Title: PSI 17/18 - Foundations of Quantum Mechanics - Lecture 10

Date: Feb 09, 2018 10:15 AM

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Abstract:

The deBroglie-Bohm interpretation

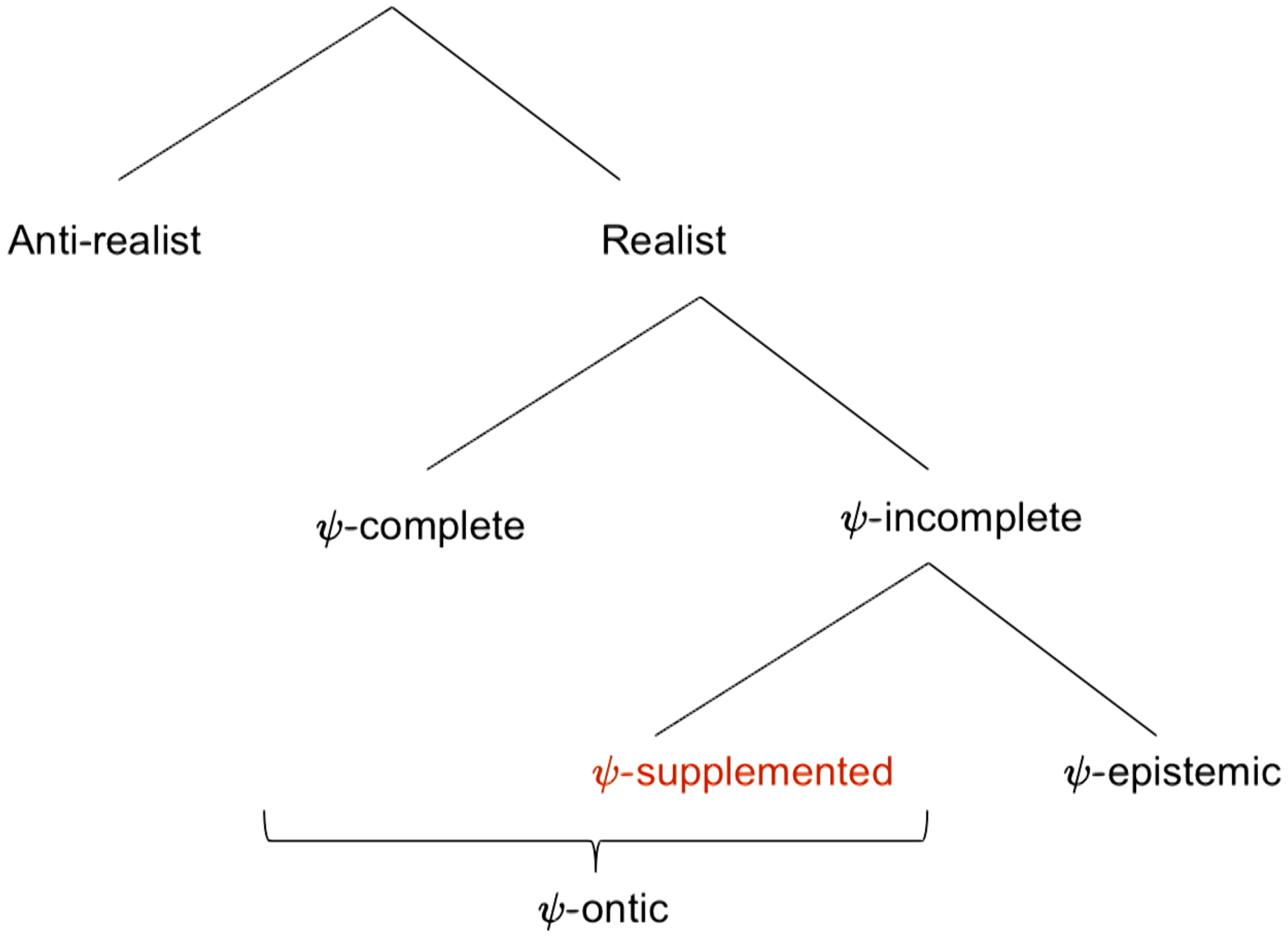
Louis deBroglie
(1892-1987)

David Bohm
(1917-1992)

"I saw the impossible done..."
John Bell

Responses to the measurement problem

1. Deny realism
   - Purely operational account of quantum theory
2. Deny the universality of unitary dynamics
   - Dynamical collapse theories
3. Deny that ψ is a complete representation of reality
   - Hidden variable models
   - Models of reality beyond hidden variables?
4. Deny indeterminism and discontinuity, except as subjective illusions
   - Everett's relative state interpretation, or "many worlds"



Anti-realist

Realist

ψ-complete

ψ-incomplete

ψ-supplemented

ψ-epistemic

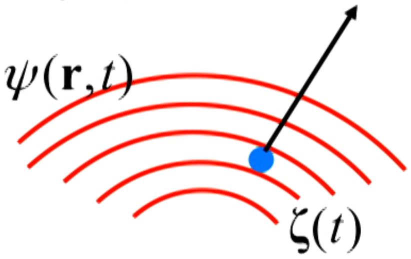
ψ-ontic

The deBroglie-Bohm interpretation for a single particle

The ontic state: $(\psi(\mathbf{r}),\zeta)$

Wavefunction

Particle position



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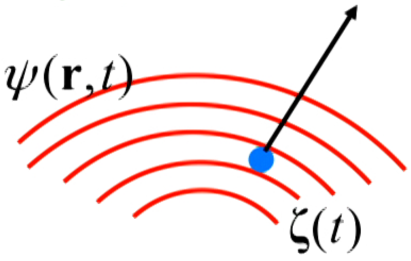

The evolution equations:

$$i\hbar\frac{\partial\psi(\mathbf{r},t)}{\partial t}=-\frac{\hbar^2}{2m}\nabla^2\psi(\mathbf{r},t)+V(\mathbf{r})\psi(\mathbf{r},t)$$

Schrödinger's eq'n

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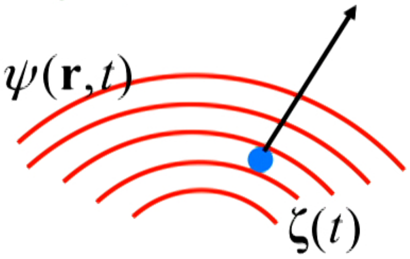

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Schrödinger's eq'n

$$\frac{d\zeta(t)}{dt} = \frac{1}{m}\left[\nabla S(\mathbf{r},t)\right]_{\mathbf{r}=\zeta(t)}$$

The guidance eq'n

where $\psi(\mathbf{r},t) = R(\mathbf{r},t)e^{iS(\mathbf{r},t)/\hbar}$

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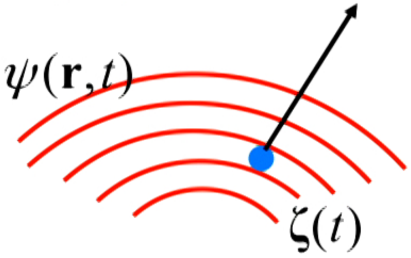


The evolution equations:

$$i\hbar\frac{\partial\psi(\mathbf{r},t)}{\partial t}=-\frac{\hbar^2}{2m}\nabla^2\psi(\mathbf{r},t)+V(\mathbf{r})\psi(\mathbf{r},t)$$ Schrödinger's eq'n

$$\frac{d\zeta(t)}{dt}=\frac{1}{m}\left[\nabla S(\mathbf{r},t)\right]_{\mathbf{r}=\zeta(t)}$$ The guidance eq'n

where $\psi(\mathbf{r},t)=R(\mathbf{r},t)e^{iS(\mathbf{r},t)/\hbar}$

Note: There is no back-action on the wave
The amplitude of the wave is irrelevant –> a pilot wave

Given $\psi(\mathbf{r},t) = R(\mathbf{r},t)e^{iS(\mathbf{r},t)/\hbar}$

The real part of the Schrodinger eq'n is:

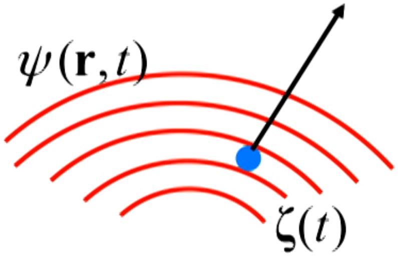
$$\frac{\partial S}{\partial t} + \frac{(\nabla S)^2}{2m} + Q + V = 0$$

where $Q(\mathbf{r},t) \equiv -\frac{\hbar^2}{2m}\frac{\nabla^2 R(\mathbf{r},t)}{R(\mathbf{r},t)}$ The "quantum potential"

The imaginary part of the Schrodinger eq'n is:

$$\frac{\partial}{\partial t}(R^2) + \nabla\cdot\left(\frac{R^2\nabla S}{m}\right) = 0$$

Newtonian form of the particle dynamics:



$$m\frac{d^2\zeta(t)}{dt^2} = -\left[\nabla V(\mathbf{r}) + \nabla Q(\mathbf{r},t)\right]_{\mathbf{r}=\zeta(t)}$$

where $Q(\mathbf{r},t) \equiv -\frac{\hbar^2}{2m}\frac{\nabla^2 R(\mathbf{r},t)}{R(\mathbf{r},t)}$ The “quantum potential”

(Note independence of quantum potential on magnitude)

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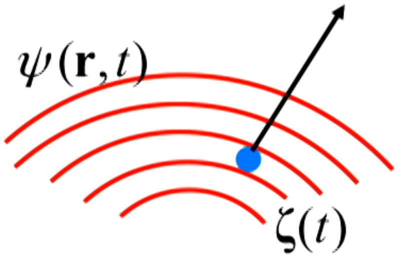

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How else does deBroglie-Bohm differ from Newtonian mechanics?

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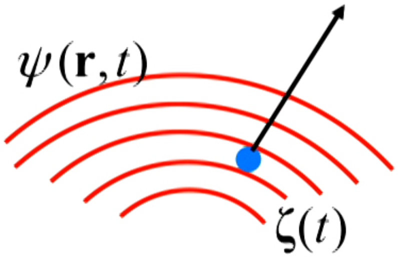

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How else does deBroglie-Bohm differ from Newtonian mechanics?

The dynamics are ***fundamentally first order***

$$\frac{d\zeta(t)}{dt} = \frac{1}{m}\left[\nabla S(\mathbf{r},t)\right]_{\mathbf{r}=\zeta(t)}$$

Acting the ∇ operator on the real part of the Schrodinger eq'n gives:

$$\nabla\left[\frac{\partial S}{\partial t}+\frac{(\nabla S)^2}{2m}+Q+V\right]=0$$

$$\left(\frac{\partial}{\partial t}+\frac{\nabla S\cdot\nabla}{m}\right)\nabla S=-\nabla(Q+V)$$

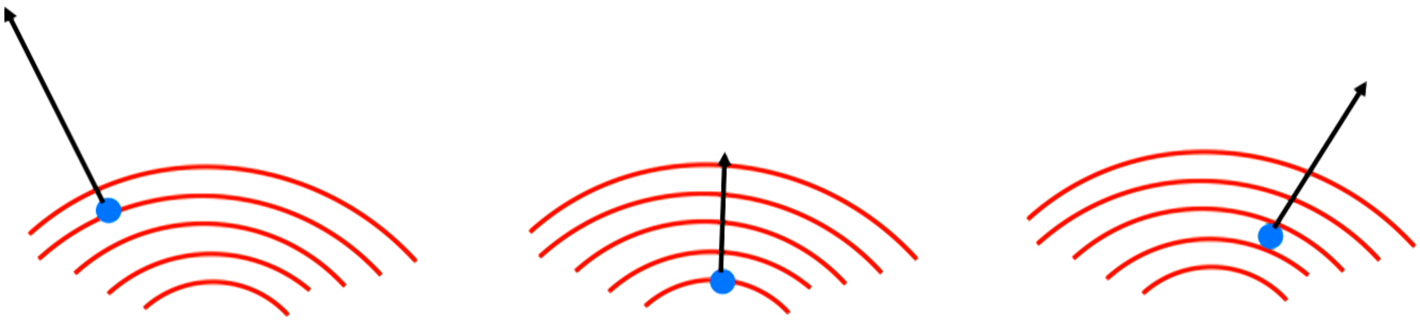
Taking the time derivative of the guidance equation gives:

$$\frac{d\zeta(t)}{dt}=\frac{1}{m}\left[\nabla S(\mathbf{r},t)\right]_{\mathbf{r}=\zeta(t)}$$

$$\frac{d^2\zeta(t)}{dt^2}=\frac{1}{m}\left(\frac{\partial}{\partial t}+\frac{d\zeta}{dt}\cdot\nabla\right)\nabla S$$

Thus

$$m\frac{d^2\zeta(t)}{dt^2}=-\left[\nabla V(\mathbf{r})+\nabla Q(\mathbf{r},t)\right]_{\mathbf{r}=\zeta(t)}$$



Epistemic state (assuming perfect knowledge of $\psi(\mathbf{r},t)$)

$\rho(\zeta)d\zeta$ = the probability the particle is within $d\zeta$ of ζ.

The “standard distribution”

$$\rho(\zeta,t)=|\psi(\zeta,t)|^2$$

Note: it is preserved by the dynamics:

if $\rho(\zeta,0)=|\psi(\zeta,0)|^2$ then $\rho(\zeta,t)=|\psi(\zeta,t)|^2$

Proof of the preservation of the standard distribution:

The velocity field is

$$\mathbf{v}(\mathbf{r},t) = \frac{1}{m}\left[\nabla S(\mathbf{r},t)\right]$$

The probability current density is:

$$\mathbf{j}(\mathbf{r},t) = \rho(\mathbf{r},t)\mathbf{v}(\mathbf{r},t)$$

Conservation of probability implies

$$\frac{\partial\rho(\mathbf{r},t)}{\partial t} = -\nabla\cdot\mathbf{j}(\mathbf{r},t) = -\nabla\cdot\left(\frac{\rho(\mathbf{r},t)\nabla S(\mathbf{r},t)}{m}\right)$$

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Recall the imaginary part of the Schrodinger eq'n:

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Recall the imaginary part of the Schrodinger eq'n:

$$\frac{\partial}{\partial t}(R^2) = -\nabla\cdot\left(\frac{R^2\nabla S}{m}\right)$$

Therefore, if $\rho(\mathbf{r},\mathrm{t}) = R^2(\mathbf{r},\mathrm{t})$ then $\frac{\partial}{\partial t}\left(\rho(\mathbf{r},t) - R^2(\mathbf{r},t)\right) = 0$

$$\psi = \sum_j c_j \psi_j$$

"waves" of the decomposition

Spatial support of $\psi_j = \{\mathbf{r} : \psi_j(\mathbf{r}) \neq 0\}$

$\zeta \in$ Spatial support of ψ_j *j*th wave is **occupied**

$\zeta \notin$ Spatial support of ψ_j *j*th wave is **empty**

If only the *k*th wave is occupied

Then the guidance equation depends only on the *k*th wave

Proof of ineffectiveness of empty waves

$$\psi = \psi_a + \psi_b$$

$$R\mathrm{e}^{iS/\hbar} = R_a\mathrm{e}^{iS_a/\hbar} + R_b\mathrm{e}^{iS_b/\hbar}$$

$$R^2 = R_a^2 + R_b^2 + 2R_aR_b\cos\left[\left(S_a - S_b\right)/\hbar\right]$$

$$\nabla S = R^{-2}\left\{\begin{matrix} R_a^2\nabla S_a + R_b^2\nabla S_b + R_aR_b\cos\left[\left(S_a - S_b\right)/\hbar\right]\nabla\left(S_a + S_b\right) \\ -\hbar\left[R_a\nabla R_b - R_b\nabla R_a\right]\sin\left[\left(S_a - S_b\right)/\hbar\right] \end{matrix}\right\}$$

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If $R_a R_b \approx 0,\ R_a\nabla R_b \approx 0,\ R_b\nabla R_a \approx 0$

then $R^2 = R_a^2 + R_b^2$ and $\nabla S = \dfrac{R_a^2\nabla S_a + R_b^2\nabla S_b}{R_a^2 + R_b^2}$

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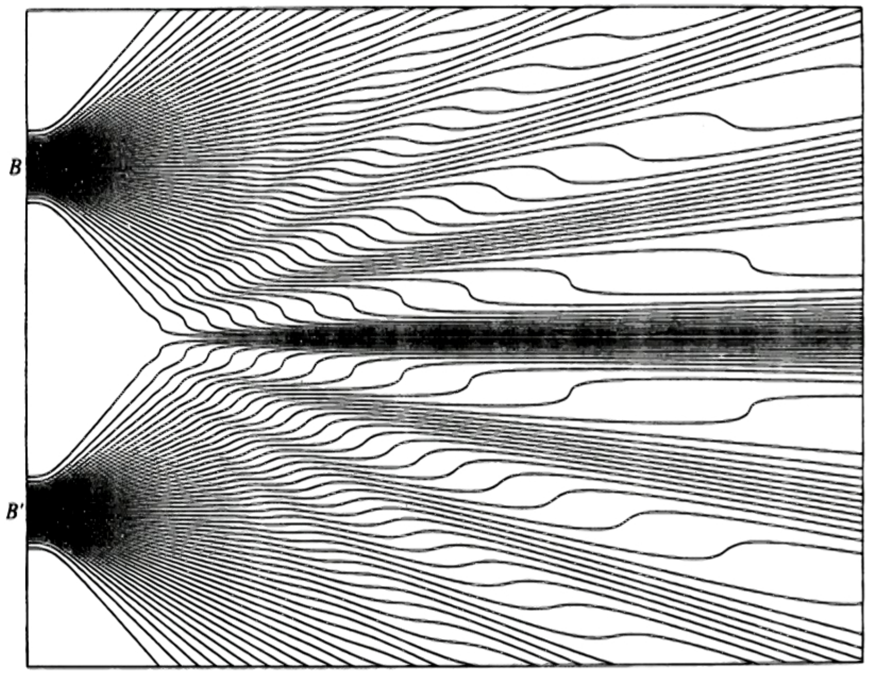
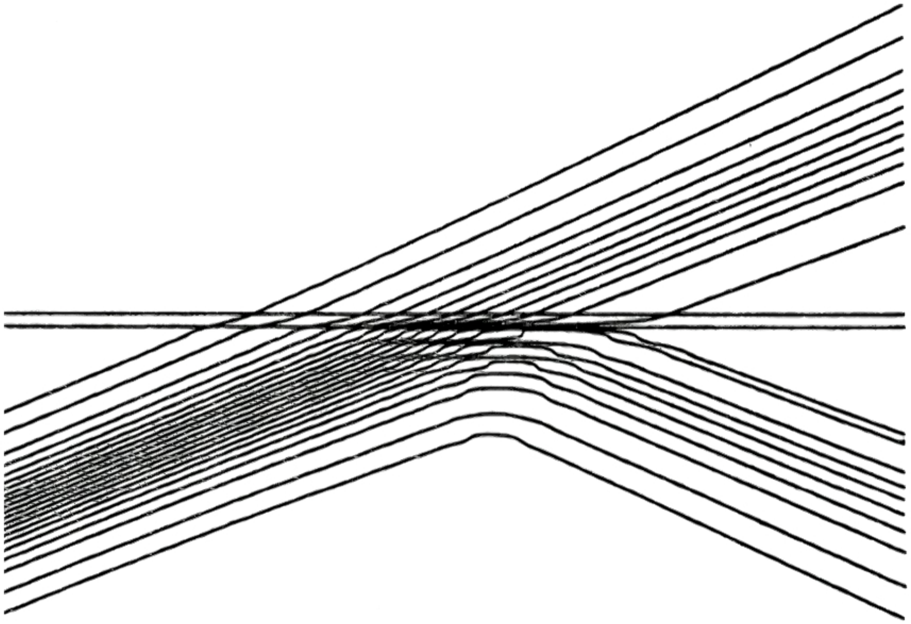
$$\frac{d\zeta(t)}{dt} = \frac{1}{m}\left[\nabla S(\mathbf{r},t)\right]_{\mathbf{r}=\zeta(t)} = \frac{\nabla S_a}{m} \quad \text{If } \zeta \in \text{ Support of } \psi_a$$

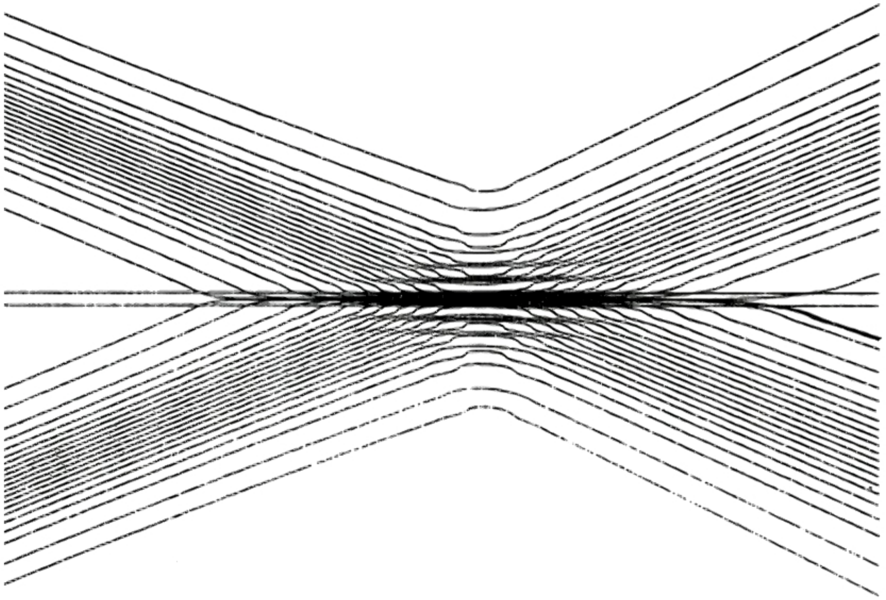
$$= \frac{\nabla S_b}{m} \quad \text{If } \zeta \in \text{ Support of } \psi_b$$



Double slit experiment



Transmission through a barrier (probability ½)



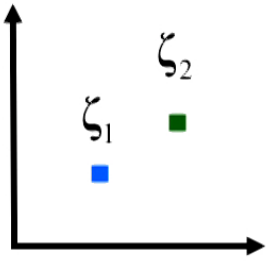
Beam splitter experiment

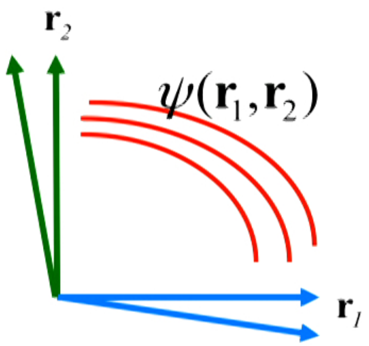
The deBroglie-Bohm interpretation for **many particles**

The ontic state: $(\psi(\mathbf{r}_1,\mathbf{r}_2),\zeta_1,\zeta_2)$

Wavefunction on configuration space

Particle positions





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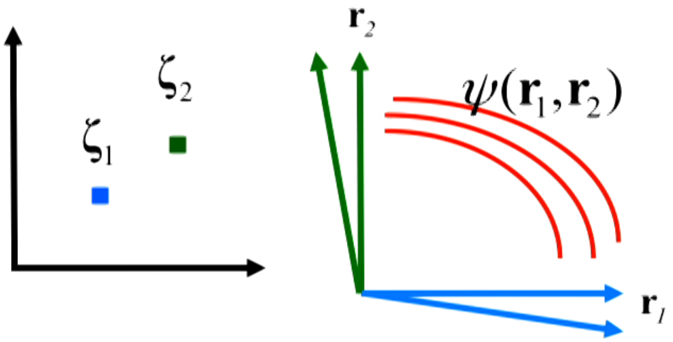

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Schrödinger's equation

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↗ Wavefunction on configuration space

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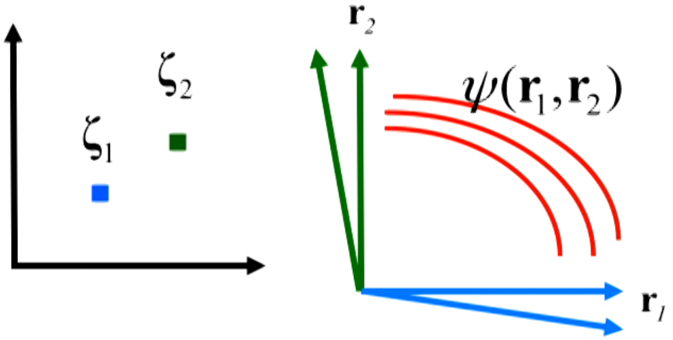

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$$\left.\begin{aligned}\frac{d\zeta_1(t)}{dt}&=\frac{1}{m_1}\left[\nabla_1 S(\mathbf{r}_1,\mathbf{r}_2,t)\right]_{\mathbf{r}_1=\zeta_1(t),\,\mathbf{r}_2=\zeta_2(t)}\\ \frac{d\zeta_2(t)}{dt}&=\frac{1}{m_2}\left[\nabla_2 S(\mathbf{r}_1,\mathbf{r}_2,t)\right]_{\mathbf{r}_1=\zeta_1(t),\,\mathbf{r}_2=\zeta_2(t)}\end{aligned}\right\}\ \text{The guidance equation}$$

where $\psi(\mathbf{r}_1,\mathbf{r}_2,t)=R(\mathbf{r}_1,\mathbf{r}_2,t)e^{iS(\mathbf{r}_1,\mathbf{r}_2,t)/\hbar}$

$$\psi(\mathbf{r}_1,\mathbf{r}_2,t)=\phi^{(1)}(\mathbf{r}_1,t)\,\chi^{(2)}(\mathbf{r}_2,t)$$

Product state

$$=R_1(\mathbf{r}_1,t)e^{iS_1(\mathbf{r}_1,t)/\hbar}\,R_2(\mathbf{r}_2,t)e^{iS_2(\mathbf{r}_2,t)/\hbar}$$

$$S(\mathbf{r}_1,\mathbf{r}_2,t)=S_1(\mathbf{r}_1,t)+S_2(\mathbf{r}_2,t)$$

$$\frac{d\zeta_1(t)}{dt}=\frac{1}{m_1}\left[\nabla_1 S(\mathbf{r}_1,\mathbf{r}_2,t)\right]_{\mathbf{r}_1=\zeta_1(t),\,\mathbf{r}_2=\zeta_2(t)}=\frac{1}{m_1}\left[\nabla_1 S_1(\mathbf{r}_1,t)\right]_{\mathbf{r}_1=\zeta_1(t)}$$

$$\frac{d\zeta_2(t)}{dt}=\frac{1}{m_2}\left[\nabla_2 S(\mathbf{r}_1,\mathbf{r}_2,t)\right]_{\mathbf{r}_1=\zeta_1(t),\,\mathbf{r}_2=\zeta_2(t)}=\frac{1}{m_2}\left[\nabla_2 S_2(\mathbf{r}_2,t)\right]_{\mathbf{r}_2=\zeta_2(t)}$$

The two particles evolve independently

$$\psi(\mathbf{r}_1,\mathbf{r}_2,t) = \sum_j c_j \phi_j^{(1)}(\mathbf{r}_1,t)\,\chi_j^{(2)}(\mathbf{r}_2,t)$$ Entangled state

$(\zeta_1,\zeta_2) \in$ support of $\phi_j^{(1)}(\mathbf{r}_1,t)\,\chi_j^{(2)}(\mathbf{r}_2,t)$ *j*th wave is **occupied**

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$(\zeta_1,\zeta_2) \notin$ support of $\phi_j^{(1)}(\mathbf{r}_1,t)\,\chi_j^{(2)}(\mathbf{r}_2,t)$ *j*th wave is **empty**

If only the *k*th wave is occupied

Then the particles evolve independently

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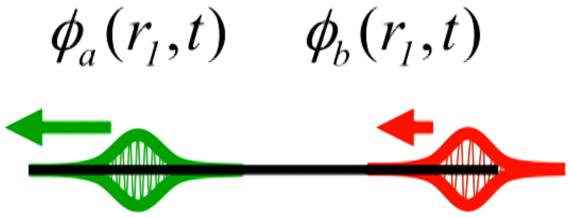
$(\zeta_1,\zeta_2)\notin$ support of $\phi_j^{(1)}(\mathbf{r}_1,t)\,\chi_j^{(2)}(\mathbf{r}_2,t)$ *j*th wave is **empty**

If only the *k*th wave is occupied

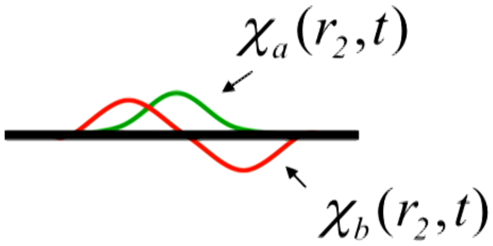
Then the particles evolve independently

But in general, they do not

This implies a failure of local causality and of Lorentz invariance at the ontological level

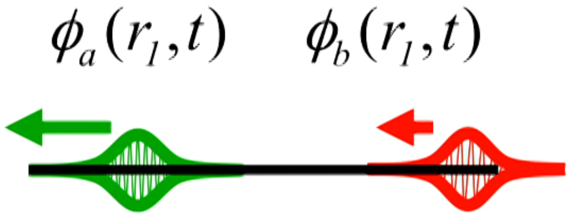


electron 1



electron 2

$$\psi(r_1,r_2;t) = c_a\phi_a(r_1,t)\chi_a(r_2,t) + c_b\phi_b(r_1,t)\chi_b(r_2,t)$$



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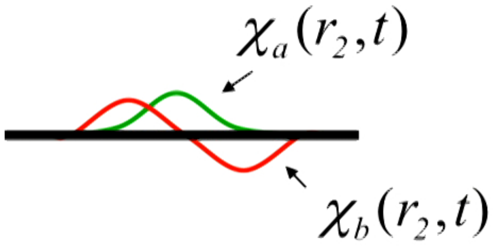

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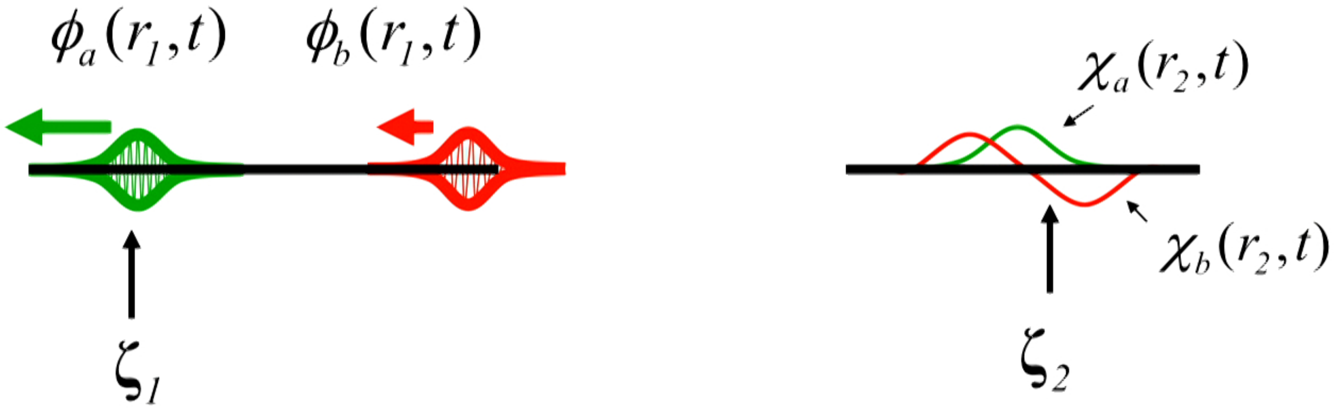

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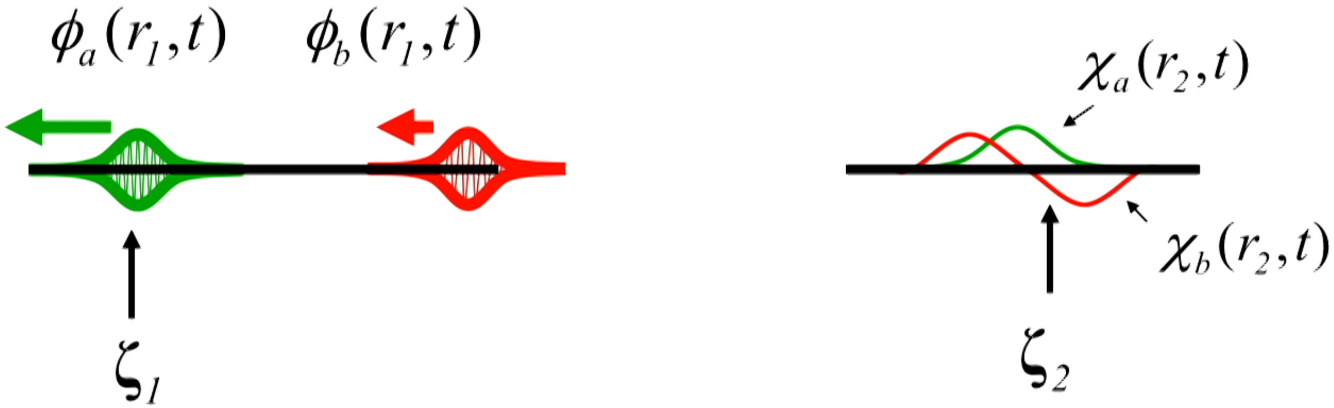
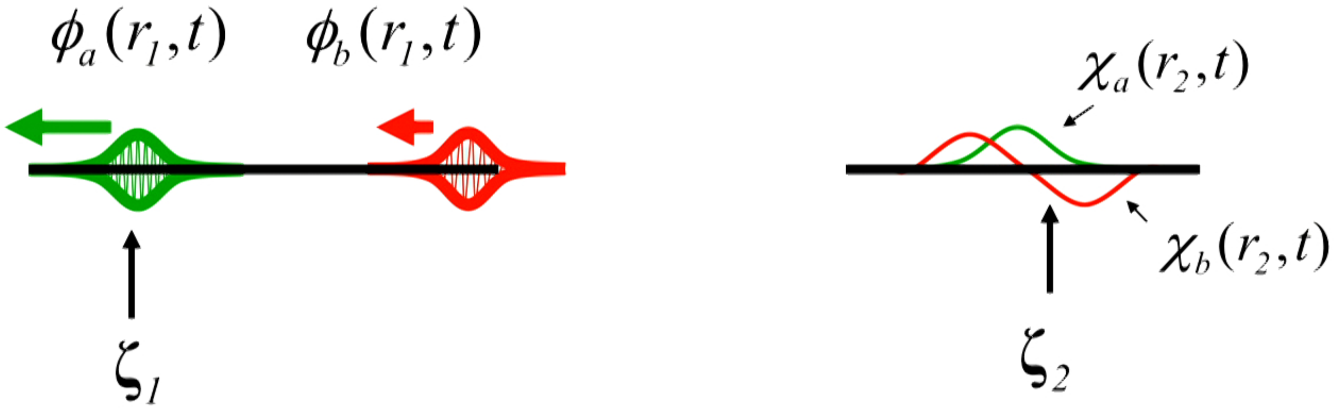


$$\psi(r_1,r_2;t) = c_a\underbrace{\boxed{\phi_a(r_1,t)\chi_a(r_2,t)}}_{\text{occupied wave}} + c_b\boxed{\phi_b(r_1,t)\chi_b(r_2,t)}$$

$$\frac{d\zeta_2(t)}{dt} = \frac{1}{m_2}\left[\nabla_2 S(\mathbf{r}_1,\mathbf{r}_2,t)\right]_{\mathbf{r}_1=\zeta_1(t),\,\mathbf{r}_2=\zeta_2(t)}$$



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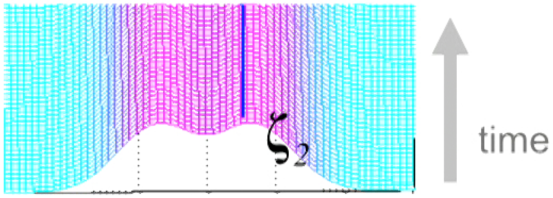

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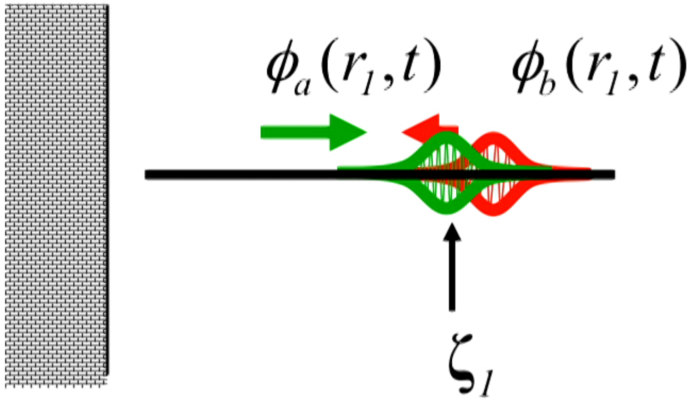

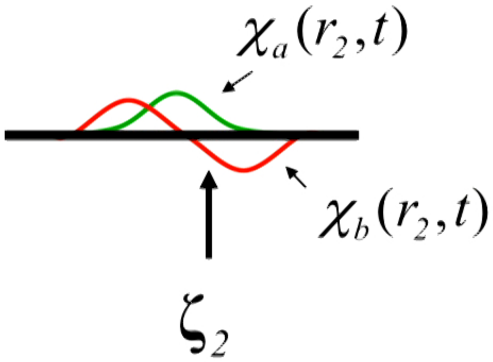

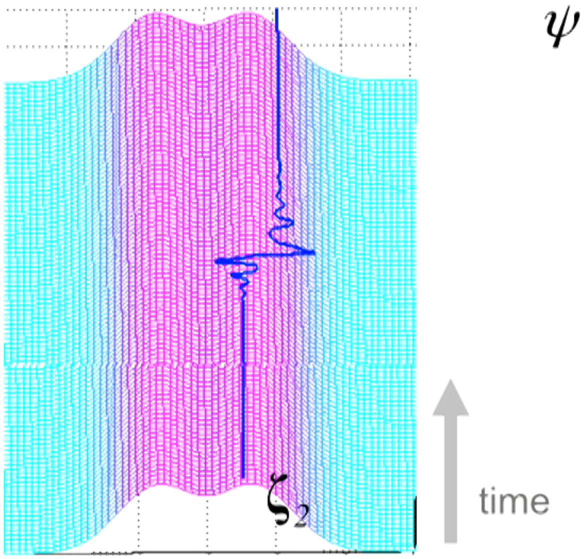

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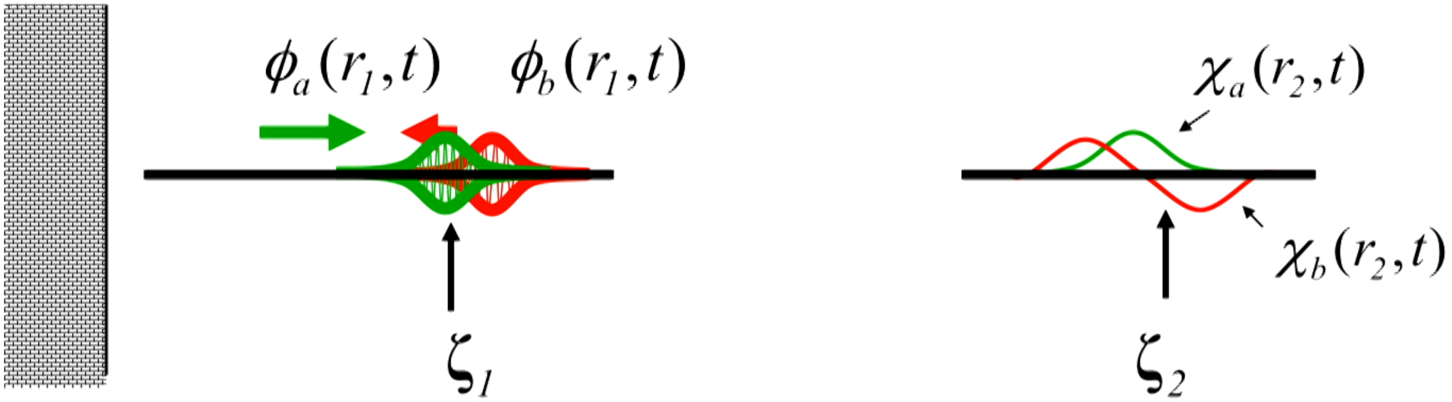

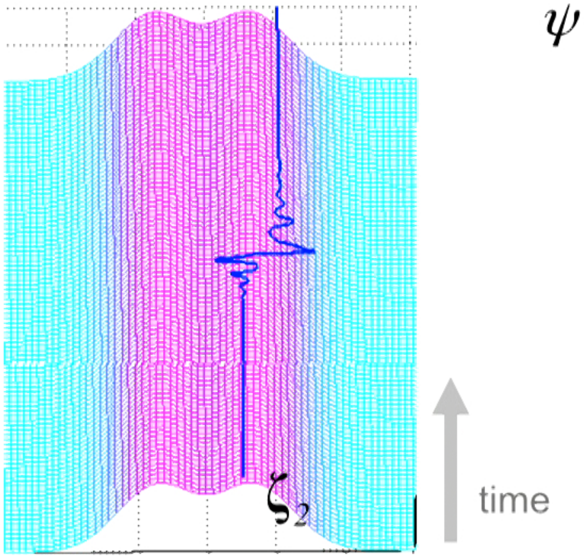

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Failure of local causality

Reproducing the operational predictions

Consider a measurement of A with eigenvectors $\phi_k(\mathbf{r})$

$$\phi_k(\mathbf{r})\chi(\mathbf{r}') \rightarrow \phi_k(\mathbf{r})\chi_k(\mathbf{r}')$$

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Assumption: different outcomes of a measurement correspond to disjoint regions of the configuration space of the apparatus

$$\chi_j(\mathbf{r}')\chi_k(\mathbf{r}') \simeq 0 \text{ if } \quad j \neq k$$

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Decoherence makes the process effectively irreversible

Criticisms

- Fails to satisfy the action-reaction principle

- The quantum state plays an epistemic role in determining the initial distribution but it also plays an ontic role in the guidance equation

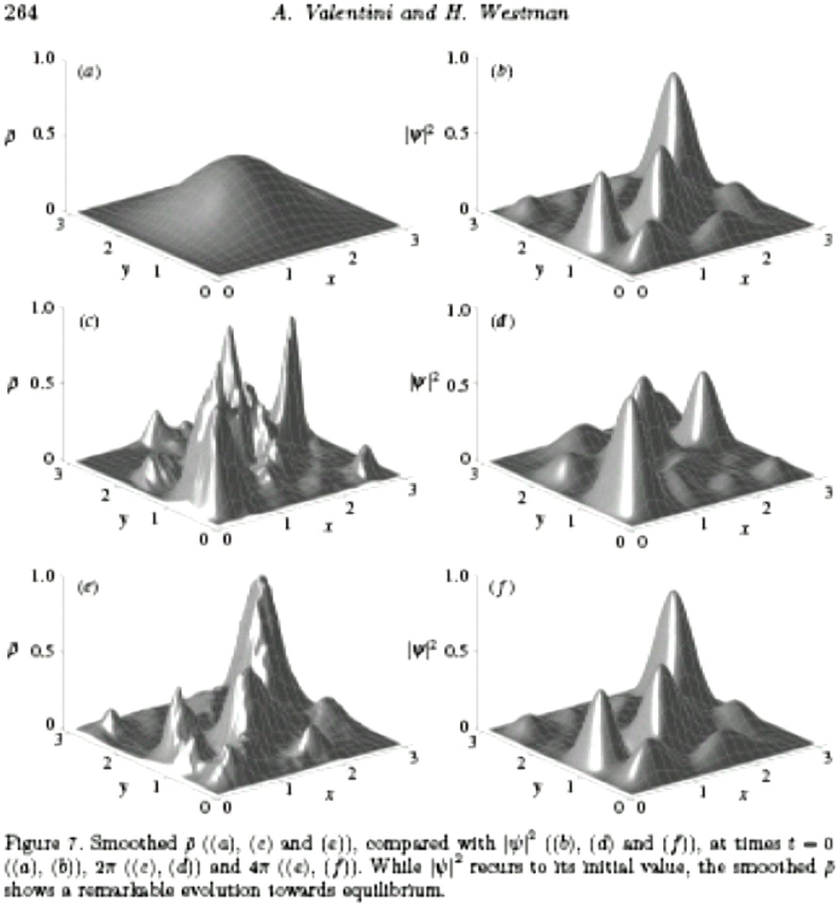
- Underdetermination of preferred variable and of the form of the dynamics

- Lorentz-invariance at the operational level, failure of Lorentz invariance at the ontological level

- Involves more contextuality and nonlocality than necessary to avoid contradiction

- Everett in denial?

The “standard distribution” as quantum equilibrium



264 *A. Valentini and H. Westman*

Figure 7. Smoothed $\bar\rho$ ((a), (c) and (e)), compared with $|\psi|^2$ ((b), (d) and (f)), at times $t = 0$ ((a), (b)), 2π ((c), (d)) and 4π ((e), (f)). While $|\psi|^2$ recurs to its initial value, the smoothed $\bar\rho$ shows a remarkable evolution towards equilibrium.