Quantum Mechanics? I'm not Copenhagen!

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Them Internets
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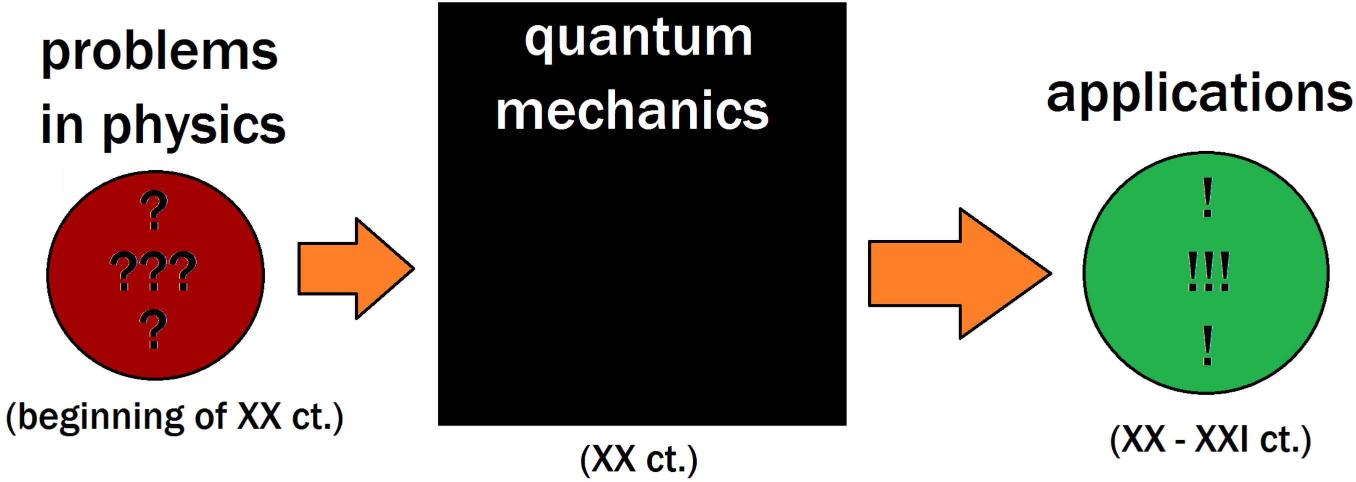
Contents

- Motivation;
- Basic description;
- Paradoxes (*questions*);
- Interpretations (*answers*);
- Discussion.

Goal: set the basic concepts and describe the existing problems.

Incomplete and not strict!

Motivation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quantum
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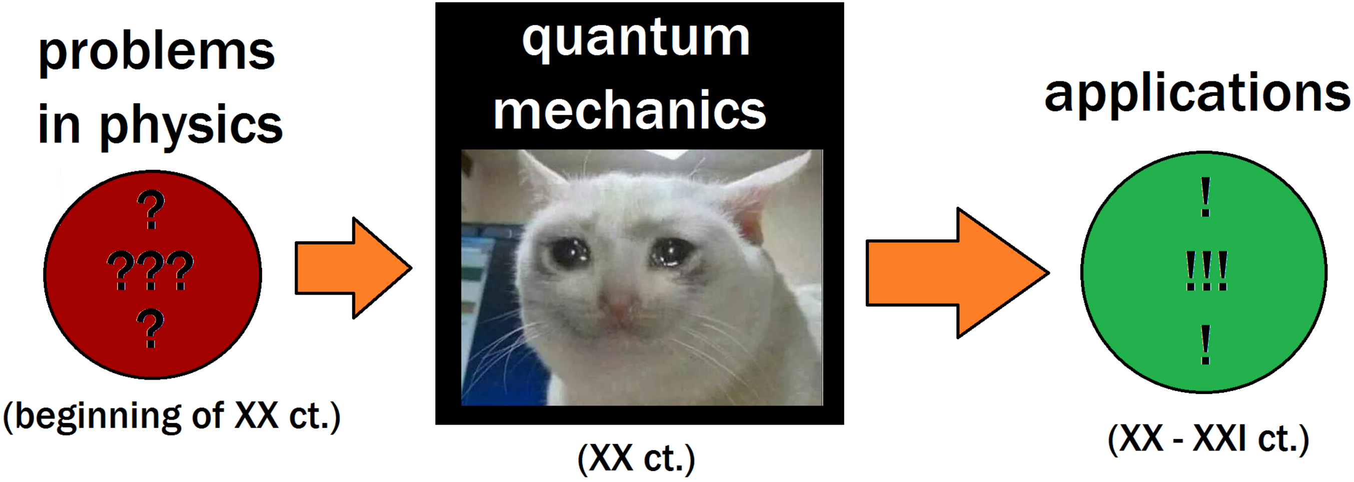
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- Etc.

Physical problems

Beginning of the XX century:

- Laws of electromagnetic emission;
- Photoelectric effect;
- Atomic structure.

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$\longrightarrow$ first steps into the quantum world:

- Planck's hypothesis – discrete character of energy (action) changes, 1900. (Nobel prize in 1918);
- Einstein's works on photoelectric effect, 1905. (N. pr. in 1921);
- Bohr's postulates on the atom, 1913. (N. pr. in 1922).

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Heisenberg, Dirac, Pauli, Ehrenfest, Sommerfeld, *Fock**, Landau, Schrödinger, Born, von Neumann, de Broglie …

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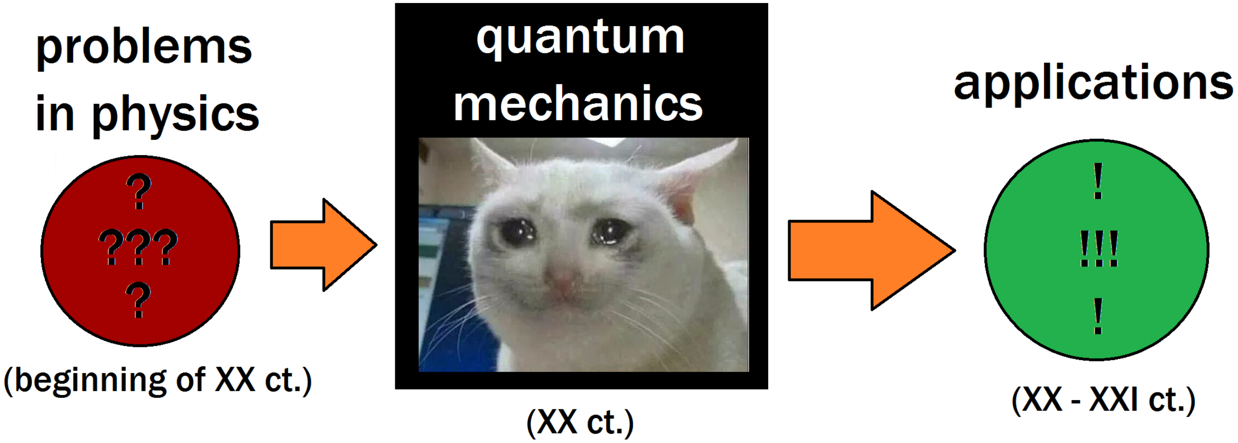
the behaviour of quantum objects is *significantly* different with respect to the classical ones.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quantum mechanics

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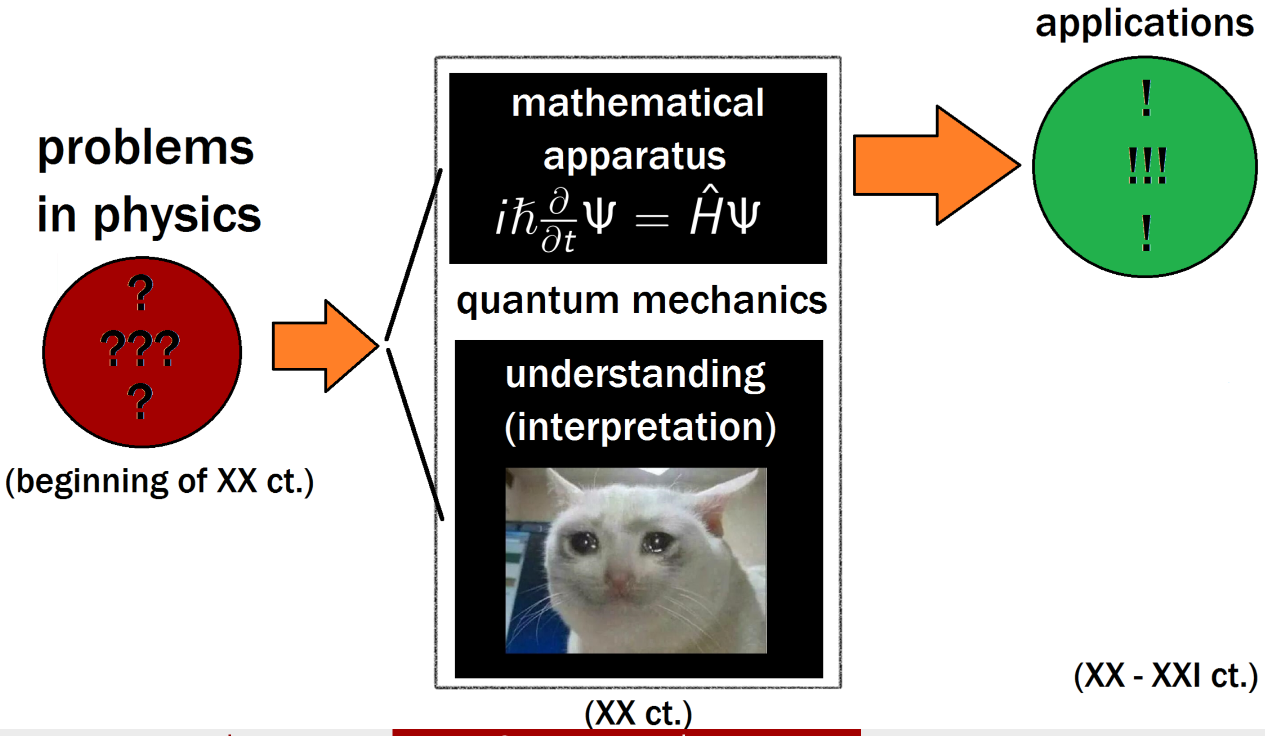
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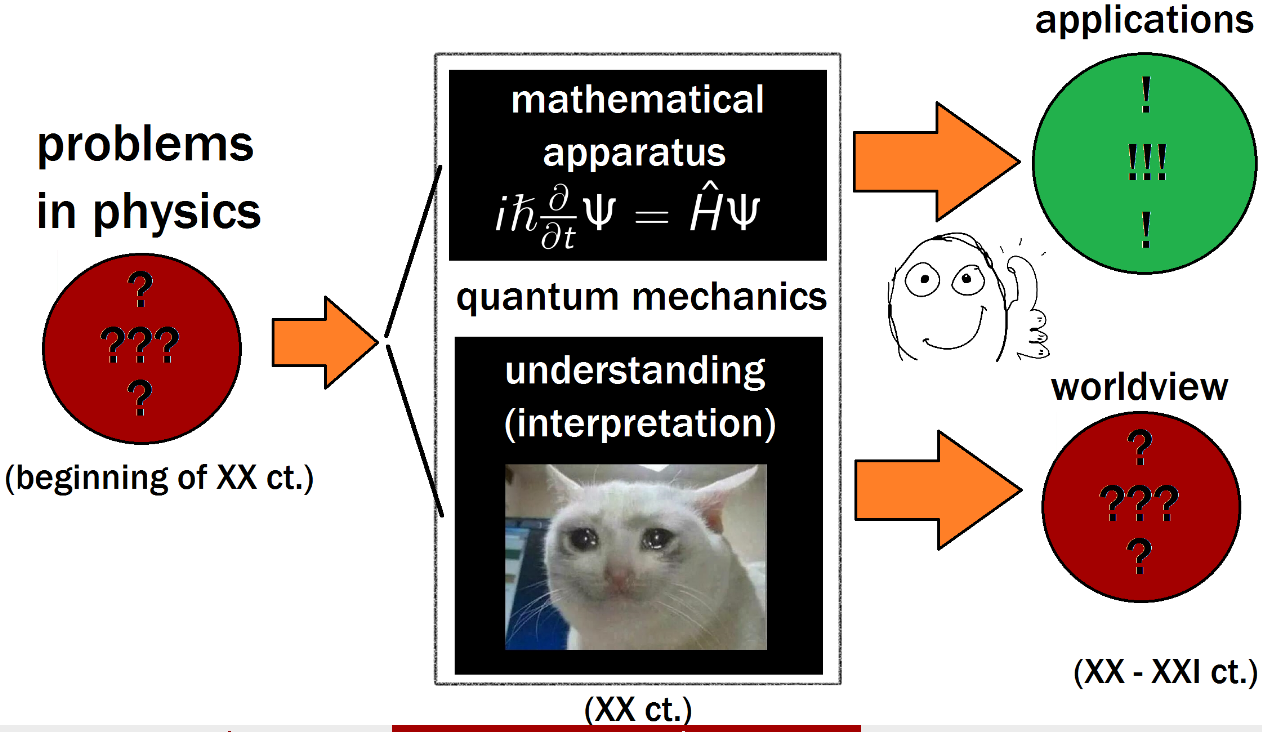
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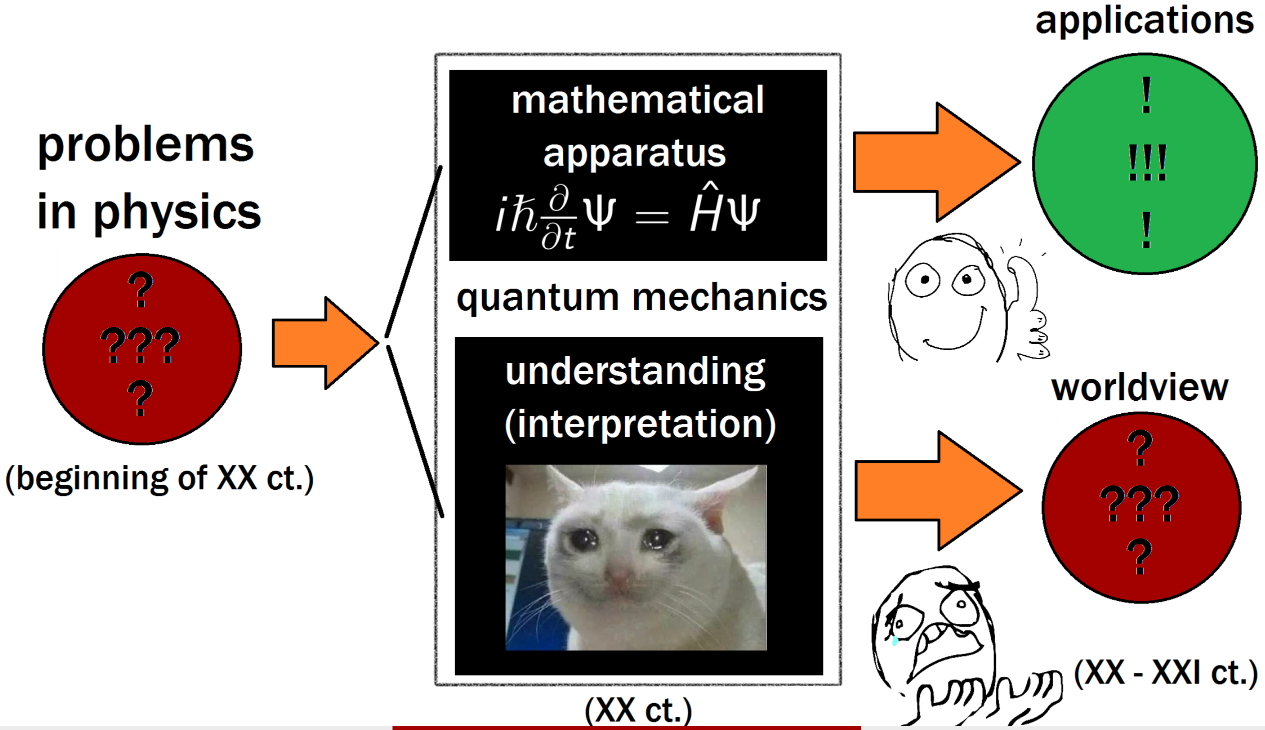
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Description of the quantum world

"I think I can safely say that nobody understands quantum mechanics." (R. Feynman, 1964).

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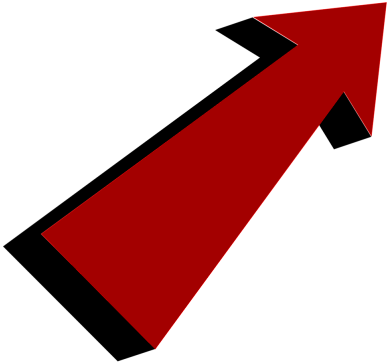
*statistical

Main concept in quantum mechanics – *quantum state*.

Which state is the quantum system in is shown by the *state vector* from the abstract *Hilbert space*.



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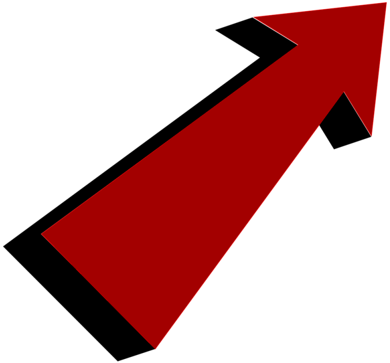


This state!

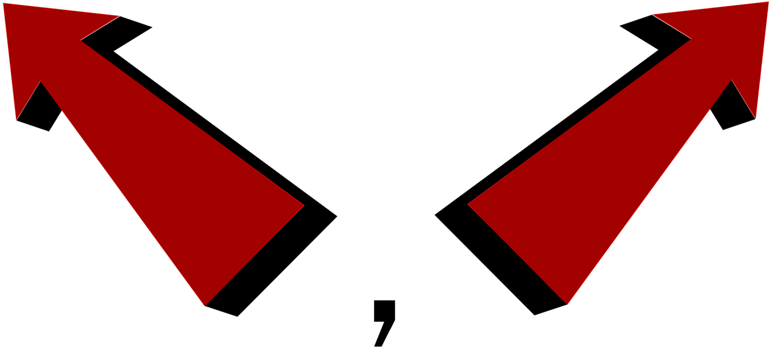
Dirac notation: $|\psi\rangle$.

Physical quantities $a \to$ operators A, acting upon state vectors:

$$A|\psi\rangle = a|\psi\rangle.$$

Principle of superposition of quantum states:
the sum of two possible quantum states is also a possible quantum state.

$$|\psi\rangle = |\psi_1\rangle + |\psi_2\rangle$$



Possible states of the quantum system

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Possible states of the quantum system

The third state *does not have* classical counterparts!

Possible states of a quantum object are not necessarily *equally probable*, i.e. the vectors of its different states might differ by their “significance” (length).

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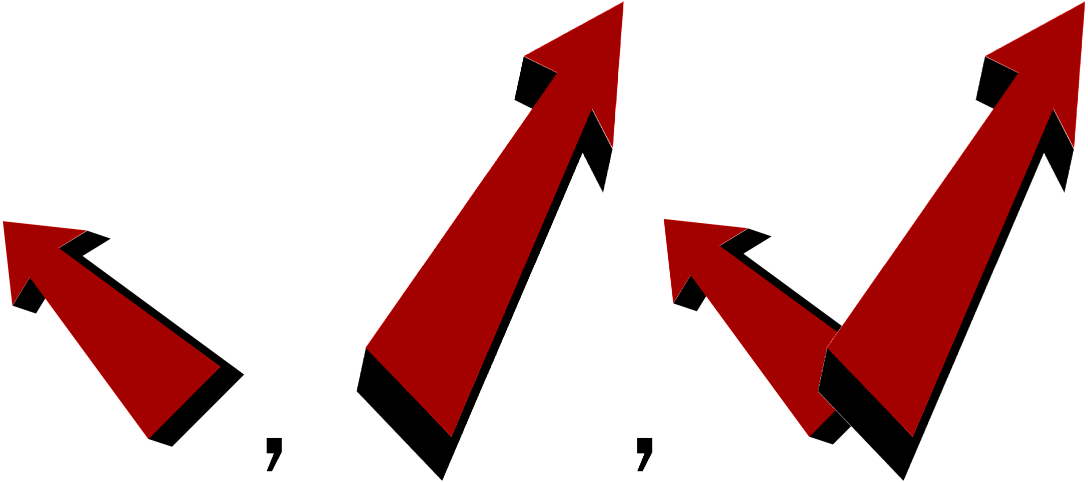

Possible states of the quantum system

System of a few quantum objects $\longrightarrow$ *entangled* states are possible.

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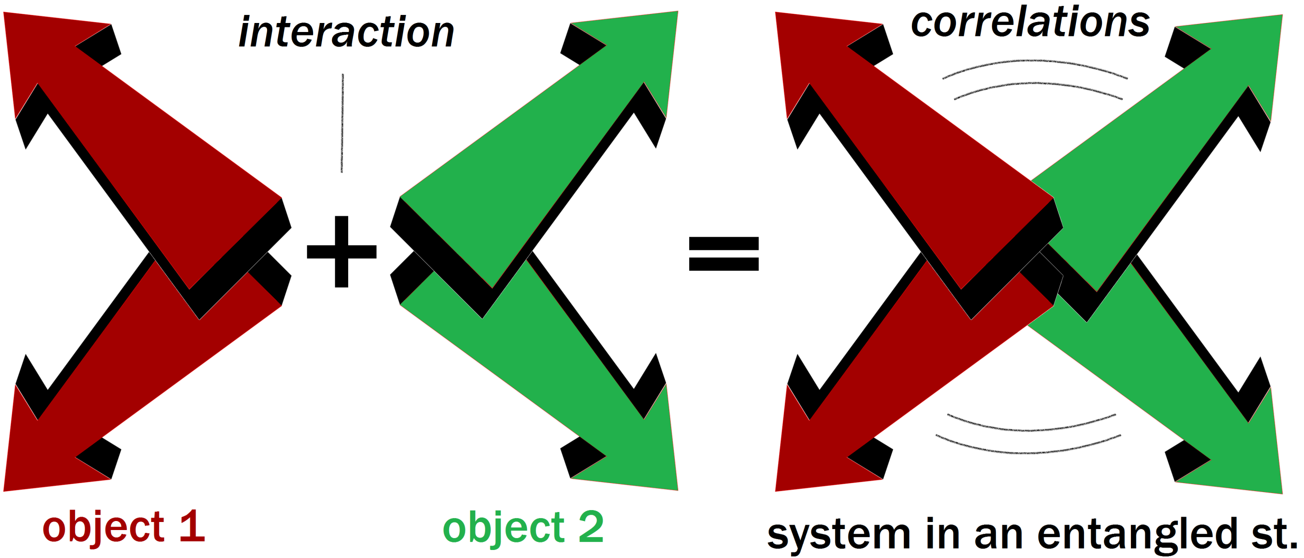
They are characterized by the *correlations* between the states of separate objects.

Interaction of two (or more) quantum objects leads to the formation of an entangled state. The states of separate objects are no longer independent.


interaction
correlations
object 1
object 2
system in an entangled st.

In summa: quantum mechanics deals with abstract state vectors and *ignores* the "usual" space and the concepts associated with it $\longrightarrow$ new effects, paradoxes etc.

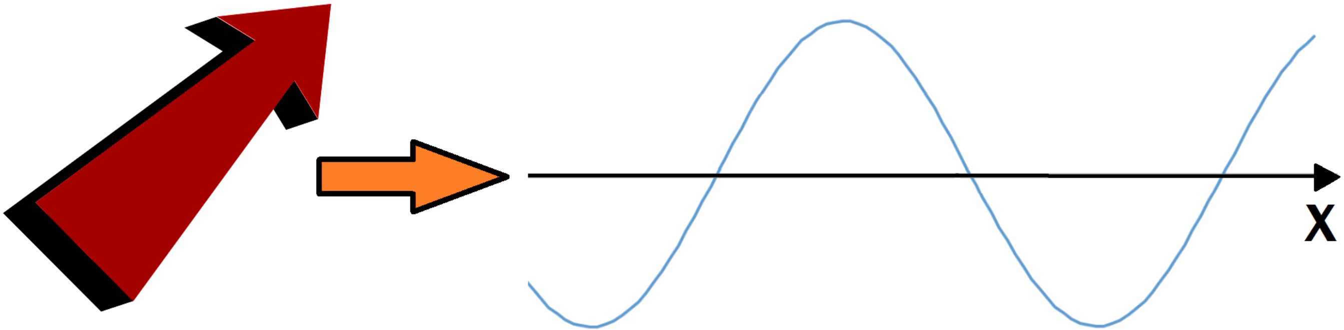
This is the main reason why quantum mechanics is fundamentally impossible to reconcile with relativity theory, which is all about space and its properties.

Closer to practice

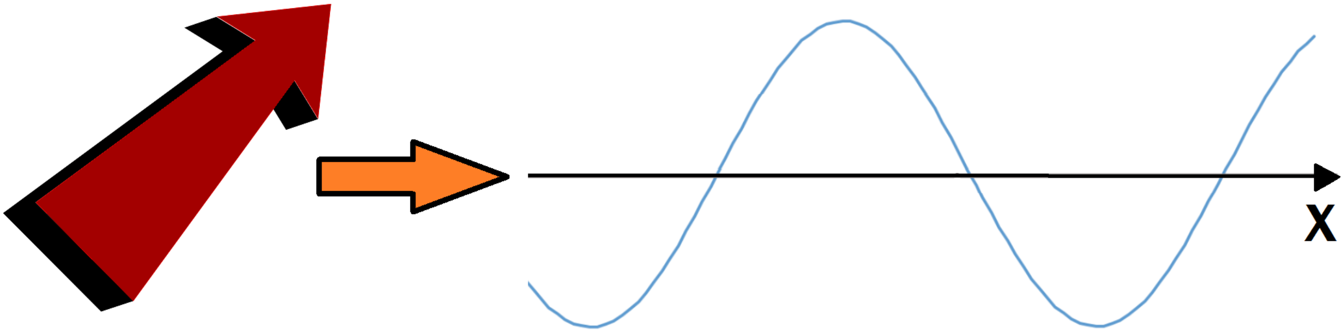
That being said, the state vector *could* be represented in a real physical space, – such representation is called a *wave function*, – but this is only one of the possible representations.

- Why is this function "wave"?
- Because *it looks like a wave*;

- Where does it follow from?
- Schrödinger's equation, which, *it seems*, is correct.



Wave function (i.e. spatial representation of the state vector) of a free (non-interacting) particle.



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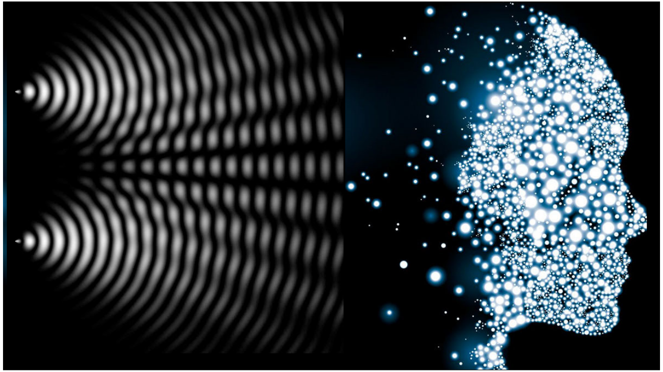
Thus, [localized] *particle* from the standpoint of quantum mechanics is described

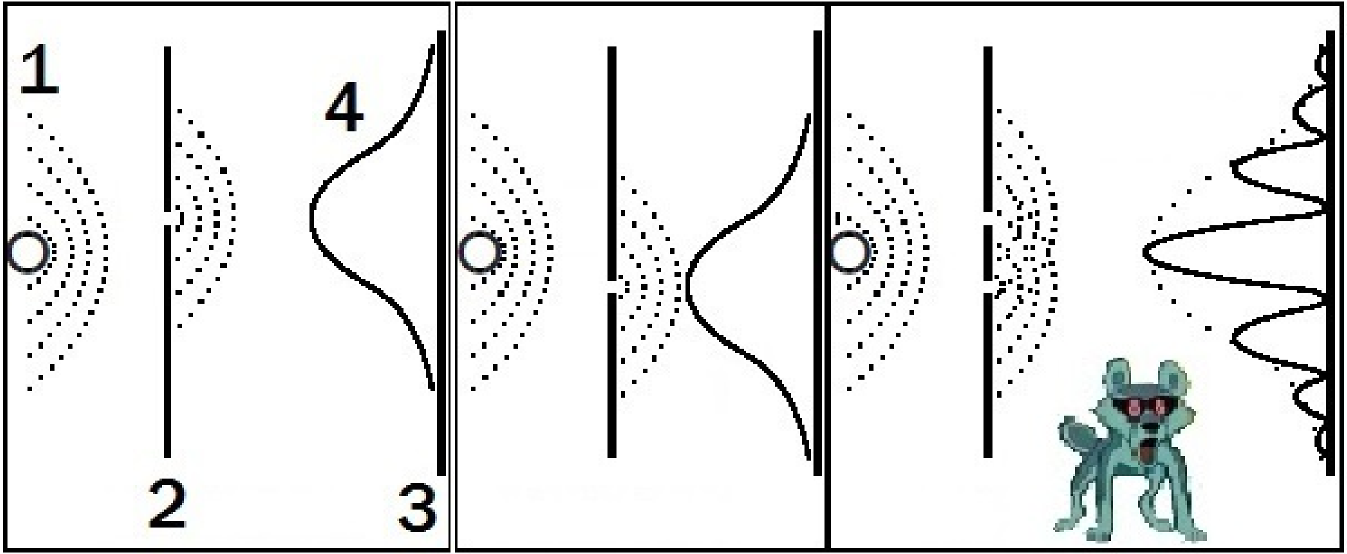
as an [infinite] *wave* – ??????

Even closer to practice

Double slit experiment – popular demonstration of quantum properties.



Double-slit experiment:
***Focking* your brain since 1927.**



1 – particle source; 2 – screen with two slits; 3 – particle detector; 4 – the statistics of detections.

1) If one slit is open, particles mostly hit the detector against it;
2) If both slits are open, the detector observes an *interference pattern*, as if the particles would "stifle" each other as couter-phased waves.

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- The same is observed if the particles are emitted *one by one*, i.e. the particle might *form an interference pattern with itself*, passing through both slits *simultaneously*.

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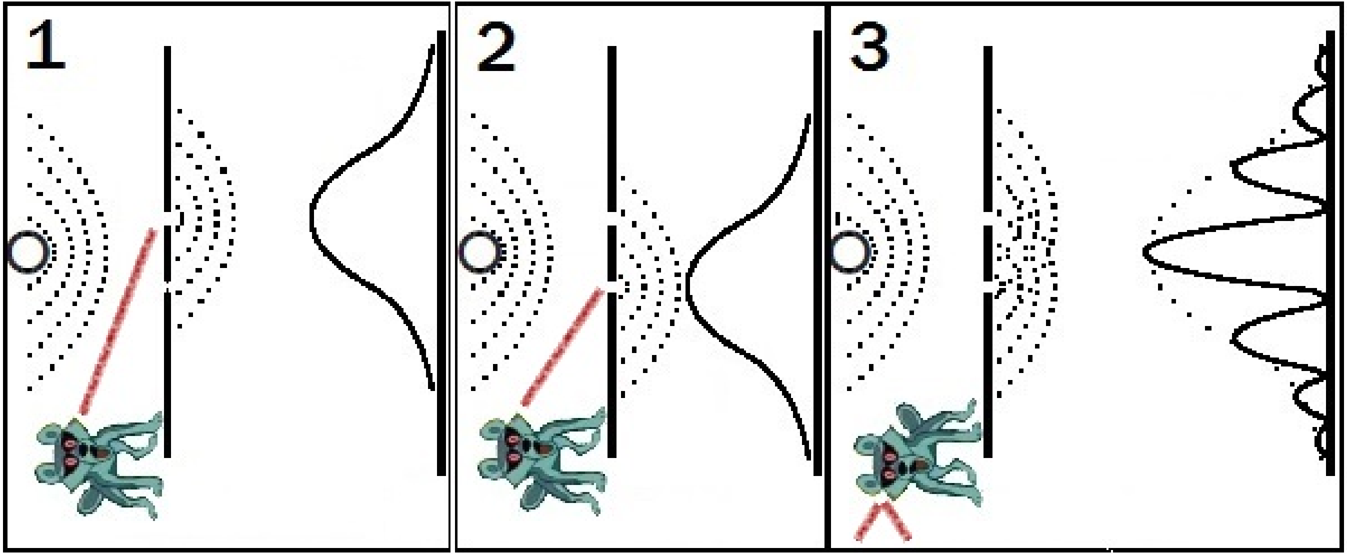
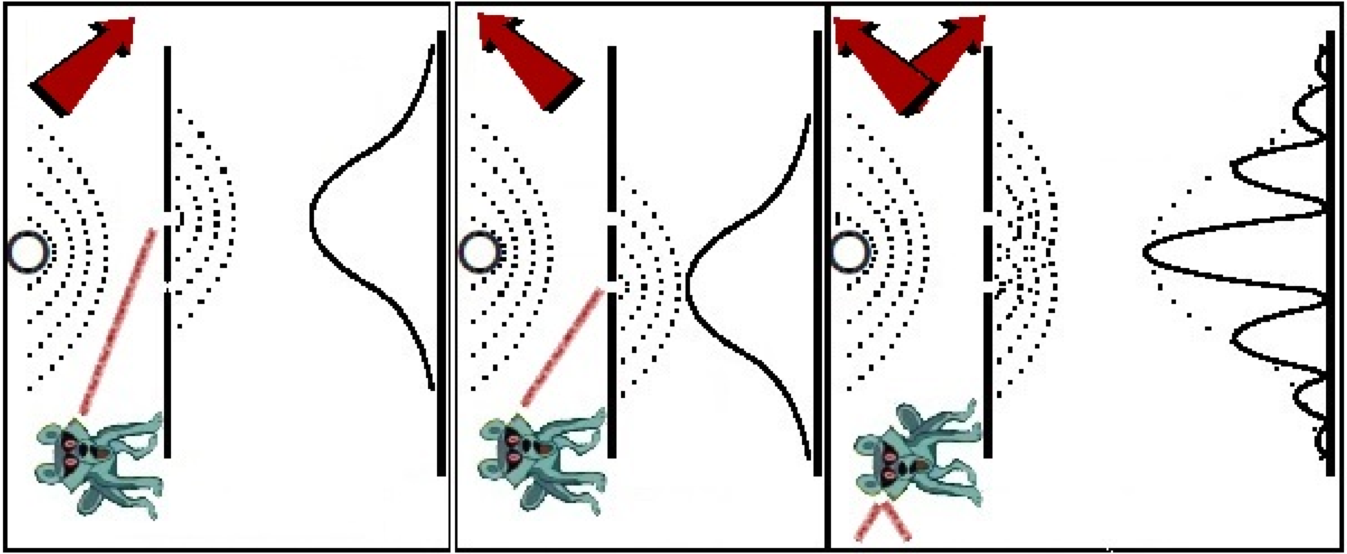
- The same is observed if the particles are emitted *one by one*, i.e. the particle might *form an interference pattern with itself*, passing through both slits *simultaneously*.
- The same is observed if the distance from the slit to the detector is very large, and we change the slit configuration *after* the particle "flew" through them (!!!), but didn't interact with the detector yet – so-called *delayed-choice experiment*.



1 – jackal observed a particle passing throught the first slit; 2 – through the second; 3 – jackal didn't observe anything.



1 – jackal observed a particle passing throught the first slit; 2 – through the second; 3 – jackal didn't observe anything.

If both slits are open, but an observation is performed (pictures 1 – 2), the particle is passing *only through one of them*. If observation is not performed (picture 3), then interference pattern is observed again.

It seems, the observation (measurement), performed by jackal, impacts the result – purely quantum result with an interference pattern is only possible without the observation.

… and even closer to practice

Uncertainty principle of Heisenberg (1927): there are pairs of physical quantities, simultaneous measurement of which is impossible to perform with infinite precision.

Examples:

- coordinate and momentum (velocity):
  $\Delta x \Delta p \geqslant \frac{\hbar}{2}$;
- energy and time:
  $\Delta E \Delta t \geqslant \frac{\hbar}{2}$.

Consequences:

1) Higher precision in measurement of the position brings less precision in momentum measurement (and vice versa);

2) The energy of a system might spontaneously change to the value of $\Delta E = \frac{\hbar}{2\Delta t}$, where Δt is the according time.
Which allows *virtual particles* to exist.

Classical mechanics:

- Position x;
- Velocity v (how quick x is changing);
- Acceleration a (how quick v is changing);
- Force (link between acceleration and mass);
- Energy – is conserved;
- Precise predictions.

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Quantum mechanics:

- State vector $|\psi\rangle$;
- Superpositions might exist;
- Position and velocity cannot be determined simultaneously;
- Acceleration cannot be determined;
- Force cannot be determined;
- Energy is not determined, or* might change;
- Probabilistic predictions.

*Quantum states with defined energy are called *stationary* states and only represent a special case.

Paradoxes and interpretations

Following from all the above – paradoxes and unusual effects:

- Waves or particles?
- Schrödinger's cat (the existence of superpositions);
- Wave function collapse (*how and where is the quantum/classical transition happening?*);
- Einstein–Podolsky–Rosen paradox (quantum teleportation).

Paradoxes and interpretations

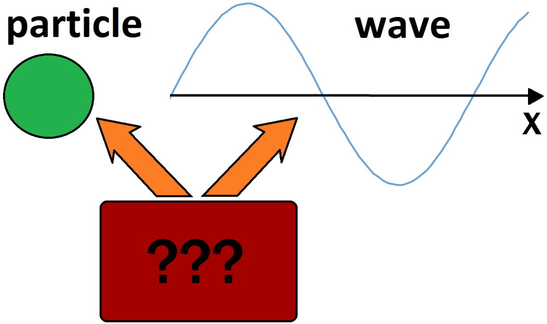
Attempts to address these questions (so-called *interpretations of quantum mechanics*):

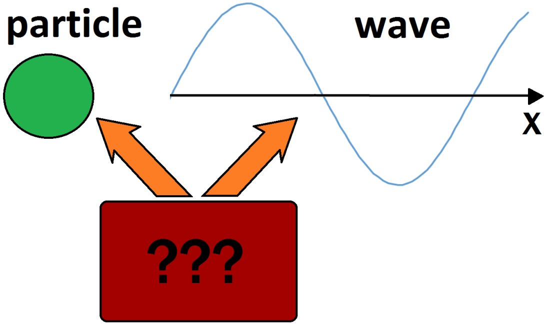
- Copenhagen;
- Many-worlds;
- Informational;
- Decoherence*;
- $\sim$ dozen of others.

*not usually acknowledged as a separate one

Waves or particles?

State vector of a quantum object in the coordinates of a “physical” space – wave (*wave function*).
But the interaction is discrete, “point-like” and local, as with particles – so what are we dealing with?..


particle
wave
x
???

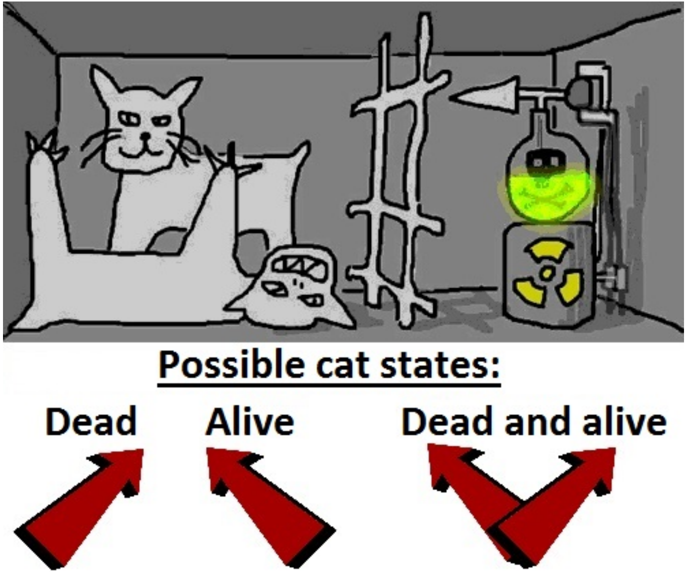


Principle of complementarity (N. Bohr): quantum objects behave as particles or waves depending on the circumstances.
The analogy (model) for what they are "in reality" still has not been found (*wave–particle duality*).

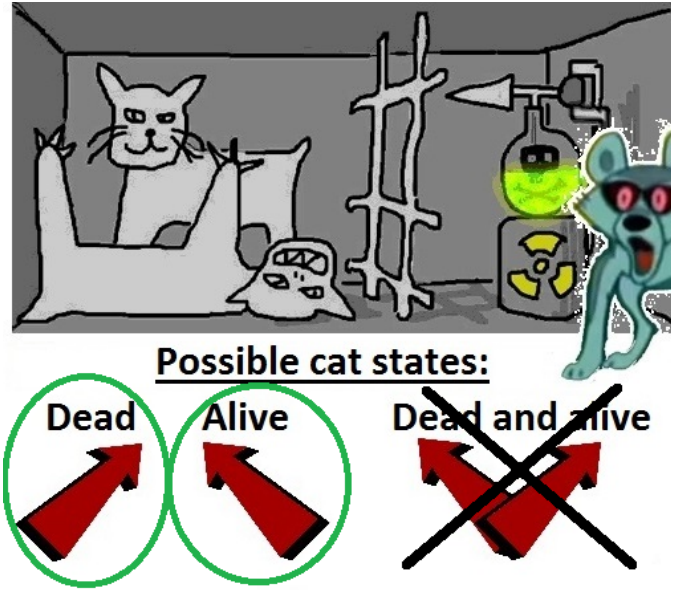
Feynman: relax, these are wavecles (wave + particle).

Schrödinger's cat

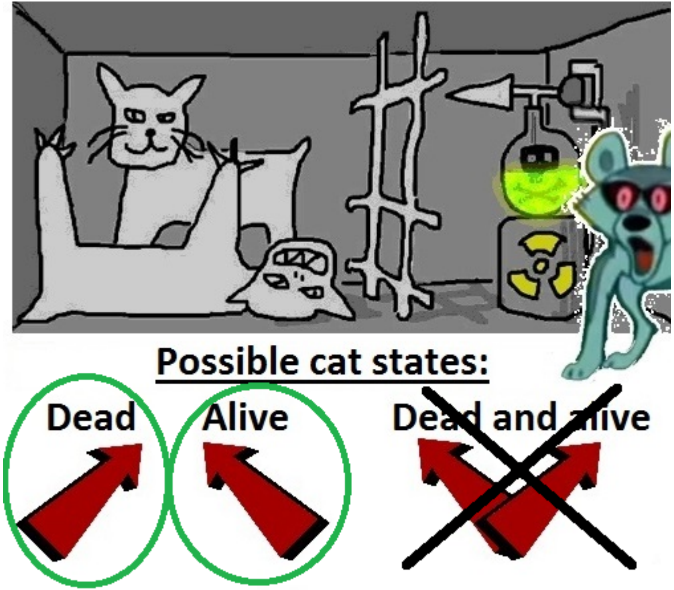
S.c. – thought experiment, which demonstrates the *absurdity of the existence of quantum superpositions*: if the state of a classical system (a cat) depends on the state of a quantum system (e.g. a decaying nucleus), then the cat itself would also *in principle* should be in a state of superposition, just like the nucleus, which is incompatible with experience.



The paradox is not about the uncertainty "dead or alive", but about the existence of a third possibility: dead and alive simultaneously, which is normal for quantum objects (see superposition principle), but is impossible for classical ones.



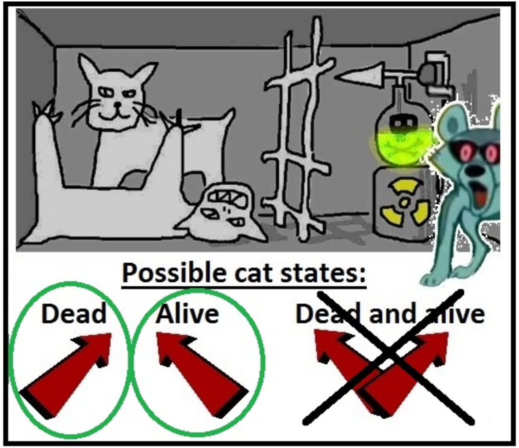
During the observation of the state of a cat, since it is a classical object, only two options are possible.

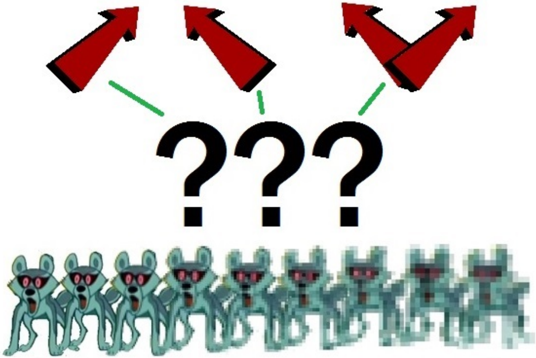


During the observation of the state of a cat, since it is a classical object, only two options are possible.

Where and how does the third option vanish?.. → problem of *wave function collapse* (= "reduction" etc.). The observer significantly changes the system. Quantum system turns into a classical one, but it is not clear, how.

Wigner's paradox (paradox of friends): enhancement of Schrödinger's cat paradox: let the jackal observe the cat's state, so *for the observer* the state of the cat became a classical one with only one of two outcomes.



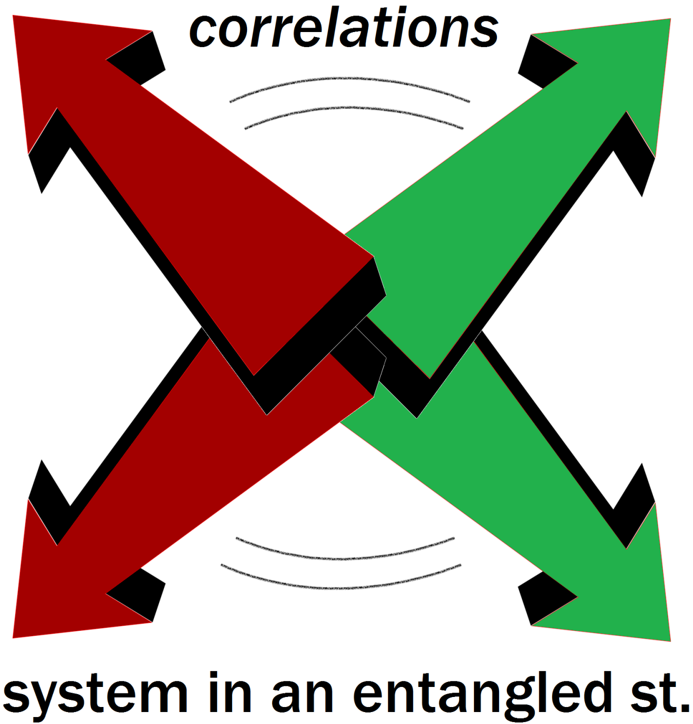


But jackal also has friends, who *did not yet observe the cat's state*. So for them the cat is also still in a state of superposition - ?.. Then *when exactly* does the collapse occur?..

Einstein–Podolsky–Rosen (EPR) paradox

In a nutshell: even if we separate two particles in entangled state for a *very big* distance, the entanglement of their states would remain. So their states would still be correlated.

Which means, the change of one particle's state would *immediately* change the state of the other, regardless of how far it is.
This is called *quantum teleportation*.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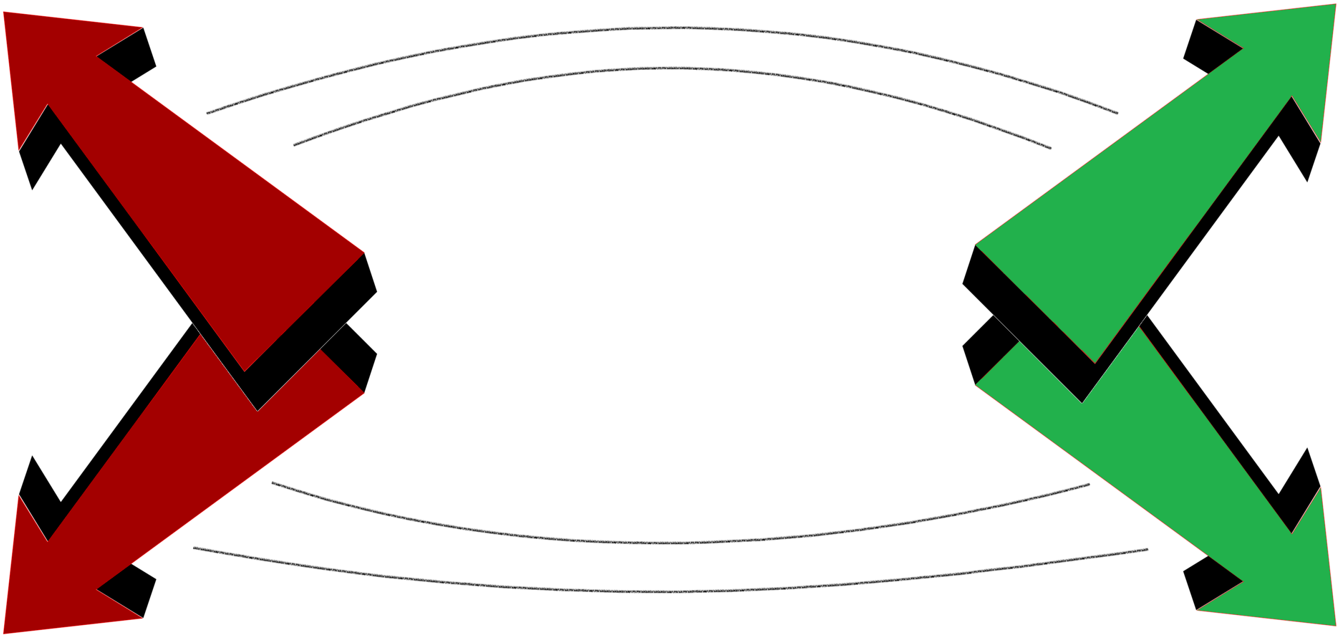
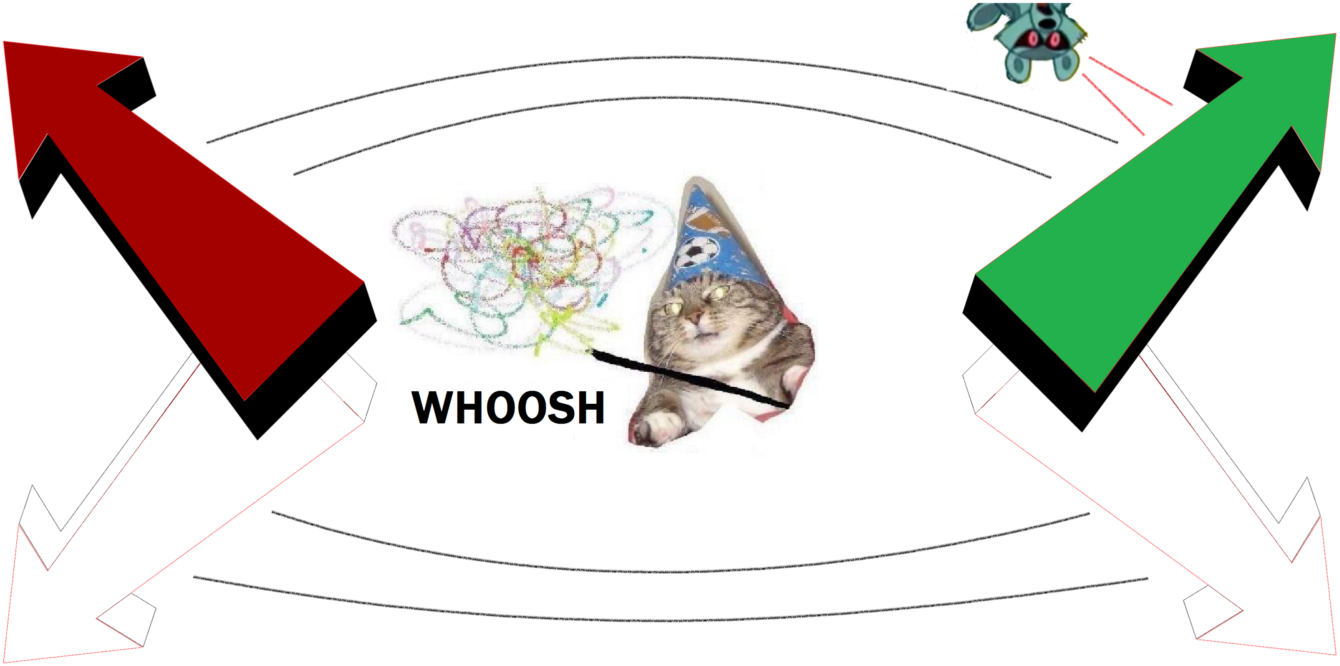
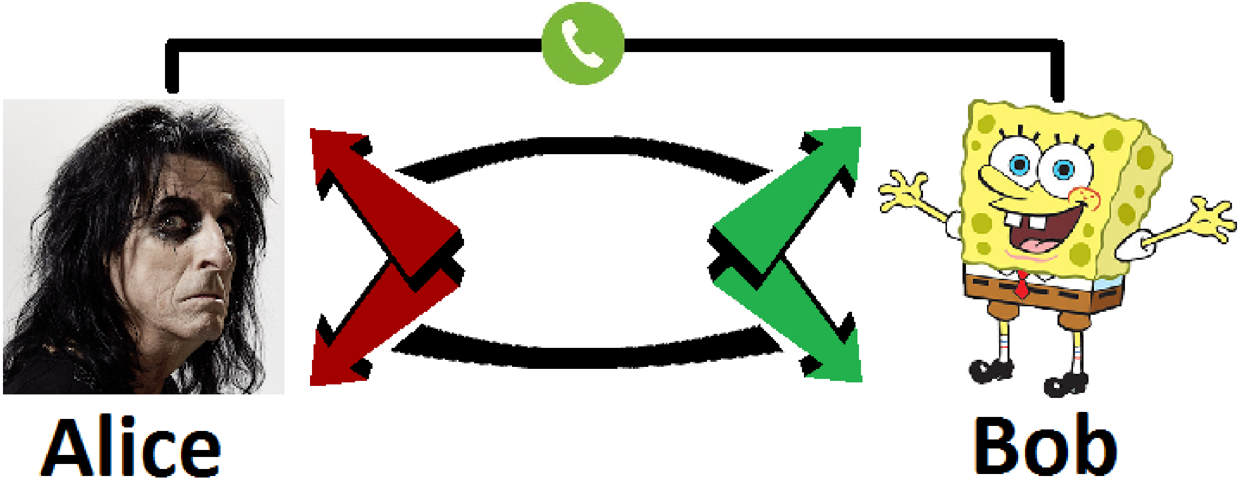
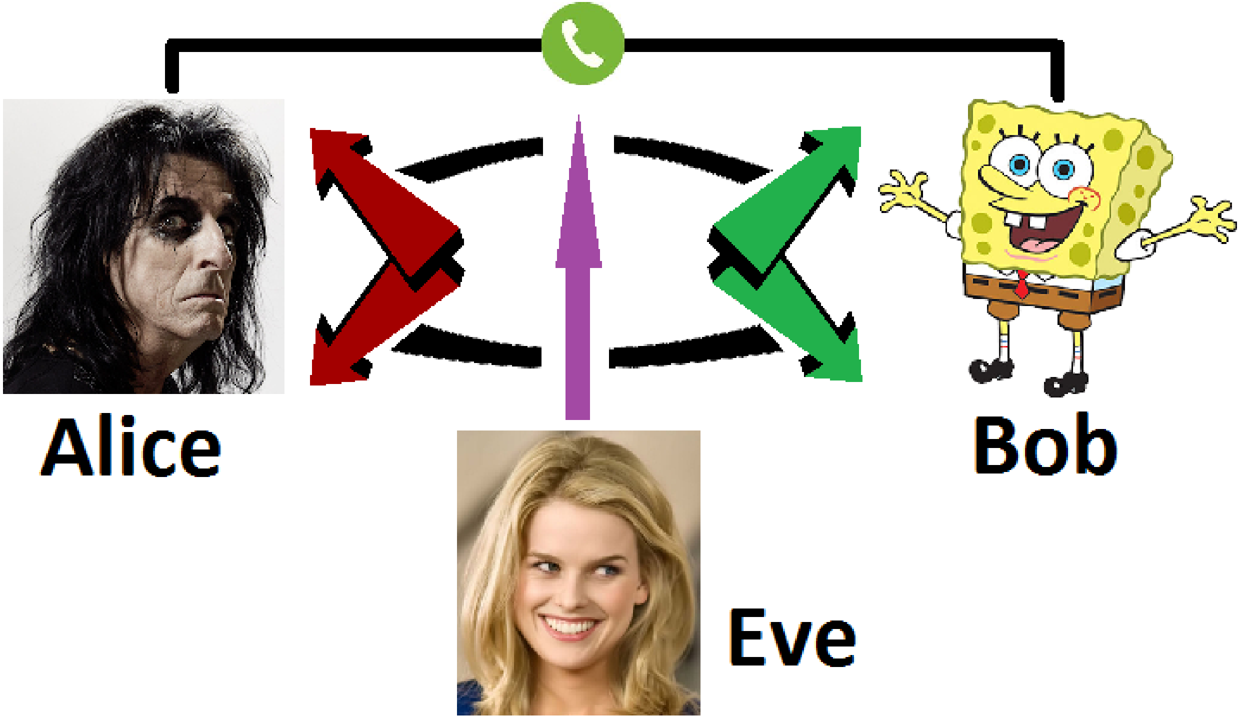


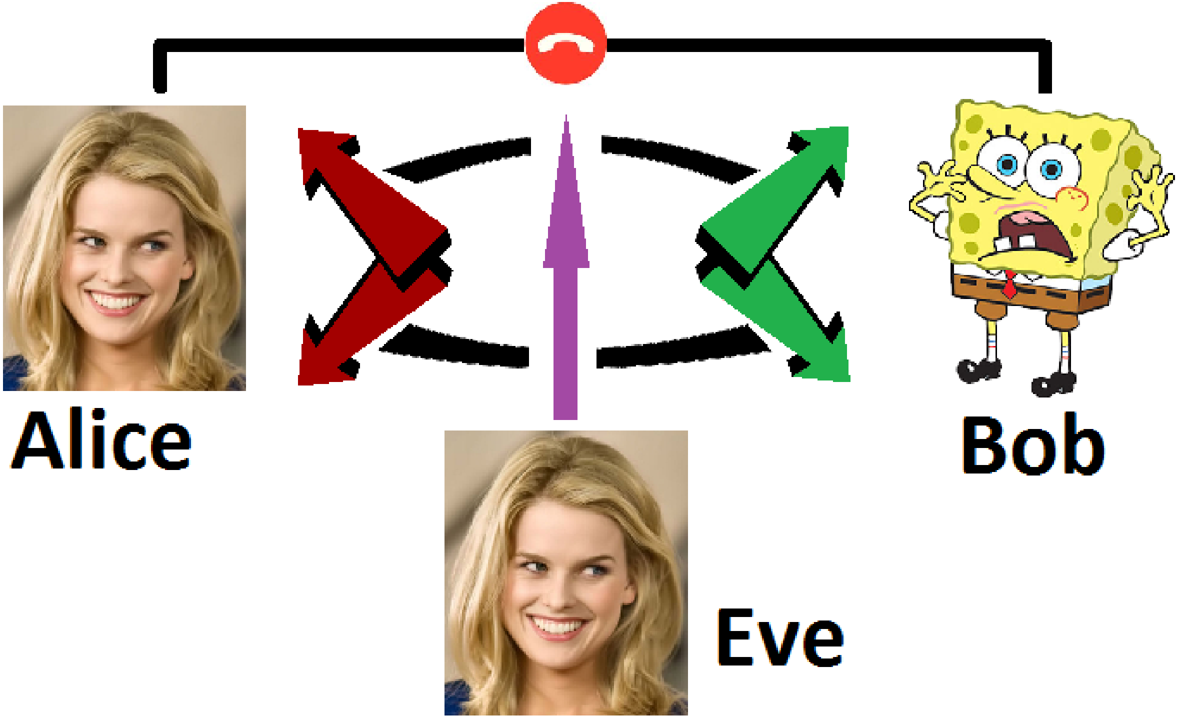

WHOOSH

Exchange of entangled particles $\rightarrow$ **quantum cryptography**.

If the quantum channel is being monitored by a third party (i.e. an additional external interaction is present), the correlation between entangled particles gets messed up, and the communicating parties would notice that by comparing the results of their measurements.


Alice
Bob


Alice
Bob
Eve


Alice
Bob
Eve

Important: quantum teleportation happens instantly, but it *does not transfer any energy, matter or information*, i.e. it does not contradict the relativity principle.

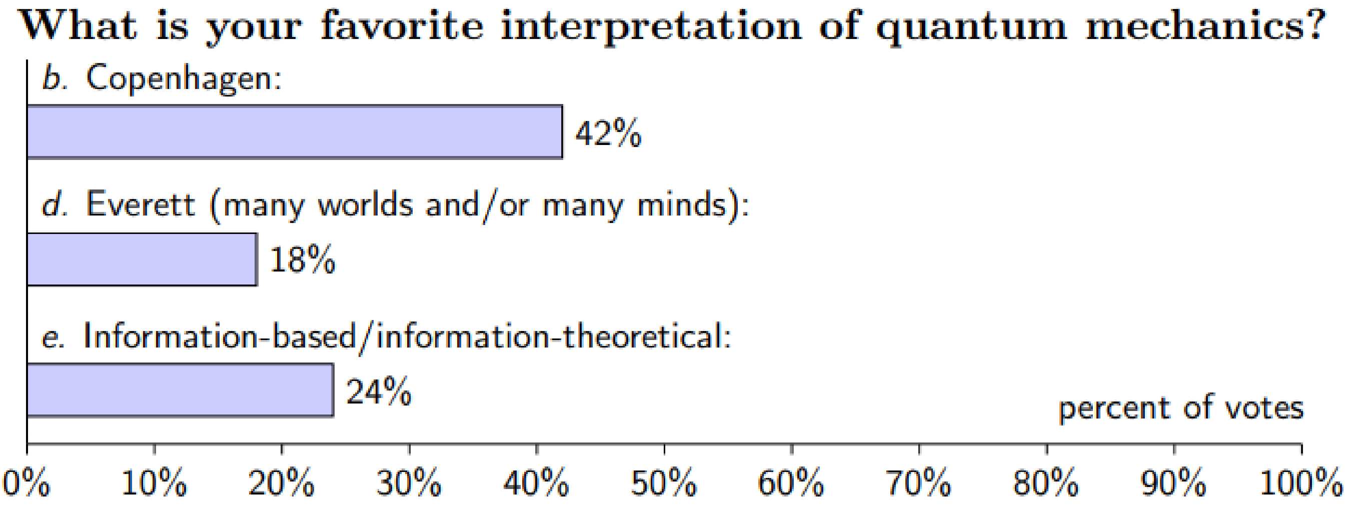
If the state of one of the particles was measured in one place, in the other place (where the other particle is) *the result of previous measurement is not known yet*, and it is still impossible to communicate it faster than light. Moreover: once measured, the particles are no longer entangled (well...), so the "quantum channel" between them closes.

Interpretations of quantum mechanics

There are about 10–20 different interpretations (i.e. *there is no agreement even about their classification*).

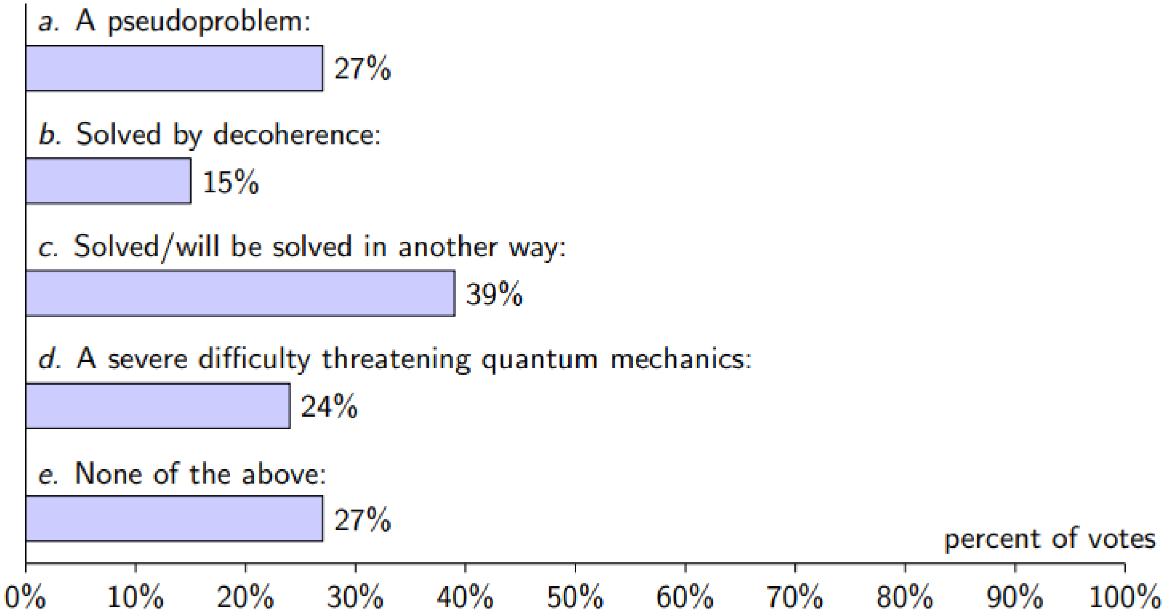
The most popular at the moment:

- Copenhagen;
- Many-worlds;
- Informational;
- Decoherence*.



Schlosshauer, Kofler, Zeilinger (2013): https://arxiv.org/pdf/1301.1069.pdf

The measurement problem



Schlosshauer, Kofler, Zeilinger (2013): https://arxiv.org/pdf/1301.1069.pdf

Copenhagen interpretation

Bohr, Heisenberg, 1925-1927.

It is postulated, that there exist two different types of objects: quantum and classical, – which behave differently.
During the interaction of a quantum object with a classical one the former loses its quantum properties (superposition states, entanglement with other objects etc.), i.e. an irreversible collapse of its state vector occurs.

Advantages:

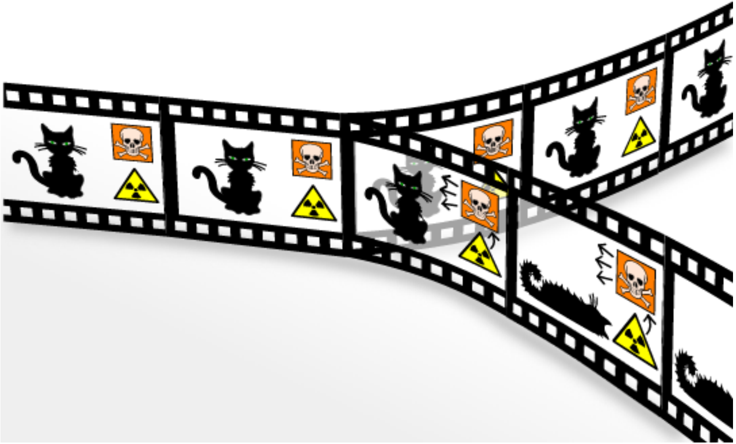
- Simplicity;
- Applicability (instrumentalism).

Disadvantages:

- It is unclear, what is the reason of fundamental difference between quantum and classical objects;
- It is unclear, at which moment a quantum object becomes a classical one (where is the boundary);
- It is unclear, what role is played by the observer (and consciousness).

Many-worlds interpretation

H. Everett, 1957.
During the measurement of a quantum state *the Universe itself splits into two branches* (or more) with different results.



Paradox of a *quantum suicide* – if the observer himself sits in a box instead of a cat, there would *always* exist a branch of the many-world Universe, where the nucleus did not decay, and the observer would be alive forever – ???

Advantages:

- Doesn't contradict the mathematical formalism of quantum mechanics;
- Explains the wave function collapse.

Disadvantages:

- The difference between quantum and classical objects is not clear;
- Contradicts Ockham's razor (many universes to explain a single particle);
- Parallel universes do not interact anymore (?) – so why do we even need them?..
- The role of consciousness is not clear (*speculations*).

Informational interpretation

1960-1980.

Two branches:

- *conservative*: quantum mechanics describes not the world itself, but only *our knowledge* about it, i.e. one shouldn't make ontological conclusions from it; state vector is only our "notebook";
- *radical*: information is the more fundamental concept than matter, energy etc., and quantum objects "precede" classical ones (J. Wheeler, "it from bit").

Advantages:

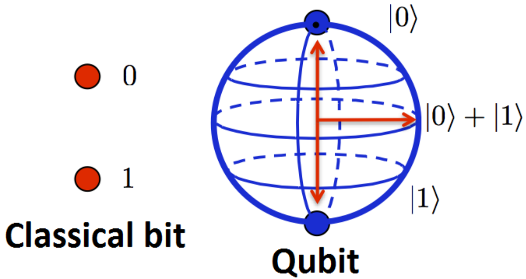
- Does not contradict the equations.

Disadvantages:

- Leaves out ontological questions (what is reality?).

Quantum computers

Quantum computers $\longrightarrow$ quantum bits (qubits) instead of classical ones; qubits might not only have a state of 0 or 1, but also their quantum superposition.



Problem in practical realization – the environment (other parts of the quantum computer etc.) interacts with the qubit and "measures" it ("opens the cat's box"), changing it into the classical 0 or 1 (so-called *decoherence* of the quantum state takes place).

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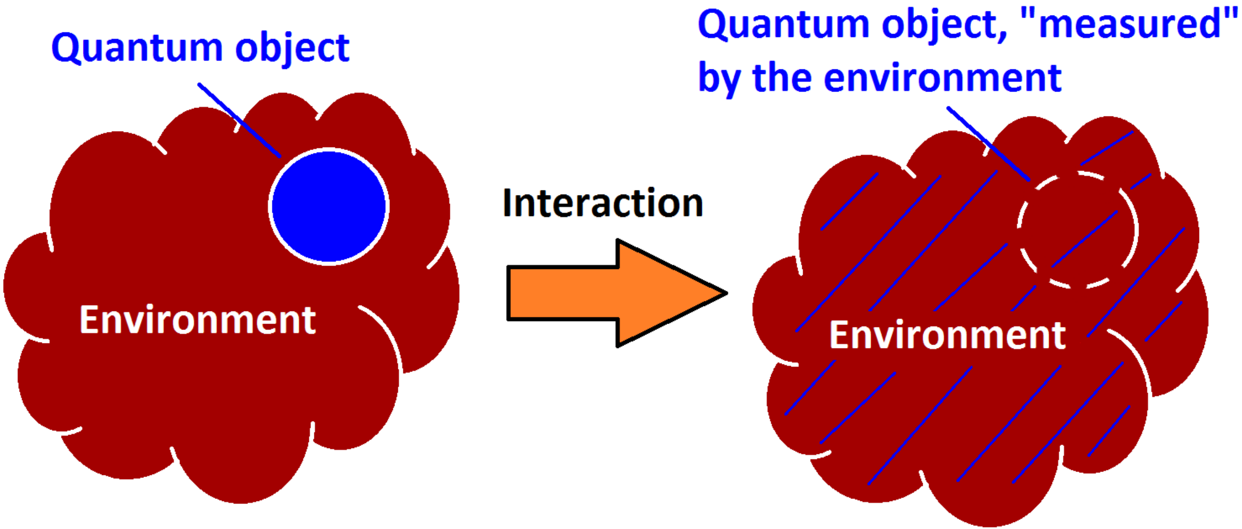
But wait a minute – can it be the explanation for wave function collapse in the first place?

Decoherence

H.–D. Zeh, 1970.

State vector collapse is explained as a consequence of the interaction with the environment – information about the superposition state is “smeared” over the environment, and if the latter is large enough, it is no longer possible to extract it (well, *theoretically* still possible – see *no-cloning* and *no-hiding* theorems in quantum information theory). It is still there, but not observed.



Characteristic time of decoherence $\sim \frac{\hbar^2}{m}$, i.e. it happens *very fast*, and the faster the more massive the environment is.

Advantages:

- All the equations of quantum mechanics are valid for all the scales, i.e., strictly speaking, *there is no boundary between the quantum and classical worlds*, classical laws are the approximations of quantum ones, valid for large systems, where superpositions quickly decay;
- Eliminates the problem of wave function collapse (it is an apparent effect, resulting from the large size of classical objects);
- Adequate answer to the role of the observer (the existence of consciousness is not required, decoherence is "objective").

Disadvantages – ???

What was omitted

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- Pauli's exclusion principle (two particles with spin $\frac{1}{2}\hbar$ cannot be in the same state);
- Multiparticle quantum systems (statistics, secondary quantization and quantum fields etc.);
- Quantum Zeno paradox: frequent observation reduces the probabil ty of change of quantum state (see *wage on a payroll card*);

- Tunneling effect (there are no impenetrable barriers; quantum objects might “leak in” anywhere);

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- Casimir effect (“free energy” from virtual particles);
- Feynman's approach (path integrals);
- Theories with hidden parameters (*Bohm's mechanics* aka pilot-wave theory etc.) – same predictions, but more simple picture (?).

Philosophical notes

- Speculations on the role of human consciousness (M. B. Mensky – consciousness as the "regulator" of the process of quantum measurement; Chopra, Wigner, Pauli etc.).

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- Quasi-religiousness ("quantum" as a shorthand for "magical"), quantum mysticism etc.
  S. I. Doronin, "Quantum magic" (2007) – a lot of doubtful hypotheses, but *suddenly* very good and coherent statement of the basic theory.

- The role of quantum entanglement: even though it is suppressed by decoherence, *in principle* it does not disappear, and states of any particles that ever interacted (directly or indirectly) should be correlated.

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- "No man is an *Iland*, intire of it selfe; every man is a peece of the *Continent*, a part of the *maine*" (J. Donne, 1627).

General conclusions

1) Quantum mechanics might be conditionally divided into the "technical" part (abstract objects and equations) and "humanities" part (picture of the world and interpretations, understanding).

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2) Technical part works decently well and has lots of practical applications.

3) Humanities' part is seriously ($\sim$ 100 years) lagging and does not provide a unified, simple and coherent view of the world.

4) Quantum world is significantly different with respect to the classical one, and it is not clear how exactly are they related and what role is played by the observer in their relation.

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5) Various attempts at answering this question and building of a humanities' part are called *interpretations of quantum mechanics*.

Thank you!