Ontology is (in my humble opinion) an important concept for physics.

Ontology of a physical theory = what exists, according to that theory.

Physicist Jeremy Bernstein [2013]:

“There are many papers I tried to read that were written by philosophers and had words like “ontology” sprinkled over them like paprika.”

It was long thought that the key to clarity in QM was to avoid talking about ontology and stick to operational statements. That thought has not paid off.

John S. Bell coined the word “beables” (as opposed to observables) of a theory for the variables representing something real, according to that theory.
Bohmian mechanics

- takes the word “particle” literally: The $k$-th particle has position $\mathbf{Q}_k(t) \in \mathbb{R}^3$ at time $t$.
- The complete description of a system is $(\mathbf{Q}_1, \ldots, \mathbf{Q}_N, \psi)$.
- The equation of motion is the simplest possible:
  \[
  \frac{d\mathbf{Q}_k}{dt} = \text{probability current} / \text{probability density}
  \]
  with current $= (\hbar/m_k) \text{Im} \langle \psi^* \nabla_k \psi \rangle$ and density $= |\psi|^2$.
- $\psi$ evolves according to the Schrödinger eq.
  \[
  i\hbar \frac{\partial \psi}{\partial t} = H\psi
  \]

Like it or don’t, it actually works: Inhabitants of a universe governed by Bohmian mechanics (with $|\psi|^2$-distributed initial configuration) would observe exactly the probabilities predicted by the quantum formalism.
Bohmian mechanics

Wave–particle dualism in the literal sense: there is a wave, and there is a particle. The path of the particle depends on the wave.

Shown: A double-slit and 80 possible paths of Bohm’s particle. The wave passes through both slits, the particle through only one.
Most paths arrive where $|\psi|^2$ is large—that’s how the interference pattern arises.
Two things are real in a Bohmian universe:

1. The particles.

2. The wave function. [Or perhaps not; maybe the wave function of the universe can be thought of as a law, rather than a thing, just like the Hamiltonian. This possibility would seem more serious if the wave function of the universe is time-independent (as in some proposals for quantum gravity) and defined in a simple way.]

\((Q, \psi) – \text{dual structure}\)
• Primitive ontology (PO) = the part of the ontology that represents matter in space-time.
• In Bohmian mechanics: the particles.
• Non-primitive ontology (NPO) = the rest of the ontology.
• In Bohmian mechanics: the wave function.

Bell talked about the “local beables” (i.e., things that exist and are localized in space).
**Definition**

Two theories are physically equivalent when they lead to the same history of the PO (or, the same probability distribution over histories of the PO).

Conversely, one could define the notion of PO in terms of physical equivalence: The PO is described by those variables which remain invariant under all physical equivalences.
Examples of physical equivalence

- **Add a constant to the Hamiltonian.** If $\psi(q, t)$ satisfies the Schrödinger equation $i\partial\psi/\partial t = H\psi$, and $H' = H + E$ for some constant $E \in \mathbb{R}$, then

$$\psi'(q, t) = e^{-iEt}\psi(q, t)$$

satisfies $i\partial\psi'/\partial t = H'\psi'$. Note that $|\psi'|^2 = |\psi|^2$, and the Bohmian trajectories are the same $\Rightarrow$ physical equivalence.

- **Gauge freedom.** BM with external magnetic field: replace $\nabla_k$ by $\nabla_k - ie_k A(q_k)$, $A =$ vector potential, $e_k =$ electric charge of particle $k$. Gauge transformation

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

does not change the trajectories nor the $|\psi|^2$ distribution.

There is a great deal of flexibility about $\psi$. 
More examples of physical equivalence

- **Choice of Hilbert space.** Let $\mathcal{H}$ be any Hilbert space (such as $L^2(\mathbb{R}^{3N})$), $H$ (the Hamiltonian) be a Hermitian operator on $\mathcal{H}$, and $P(q)$ be, for every $q \in \mathbb{R}^{3N}$, a projection (such as, $P(q) = |q\rangle\langle q|$). Bohm’s equation of motion can be re-written

$$\frac{dQ_k}{dt} = \frac{1}{\hbar} \text{Im} \frac{\langle \psi | P(q)[\hat{Q}_k, H] | \psi \rangle}{\langle \psi | P(q) | \psi \rangle} (q = Q(t)),$$

with $\hat{Q}_k = \int q_k P(q) \, dq$ the position operator of the $k$-th particle. Let $\mathcal{H}'$ be another Hilbert space, $H'$ a Hamiltonian on $\mathcal{H}'$, $P'(q)$ projections on $\mathcal{H}'$. If there is $U : \mathcal{H} \to \mathcal{H}'$ unitary with $H' = UHU^{-1}$ and $P'(q) = UP(q)U^{-1}$, then (1) yields the same trajectories and probabilities $\Rightarrow$ physical equivalence.

- **Schrödinger picture vs. Heisenberg picture.** In the former, $\psi$ changes with time while $P(q)$ (and, in orthodox QM, the observables) are fixed. In the latter, $P(q)$ (and the observables) change with time, $P(q, t) = e^{iHt}P(q)e^{-iHt}$, while $\psi$ is fixed. Eq. (1) $\Rightarrow$ the same trajectories and probabilities $\Rightarrow$ physical equivalence.

There is no fact about whether the Schrödinger picture or the Heisenberg picture is “right.”
Another example:

- **Symmetrization postulate.** For $N$ identical particles, the appropriate configuration space is that of unordered configurations $\{q_1, \ldots, q_N\}$, instead of ordered configurations $(q_1, \ldots, q_N)$, denoted $N\mathbb{R}^3$ instead of $\mathbb{R}^{3N}$.

If $\psi : \mathbb{R}^{3N} \to \mathbb{C}$ is either symmetric or anti-symmetric, then any ordering leads to same motion of the particles (up to re-ordering), so $\psi$ defines trajectories in $N\mathbb{R}^3$. (We see how it can make sense, in BM, that $\psi$ is defined on a different space than the configuration space.)

Alternatively, for a suitable vector bundle $F$ called the fermionic line bundle, a cross-section $\tilde{\psi} : N\mathbb{R}^3 \to F$ can represent a fermionic wave function, yielding the same trajectories in $N\mathbb{R}^3$ as a certain anti-symmetric $\psi : \mathbb{R}^{3N} \to \mathbb{C}$.

$\Rightarrow$ physical equivalence between $\tilde{\psi}$ and $\psi$
Another example of a primitive ontology

A “flash” is a material world point (i.e., point in space-time), in constrast to the material world line of a particle.
Flash theory
Flash theory
Flash theory
Flash theory

Roderich Tumulka

Primitive Ontology
Flash theory

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Primitive Ontology
The flash ontology has been used particularly in connection with the GRW collapse theory.
Spontaneous collapse: GRW theory

Key idea:

The Schrödinger equation is only an approximation, valid for systems with few particles \((N < 10^4)\) but not for macroscopic systems \((N > 10^{23})\). The true evolution law for the wave function is non-linear and stochastic (i.e., inherently random) and avoids superpositions (such as Schrödinger’s cat) of macroscopically different contributions.

Put differently, regard the collapse of \(\psi\) as a physical process governed by mathematical laws.

Explicit equations by Ghirardi, Rimini, and Weber (1986)

The predictions of the GRW theory deviate very very slightly from the quantum formalism. At present, no experimental test is possible.
GRW’s stochastic evolution for $\psi$

- is designed for non-relativistic quantum mechanics of $N$ particles
- meant to replace Schrödinger eq as a fundamental law of nature
- involves two new constants of nature:
  - $\lambda \approx 10^{-15}$ sec$^{-1}$, called collapse rate per particle.
  - $\sigma \approx 10^{-7}$ m, called collapse width.
- Def: $\psi$ evolves as if an observer outside the universe made, at random times with rate $N\lambda$, quantum measurements of the position observable of a randomly selected particle with inaccuracy $\sigma$.
- “rate $N\lambda$” means that
  \[
  \text{prob( an event in the next } dt \text{ seconds) } = N\lambda \, dt.
  \]
- more explicitly: Schrödinger evolution interrupted by jumps of the form
  \[
  \psi_{T^+} = e^{-\frac{(q_k-q)^2}{4\sigma^2}} \psi_{T^-},
  \]
  i.e., multiplication by a Gauss function with random label $k$, center $q$ and time $T$.
- A flash occurs at $(T, q)$ for each collapse.
GRW’s spontaneous collapse

before the “spontaneous collapse”:

and after:
Another proposal [Ghirardi 1995]:

- Use the same stochastic evolution for the wave function, but not the flash ontology.
- Instead, postulate that matter is continuously distributed in space with density $m(x,t)$ given by

$$m(x,t) = \sum_{i=1}^{N} m_i \int_{\mathbb{R}^{3N}} dx_1 \cdots dx_N \delta^3(x - x_i) \left| \psi_t(x_1 \cdots x_N) \right|^2.$$

- It turns out that GRWm is empirically equivalent to GRWf, although the two theories have very different stories about what happens in reality.
Let $\psi$ evolve according to the stochastic GRW evolution.

Use a particle ontology, with the initial configuration $|\psi|^2$-distributed, and the particles moving according to Bohm’s equation of motion.

In contrast to BM, the $|\psi|^2$ distribution is not conserved (i.e., $Q(t)$ will not be $|\psi|^2$ distributed).

Consider Schrödinger’s cat. Thanks to $Q$, it is already dead or alive before the collapse; suppose it is alive. The collapse (that occurs quite soon, say at time $T$) may favor $\psi_{\text{alive}}$ and shrink $\psi_{\text{dead}}$ enormously. But $Q(T)$ does not change immediately. Is the cat dead or alive? That is, should we draw conclusions from $\psi$ or from $Q$? Taking the PO seriously, from $Q$.

From $T$ onwards, $Q$ behaves in a catastrophic way.

GRWp is grossly empirically inadequate. It is not empirically equivalent to GRWm, GRWf, or BM.
When deriving predictions ("with probability $p$, the pointer will be in position $x$"), one derives statements about the primitive ontology (the pointer is where its flashes are).

Lorentz invariance requires that the flashes transform like space-time points. However, there is no simple relation between $\psi_\Sigma$ and $\psi_{\Lambda(\Sigma)}$.

Where we (and tables and chairs) are in the picture of the theory.
Tim Maudlin (2014)

“A theory’s specification of the fermion density in every region of the universe entails the distribution of matter at macroscopic scale. And if what it predicts at macroscopic scale matches everything we think we know about the world at macroscopic scale (including where the pointers ended up pointing, where the ink is on the paper, the shape of the earth, the dimensions of the Empire State building, etc., etc., etc.) then the theory is empirically adequate in any reasonable sense. There may be objections to such a theory, but they cannot rightfully be called empirical objections.”
Many people have regarded GRW∅ as an acceptable theory, including David Albert, Alberto Rimini, and Philip Pearle.

After all, it was the motivation behind GRW theory to do without ontology in addition to $\psi$: otherwise, we could have used Bohmian mechanics.

In fact, in the measurement problem (which has 3 ways out: either there are things in addition to $\psi$, or the evolution of $\psi$ is not always unitary, or all measurement outcomes are somehow realized), the GRW theory was supposed to choose the second option, not the first.

GRW∅ seems more parsimonious than GRWm or GRWf. Do we really need a PO?
Schrodinger's Cat

1. Radioactive material has a 50:50 chance of triggering the Geiger counter.
2. If the Geiger counter is triggered, the hammer falls.
3. The hammer breaks the poison bottle.
4. Cat dies if the poison bottle breaks.
5. Cat lives if the Geiger counter does not trigger the hammer and releases the poison.
GRW theory without primitive ontology is problematical

- There is a logical gap in the reasoning: “If $\psi$ is the wave fct of a live cat then there is a live cat.”

- For spacelike 3-surface $\Sigma = A \cup B$ with $A \cap B = \emptyset$, the state of $A$ is $\rho_A = \text{tr}_B |\psi_\Sigma\rangle\langle\psi_\Sigma|$. But this depends on $B$: For $\Sigma' = A \cup B'$, $\psi_{\Sigma'}$ may be very different from $\psi_\Sigma$ (collapses in-between), and $\text{tr}_{B'} \psi_{\Sigma'}$ may be very different from $\text{tr}_B \psi_\Sigma$.

- After Schrödinger’s cat collapses to $|\text{alive}\rangle$, the amplitude of $|\text{dead}\rangle$ is tiny but not exactly zero. What right then do we have to say that the cat is alive?

- ... and ultimately, there is no matter in space-time.

These problems evaporate with a primitive ontology.
Why GRW∅ seems to work

The GRW wave function $\psi_t$ is, at almost all times, concentrated on a set of configurations that are macroscopically equivalent. Thus, we can read off from $\psi_t$ what the macro-state is: Just pretend there were particles whose configuration is $|\psi|^2$ distributed, and take their macro-state. (Some thought reveals that flashes and $m(x, t)$ will agree with that.)

So $\psi_t$ contains all the information about what the macro-configuration would look like, if there were any matter that could have this macro-configuration.

In GRW∅, we need to assume a re-interpretation of English phrases: We need to assume that the phrase “the cat is alive” does not mean that there is a cat which is alive, but that $\psi$ is concentrated in a region $R$ of configuration space such that if there were particles with a configuration $Q$ from $R$ then there were a live cat. (Seems odd.)
### S∅: Everett’s (1957) Many-Worlds Theory

There exists only the wave function $\psi$ of the universe, and nothing else. $\psi$ evolves according to the usual Schrödinger equation. Contributions to $\psi$ corresponding to macroscopically different situations represent parallel, equally real worlds.

### Sm: Schrödinger’s (1926) Many-Worlds Theory

- Matter is continuously distributed in space with density
  \[
  m(t, x) = \sum_{i=1}^{N} m_i \int_{\mathbb{R}^{3N}} dx_1 \cdots dx_N \delta^3(x - x_i) |\psi_t(x_1 \cdots x_N)|^2.
  \]
- $\psi$ evolves according to the usual Schrödinger equation.


Sm has a primitive ontology, S∅ does not. For similar reasons as with GRW, Sm is acceptable and S∅ not.
Many worlds

Schrödinger’s 1926 proposal:

Matter is distributed continuously in space with density

\[ m(q, t) = \sum_{k=1}^{N} \int_{\mathbb{R}^{3N}} \delta^3(q - q_k) |\psi_t(q)|^2 dq. \]

\( \psi_t \) evolves according to the Schrödinger eq.

He soon abandoned this theory because he thought it made wrong predictions. But actually, it is a many-worlds theory making right predictions: it implies the quantum formalism.

For Schrödinger’s cat, \( \psi = \frac{1}{\sqrt{2}} \psi_{\text{dead}} + \frac{1}{\sqrt{2}} \psi_{\text{alive}} \), it follows that \( m = \frac{1}{2} m_{\text{dead}} + \frac{1}{2} m_{\text{alive}} \).

There is a dead cat and a live cat, but they are like ghosts to each other (they do not notice each other), as they do not interact. So to speak, they live in parallel worlds.
The marvelous point

This is David Albert’s version of Bohmian mechanics (rejecting the need for a PO):

- There are not $N$ particles in the universe, there is only one.
- Physical space is not 3-dimensional, it is $3N$-dimensional.
- Use Schrödinger’s wave function on $\mathbb{R}^{3N}$ and Bohm’s trajectory for the configuration in $\mathbb{R}^{3N}$, and think of them as a 1-particle wave function and a 1-particle trajectory in physical space.
- It is an illusion that space is 3-dimensional, and that there are more than 1 particle, and the idea is that the laws of physics can somehow explain why it appears to humans as if space were 3-dimensional and there were more than 1 particle.
If there is only 1 particle, then there are no humans to whom anything could appear in any way.

More basically, if you believe that there are chairs or human beings, or that space is 3-d, then you believe that the marvelous-point theory is wrong.

By the way, there is also no good reason any more why configuration space should be $\mathbb{R}^3N$, or why wave functions on $\mathbb{R}^{3N}$ should be symmetric or anti-symmetric.

David invokes a functionalist analysis of the relations between different aspects of the trajectory of the marvelous point and concludes that since the coordinates of the trajectory influence each other in just the same way as different particles would do, they play the same causal role.

Given the obvious translation between any motion of the marvelous point and the motion of $N$ points in $\mathbb{R}^3$, the reasoning amounts to claiming that the marvelous point contains, or represents, a live cat whenever the corresponding motion of $N$ particles would form a live cat.
Ultimately, the different views about PO are based on different views about the mind-body problem.
What is the mind-body problem?

The color red looks a particular way to me that I can’t express in words; I would guess it looks the same way to Ned, but I can’t really check. The conscious experience of red is different from the knowledge that the light that reached my eye had a wave length of 800 nanometers and is called “red” in English.

Let’s try to come up with an explanation of this experience. Problem: Whatever particle trajectories a physical theory came up with, it would not explain the experience of red. (The “hard problem” of consciousness.) In contrast, all the information processing (from light of 800 nm to the English word “red”) poses no obstacle for an explanation in terms of particle trajectories. (The “easy problem” of consciousness.) The problem is not specific to particles, would be the same with fields.

Homework: Write a computer program that makes the computer see red.

Note: Here, consciousness does not mean being awake, or aware, or knowing oneself; but seeing colors.
The functionalist does not think there is a mind-body problem. To him, there is nothing more to the mind than information processing.

I think there is a mind-body problem, and I don't see how it could ever be solved. I conclude that there are facts in the world beyond the physical facts. (By the way, I am an atheist.) Nevertheless, I can live with that.

How the mind-body problem affects physics

A goal of a fundamental physical theory is to explain our experiences. In order to even connect with our experiences, it would seem that the theory has to solve the mind-body problem, which seems hopeless.

Luckily, there is a simple way out (as emphasized by Tim Maudlin). Suppose the theory implies the existence of macroscopic objects in 3-space in particular macroscopic configurations. And suppose that we are not completely deluded about the world around us, that instrument pointers actually point more or less the way we think, and that we can read more or less correctly. Then we can compare the predicted macro-configurations to the perceived macro-configurations, and claim, in case of agreement, that the theory is empirically adequate.

It actually works like that in classical physics, and in any theory with a primitive ontology.
“A theory’s specification of the fermion density in every region of the universe entails the distribution of matter at macroscopic scale. And if what it predicts at macroscopic scale matches everything we think we know about the world at macroscopic scale (including where the pointers ended up pointing, where the ink is on the paper, the shape of the earth, the dimensions of the Empire State building, etc., etc., etc.) then the theory is empirically adequate in any reasonable sense. There may be objections to such a theory, but they cannot rightfully be called empirical objections.”
Thank you for your attention