The Role of the Wave Function in the GRW Matter Density Theory

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Outline

Primitive Ontologies for Quantum Mechanics

Basic assumption

A fundamental physical theory should describe the behaviour of matter in space and time. In other words, it should specify a primitive ontology (PO) and describe its development in time.

Different PO-versions of quantum mechanics are obtained via different choices of the PO (particles, fields, flashes) and/or of the dynamical laws governing its behaviour (Allori et al. 2008, sect. 6).

A challenge for every PO approach

The wave function ψ is essential for the empirical success of quantum mechanics, but is not itself part of the PO. One thus needs to clarify the status of the wave function and the way in which it "governs" the behaviour of the PO.

Two PO-approaches to Quantum Mechanics

Bohmian Mechanics (BM)

PO: particles with positions $Q_1(t), \ldots, Q_N(t)$

Guidance equation: $\frac{\mathrm{d}Q_i}{\mathrm{d}t} = \frac{\hbar}{m_i} \Im \frac{\psi^* \nabla_i \psi}{\psi^* \psi}(Q_1, \ldots, Q_N)$

Schrödinger equation: $i\hbar \frac{\partial \psi}{\partial t} = H\psi$

Ghirardi-Rimini-Weber Matter Density Theory (GRWm)

PO: continuous matter field with density $m(\boldsymbol{x}, t)$

Matter density:

$$m(\boldsymbol{x}, t) = \sum_{i=1}^{N} M_i \int_{\mathbb{R}^{3N}} \mathrm{d}\boldsymbol{q}_1 \ldots \mathrm{d}\boldsymbol{q}_N \delta^3(\boldsymbol{q}_i - \boldsymbol{x}) |\psi(\boldsymbol{q}_1, \ldots, \boldsymbol{q}_N, t)|^2$$

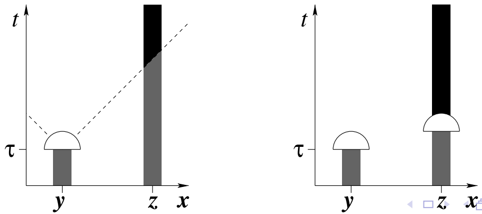
Schrödinger dynamics plus collapses at random times T:

$\psi_T \mapsto \psi'_T = \frac{\Lambda_I(\boldsymbol{X})^{1/2}\psi_T}{\|\Lambda_I(\boldsymbol{X})^{1/2}\psi_T\|}$, with $\Lambda_i(\boldsymbol{x}) = \frac{1}{(2\pi\sigma^2)^{3/2}} e^{-\frac{(\hat{\boldsymbol{Q}}_i - \boldsymbol{x})^2}{2\sigma^2}}$ and $\boldsymbol{X} \in \mathbb{R}^3$, $I \in \{1, \ldots, N\}$ random.

Spontaneous Localization Models beyond GRW

- CSL: ψ (and thereby $m(\boldsymbol{x},t)$) evolves continuously instead of collapsing instantaneously. However, for large systems, the difference between the two kinds of evolution becomes negligible.
- CSL attributes the stochastic evolution of ψ to a noise field filling space (review: Bassi et al. 2013). This raises the question of the ontological status of that field (and its relation to m).
- Lorentz invariant definition of m (Bedingham et al. 2014):

$$m(x) = \sum_{i=1}^{N} M_i \int_{PLC(x)} \mathrm{d}q_1 \ldots \mathrm{d}q_N \delta^4(q_i - x)|\psi(q_1,\ldots,q_N)|^2$$



The Status of ψ in Bohmian Mechanics: The Options

Belot (2012), Esfeld et al. (2013)

1. ψ as object
   - field on (3N-dimensional) configuration space
   - “multi-field” assigning properties to N-tuples of points in (3-dimensional) space
2. ψ as law
   - Humeanism: ψ not part of the ontology, only part of the best system describing the history of the PO
   - dispositionalism: laws grounded in dispositional properties (see 3 below)
   - primitivism: laws as fundamental, ψ is part of the basic ontology (in virtue of its nomological status).
3. ψ as property
   - ψ denotes a property of the N-particle system, which confers on the particles a disposition to move according to the guidance equation.

The Wave Function in GRWm: The Extreme Options

The status of the wave function: summary of the options

	ontologically independent	ontologically dependent
material	ψ as object (field/multi-field)	ψ as property (dispositionalism)
(purely) nomological	ψ as law (primitivism)	ψ as law (Humeanism)

ψ as object:

- No principled difference between BM and GRWm.
- Exception: BM exhibits causal asymmetry between ψ and the PO, in GRWm their development is strictly parallel.

ψ as Humean law:

- Again, similar in BM and in GRWm: ψ's supervenience on the spatiotemporal distribution of the PO does not depend on the *kind* of PO (particles or fields) that is postulated.

The Wave Function in GRWm: Primitivism about Laws

- Major difficulty for primitivism: ψ is (in general) time-dependent, which is not what we expect from a fundamental law of nature.
- However, BM allows for a stationary universal wave function defining a non-trivial dynamics for the PO and time-dependent effective wave-functions of subsystems.
- The same is not true in GRWm: if ψ is stationary, nothing moves.

Upshot

Primitivism about laws with respect to ψ is less attractive in GRWm than in BM. Conversely, primitivism offers reason for preferring BM to GRWm.

The Wave Function in GRWm: Dispositionalism

- Basic difference: While BM involves a “sure fire” disposition, GRW deals with a propensity.
- The property denoted by ψ must be holistic: Attributing it to individual parts of the PO would contradict empirical results (e.g., violations of Bell’s inequalities).
- In BM, this holism is combined with an atomistic ontology (particles individuated by their trajectories).
- GRWm yields a more unified ontology, since the PO is itself holistic (one matter field).

Upshot

GRWm is more hospitable to dispositionalism than BM. So the dispositionalist has reason to prefer GRWm to BM.

An objection: GRWm ontology is not so unified after all, due to residues of atomism (“particle” lables) in its formulation.

Component Fields of the Matter Density

Mathematically, $m(x,t)$ is a sum of *N* “component fields”:

$$m(x,t) = \sum_{i=1}^{N} m_i(x,t) = \sum_{i=1}^{N} M_i \int_{\mathbb{R}^{3N}} \mathrm{d}q_1 \dots \mathrm{d}q_N \delta^3(q_i - x) |\psi(q_1, \dots, q_N)|^2$$

This mathematical structure has physical significance only insofar as there are subsets $S \subset \{1, \dots, N\}$ such that $\sum_{i \in S} m_i(x,t)$ is non-entangled with $\sum_{i \notin S} m_i(x,t)$ (cf. Ghirardi, Marinatto and Weber 2002).

The dynamics then introduces some separability into the holistic GRWm ontology, which makes physics (as we know it) possible.

Component Fields and the Collapse Dynamics

The collapse operator $\Lambda_i(x)$ is associated to one component field $m_i(x,t)$, but this only matters if $m_i(x,t)$ is non-entangled with the rest of the world (in which case the collapse is both extremely improbable and observationally irrelevant).

In general, the collapse will hit a component of an entangled subsystem $\sum_{i \in S} m_i(x,t)$, in which case the specific choice of $i \in S$ is irrelevant.

Illustration: detecting a single "particle" in GRWm

1. Start with a matter field such that for some $i \in \{1, \ldots, N\}$, $m_i(x,t)$ is (for some period of time) non-entangled with the environment (“one-particle state”).
2. Couple $m_i(x,t)$ with a many-component system (“measuring device”), which ensures collapse and macroscopic observability.

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