_i|\phi_i\rangle \otimes |A_i\rangle$

factorized *entangled*

5. The microsystem and apparatus are entangled ⇒ they have no individual properties. In particular the apparatus cannot be claimed to possess the macroproperties which are associated to our definite perceptions.

One can significantly summarize the macro-objectification problem by making reference to the illuminating sentence by Bell:

> *Nobody knows what quantum mechanics says exactly about any situation, for nobody knows where the boundary really is between wavy quantum systems and the world of particular events.*
>
> *J.S. Bell*

Various scientists have suggested that the difficulties arise from having adopted the too idealized von Neumann measurement scheme.

A. Bassi and G.C. Ghirardi: *"A general argument against the universal validity of the superposition principle"* - Phys. Lett. A, 275 (2000).

Assumptions:
i) the "values" of the observables can be determined with reasonable reliability,
ii) the superposition principle has unrestricted validity.

Implications:
1). The occurrence of the embarrassing superpositions of macroscopically and perceptibly different states of a macrosystem cannot be avoided.

Our paper has given rise to an illuminating debate with B. d'Espagnat which is worth mentioning.

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A note on measurement

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Abstract

Grounded on the quantum measurement riddle, a general argument against the universal validity of the superposition principle was recently put forward by Bassi and Ghirardi (Phys. Lett. A 275 (2000) 373). It is pointed out that this argument is valid only within the realm of the philosophy of "objectivistic realism" which is not a necessary part of the foundations of physics, and that recent developments including decoherence theory do account for the *appearance* of macroscopic objects without resorting to a break of the principle.

How do we know that there is a stone on the path, or a tree in the courtyard? Obviously (as many philosophers have kept stressing) by having a look. So that, if we were extremely cautious not to make unwarranted statements, we should not bluntly say that there is a stone on the path (or a tree in the courtyard). We should say: "We know that if we had a look at the path, to check whether or not we have the impression of seeing a stone, we should actually get the impression in question". As long as we remain within the realm of pure thinking, this remark does not amount to taking an option for or against objectivistic realism. It is just a matter of cautiousness, that is, of taking care not to make unjustifiable claims. It may be that objectivistic realism is true. But, since it is unprovable, it may also be that it is not. So, we keep on the safe side by not implicitly postulating it.

poses we are therefore fully justified — even if we are not diehard realists — in using the shorter, so-called "realistic", sentences, that describe objects as "really being" here or there. In the quantum mechanical realm the situation, however, is different. As everybody knows, this is a domain in which too "realistic" sentences, implicitly postulating that all the quantities of interest always *have* values, would lead us astray. And we may well suspect that, when we assume quantum mechanics is universal and apply it to macroscopic systems, something similar may be true also concerning some sentences bearing on such systems. But still: even in the realm of atomic and subatomic physics there is at least one circumstance in which the use of "realistic" sentences — involving the verbs "to have" and "to be" — is both harmless and convenient. This is when *we* know (for sure) beforehand that, if we nificant recent development consists in the fact that, due to the (universally existing) interaction between a macroscopic system and its environment (including its "internal" one, that is, the set of its atomic variables), it could be shown (i) that the (predictive) M rules follow from the (predictive) basic quantum rules (see [6, Chapters 6 and 7]), and (ii) that, for macroscopic systems, the *appearances* are those of a classical world (no interferences, etc.), even in circumstances, such as those occurring in quantum measurements, where quantum effects take place and quantum probabilities intervene (see, e.g., [7]). This is the true significance of decoherence theory. In other words, this theory has no meaning within objectivistic realism and should not therefore be understood as signifying that a "real" collapse occurs, when "real" is understood in the sense it has within the philosophy in question. But it remains true that decoherence explains the just mentioned *appearances* and this is a most important result. It may be considered as implying that, from a quite strictly scientific viewpoint,[2] the above mentioned Bassi and Ghirardi claim is not justified. As long as we remain within the realm of mere predictions concerning what we shall observe (i.e., what will *appear* to us) — and refrain from stating anything concerning "things as they *must* be before we observe them" — no break in the linearity of quantum dynamics is necessary.

On the other hand, this conclusion should not be interpreted as meaning that investigations bearing on the so-called "measurement theory" have proven nothing. What they proved (within the realm of the completeness assumption) is that we must *either* accept the break *or* grant that man-independent reality — to the extent that this concept is meaningful — is something more "remote from anything ordinary human experience has access to" than most scientists were up to now prepared to believe (although science formerly contributed decisively to making plausible the idea that Reality is not at all what it looks like). This is an important result, to the derivation of which the Bassi and Ghirardi paper unquestionably brought a very significant contribution.

Appendix

Now, in thus comparing options A and B, was I unfair to the former? After reading a preliminary version of this Letter, Prof. G.C. Ghirardi reminded me that also option B has its limitations, an important one proceeding from the fact that a (nonpure) density matrix corresponds to several proper mixtures. Consequently (as pointed out by Joos [8] and rediscovered independently by myself [9]) when, for example, decoherence is applied to the localization of macroscopic objects (dust grains, say), it does not suffice, by itself, to prove that in an ensemble of such objects each element occupies — or will be seen as occupying — some definite place. In other words, the localization process is not just a consequence of the formalism. It is also due to our human way of perceiving so that, if we stick to the conventional notion of "states" (states of "systems" or of "the World"), we have to grant that within option B perceptions are linked in quite a loose way with the said states (as described by density matrices). As Prof. Ghirardi stressed to me, there is, after all, no considerable difference between such a state of affairs and the ancient view of London and Bauer and Wigner, according to which the wave function is reduced by an individual conscious act of perception.

There is, I must admit, substantial truth in this remark. On the other hand, I claim that this disadvantage of the decoherence approach is, if not completely removed, at least considerably alleviated if option B is understood as centered on predictivity, as sketched in the first paragraph of the present Letter. More precisely, although, personally, I tend to view physics without metaphysics as being conceptually incomplete, I consider nevertheless that we should be careful not to include some admixture of the latter in

!!

Entanglement, nonlocality and the quantum "spooky action-at-a-distance".

This point is easily understood by looking to the celebrated EPR-Bohm set-up.

System: two far away spin ½ particles in the singlet spin state:

$$|\Phi(1,2)\rangle = \frac{1}{\sqrt{2}}[|z\uparrow\rangle_1|z\downarrow\rangle_2 - |z\downarrow\rangle_1|z\uparrow\rangle_2] \otimes |R\rangle_1|L\rangle_2$$

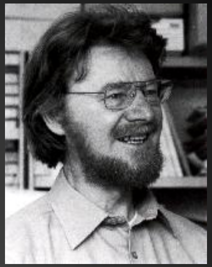
- As we know in such a state the probabilities of the outcomes of all conceivable spin measurements equal ½.

- However, a spin measurement along *z* at R, yielding the outcome +1, induces the instantaneous reduction of the state to:

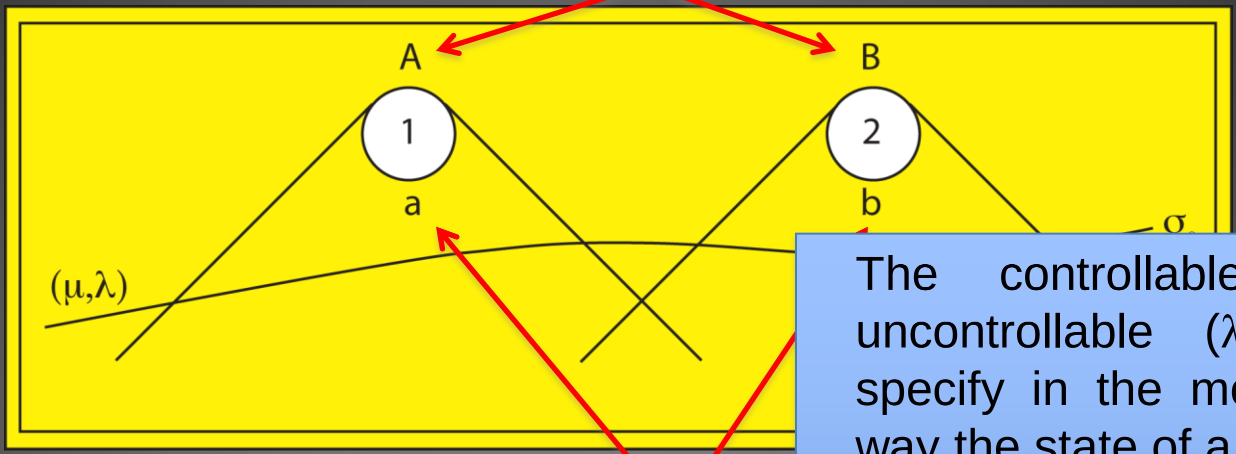
$$|\Phi_{Red}(1,2)\rangle = |z\uparrow\rangle_1|R\rangle_1 \otimes |z\downarrow\rangle_2|L\rangle_2$$

- Accordingly, the probability of getting the outcome -1 in a measurement of $\sigma_z^{(2)}$ at L takes instantaneously the value 1, i.e. an objective properties has emerged!

Deepening the nonlocal character of natural processes: Bell's theorem.



Outcomes



Settings

The controllable (μ) and uncontrollable (λ) variables specify in the most accurate way the state of a system.
If one disregards λ and identifies μ with ψ one might be dealing with Q.M.; if one disregards μ and takes only λ one is dealing with a genuine HVTH; if one keeps both μ and λ one deals with a theory like Bohmian mechanics.

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C

Any conceivable theory for which the maximal specification of the state determines all single and multiple probabilities of the outcomes, and respects the Locality condition involving space-like events (No other condition!):

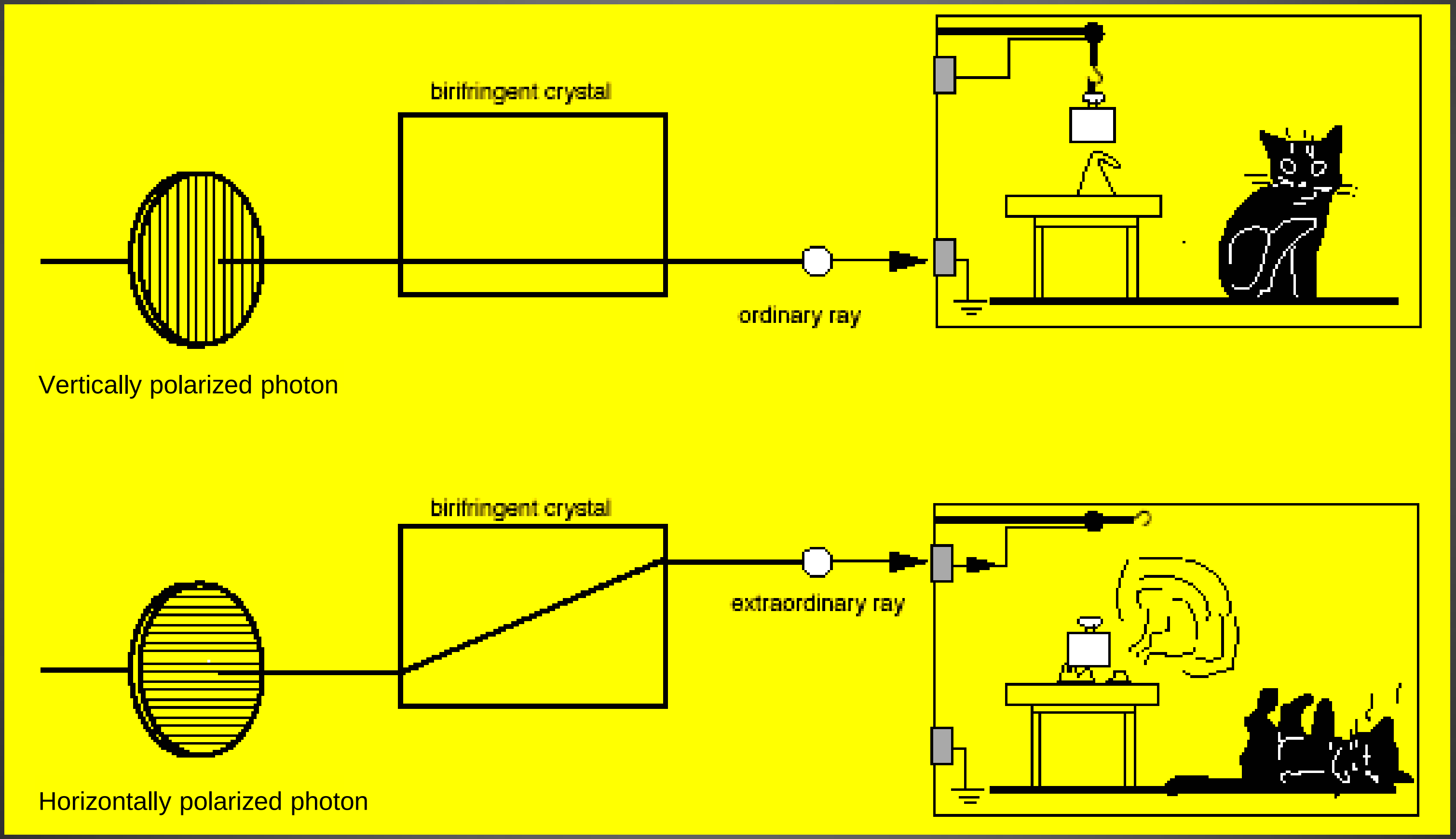
$$P(A, B|a, b; \lambda, \mu) = P(A|a, *; \lambda, \mu) \cdot P(B|*, b; \lambda, \mu)$$

cannot reproduce all quantum probabilities implied by an entangled state.

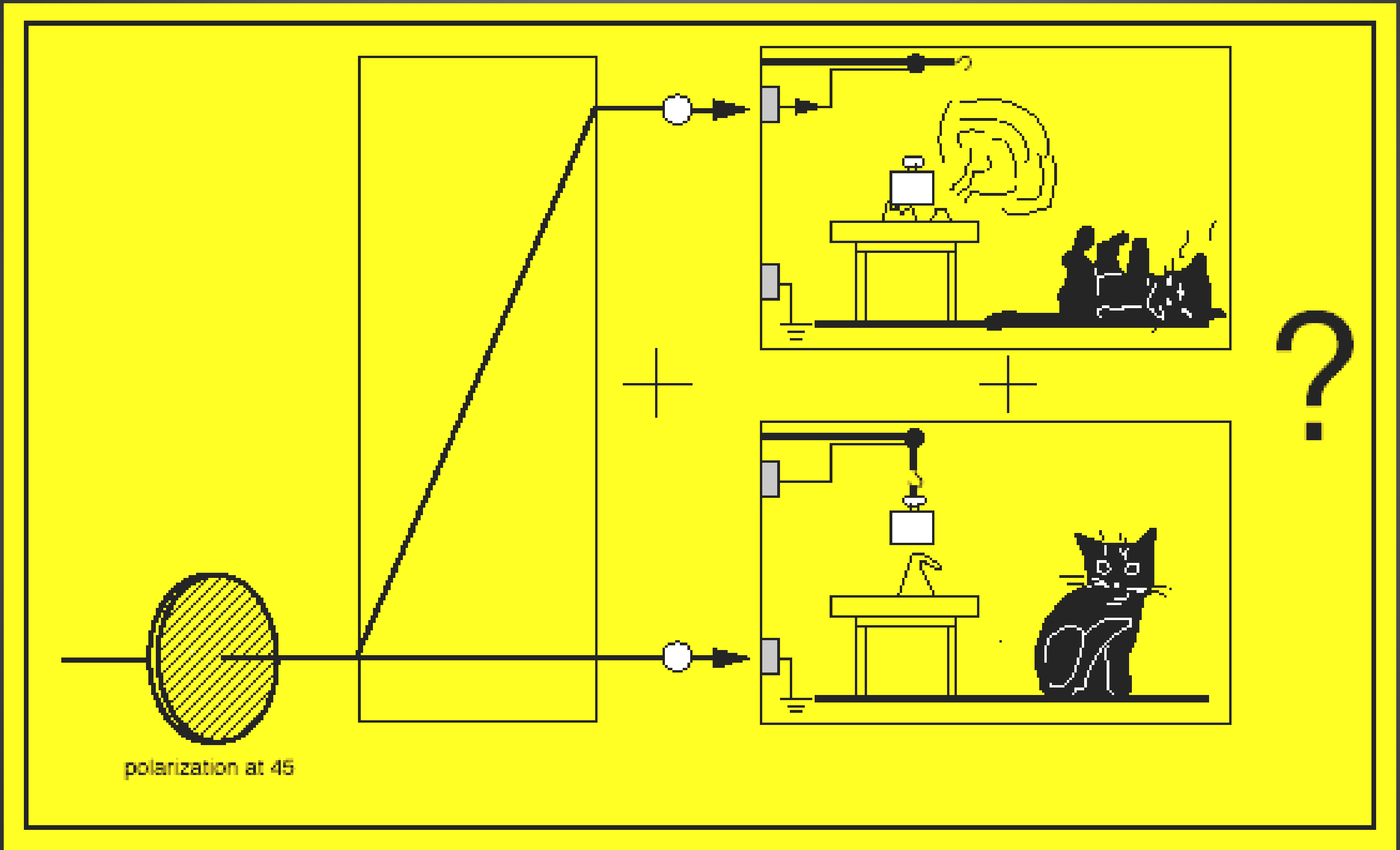
Nature is not locally causal!

The macro-objectification (or measurement) problem

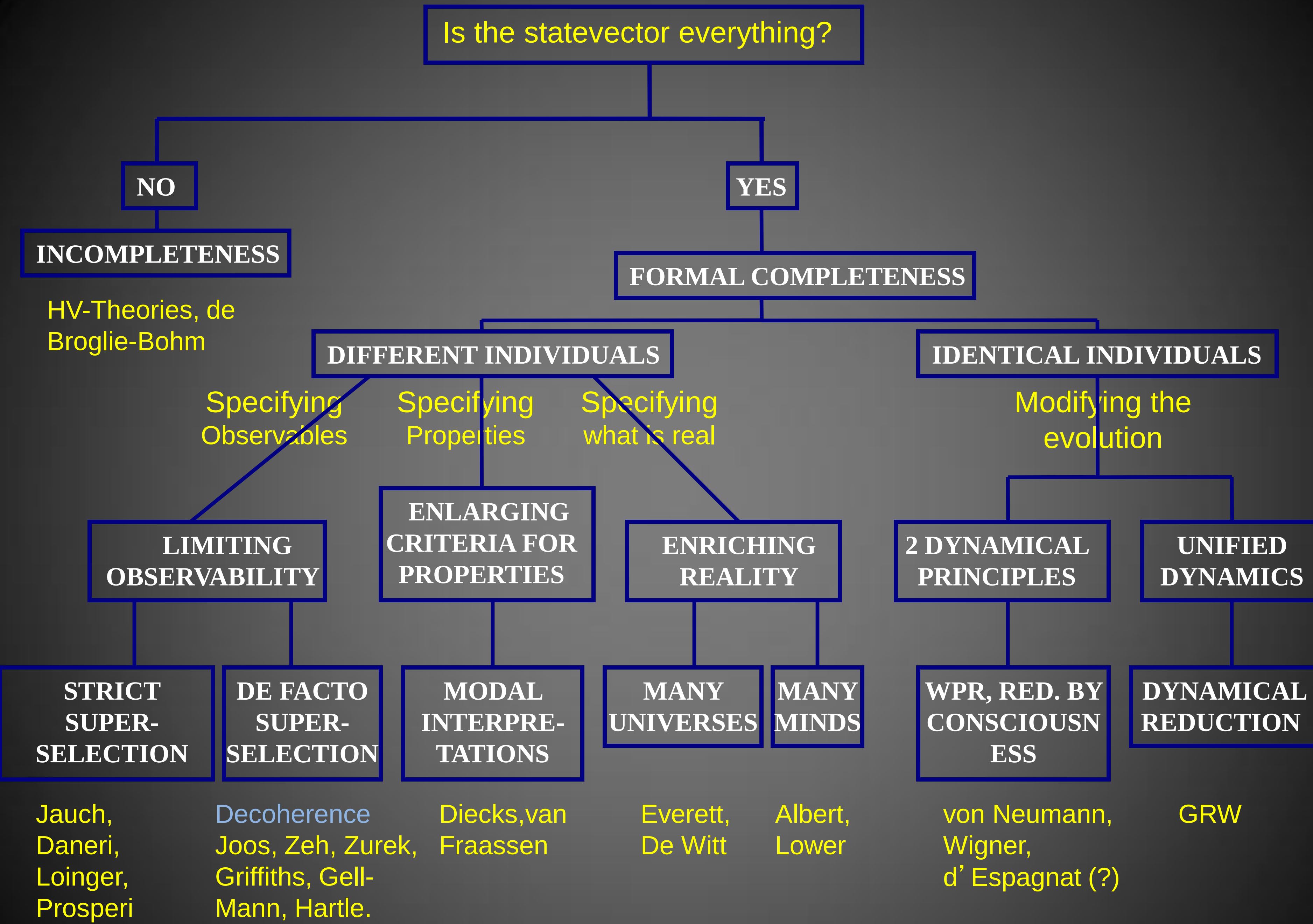
Let us oversimplify the crucial problem we have raised by resorting to the celebrated Schrödinger’s cat example:



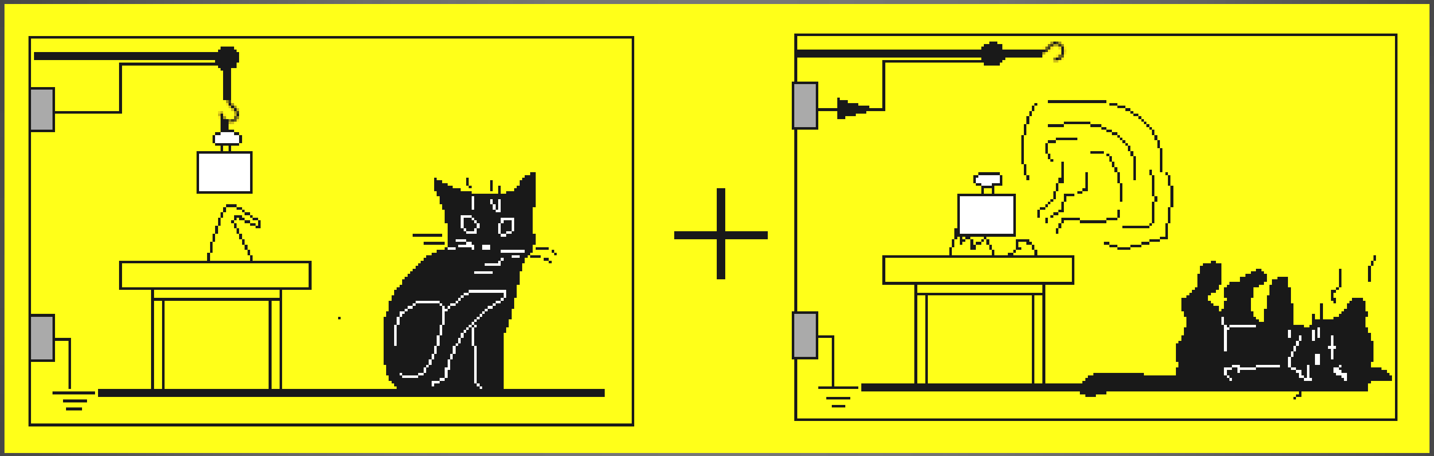
From this point of view the macro-objectification problem can be summarized by this picture



Let us comment on some of the most relevant solutions which have been proposed

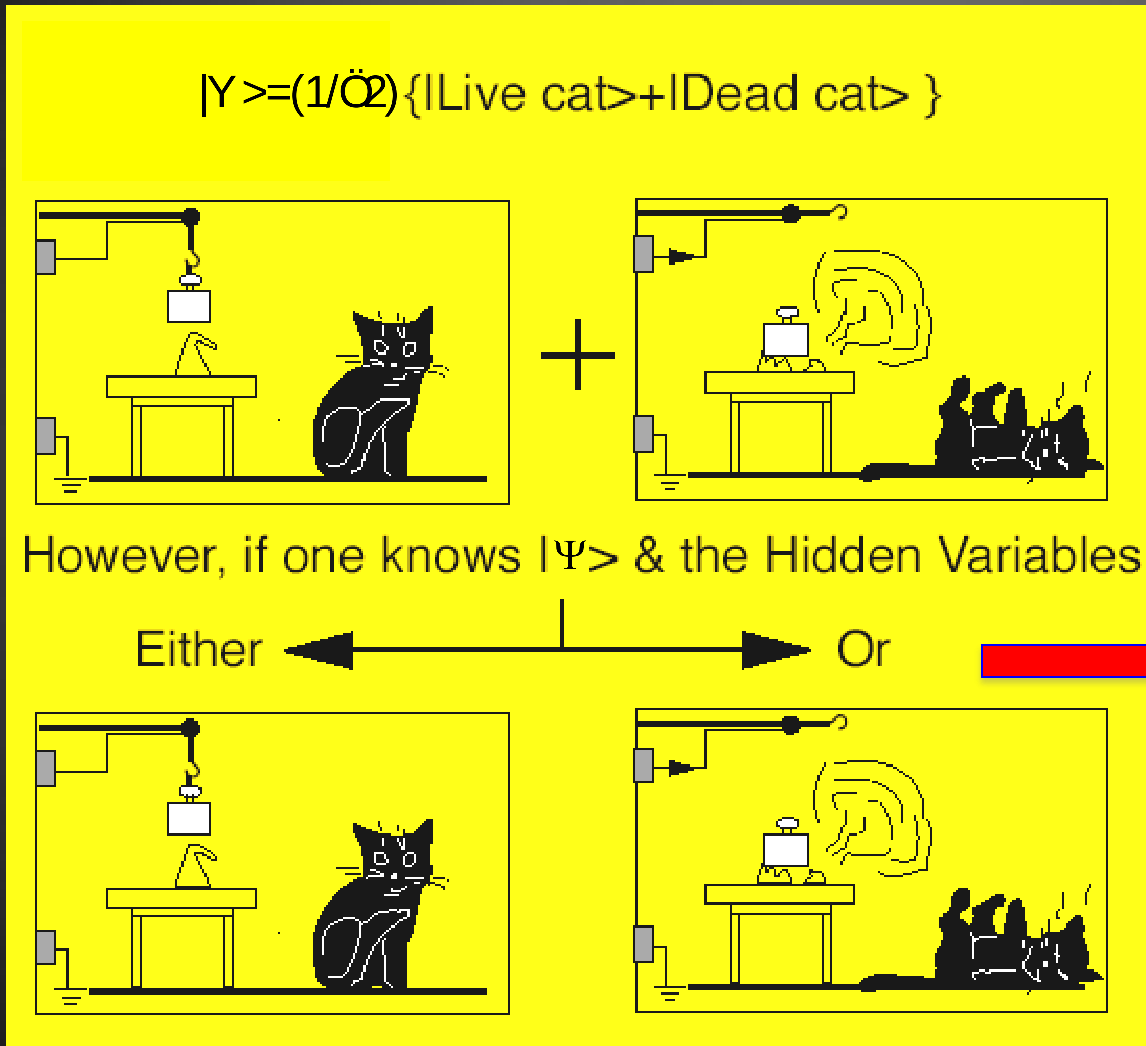

Is the statevector everything?
NO
YES
INCOMPLETENESS
HV-Theories, de Broglie-Bohm
FORMAL COMPLETENESS
DIFFERENT INDIVIDUALS
IDENTICAL INDIVIDUALS
Specifying Observables
Specifying Properties
Specifying what is real
Modifying the evolution
LIMITING OBSERVABILITY
ENLARGING CRITERIA FOR PROPERTIES
ENRICHING REALITY
2 DYNAMICAL PRINCIPLES
UNIFIED DYNAMICS
STRICT SUPER-SELECTION
DE FACTO SUPER-SELECTION
MODAL INTERPRE-TATIONS
MANY UNIVERSES
MANY MINDS
WPR, RED. BY CONSCIOUSN ESS
DYNAMICAL REDUCTION
Jauch, Daneri, Loinger, Prosperi
Decoherence
Joos, Zeh, Zurek, Griffiths, Gell-Mann, Hartle.
Diecks,van Fraassen
Everett, De Witt
Albert, Lower
von Neumann, Wigner, d’Espagnat (?)
GRW

We will briefly comment on some of the solutions, with reference to the puzzling superposition of macroscopically distinguishable states, i.e. to Schrödinger's cat.



Incompleteness: the state is not everything.

Bohm Zanghì Dürr Goldstein



Typical example: Bohiam Mechanics, a deterministic completion of Q.M. predictively equivalent to it. (Note: von Neumann was wrong!).

This is related to the fact that, in such a theory, the photon is not " on both paths", but definitely on one of them which is determined by the value of the unaccessible hidden variables

In Bohmian Mechanics the H.V. are the positions of all particles (of your Universe) and they supplement the wavefunction in determining the dynamics.

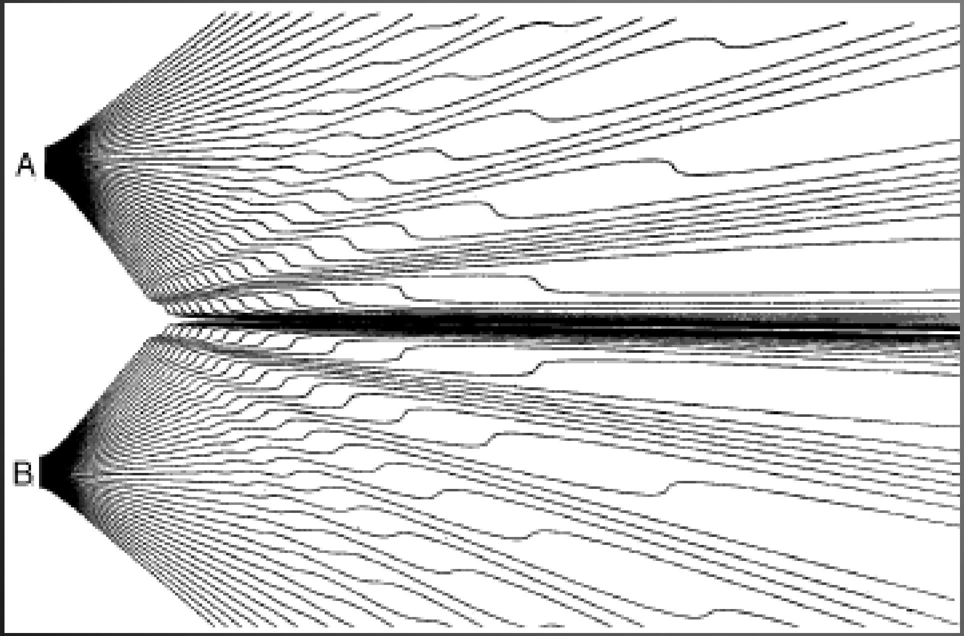
Ontology: what is real are the positions of all particles!

Formalism:

$$i\hbar\frac{d\psi(q_1(t),...,q_n(t))}{dt} = H\psi(q_1(t),...,q_n(t))$$

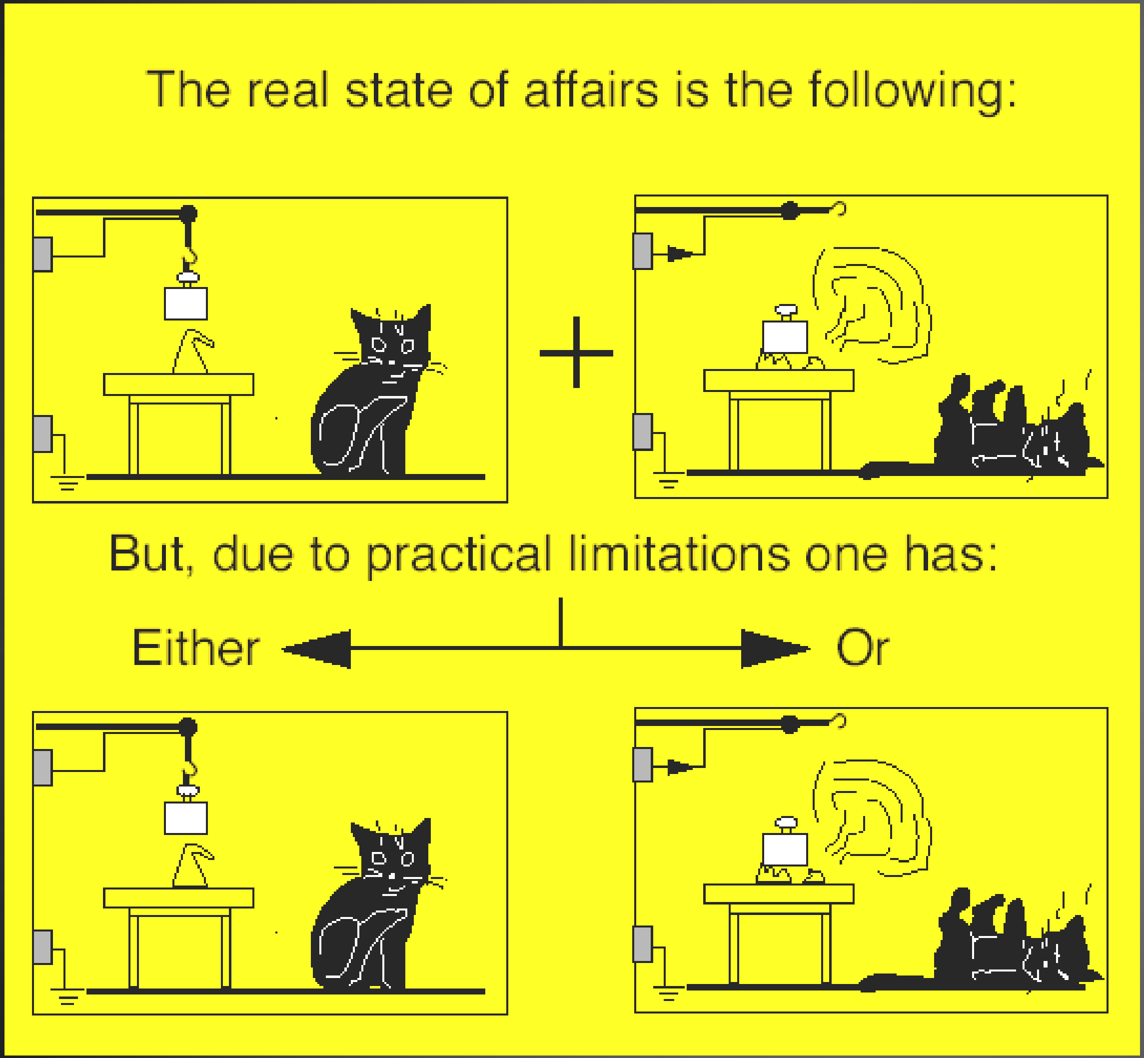
$$\frac{dq_j(t)}{dt} = \frac{\hbar}{m_i} Im\frac{\psi^*(q_1,...,q_n,t)\nabla_j\psi(q_1,...,q_n,t)}{\psi^*(q_1,...,q_n,t)\psi(q_1,...,q_n,t)}$$

implications: $\rho(q_1(0),...,q_n(0)) = |\psi(q_1(0),...,q_n(0))|^2 \rightarrow \rho(q_1(t),...,q_n(t)) = |\psi(q_1(t),...,q_n(t))|^2$

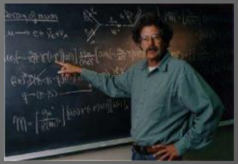


The wavefunction which is present at the right of the slits, amounts to the presence of a quantum velocity field which "guides" the particles going through any of the slits, in such a way to generate the interference pattern.

Limiting observability; strict or de-facto superselection rules, or, invoking decoherence.



Resorting to decoherence has become very fashonable in recent years. One might mention Joos and Zeh approaches, Zurek's repeated use of it, up to the so called "Decoherent Histories approach" (Griffiths, Gell-Mann, Hartle, Omnés).



Griffiths

Gell-Mann

Hartle

Zurek

Basic philosophy $$\sum c_i|\phi_i\rangle \otimes |A_i\rangle \rightarrow \sum c_i|\phi_i\rangle \otimes |A_i\rangle \otimes |E_i\rangle.$$

Disregarding the orthogonal enviroment states which one cannot control (i.e. taking a partial trace over their degrees of freedom) one gets a reduced statistical operator:

$$\rho^{S+A} = \sum |c_i|^2 [|\phi_i\rangle \otimes |A_i\rangle\langle\phi_i| \otimes\langle A_i|].$$

Which one reads as describing the statistical mixture of the “nice” states $|\phi_i\rangle \otimes |A_i\rangle$ in which the system “has a property” and the apparatus registers an outcome matching such a property and corresponding to our definite perceptions.

Decoherence ⇒ Statistical operator ρ ⇒ Ensembles

1. We often deal (and we must do so in modern technological applications) with individuals physical systems.

2: In Q.M. : {Statistical Ensembles} ⇒ {Statistical operators}

∞ - many to 1

For instance, the two ensembles:

$$\mathcal{E} = \{1/2, |Alive>; 1/2, |Dead>\}$$

$$\mathcal{E}^* = \{1/2, \frac{1}{\sqrt{2}}[|Alive> + |Dead>]; 1/2, \frac{1}{\sqrt{2}}[|Alive> - |Dead>]\}$$

correspond to the same ρ. So, why can we legitimately claim that the situation corresponds to the first alternative?

The just mentioned difficulty has been plainly recognized even by the more convinced supporters of the decoherence approach. In fact, in their fundamental paper : *The emergence of classical properties through interaction with the environment*, Z.Phys.B.- Condensed matter 59, 223 (1985), E. Joos and H.D. Zeh have claimed:

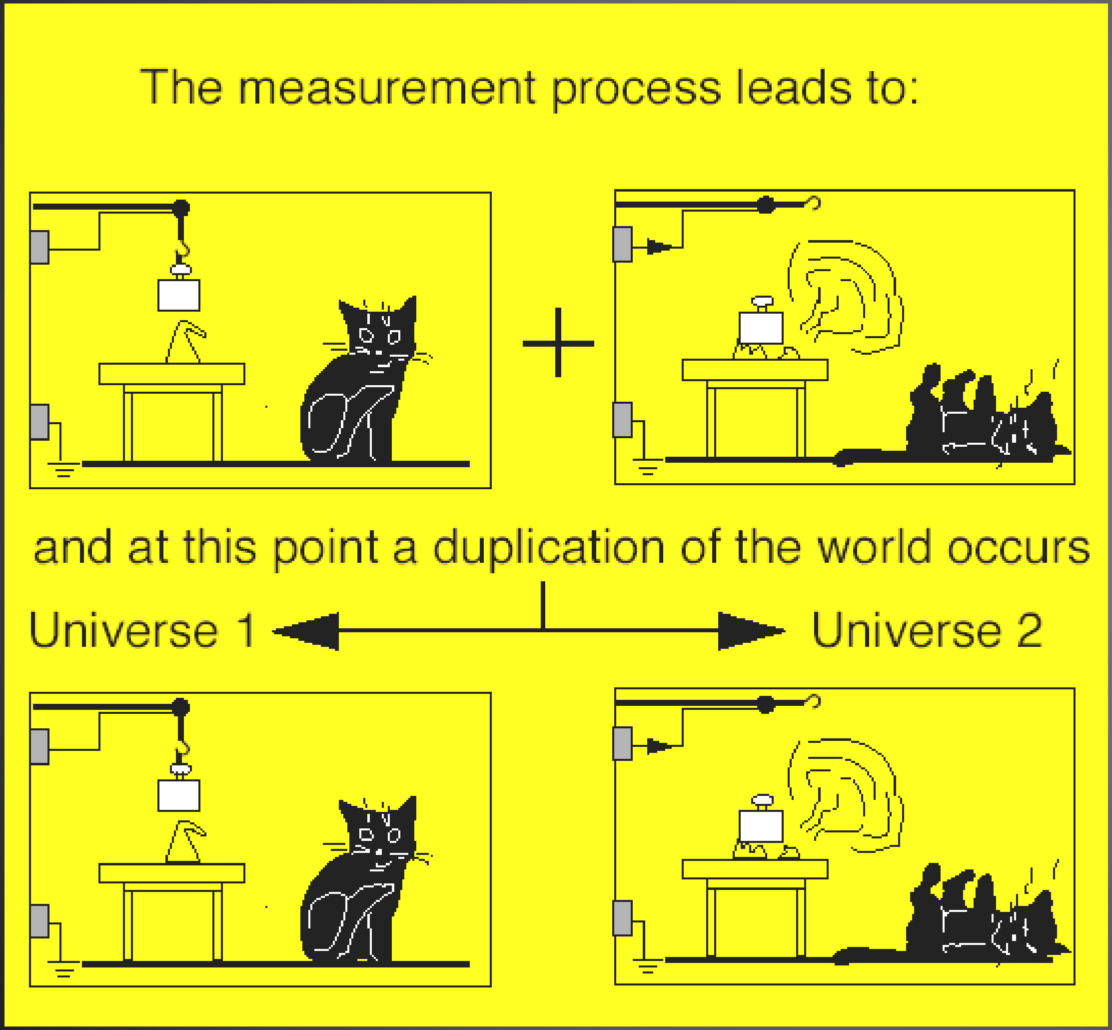
Of course, no unitary treatment of the time dependence can explain while only one of these dynamically independent components is experienced.

and they have also made clear that the fact that, in spite of this, we always have definite perceptions might:

perhaps be justified by a fundamental underivable assumption about the local nature of the observer.

See also: S. Adler: *Why decoherence has not solved the measurement problem: a response to P.W. Anderson*, quant-ph/0112095

Enriching reality: the many-worlds interpretation



All potentially possible events occur in different universes

Everett III

De Witt

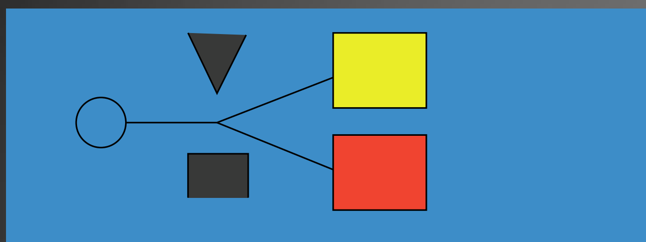
Remarks

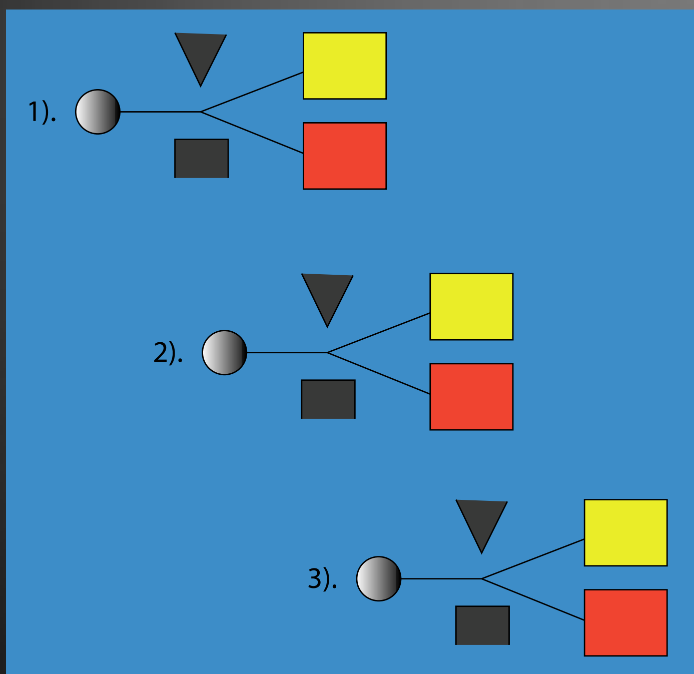
$$Suppose: \quad |\psi\rangle = \frac{1}{\sqrt{3}}|z, up = yellow\rangle + \sqrt{\frac{2}{3}}|z, down = red\rangle$$

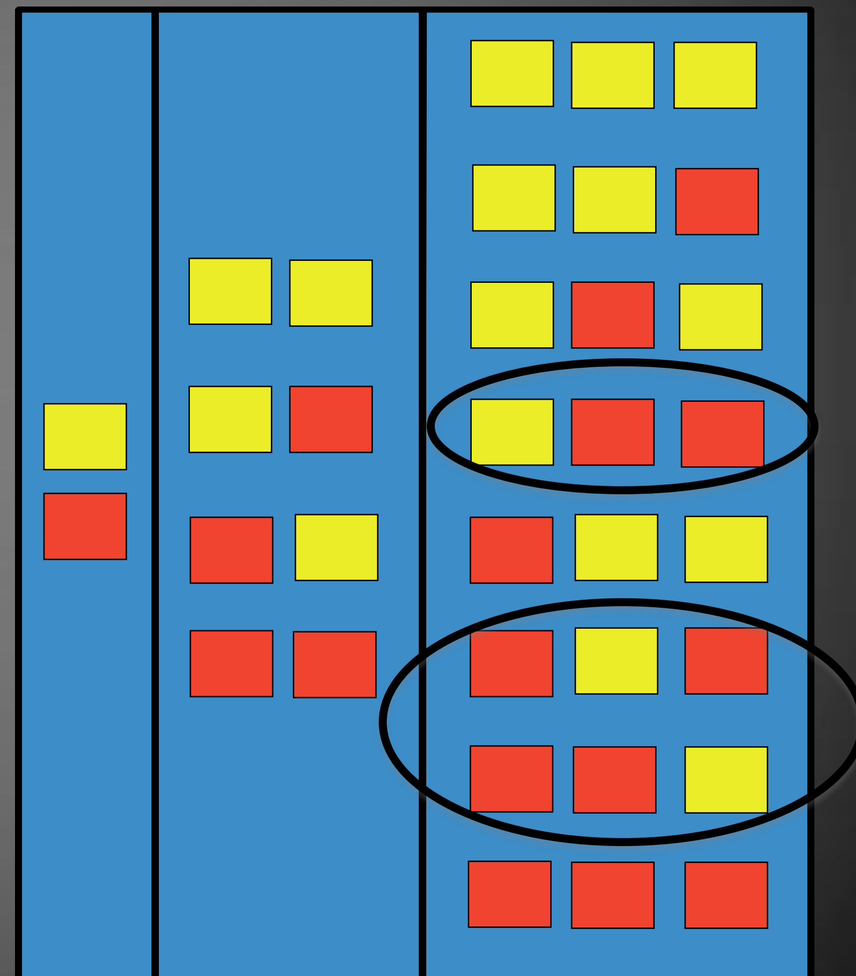
- When does the "splitting" occur?

Actually the relative frequencies of the two outcomes are not related to the coefficients of the superposition

- The probabilistic features of the theory are badly violated (Hilary Putnam)



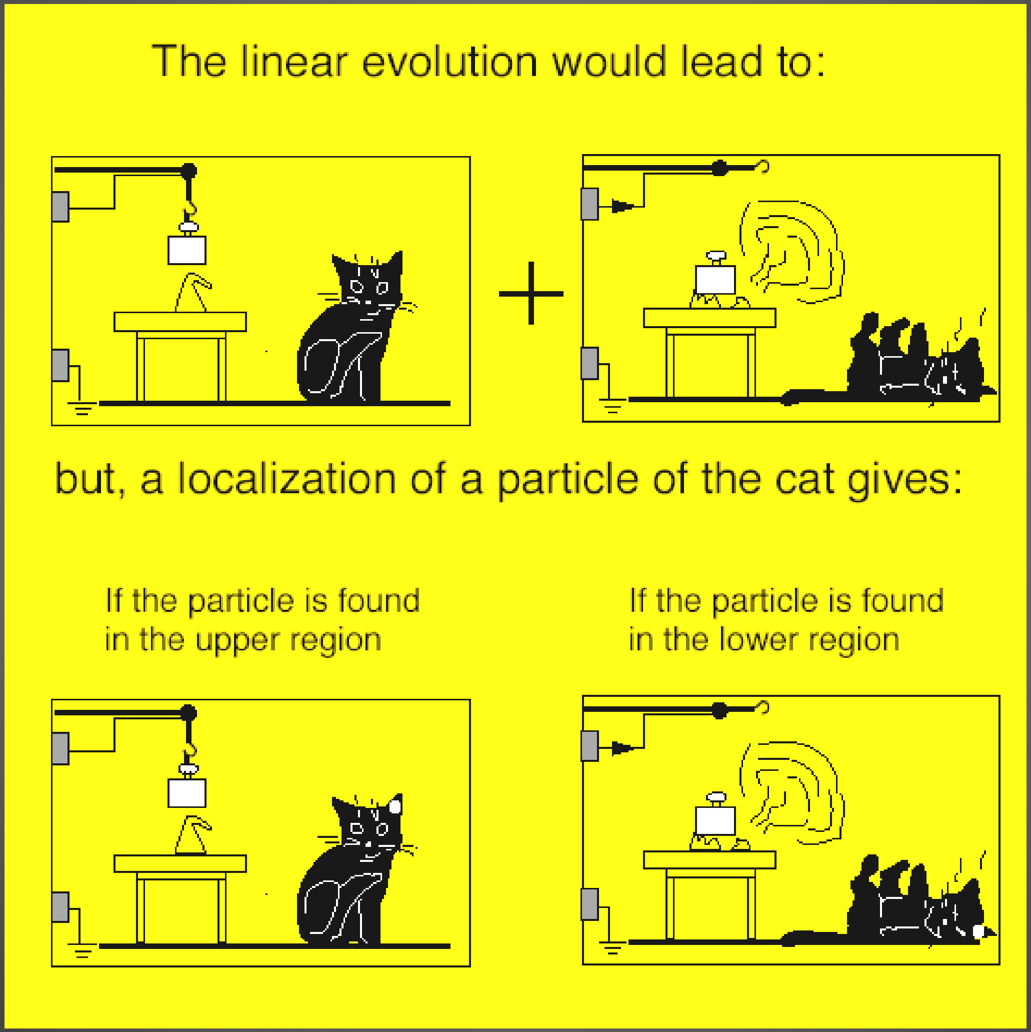




3/8=37% vs 2/3=66%

Collapse Theories or Dynamical Reduction.

Ghirardi
Rimini
Weber



A unique, mathematically precise dynamics governs all natural processes.

Let us begin with the most simple version of it: the phenomenological (for me) GRW theory.

Collapse theories

The central idea is to modify the linear and deterministic evolution implied by Schrödinger's equation by adding nonlinear and stochastic terms to it, the aim being the one of "solving" the measurement problem.

As it is obvious, and as it has been stressed by many scientists (Einstein, Bohm, Feynman) the situations characterizing macro-objects correspond to perceptually different locations of (some) of their macroscopic parts (in actual laboratory experiments, typically the "pointer"). The preferred basis problem.

With these premises we can be fully specific about the original collapse model. It is based on three axioms.

G.C. Ghirardi, A. Rimini and T. Weber, Phys. Rev. D, 36, 3287 (1987).

1. States. A Hilbert space $\mathcal{H}$ is associated to any physical system and the state of the system is represented by a (normalized) vector $|\psi_t\rangle$ in $\mathcal{H}$

Note: localizations occur with higher probability where there would be an higher probability of finding the particle in a standard measurement process

2. Dynamics. The evolution of the system obeys Schrödinger's equation. Moreover, at random times, with a Poissonian distribution with mean frequency λ, each particle of any system is subjected to a spontaneous localization process of the form :

$$|\psi_t\rangle \rightarrow \frac{L_n(\mathbf{x})|\psi_t\rangle}{\|L_n(\mathbf{x})|\psi_t\rangle\|} \qquad L_n(\mathbf{x}) = (\frac{\alpha}{\pi})^{3/4} exp[-\frac{\alpha}{2}(\hat{\mathbf{x}}_n - \mathbf{x})^2],$$

the probability density for a collapse at **x** beeing $p(\mathbf{x}) = \|L_n(\mathbf{x})|\psi_t\rangle\|^2$.

3. Ontology. Let $\psi_t(\mathbf{x}_1, ..., \mathbf{x}_N)$ be the wavefunction in configuration space. Then

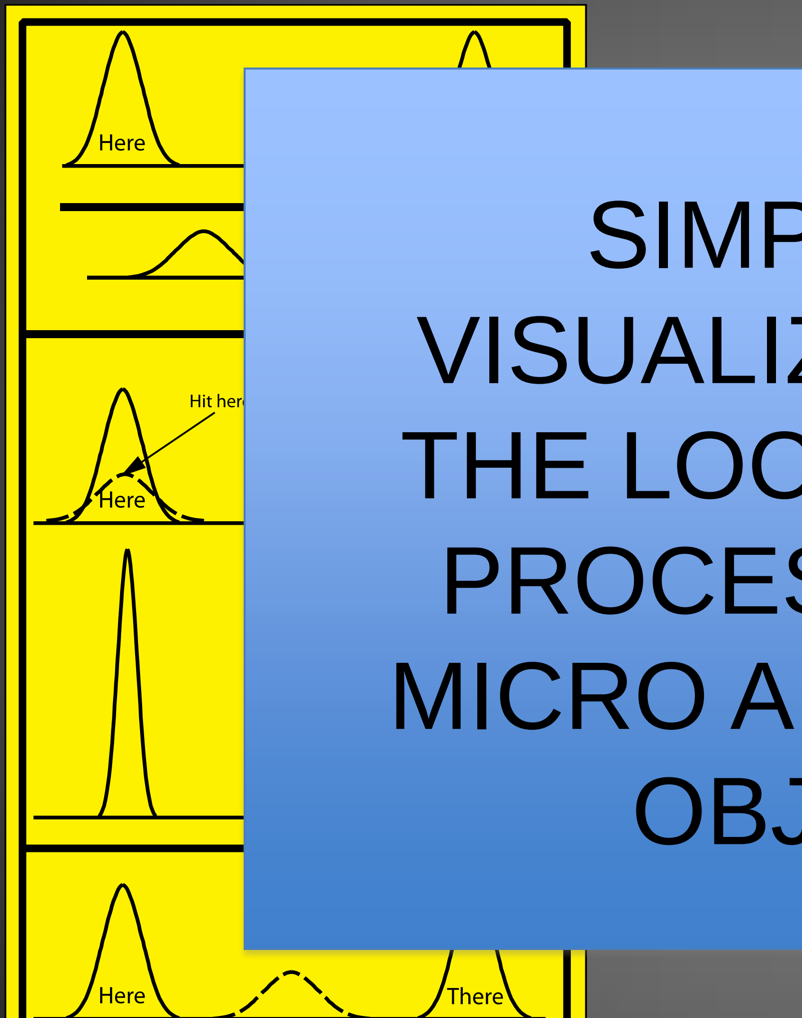
$$m(\mathbf{x}, t) \equiv \sum_{n=1}^{N} m_n \int d^3x_1 ... d^3x_N \delta^{(3)}(\mathbf{x}_n - \mathbf{x}) |\psi_t(\mathbf{x}_1, ..., \mathbf{x}_N)|^2$$

is assumed to describe the *density of mass* distribution of the system in three-dimensional space as a function of time.

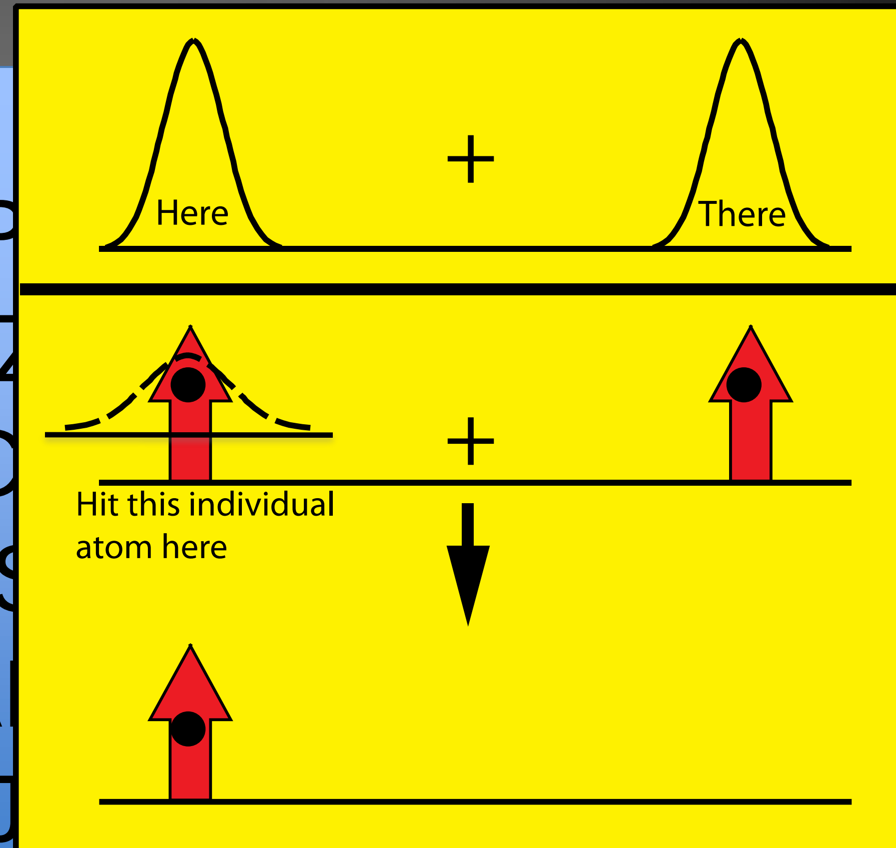
G.C. Ghirardi, R, Grassi, F. Benatti, Found. Phys 25, 5 (1995).

Localization of a microscopic system

The fundamental trigger process in the case of a macroscopic almost rigid body

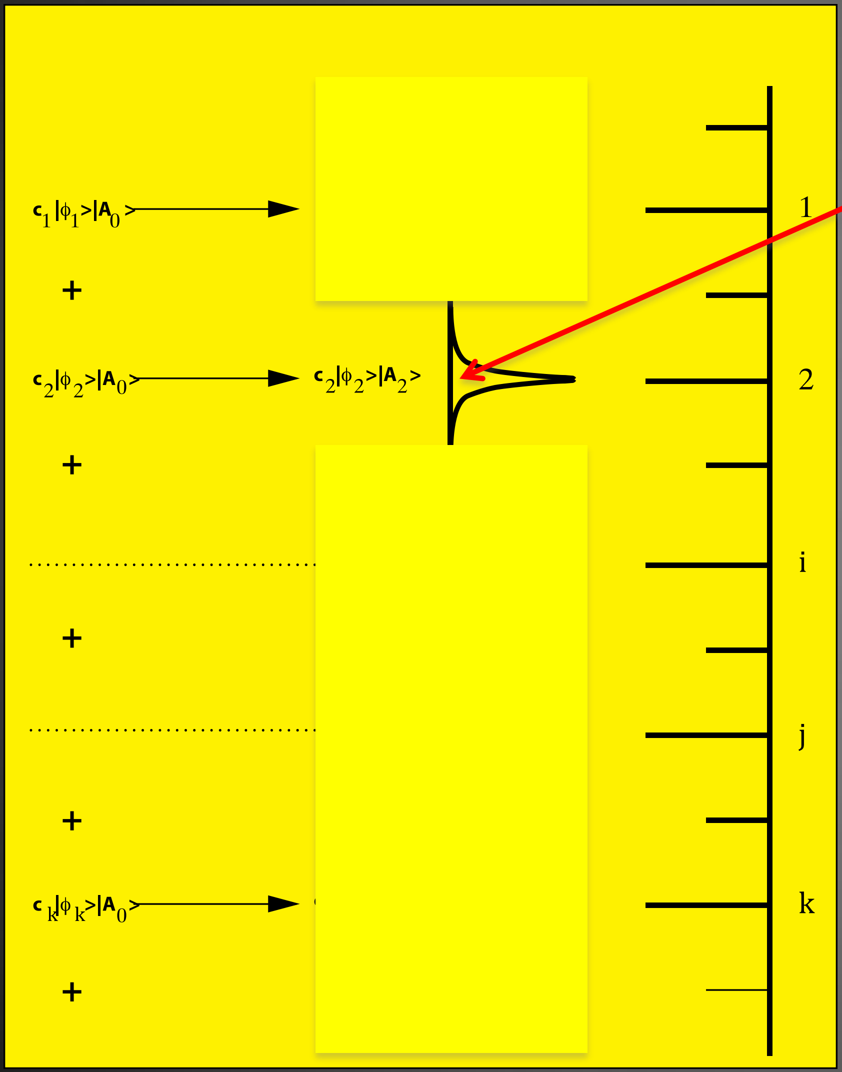


Hittings where indicated are practically impossible and would, if they occur, leave essentially unaltered the wavefunction (after normalization)



For simplicity I will deal with the pointer as if it would be a point like object whose position is its c.o.m. position.

The dynamical emergence of the properties of the parts of the Unbroken Universe



Suppose a spontaneous localization occurs at this point

Then

Thus, we end up, with the correct quantum probabilities, with a state :

$$|\phi_r\rangle \otimes |A_r\rangle$$

which is “practically” an extremely well localized and non entangled (system-apparatus) state: the pointer has a precise objective location.

Choosing the values of the constants of the theory.

The original choice (for a nucleon) has been:

$$(\lambda \simeq 10^{-16} sec^{-1}, \alpha \simeq 10^{10} cm^{-2})$$

A microscopic system suffers a localization about every 10^{7} years ! A macroscopic one about every 10^{-7} sec. !

Bell (at ICTP-1989):

These numbers are new constant of nature like the fine structure constant.

That's, in my opinion a very good solution for these problems in the context of nonrelativistic Q.M. And if I were teaching nonrelativistic quantum mechanics that is the line that I would take. … Instead of all that talk I would have this new equation and you would see that big objects have definite configurations … and you would see that little objects like hydrogen atoms are fully represented by the Schrödinger wavefunction.

Some important remarks.

•The physics is determined essentially by the product $\alpha\lambda$, with the only proviso that the localization accuracy must be much larger than atomic dimensions.

•Changing the above product by some orders (?) of magnitude contradicts known facts.

•The model qualifies itself as a rival of QM and suggests where to look for the breaking of the superposition principle.

n_1	n_2	n_3	n_4	...	...
...	...	...	...	...	...
...					...
					...
					...

Discretize the space and specify the occupation numbers:

$$|\Psi\rangle = \frac{1}{\sqrt{2}}[|n_1, n_2, ..., n_k, ...\rangle + |m_1, m_2, ..., m_k, ...\rangle].$$

Decoupling rate: $e^{-\lambda t \sum (n_i - m_i)^2}$

$$\lambda \simeq 10^{-16} sec^{-1}; \quad perceptual \;\; time \simeq 10^{-2} \;\; sec.$$

In the worst case: $n_i - m_i = 0, 1$. For 10^{18} differently occupied cells the damping factor cancels one of the terms.

The universal dynamics does not tolerate, for typical perceptual times, the persistence of the superposition of two states differing for the different location of a Planck mass in the whole universe!

A mathematically more general version (continuous hittings).

Stratonovich stochastic differential equation

$$d|\psi_t\rangle = \left[-\frac{i}{\hbar} H dt + \sum_{i=1}^{N} \sqrt{\gamma_i} \int d^3x \Lambda_i(\mathbf{x}) dW_t^{(i)}(\mathbf{x}) - \sum_{i=1}^{N} \gamma_i \int d^3x \Lambda_i^2(\mathbf{x}) dt \right] |\psi_t\rangle.$$

$W^{(i)}_t(x)$ a set of real Wiener processes such that

$$\mathbf{E}[dW^{(i)}(\mathbf{x})] = 0; \quad \mathbf{E}[dW_t^{(i)}(\mathbf{x}) dW_t^{(j)}(\mathbf{y})] = \delta_{i,j} \delta^{(3)}(\mathbf{x} - \mathbf{y}) dt.$$

The above (Raw) equations are linear but they do not preserve the norm. Prescription: determine $|\psi_t\rangle$ and then normalize it (it does not matter when). The physically relevant equations (Cooked) are obtained by the replacement:

$$P_{Cook}[W^{(i)}(t,t_0)] = P_{Raw}[W^{(i)}(t,t_0)]\|\psi(t,t_0\rangle\|^2.$$

The dynamics induces individual reductions. The statistical operator obeys an equation of the QDS type:

$$\frac{d}{dt}\rho(t) = -\frac{i}{\hbar}[H,\rho(t)] - \frac{1}{2}\sum_{i=1}^{N}\gamma_i \int d^3x[\Lambda_i(\mathbf{x}),[\Lambda_i(\mathbf{x}),\rho(\mathbf{t})]].$$

The basic ideas (an oversimplified version) and achievements:

1. The standard Q-dynamics leads to definite "different positions" of the pointer (different mass densities) according to the specific eigenstates triggering the apparatus,

1. The experiment must be calibrated (establishing the correspondence-POV&POVM),

2. Our perceptions correspond to definite positions (definite mass density distribution).

---

a. A universal dynamical equation,

b. No mention of measurements, observers and so on,

c. Macrosystems are extremely well localized (for 1g, c.o.m spread $\sigma_q \simeq 10^{-12}$ cm)

Before concluding this part there is something more to say.

We have used, in our formulation only the universal dynamical principle, the calibration of the experiment and the assumed correspondence of our perceptions to the definite positions of the pointers. But much more is implied.

We have proved that, by taking into account all our assumptions and the implications of the formalism and by resorting to the Riesz representation theorem the probabilities concerning the various possible outcomes implied by the formalism can be expressed as the average values over the initial state of the *effects associated to a Positive Operator Valued Measure (POVM)* on the Hilbert space of the measured system.

Moreover if we require reproducibility of the experiments (i.e. that repeating a measurement one gets the same outcome he has just obtained) then *the POVM reduces to a Projection Valued Measure (PVM)*.

Concluding: our general ***physical*** approach leads to a natural ***deduction*** of the quantum rules in their most general and axiomatic form

A. Bassi, G.C. Ghirardi, D.G.M. Salvetti, J. Phys. A: Math. Theor., 40, 13755 (2007).

A. Einstein, in: Replay to critics.

Einstein: ... *In the macroscopic sphere it simply is considered certain that one must adhere to the program of a realistic description in space and time; whereas in the sphere of microscopic situations one is more readily inclined to give up, or at least to modify this program. …*

But the "macroscopic" and the "microscopic" are so inter-related that it appears unpractical to give up this program in the microscopic alone.

The relativistic issue: J. Bell at the memorial Bruno Touschek lecture

Bruno Touschek Lectures

1 Quantum mechanics, an inexact science

Bruno Touschek Lectures

3. Exactness with nothing but the wavefunction

Conclusion

There are too many ways of embedding PQM in an exact theory.

But so far we do not know how to do it, or if it can be done, with Lorentz invariance.

LI is now big problem

Ghirardi & Grassi: Any deterministic theory agreeing with Q.M. admits, at most, a relativistic generalization involving a (hidden) preferred reference frame.

Bohm & Hiley, Duerr, Goldstein & Zanghì, Tumulka.

Collapse theories, in principle, admit " genuinely Lorentz Invariant " generalizations. A lively debate is going on.

The problem of making the reduction process compatible with relativity has been tackled, many years ago, by Landau & Peierls, Bohr & Rosenfeld, Hellwig & Kraus, and in a series of fundamental papers by Aharonov & Albert.

The situation:

- The original relativistic version of GRW (P. Pearle) has been proved (G.C.G., R. Grassi,P. Pearle) to be perfectly relativistic (it had other shortcuts related to stochasticity-divergences),

- There is a genuinely relativistic toy model of a theory inducing reductions (G.C.G. 2000),

- F. Dowker and collaborators worked out a relativistic collapse model on a discrete space-time that does not require a preferred slicing (D& Henson, D&Herbauts, 2004).

- R. Tumulka has presented (2007) a fully satisfactory and genuinely relativistic DRM for a system of noninteracting fermions,

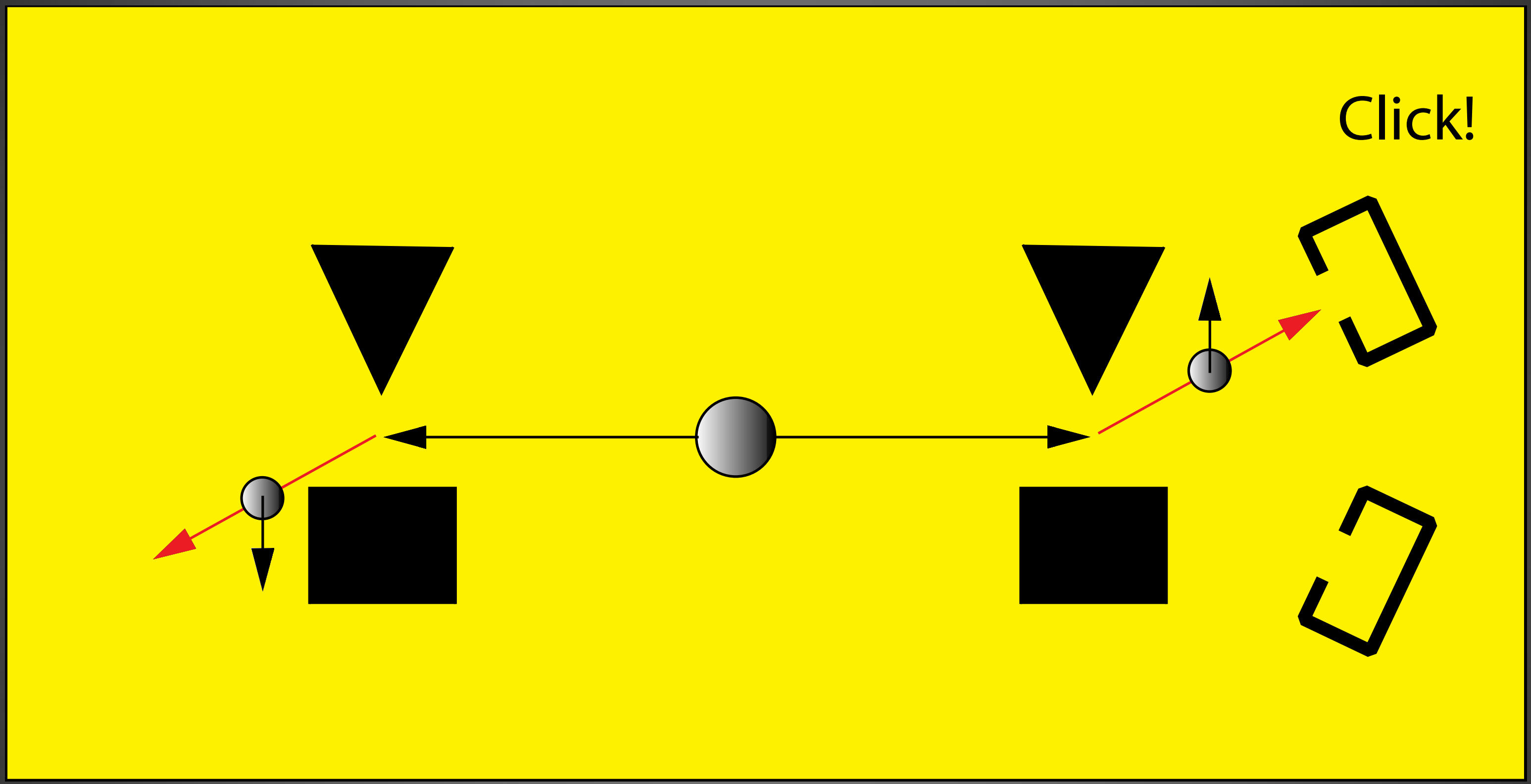
- D. Bedingham (Duerr,Ghirardi,Goldstein,Tumulka & Zanghì) have shown (2011) that it is possible to work out a relativistic model with the mass density interpretation as its P.O.

An appropriate evaluation of the status of the problem:

A somewhat surprising feature of the present situation is that we seem to arrive at the following alternative: Bohmian mechanics shows that one can explain quantum mechanics, exactly and completely, if one is willing to pay with using a preferred slicing of space-time; our model suggests that one should be able to avoid a preferred slicing if one is willing to pay with a certain deviation from quantum mechanics. R. Tumulka

Thanks!

Depicting the instantaneous action-at-a-distance.

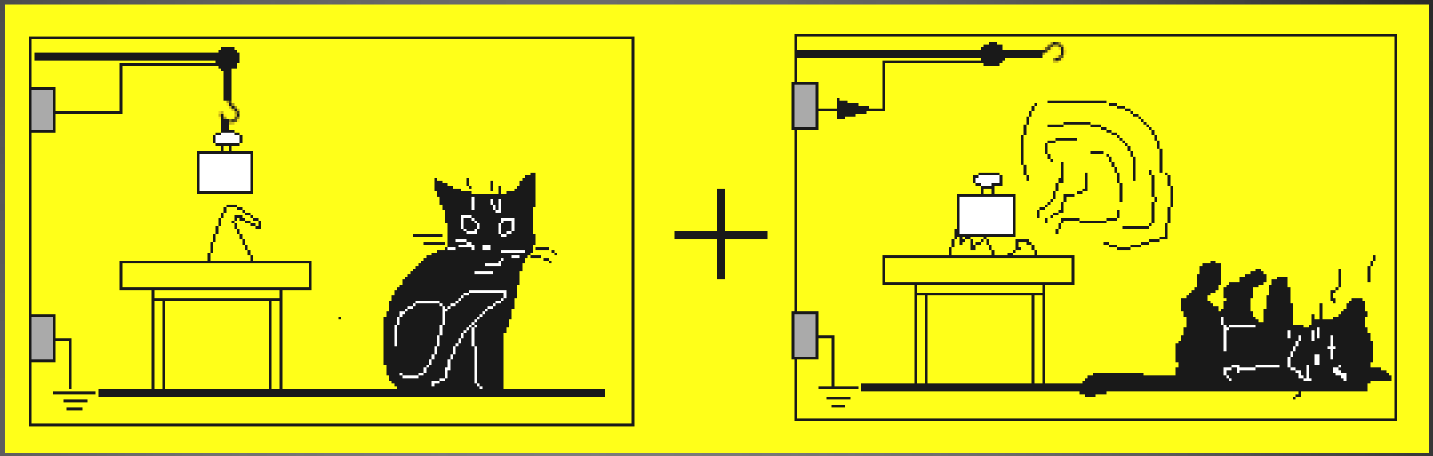


Many years ago we (Ghirardi, Rimini, Weber, 1980) have proved that, in the case of standard Q.M., it turns out to be actually impossible to take advantage of quantum nonlocality for faster than light signalling.

Reduction by the conscious act of perception

von Neumann

Wigner



This is the state describing our "Physical System" (???). But the act of conscious perception is not a physical process, and it is the only process which breaks the linear nature of the theory.

Once more a shifty split!	*What is conscious?* J.S. Bell.