HOW TO RECONCILE NON-LOCAL REALITY AND LOCAL NON-REALITY

Hrvoje Nikolić
Rudjer Bošković Institute, Zagreb, Croatia

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Outline:

1. Main ideas

2. Essential and inessential aspects of Bohmian interpretation

3. Reduced nonlocality from reduced particle ontology

4. Many observers

5. Conclusion

- based on H.N., "Solipsistic hidden variables",
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1. MAIN IDEAS

Bell theorem $\rightarrow$ 2 confronting views:

(i) non-realism: nature is local but objective reality doesn't exist

(ii) realism: objective reality exists but is not local

- Realist: How can you believe that things do not exist before measurement? It doesn't make sense to me.

- Non-realist: How can you believe in HV's which cannot be observed? It doesn't make sense to me.

Motivation:
- To reduce the confrontation between these two views
- To demonstrate that an intermediate option
  is at least not impossible

I propose a "hybrid" approach:
- some elements of each of the two views are combined
  into a new interpretation
- to a certain extent it retains both objective reality and locality

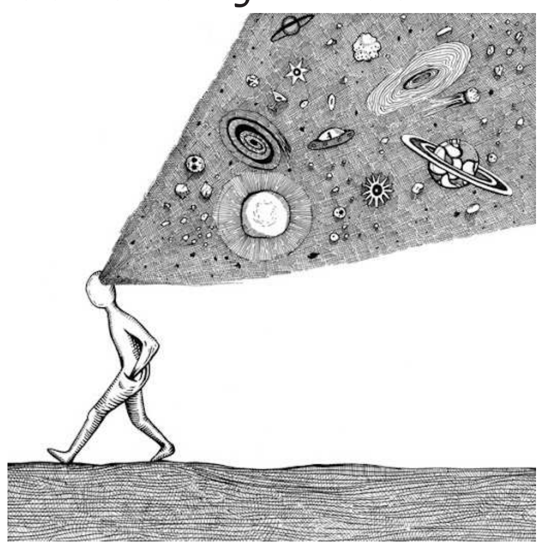
The price to pay: SOLIPSISTIC* REALITY

**In philosophy, the view that subjective mental experiences are the only true reality.*

Old philosophical questions:

Perhaps what we observe is not real?

Perhaps the whole Universe is only in our minds?



Orthodox view of QM:
- There is no reality except observations.
- All observations are local (e.g., in brain).

$\Rightarrow$ locality

But can observations correspond to something real, and still local?
Yes: e.g., some objective processes in the brain.

The problem of 2 observers (Alice and Bob):
Locality $\Rightarrow$ Alice's observation not correlated with Bob's observation.
QM $\Rightarrow$ Alice can hear that Bob says what his observation is,
and it must be correlated with other Alice observations.

- But this is a correlation between one *Alice* observation with another *Alice* observation.
- Alice cannot read Bob's mind, so theory does not need to predict correlations between Alice observations and Bob observations.

I will show that such *local solipsistic reality* naturally emerges from a simple variation of nonlocal Bohmian interpretation.

2. ESSENTIAL AND INESSENTIAL ASPECTS OF BOHMIAN INTERPRETATION

Standard (top-down) approach:
- first postulate particle trajectories
- then explain why it is compatible with QM

To understand more deeply why this interpretation works we present a reversed (bottom-up) approach:
- first present interpretation-independent essentials of quantum theory of measurements and its problems
- then ask what kind of new objects should we have to solve these problems

2.1 Interpretation-independent essentials of the quantum theory of measurement

Measure observable $\hat{K}$ with eigenstates $|k\rangle$.
Measuring apparatus in initial state $|\Phi_0\rangle$.
Interaction $\Rightarrow$ unitary transition

$$|k\rangle|\Phi_0\rangle \to |k'\rangle|\Phi_k\rangle$$

$|\Phi_0\rangle$ and $|\Phi_k\rangle$ are *macroscopically distinguishable*
$\Rightarrow$ wave functions have a negligible overlap in *configuration space*

$$\Phi_{k_1}(\vec{x})\Phi_{k_2}(\vec{x}) \simeq 0 \quad \text{for} \quad k_1 \neq k_2$$

where $\Phi_k(\vec{x}) \equiv \langle \vec{x}|\Phi_k\rangle$,

$$\vec{x} \equiv (\mathbf{x}_1, \ldots, \mathbf{x}_n)$$

n = number of particles constituting the apparatus

$$\int d^{3n}x \, |\Phi_k(\vec{x})|^2 = 1$$

For a superposition $|\psi\rangle = \sum_k c_k |k\rangle$:

$$|\psi\rangle|\Phi_0\rangle \to \sum_k c_k |k'\rangle|\Phi_k\rangle$$

Why this "collapses" to $|k'\rangle|\Phi_k\rangle$?

$|\Phi_k\rangle$ are macroscopically distinguishable.
$\Rightarrow$ Superposition consists of many distinguishable branches.
Each branch evolves as if other branches did not exist.
$\Rightarrow$ From perspective of any branch, other branches do not exist.
Explains the collapse if one remaining question can be answered:

Why should we take a view from the perspective of a branch as the physical one?

Interpretation-independent answer does not exist.
$\Rightarrow$ Need interpretation of QM.

2.2 The role of particle positions

Possible answer:
Because wave function itself is the only physical object.
$\Rightarrow$ Many-world interpretation.
Problem:
Born rule cannot be explained without additional ad hoc assumptions.

Different answer:
Particular branch becomes physical because
it becomes *filled with* something physical.

Entity which fills one branch should not fill any other branch.
$\Rightarrow$ Filling entity should be well localized in configuration space.
$\Rightarrow$ Filling entity is described by position

$$\vec{X} \equiv (\mathbf{X}_1, \ldots, \mathbf{X}_n)$$

n = number of particles constituting the *apparatus*.

$\Rightarrow$ Apparatus made of pointlike particles.
However, apparatus particles are not necessary the only real physical entity.
If apparatus particles are real and pointlike, so may be all particles in the universe:

$$\mathbf{X}_1, \ldots, \mathbf{X}_n, \mathbf{X}_{n+1}, \ldots, \mathbf{X}_N$$

N = total number of particles in the Universe

Probability density of particle positions:

$$\rho(\mathbf{x}_1, \ldots, \mathbf{x}_N, t) = |\Psi(\mathbf{x}_1, \ldots, \mathbf{x}_N, t)|^2$$

cannot be tested in practice (one cannot observe all particles in the Universe).
- One really observes macroscopic observable describing
the measuring apparatus.

$\Rightarrow$ Phenomenologically more interesting is apparatus probability density

$$\rho^{(\text{appar})}(\mathbf{x}_1, \ldots, \mathbf{x}_n, t) = \int d^3x_{n+1} \cdots d^3x_N \, \rho(\mathbf{x}_1, \ldots, \mathbf{x}_n, \mathbf{x}_{n+1}, \ldots, \mathbf{x}_N, t)$$

$\Rightarrow$

$$\rho^{(\text{appar})}(\vec{x}) \simeq \sum_k |c_k|^2 \, |\Phi_k(\vec{x})|^2$$

$\Rightarrow$ Probability to find the apparatus particles in the support of $\Phi_k(\vec{x})$:

$$p_k = \int_{\text{supp } \Phi_k} d^{3n}x \, \rho^{(\text{appar})}(\vec{x}) \simeq |c_k|^2$$

- this is the Born rule.

$\Rightarrow$ It is sufficient that *only apparatus particles* exist
and have the quantum probability distribution.
- A simple way to provide this is to require that *all particles* exist
and have the quantum probability distribution.

2.3 The role of particle trajectories

Probability density depends on time
$\Rightarrow$ particle positions depend on time $\Rightarrow$ trajectories.

Trajectories may be smooth $\Rightarrow$ velocity well defined.

What law the velocity should obey?
Compatibility with quantum probability density $\rho(\mathbf{x}_1, \ldots, \mathbf{x}_N, t)$
$\Rightarrow$ velocity $\mathbf{v}_a(\mathbf{X}_1, \ldots, \mathbf{X}_N, t)$ must obey continuity equation

$$\frac{\partial \rho}{\partial t} + \sum_{a=1}^{N} \boldsymbol{\nabla}_a (\rho \mathbf{v}_a) = 0$$

The simplest choice

$$\mathbf{v}_a = \mathbf{v}_a^{(\mathrm{Bohm})}$$

$$\mathbf{v}_a^{(\text{Bohm})} \equiv \frac{-i\hbar}{2m_a} \frac{\Psi^* \overleftrightarrow{\boldsymbol{\nabla}}_a \Psi}{\Psi^*\Psi} = \frac{\text{Re}(\Psi^* \hat{\mathbf{v}}_a \Psi)}{\Psi^*\Psi}$$

$\hat{\mathbf{v}}_a = \hat{\mathbf{p}}_a / m_a$ = velocity operator

$\hat{\mathbf{p}}_a = -i\hbar \boldsymbol{\nabla}_a$ = momentum operator

The velocity of a'th particle

$$\frac{d\mathbf{X}_a}{dt} = \mathbf{v}_a(\mathbf{X}_1, \ldots, \mathbf{X}_N, t)$$

- nonlocal because it may depend on positions of all particles in the Universe
- consequence of the fact that we *assumed* that all particles have positions
- on the other hand, we have seen that only apparatus particles are really essential
- if only they exist, perhaps it could avoid nonlocality

In the rest we explore that possibility.

3. REDUCED NONLOCALITY FROM REDUCED ONTOLOGY

Continuity equation for all particles in the Universe integrate over $\int d^3x_{n+1}\cdots d^3x_N$:

$$\frac{\partial\rho^{(\text{appar})}(\mathbf{x}_1,\ldots,\mathbf{x}_n,t)}{\partial t}+\sum_{b=1}^{n}\boldsymbol{\nabla}_b\int d^3x_{n+1}\cdots d^3x_N\,\rho\mathbf{v}_b^{(\text{Bohm})}$$

$$+\sum_{a=n+1}^{N}\int d^3x_{n+1}\cdots d^3x_N\,\boldsymbol{\nabla}_a(\rho\mathbf{v}_a^{(\text{Bohm})})=0$$

Gauss theorem $\Rightarrow$ last term is surface integral $\Rightarrow$ vanishes
$\Rightarrow$ apparatus continuity equation:

$$\frac{\partial\rho^{(\text{appar})}(\vec{x},t)}{\partial t}+\sum_{b=1}^{n}\boldsymbol{\nabla}_b[\rho^{(\text{appar})}(\vec{x},t)\mathbf{v}_b^{(\text{appar})}(\vec{x},t)]=0$$

$$\mathbf{v}_b^{(\text{appar})}(\vec{x},t)\equiv\frac{\int d^3x_{n+1}\cdots d^3x_N\,\rho\mathbf{v}_b^{(\text{Bohm})}}{\rho^{(\text{appar})}(\vec{x},t)}$$

Integrals over $\int d^3x_{n+1} \cdots d^3x_N$ can be written more elegantly in terms of partial traces.

Density matrix:

$$\hat{\rho}(t) = |\Psi(t)\rangle\langle\Psi(t)|$$

$\Rightarrow \rho^{(\text{appar})}(\vec{x}, t) =$ diagonal matrix elements of reduced density matrix

$$\rho^{(\text{appar})}(\vec{x}; \vec{x}'; t) = [\mathrm{Tr}_{(\text{no-appar})}\hat{\rho}](\vec{x}; \vec{x}'; t)$$

$\mathrm{Tr}_{(\text{no-appar})} =$ partial trace over all no-apparatus degrees of freedom

Velocity:

$$\mathbf{v}_b^{(\text{appar})}(\vec{x}, t) = \frac{\mathrm{Re}[\mathrm{Tr}_{(\text{no-appar})}\hat{\mathbf{v}}_b\hat{\rho}](\vec{x}; \vec{x}; t)}{[\mathrm{Tr}_{(\text{no-appar})}\hat{\rho}](\vec{x}; \vec{x}; t)}$$

Measurable predictions of QM can be reproduced by postulating that apparatus particles have trajectories

$$\frac{d\mathbf{X}_b}{dt} = \mathbf{v}_b^{(\text{appar})}(\mathbf{X}_1, \ldots, \mathbf{X}_n, t)$$

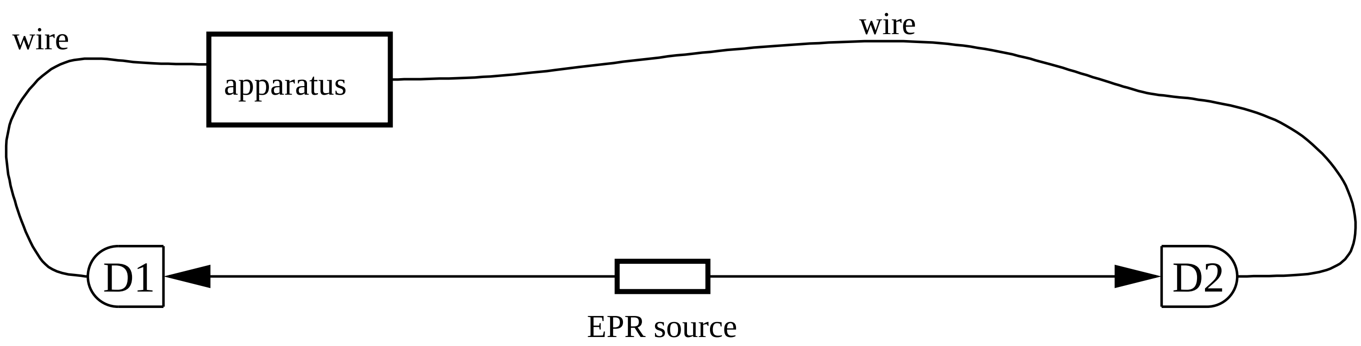
$b = 1, \ldots, n \ll N$

Important properties:

1. *Only the apparatus particles have trajectories.*

2. *Velocity of* b*'th particle of the apparatus depends only on the other positions of apparatus-particles, not on positions of any other particles in the Universe.*

3.2 Example: Measurement of EPR correlations



Before detections at detectors D1 and D2, entangled EPR state:

$$|\psi\rangle = \frac{|\uparrow\rangle|\downarrow\rangle + |\downarrow\rangle|\uparrow\rangle}{\sqrt{2}} = \sum_{k_1,k_2} c_{k_1k_2}|k_1\rangle|k_2\rangle$$

$|k_1\rangle$, $|k_2\rangle$ = eigenstates of observables to be detected by D1, D2

After detections at D1 and D2 and measurement by apparatus:

$$|\Psi\rangle = \sum_{k_1,k_2} c_{k_1k_2}|k_1\rangle|k_2\rangle|D1_{k_1}\rangle|D2_{k_2}\rangle|\Phi_{k_1,k_2}\rangle$$

$|D1_{k_1}\rangle$ = macroscopically distinguishable states of detector D1
$|D2_{k_2}\rangle$ = macroscopically distinguishable states of detector D2
$|\Phi_{k_1,k_2}\rangle$ = macroscopically distinguishable states of measuring apparatus

How our hidden variables (particle trajectories) avoid nonlocality of the Bell theorem?

Bell theorem assumes:
- HV associated with entangled particles (basis $|k_1\rangle|k_2\rangle$)
- HV associated with separated detectors (basis $|D1_{k_1}\rangle|D2_{k_2}\rangle$)

If such HV exist $\Rightarrow$ Bell theorem: such HV must be nonlocal!

In our theory such HV do not exist:
HV attributed *only* to local measuring apparatus (basis $|\Phi_{k_1,k_2}\rangle$)

3.3 Solipsistic interpretation

What measuring apparatus could be more real than anything else?

Perhas brain?

Or perhaps only neurons responsible for consciousness?

Or perhaps something more directly correlated with consciousness?

Whatever it is, we can call it - *observer*.

4. MANY OBSERVERS

- for simplicity 2 observers (Alice and Bob)

Before observation, entangled pair of particles:

$$|\psi\rangle = \frac{|{\uparrow_1}\rangle \otimes |{\downarrow_2}\rangle + |{\downarrow_1}\rangle \otimes |{\uparrow_2}\rangle}{\sqrt{2}}$$

Alice observes particle 1, Bob observes particle 2:

$$|\Psi\rangle = \frac{1}{\sqrt{2}} |{\uparrow_1}\rangle |\Phi_{\uparrow}^{(\mathsf{A})}\rangle \otimes |{\downarrow_2}\rangle |\Phi_{\downarrow}^{(\mathsf{B})}\rangle + \frac{1}{\sqrt{2}} |{\downarrow_1}\rangle |\Phi_{\downarrow}^{(\mathsf{A})}\rangle \otimes |{\uparrow_2}\rangle |\Phi_{\uparrow}^{(\mathsf{B})}\rangle$$

Positions of Alice-particles and Bob-particles:

$$\vec{X}^{(\mathsf{A})} \equiv (\mathbf{X}_1^{(\mathsf{A})}, \ldots, \mathbf{X}_{n_\mathsf{A}}^{(\mathsf{A})}), \qquad \vec{X}^{(\mathsf{B})} \equiv (\mathbf{X}_1^{(\mathsf{B})}, \ldots, \mathbf{X}_{n_\mathsf{B}}^{(\mathsf{B})})$$

Independent Alice and Bob velocities:

$$\mathbf{v}_b^{(\mathsf{A})}(\vec{x}^{(\mathsf{A})},t) = \frac{\mathrm{Re}[\mathrm{Tr}_{(\text{no-A})}\hat{\mathbf{v}}_b\hat{\rho}](\vec{x}^{(\mathsf{A})};\vec{x}^{(\mathsf{A})};t)}{[\mathrm{Tr}_{(\text{no-A})}\hat{\rho}](\vec{x}^{(\mathsf{A})};\vec{x}^{(\mathsf{A})};t)} \qquad b = 1,\ldots,n_{\mathsf{A}}$$

$$\mathbf{v}_b^{(\mathsf{B})}(\vec{x}^{(\mathsf{B})},t) = \frac{\mathrm{Re}[\mathrm{Tr}_{(\text{no-B})}\hat{\mathbf{v}}_b\hat{\rho}](\vec{x}^{(\mathsf{B})};\vec{x}^{(\mathsf{B})};t)}{[\mathrm{Tr}_{(\text{no-B})}\hat{\rho}](\vec{x}^{(\mathsf{B})};\vec{x}^{(\mathsf{B})};t)} \qquad b = 1,\ldots,n_{\mathsf{B}}$$

Independent Alice and Bob probability densities:

$$\rho^{(\mathsf{A})}(\vec{x}^{(\mathsf{A})},t) = [\mathrm{Tr}_{(\text{no-A})}\hat{\rho}](\vec{x}^{(\mathsf{A})};\vec{x}^{(\mathsf{A})};t)$$

$$\rho^{(\mathsf{B})}(\vec{x}^{(\mathsf{B})},t) = [\mathrm{Tr}_{(\text{no-B})}\hat{\rho}](\vec{x}^{(\mathsf{B})};\vec{x}^{(\mathsf{B})};t)$$

Satisfy independent Alice and Bob continuity equations:

$$\frac{\partial\rho^{(\mathsf{A})}(\vec{x}^{(\mathsf{A})},t)}{\partial t} + \sum_{b=1}^{n_{\mathsf{A}}} \boldsymbol{\nabla}_b[\rho^{(\mathsf{A})}(\vec{x}^{(\mathsf{A})},t)\mathbf{v}_b^{(\mathsf{A})}(\vec{x}^{(\mathsf{A})},t)] = 0$$

$$\frac{\partial\rho^{(\mathsf{B})}(\vec{x}^{(\mathsf{B})},t)}{\partial t} + \sum_{b=1}^{n_{\mathsf{B}}} \boldsymbol{\nabla}_b[\rho^{(\mathsf{B})}(\vec{x}^{(\mathsf{B})},t)\mathbf{v}_b^{(\mathsf{B})}(\vec{x}^{(\mathsf{B})},t)] = 0$$

$\Rightarrow$ independent Alice and Bob particle trajectories:

$$\frac{d\mathbf{X}_b^{(\mathsf{A})}}{dt} = \mathbf{v}_b^{(\mathsf{A})}(\vec{X}^{(\mathsf{A})}, t), \quad b = 1, \ldots, n_{\mathsf{A}}$$

$$\frac{d\mathbf{X}_b^{(\mathsf{B})}}{dt} = \mathbf{v}_b^{(\mathsf{B})}(\vec{X}^{(\mathsf{B})}, t), \quad b = 1, \ldots, n_{\mathsf{B}}$$

- Locality: Bob particle velocities not depend on Alice particle positions (and vice versa).
- Alice particles may not fill the same branch of wave function as Bob particles.

(In nonlocal Bohmian mechanics, all particles fill the same branch.)

Is that consistent?

What if Alice and Bob measure the same observable?

Superposition before measurement:

$$|\psi\rangle = \frac{|\uparrow\rangle + |\downarrow\rangle}{\sqrt{2}}$$

After measurement:

$$|\Psi\rangle = \frac{1}{\sqrt{2}}|\uparrow\rangle|\Phi_{\uparrow}^{(A)}\rangle|\Phi_{\uparrow}^{(B)}\rangle + \frac{1}{\sqrt{2}}|\downarrow\rangle|\Phi_{\downarrow}^{(A)}\rangle|\Phi_{\downarrow}^{(B)}\rangle$$

Possible that Alice is in branch $\Phi_{\uparrow}^{(A)}(\vec{x}^{(A)})$, Bob is in branch $\Phi_{\downarrow}^{(B)}(\vec{x}^{(B)})$.
$\Rightarrow$ They disagree whether the spin is $|\uparrow\rangle$ or $|\downarrow\rangle$.

Seems to contradict the predictions of QM, but it does not!
Neither Alice nor Bob can observe any contradiction because:
- Bob particle positions are *hidden* variables for Alice
- Alice particle positions are *hidden* variables for Bob

This is just the solipsistic interpretation:
- Bob's mental experiences are hidden to Alice
- Alice's mental experiences are hidden to Bob

4. CONCLUSION

- Bell theorem against local HV
  does not exclude local *solipsistic* HV.

- Solipsistic HV associates reality with observers
  but not with observed objects.

- A model for solipsistic HV provided
  by a variation of Bohmian interpretation.

- Different observers not correlated,
  but all observable predictions compatible with those of QM.

Thank You!