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Primitive Ontology and the Structure of Fundamental Physical Theories

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or August 24th?

the non-Vulcanian side of Shelly

Fundamental Physical Theories

- Physical: a theory of the physical world
  - describe the world/ behaviour of things
    - postulate the existence of some invisible/counter-intuitive/not obvious entities
    - Examples:
      - ancient Greek atomism
      - classical mechanics
      - quantum mechanics

Fundamental Physical Theories

- Fundamental: explain the behaviour of all things
    - physics vs chemistry vs biology …
  - Reductionism: description of the behaviour of macroscopic things in three-dimensional space
    - statistical mechanics vs thermodynamics
  - explanation of"how we think there are things that actually aren't there"
    - example: color

Fundamental Physical Theories

- Theory:
  - conjectural nature
  - creative element
  - role of explanation

FPT: Common Structure

- what a FPT can/should be able to explain:
- the behaviour of everything (=motion of macroscopic objects in ordinary space)

FPT: Common Structure

- what a FPT cannot explain:
- the mind-body problem
  - ex: perception of color vs color

FPT: Common Structure

- They need to be about something: they should have a clear ontology
- What they are fundamentally about is what Shelly (and Nino and Detlef) called the primitive ontology (PO)
- They also need dynamical variables

The need for a clear ontology

- If one wants to be a REALIST w.r.t. a Fundamental Physical Theory, then it must be clear what the theory is about:
  - What are the **entities** that are 'out there' in the world and and what is their mathematical representation?
- If we do not specify the ontology, the theory is only **empty mathematics**

The notion of Primitive Ontology

- The primitive ontology of the theory is what the theory is fundamentally about
- A bunch of variables in the FPT:
  - The primitive ontology is the stuff physical things are made of
  - as opposed to the dynamical variable(s)

The dynamics of the PO

- It is not sufficient to specify only what is the PO - we also need to specify how it "behaves":

What is the law of motion for the PO?

- The variables describing the **PO** must be distinguished from the other **"auxiliary" (or nomological)** variables that allow for the implementation of a dynamical law for the primitive variables

The PO and its dynamics

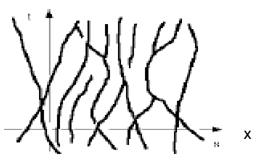
(what there is) & (how it behaves)

↕ ↕

(Primitive) & (nomological) variables

Decorations

- Dual structure: (**X**; Φ)
- **X** (=PO): "decoration" of space-time
- Φ: governing the motion of **X**



FPT: Common Structure

- X (primitive ontology): what matter is
- Φ (the dynamical variable): how matter moves
- μ (measure of typicality): what the majority of histories of X are doing

FPT: Common Structure

- in a space-time setting the description is in terms of (Ω, μ):
  - *Ω: the space of histories*
  - *μ: the measure of typicality*

Fundamental Physical Theories

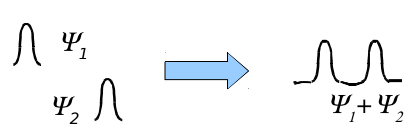
- FPT are what physicists should be looking for
- Examples of FPT:
  - classical mechanics
  - classical electrodynamics
  - General relativity
  - String theory
  - … quantum mechanics ?

What is Quantum Mechanics?

- It is supposed to be a FPT
- The fundamental object of the theory is the wave function Ψ: it completely describes the state of a physical system
  - The wave function lives in configuration space (dimension d~10^{23})
  - The wave function evolves in time according to an equation called Schrödinger's equation

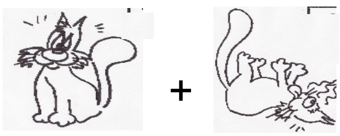
What is Quantum Mechanics?

- The equation is Linear: If Ψ_1 and Ψ_2 describe possible physical states at a given time t, also $\Psi_1+\Psi_2$ does
  - State: all you need to specify in order to completely describe the system



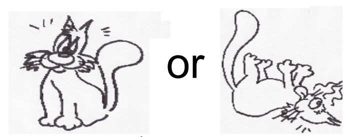
Impossible cats

- Because of linearity of the evolution equation, the wave function evolves into a superposition state:
- It is the sum of two macroscopically distinct states of affairs of the system under consideration (cat alive and cat dead)



Impossible cats

- From experience we know that macroscopic systems are NEVER in a superposition. Rather, they are always in well defined states



Impossible cats

- But we just saw that IF the wave function provides a complete description of a system AND it evolves according to Schrödinger's equation, THEN it produces such superpositions
- Therefore, IF we want quantum mechanics to describe what really happens (that is, if we want measurements to have results), THEN ....

Impossible cats

- Bell's famous alternatives:
  - Either the wave function does not provide the complete description
  - OR it does not evolve according to Schrödinger's equation

Impossible cats

Moral of the story:

- The three claims
  - 1:The wave function provides a complete description
  - 2:The wave function evolves according to Schrödinger's equation
  - 3:Measurements have results
- Are incompatible

Solutions to the measurement problem (without the observer)

- Deny claim 1 (the wave function provides a complete description)
  - Add particles positions (Bohmian Mechanics, BM)
- Deny claim 2 (the wave function evolves according to Schrödinger's equation)
  - The wave function evolves according to a stochastic equation (GRW theory)
- Deny claim 3 (measurements don't have results)
  - There is a multiverse of different worlds (Many Worlds, MW)

Bohmian Mechanics

- Complete description (Q, Ψ):
  - $Q=(Q_1, \dots, Q_N)$, Q_k in $\mathbf{R}^3$, k=1,...,N
  - $\Psi(Q)=\Psi(Q_1, \dots, Q_N)$

Bohmian Mechanics

•Guide equation

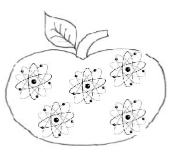
$$\frac{dQ_i}{dt} = v_i^\psi(Q_1,\dots,Q_N) = \frac{\hbar}{m_i}\mathrm{Im}\frac{\psi^*\nabla_i\psi}{\psi^*\psi}(Q_1\dots,Q_N)$$

•Schrödinger equation

$$i\hbar\frac{\partial\psi}{\partial t} = H\psi \qquad H = -\sum_{k=1}^{N}\frac{\hbar^2}{2m_k}\nabla_k^2 + V$$

Bohmian metaphysics

- BM is about particles in 3-dimensional space :
  - The microscopic description of reality is discrete (particle-like)



GRW Theory

- $\Psi(Q)=\Psi(Q_1, \dots, Q_N)$
- $Q=(Q_1, \dots, Q_N)$, Q_k in $\mathbf{R}^3$, k=1,...,N
- "particles" are not really there

GRW Theory

- For any point x in $\mathbf{R}^3$ ⟶ $\Lambda_i(x) = \frac{1}{(2\pi\sigma^2)^{3/2}} e^{-\frac{(\hat{Q}_i - x)^2}{2\sigma^2}}$
- The evolution for ψ is Schrödinger interrupted by collapses

$\sigma \sim 10^{-7} m$

$\lambda \sim 10^{-15} s^{-1}$

- A collapse center with center x and label i will occur at rate ⟶ $r(x, i|\psi) = \lambda \langle\psi\,|\,\Lambda_i(x)\psi\rangle$
- When this happens:

$$\psi \longrightarrow \Lambda_i(x)^{1/2}\psi / \|\Lambda_i(x)^{1/2}\psi\|$$

GRW metaphysics?

- In GRW there seem to be just the wave function.
- Is GRW a theory about the wave function? is Ψ the PO of GRW?
- Problems of considering tables and chairs as made of wave functions:
  - The wave function lives in a space with a very large number of dimensions (~10^{23})
  - Where is three-dimensional space?

GRW metaphysics?

- "[...] the wave function as a whole lives in a much bigger space, of 3N dimensions. It makes no sense to ask for the amplitude or phase or whatever of the wave function at a point in ordinary space. It has neither amplitude nor phase nor anything else until a multitude of points in ordinary three-space are specified." [Bell, 1987]

Mass density GRW - GRWm

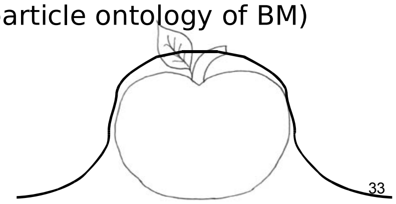
- GRWm is a theory about the behaviour of a field *m(x, t)* on three-dimensional space

$$m(x,t) = \sum_{i=1}^{N} m_i \int_{\mathbb{R}^{3N}} dq_1 \cdots dq_N \, \delta(q_i - x) \left|\psi(q_1,\ldots,q_N,t)\right|^2$$

- This is reminiscent of Schrödinger's early view of the wave function as representing a continuous matter field.

GRWm metaphysics

- The microscopic description of reality provided by the matter density field *m(x, t)* is continuous (in contrast with the particle ontology of BM)



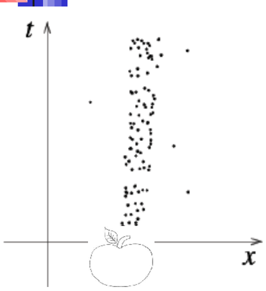
Flashy GRW - GRWf

- GRWf is a theory about a set of "events" in space-time, the flashes = the points in s-t corresponding to the collapses of the wave function
  - The wave function evolves in a random way
  - F is a random set of space-time

$$F = \{(X_1, T_1), \ldots, (X_k, T_k), \ldots\}$$

$N = 10^{23} \rightarrow 10^{8}$ flashes/second

GRWf metaphysics



- The microscopic description of reality provided by GRWf is discrete in space-time
- "the world is a galaxy of such events" [Bell 1976]

The notion of Primitive Ontology

- The wave function in GRWf and GRWm do not belong to the primitive ontology: according to these theories, **physical objects are not made of wave functions**

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The common structure of BM and GRW – the PO

They both have a Primitive Ontology (PO)

- Bohmian Mechanics:
  - PO= Positions of particles
- GRW theory:
  - PO=
    - GRWf: flashes (random events in space-time)
    - GRWm: 3-d density of mass field
  - Different choices of PO define **different physical theories**

The common structure of BM and GRW – PO's dynamics

Dynamics for the PO: the wave function

- Bohmian Mechanics:
  - Deterministic evolution for Ψ (Schrödinger's equation)
- GRW theory:
  - The wave function evolves randomly
- In both cases, the wave function induces a law for the PO

The role of the wave function

- PO=output of a FPT
- Nomological variables: algorithm to generate the output
  - Different algorithms can produce the very same output
    - EX: different sorting algorithms
    - Selection sort: find the minimum value in the list, swap it with the value in the first position, repeat the steps for rest of the list
    - Bubble sort: stepping through the list to be sorted, comparing two items at a time and swapping them if in the wrong order

PO and Physical Equivalence

- Theories with the same "output" are physically equivalent
- **Two theories are physically equivalent if they lead to the same histories for the PO (regardless to the evolution for the nomological variable)**

PO and Physical Equivalence

- Gauge transformation:

$$\psi \mapsto e^{i\sum_k e_k f(q_k)}\psi, \quad A \mapsto A + \nabla f$$

- Heisenberg picture:

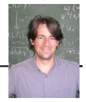
$$\frac{dQ_i}{dt} = -\frac{1}{\hbar}\mathrm{Im}\frac{\langle\psi|P(dq,t)[H,\widehat{Q}_i(t)]|\psi\rangle}{\langle\psi|P(dq,t)|\psi\rangle}(q = Q(t))$$

- The history of the PO does not change

The flexible wave function

- Since what is important is the history of the PO and not the variable used to implement the law for the PO, we have a lot of flexibility:
  - Formulation of GRWf in which the wave function does not collapse
    - Physically equivalent to GRWf with stochastically evolving wave function
  - Formulation of BM in terms of a collapsed wave function
    - Physically equivalent to BM with linearly evolving wave function

Problems with Ψ as nomological ?



- Ψ evolves in time
  - Quantum cosmology suggests the universal wave function is static (Shelly and Stefan)
- Ψ is controllable
  - Not the universal wave function

- "There are different degrees of reality"
  - If one is nominalists wrt laws, the wave function does not exist
  - If one is realist, it exists as an abstract entity
  - Fay have tried to eliminate the wave function

PO and symmetries

- Symmetries are "properties" of the law which governs the dynamics of the PO

PO and symmetries

- $L_\psi(X)$: (probability) law for X
- $X \longrightarrow X_g$ natural geometrical action of g on X
- The law is symmetric under g if
  $L_{\psi g}(X_g)=L_\psi(X)$

for suitable action $\psi \longrightarrow \psi_g$ of g on ψ

PO and symmetries

- Easy part: X transform the right way
- Novelty: ψ is allowed to transform in any fancy way
- EX: Galilean boosts in BM

$$\tilde{Q}_i(t) = Q_i(t) + vt$$

$$\tilde{\psi}_t(q_1,\ldots,q_N) = \exp\left(\frac{i}{\hbar}\sum_{i=1}^{N} m_i(q_i \cdot v - \tfrac{1}{2}v^2 t)\right)\psi_t(q_1 - vt,\ldots,q_N - vt)$$

after $V(q_1,\ldots,q_N)$ is replaced by $V(q_1 - vt,\ldots,q_N - vt)$

PO and relativity

- The flashy ontology was invented by Bell [1987] as a step toward a relativistic GRW theory:

"I am particularly struck by the fact that the model is as Lorentz invariant as it could be in the non relativistic version. It takes away the ground of my fear that any exact formulation of quantum mechanics must conflict with fundamental Lorentz invariance."

PO and relativity

- Since symmetries concern the histories of the PO (and not the wave function) **Different** PO may lead to **different** symmetries
  - Example:
    - GRWf can be made relativistically invariant (Roderich)
    - GRWm is NOT relativistically invariant

Quantum state and the PO

	PO	state
BM	*x*	(x,Ψ)
GRWm	*m(x)*	Ψ
GRWf	$F=\{(x_i,t_i)\}$	Ψ

- In GRWf, GRWm the PO is determined by the state Ψ:

  Ex: $m(x)=f(\Psi)$, Flashes = $f\,'(\Psi)$

The measurement problem revisited

- The moral of the measurement problem is NOT the one of Bell
  - in terms of the wave function
- Rather, it is that the wave function should not be regarded as representing physical objects
  - in terms of the PO

The measurement problem revisited

- "Bohm"-like solutions of the measurement problem:
  - PO independent on Ψ
- "GRW"-like solutions of the measurement problem:
  - PO is a function of Ψ

The measurement problem revisited - "Bohmianization"?

Ψ → *cat problem* →

→ (Ψ, Q) →

→ Ψ → *mass density* →

flashes → (Ψ, X)

→ *X* → $X=f(\Psi)$

$X=Q$

The measurement problem revisited - "Bohmianization"?

Ψ → *the wf is not the PO* →

X → (X,Ψ) → $X=f(\Psi)$ *GRW-like*

→ $X=Q$ *Bohmian*