EPFL Master course Philosophical perspectives on science and its history

Philosophy of quantum physics: non-locality, the measurement problem & the ontology

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Quantum physics
Einstein's boxes (1927)

- Box with one particle prepared in Lausanne.
- Box divided in two halves. One half-box sent to New York, the other one sent to Tokyo.
- QM textbook formalism: wave function represents particle as being distributed over both half-boxes (superposition) = probability to find particle in New York 0.5, probability to find particle in Tokyo 0.5.
- Alice opens her box in New York and finds it empty.

→ Fact that there is a particle in the box that Bob receives in Tokyo.

- QM textbook formalism: wave function represents particle as being localized in Tokyo ("collapse of the wave-function").

The physical problem of interpretation

- **collapse of the wave function: *epistemological*, updating of available information**

→ **particle is always localized either in the box travelling to New York or in the box travelling to Tokyo (= moves on classical trajectory, not influenced by operations on the other box). When Alice opens her box in New York, she simply receives the information where the particle is.**

quantum formalism incomplete because it does not tell us where the particle is: formalism provides probabilities for measurement outcome statistics, but does not represent real evolution of objects

- **collapse of the wave function: *ontological*, process in nature**

→ **When Alice opens her box in New York, she creates the fact that there is a particle in the box in Tokyo.**

Einstein: “spooky action at a distance”

measurement problem & problem of non-locality

Heisenberg (1930)

"… one sees that this action is propagated with a velocity greater than that of light. However, it is also obvious that this kind of action can never be utilized for the transmission of signals so that it is not in conflict with the postulates of the theory of relativity."

Quantum entanglement

- **Einstein, Podolsky, Rosen (EPR) (1935): two particles, two observables: position and momentum**
- **Bohm (1951): two particles, two observables: spin in different directions**

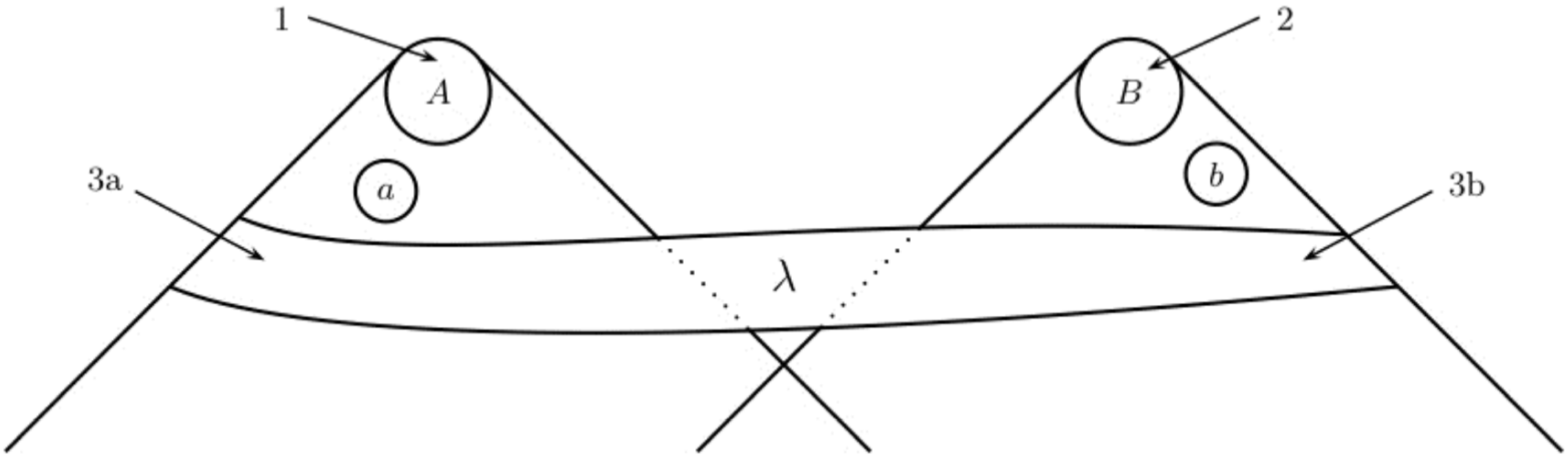
(1) $\psi_{12} = 1/\sqrt{2}\,(\psi^{+}{}_{1} \otimes \psi^{-}{}_{2} - \psi^{-}{}_{1} \otimes \psi^{+}{}_{2})$

(2) $\psi_{12} = \psi^{+}{}_{1} \otimes \psi^{-}{}_{2}$ **Prob. 0.5**

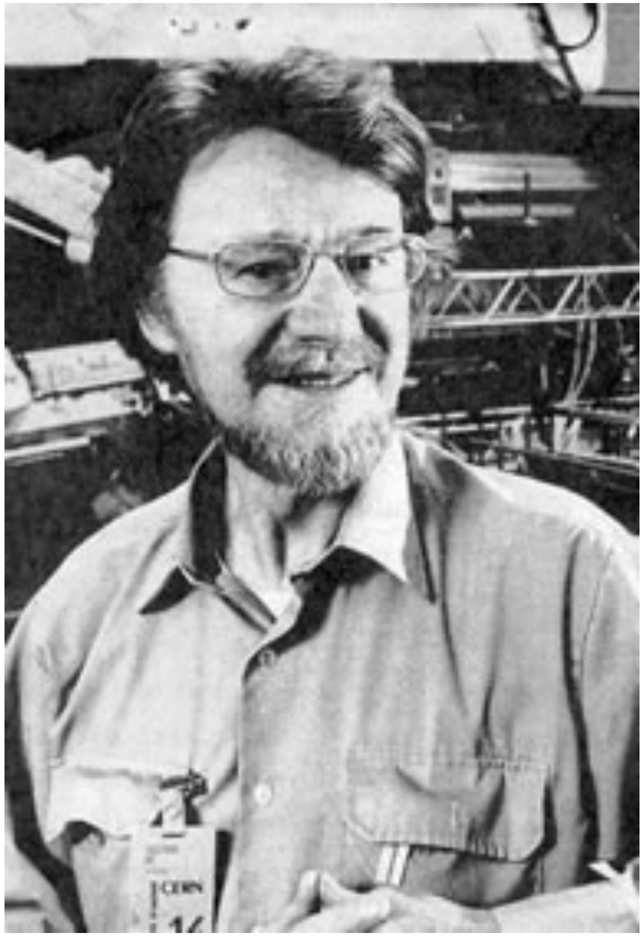
(3) $\psi_{12} = \psi^{-}{}_{1} \otimes \psi^{+}{}_{2}$ **Prob. 0.5**

Quantum non-locality

Bell's locality condition



Bell's Theorem (1964)



- "no conspiracy": a and b are independent of λ
- locality: given λ, a and A are independent of b and B (and *vice versa*); the probability for a certain value of A does not change, if b and B are given (and *vice versa*)

  $P(A \mid a, b, B, \lambda) = P(A \mid a, \lambda)$

  $P(B \mid a, b, A, \lambda) = P(B \mid b, \lambda)$
- There is no theory possible that is in accord with the empirical predictions of QM and that satisfies locality.
- constraint on any future theory

Bell’s Theorem (1964)

Einstein’s boxes (1927)

Einstein-Podolsky-Rosen (EPR) (1935)

- EITHER spooky action at a distance

→ absurd

- OR QM incomplete
- Bell (1964): impossible to complete QM respecting the principle of locality (possible in the case of Einstein’s boxes, but impossible in the general case)
- task after Bell: find an understanding of QM without falling into the pitfall of “spooky action at a distance”
- retreat to instrumentalism (algorithm to predict measurement outcome statistics) provides no dynamics for the processes that occur in nature

Operators / observables

- operators / observables: information about the behaviour of quantum systems in an experimental context
- incompatible operators / observables

→ impossible to take quantum systems to possess a value of all these operators / observables

(theorems of Gleason and Kochen & Specker)

→ impossible to consider operators / observables as properties of quantum systems

("naïve realism about operators")

→ No way from operators to ontology!

Dynamics

- Schrödinger equation

$$i\hbar \frac{\partial \Psi_t}{\partial t} = H\Psi_t$$

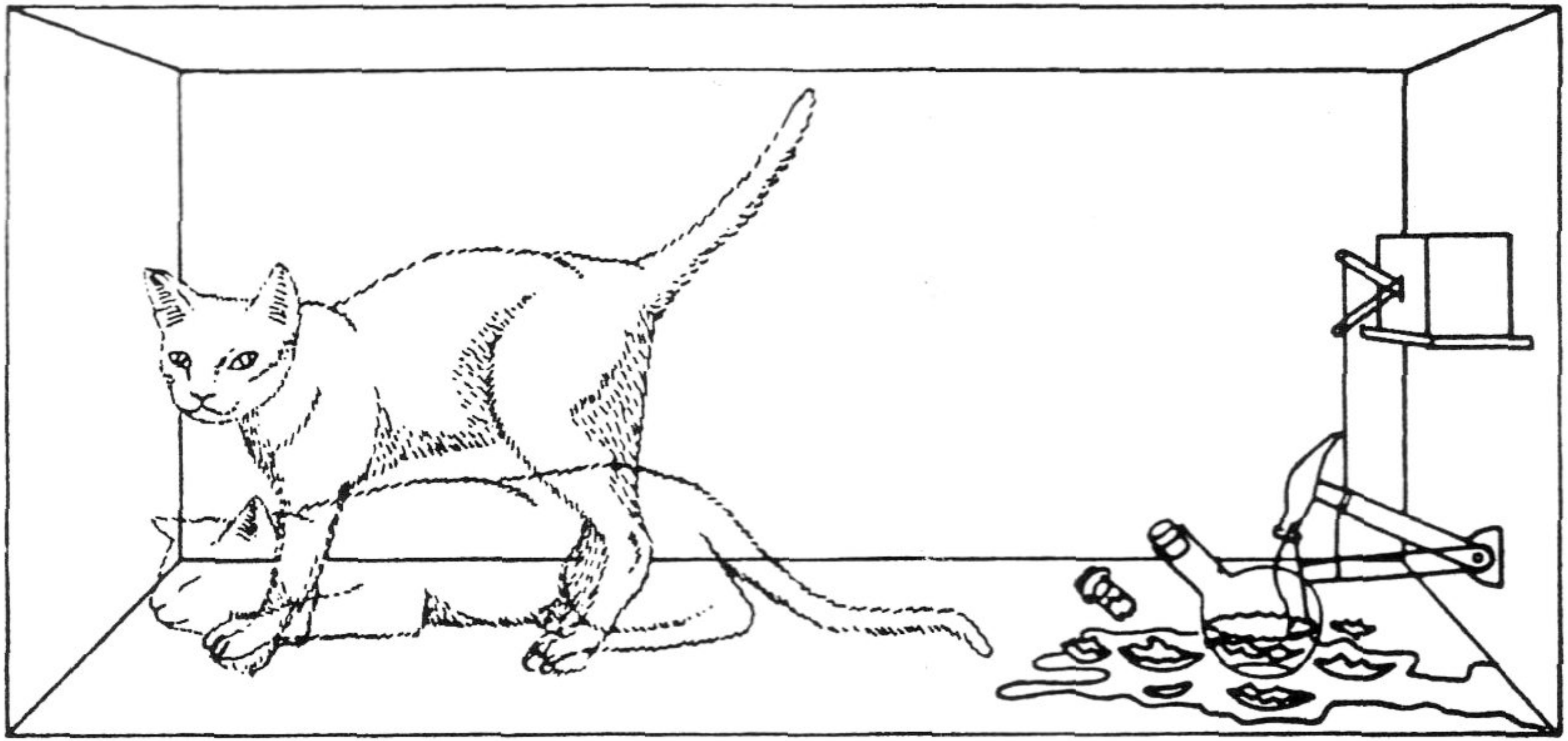
- temporal development of wave function
- allows to calculate probabilities for outcomes of measurements of operators
- temporal development of these probabilities

The measurement problem
Tim Maudlin (1995)

- A The wave function of a system is *complete*, i.e. the wave function specifies all of the physical properties of a system.
- B The wave function always evolves in accord with a linear dynamical equation / with a deterministic dynamical equation (e.g. the Schrödinger equation).
- C Measurements of, e.g., the spin of an electron always 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). / Measurement situations which are described by identical initial wave functions sometimes have different outcomes, and the probability of each possible outcome is given by Born's rule.

A and B entail not C.

Schrödinger's cat

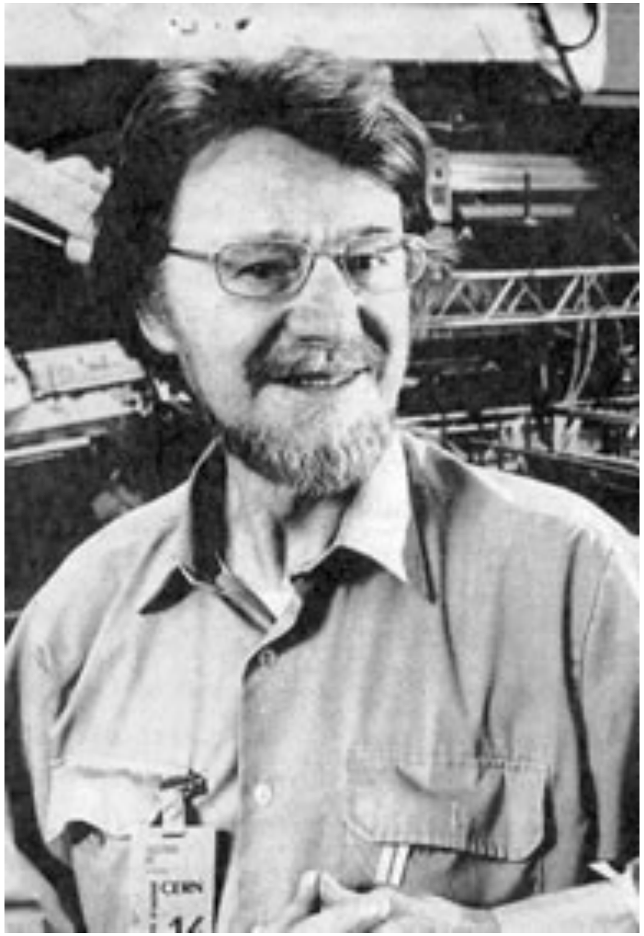


John von Neumann : *Mathematical foundations of quantum mechanics* (1932)

two different evolutions:

- Schrödinger equation:
  deterministic
  entanglement
- postulate of state reduction in measurement ("collapse of the wave function") :
  indeterministic
  dissolves entanglement
  completely *ad hoc;* no physical difference between measurement and other interactions
  no physical difference between measurement apparatuses and other systems

John Bell (1990)



"What exactly qualifies some physical systems to play the role of 'measurer'? Was the wavefunction of the world waiting to jump for thousands of millions of years until a single-celled living creature appeared? Or did it have to wait a little longer, for some better qualified system … with a PhD?"

The problem of understanding QM

- QM formalism provides probabilities for measurement outcome statistics, but cannot even accommodate the fact that there are measurement outcomes (unless “collapse of the wave function” conceived as process in nature)
- classical trajectories cannot yield QM probabilities (Bell’s theorem)
- collapse of the wave-function as process in nature

→ “spooky action at a distance” (Einstein)

Not C: many worlds
Hugh Everett (1957)

- **idea:** every possible event (measurement outcome) actually exists in a branch of the universe; split of the universe in many branches
- **law:** branches represented by wave function of the universe; always develops according to Schrödinger equation
- **task:** explain why world appears as if there were objects localized in 4d space-time

Not C: many worlds open questions

1) How shall one conceive the process of the development of multiple branches of the universe?

- Schrödinger equation reversible; is the splitting of the universal wave function into many branches reversible? Can there be a fusion of branches?

2) What is the relationship between the branches and (the appearance of) 4d space-time?
3) What does the fact signify that the wave function can be employed to calculate probabilities for measurement outcomes?

- Everything that is possible according to the theory exists in fact.

→ It seems that there is no place for probabilities, not even subjective probabilities: every possible future of any person becomes real in a branch of the universe.

Not B: other dynamics
Ghirardi, Rimini, Weber (GRW) (1986)

- idea: one single dynamics that includes wave function collapse in a non *ad hoc* manner
- spontaneous localization: add to Schrödinger equation parameters that indicate probability for wave function to localize spontaneously in configuration space.
- micro-system extremely low probability to localize spontaneously (once in 10^{15}s)
- macrosystem composed of very many microsystems (10^{23}): always one of these systems undergoes spontaneous localization

Not B: other dynamics
What is the ontology?

- law for temporal development of Ψ in configuration space does not tell us what in the world Ψ represents

→physical objects have to be introduced as "additional variables", law necessary that establishes a link between Ψ and physical objects

Ghirardi: matter field

- matter = continuous stuff (gunk); field, wave
- E.g. an electron, when it is not in a state in which it has a precise position, is smeared out all over physical space, constituting a matter density that is thicker in some regions of space than in others.
- no particles: matter = one single substance distributed all over space with different degrees of density at the points of space; developing according to GRW equation, localizes spontaneously in certain regions of space, thus building up localized macrophysical objects
- spontaneous localization: instantaneous transport of matter across arbitrary distances in space (delocalization)

→ Einstein: “spooky action at a distance”

Bell on GRW: flash-events

- sponateneous localization of Ψ in configuration space → flash at point in physical space
- The flashes are *all* that exists in physical space. GRW equation indicates probabilities for occurrence of new flashes given initial distribution of flashes; macro objects = galaxies of flashes
- no particles, no wave / field: isolated events

→ There is nothing with which a measurement apparatus interacts. (Einstein's boxes: measurement in New York inter-action with nothing, but produces instantaneously flash in Tokyo)

Bell's reply

- **all measurement outcomes = definite position of something**
- **When a macrophysical object is localized, then the microphysical objects that compose the macro-object are also localized.**
- **common sense realism: macro-objects are localized independently of whether or not someone observes them → micro-objects are localized independently of measurements.**
- **Micro-objects can be localized when composing macro-objects iff they're are *always* localized.**

Consequences

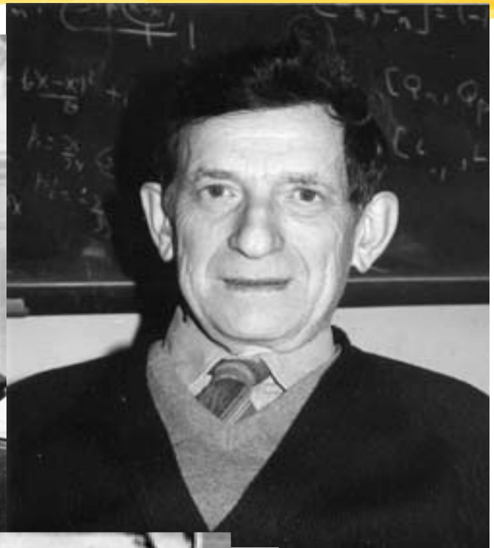
1) objects as in classical mechanics: particles localized at points in physical space

→ not A: the wave-function does not reveal the actual particle configuration

2) non-local law of their temporal development

- What changes in comparison to classical mechanics are not the physical objects, but the law of their temporal development

De Broglie (1927), Bohm (1952, 1993), Bell (1966, 1982)



- particles that always have a definite position in space

→ localization and individuality

→ velocity, trajectory

- law: input: particle positions; output: velocity of the particles

  by means of the wave function $$\frac{dQ}{dt} = \mu\Im \frac{\nabla\Psi_t(Q)}{\Psi_t(Q)}$$

- wave function develops according to Schrödinger equation

Bohmian mechanics

1) What is matter? = What are the physical objects?

   naked particles; characterized only by their spatial relations → spatial configuration of matter

   change in the spatial relations among the particles

2) What are the laws of the temporal development of the objects?

- wave function represents dynamical structure in which the particles stand, fixes their velocity

→ first order theory: initial configuration of particles = position as initial condition & initial wave function, instead of initial position, initial velocity & forces

→ correlated particle motion, no spooky action at a distance

Bohmian mechanics

- probabilities as in classical statistical mechanics: ignorance of initial conditions
- law linked with probability measure such that universe is in quantum equilibrium = represented by $[\Psi]^2$

→ Born's rule for subsystems = QM probabilities deduced from Bohmian mechanics

- slight variation in initial conditions, big variation in resulting trajectories ➔ no point in calculating individual trajectories (as in coin flip)
- operators / observables: behaviour of quantum systems in experimental situations = change of position / trajectory

Bohmian mechanics

3) How do the physical objects and their properties explain the observable phenomena?

- macroscopic objects composed of microscopic particles
- form of motion of particles explains variations in observable phenomena (including QM observables such as spin)
- wave function determining particle velocities explains non-local correlations in EPR-experiment
- decoherence of universal wave function (effective wave functions for sub-systems of the universe) explains classical behaviour (e.g. in the case of Einstein's boxes)

Positivist fallacies from textbook QM

- Heisenberg indeterminacy relations: not possible to measure position and momentum of quantum particles with arbitrary precision
- ➔particles do not have position & momentum = no trajectories
- trajectories to explain measurement outcomes
- quantum particles in entangled states not distinguishable by means of operators
- ➔ quantum particles not individual systems
- particles distinguished by position
- only probabilities for measurement outcomes
- ➔ particle motion indeterministic
- deterministic law of motion from which statistical predictions follow (Born's rule); probabilities as in statistical mechanics

Positivist fallacies from textbook QFT

- appearance and disappearance of particles, dependent on observer; particle creation and annihilation operators
- ➔ no fixed number of permanent particles
- measurement problem in QFT as in QM; solutions as in QM; possible solution: fixed number of permanent particles & deterministic law of motion from which the statistical predictions of the textbook formalism follow

Envoi

- pertinent question: What is the primitive ontology? What is the dynamical structure of a given theory?
- How do both explain the evidence?
- physics since Democritus: simplicity and beauty of atomism: point particles individuated through spatial relations & change of these relations; everything else explained in terms of these relations and their change
- primitive ontology remains the same, dynamical structure changes as we make progress in representing the actual particle motion