IPP-QM-5: Dynamical collapse theories

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2. Density operators and entanglement
3. Decoherence
4. The measurement problem
5. Dynamical collapse theories
6. Bohmian mechanics
7. Everettian structure
8. Everettian probability
9. EPR and Bell's theorem
10. The Bell-CHSH inequalities and possible responses
11. Contextuality
12. The PBR theorem
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14. Pragmatism and QBism
15. Relational quantum mechanics
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Today

Dynamical collapse theories

The GRW theory

Objections to GRW

Modifications/alternatives to GRW

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Moreover, we don't have any idea how collapse is supposed to work! (See Bell's 'Against 'Measurement''.)

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1. Modification must have no noticeable effects on microscopic systems.
2. Modification must prevent macroscopic superpositions.
3. Collapse must occur in accordance with the Born rule. (I.e., $\alpha \left|\uparrow\right\rangle + \beta \left|\downarrow\right\rangle$ must collapse to either $\left|\uparrow\right\rangle$ with probability $|\alpha|^2$, or $\left|\downarrow\right\rangle$ with probability $|\beta|^2$.)

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- If particles are entangled, then if any one particle collapses, the quantum state for the whole system collapses.
- If τ is set correctly (e.g. $\tau = 10^{-16}\text{s}^{-1}$), this will ensure that isolated particles collapse very slowly (roughly, after 100 million years), but large, *entangled* systems will collapse much faster.

Technical problem with the toy model

The collapses described above leave the particles which undergo them in perfect eigenstates of the position operator, and of course that entails that the momenta *and the* energies *of those particles (whatever their values may have been just* prior *to those collapses) will be completely uncertain just following those collapses, and* that *will give rise to a host of problems: The momenta which electrons in atoms might sometimes acquire in the course of such collapses, for example, would be enough to knock them right out of their orbits; and the energies which certain of the molecules of a gas might sometimes acquire in the course of such collapses would be enough to spontaneously* heat those gases up*, and those sorts of things are experimentally known* not to occur*.* (Albert 1992, p. 97)

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This is the essence of what the GRW dynamical collapse theory seeks to do.

Today

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The GRW theory

Objections to GRW

Modifications/alternatives to GRW

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- $\mathcal{N}$ is a normalisation factor.
- τ and L are new constants of nature.

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Exercise: Think about how the GRW dynamical collapse timescale interacts with the decoherence timescales discussed in Lecture 3.

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But there are obvious problems with this....

The problem of structured tails

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As Wallace writes:

> *Why should the continued presence of the 'there' term in the superposition—the continued indefiniteness of the system between 'here' and 'there'—be ameliorated in any way at all just because the 'there' term has low amplitude?* (Wallace 2008, p. 43)

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This is the 'problem of structured tails', which is an issue specific to dynamical collapse theories such as GRW.

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But, as Wallace writes on this problem:

> This *problem has little or nothing to do with the GRW theory. Rather, it is an unavoidable consequence of using wave packets to stand in for localised particles. For* no *wave packet evolving unitarily will remain in any finite spatial region for more than an instant.* (Wallace 2008, p. 43)

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This is the 'problem of bare tails', which is *not* an issue specific to dynamical collapse theories such as GRW.

The two problems

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Still, let's look at how people have tried to tackle the problem of bare tails.

Addressing bare tails

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Albert and Lower (1996) suggest we get achieve this by dropping the *eigenvector-eigenvalue link*, and replacing it with a so-called *fuzzy link*.

The fuzzy link

Eigenvector-eigenvalue link: A system in a state $|\psi\rangle$ has a definite value of the physical quantity associated to some observable $\hat{X}$, iff

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$$\left|\hat{X}\,|\psi\rangle - x\,|\psi\rangle\right| \leq \lambda,$$

for some small λ.

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- Particle 1 is in some box (according to the fuzzy link).
- Particle 2 is in that box (according to the fuzzy link) ...
- ... Particle n is in that box (according to the fuzzy link).
- On the fuzzy link, this *does not imply*: N particles are in the box.

The counting anomaly in more detail

- Suppose that the wavefunction of each particle is very strongly peaked inside the box, so that if $\hat{X}_i$ is the 'particle i is in the box' operator, then $\left|\hat{X}_i \left|\psi\right\rangle - x \left|\psi\right\rangle\right| \sim \epsilon$, for $\epsilon \ll \lambda$, so that each particle should be counted as being inside the box.

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- Suppose each particle has identical state $\left|\psi\right\rangle$; i.e. suppose that each $\left|\psi\right\rangle$ is highly localised in the box, as above. Then the overall state of the N particles is $\left|\Psi\right\rangle = \bigotimes_{i=1}^{N} \left|\psi\right\rangle$.

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- Then $\left|\hat{X} \left|\Psi\right\rangle\right| = \prod_{i=1}^{N} \left|\hat{X}_i \left|\psi\right\rangle\right| = (1 - \epsilon)^N$.

Wallace on the counting anomaly

[T]his is unfortunate for the Fuzzy Link. For no matter how small ϵ may be, there will be some value of N for which $(1-\epsilon)^N < \lambda$. And for that value of N, the Fuzzy Link tells us that it is false that all N particles are in the box, even as it tells us that, for each of the N particles, it is true that that *particle is in the box.* (Wallace 2008, p. 44)

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The mass density link doesn’t face the counting anomaly, but some argue that it has problems of its own...

The location anomaly

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> *This anomaly arises when we consider the process of looking at the box and physically counting the number of particles in it. The ordinary quantum theory—which the GRW theory is supposed to reproduce—then predicts that the expected number of particles found in the box will be somewhat less than N. Lewis claims that this clash between the predictions of how many particles are found in the box and how many are actually in the box "violates the entailments of ordinary language" (Lewis 2005, p. 174).* (Wallace 2008, pp. 46-47)

Responding to the location anomaly

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> *[W]e have a theory which (a) gives a perfectly well-defined description of how many particles are in the box; (b) allows a precise description, in terms acceptable to the realist, of the measurement process by which we determine how many particles are in the box; (c) predicts that if the number of particles is sufficiently (i.e., ridiculously) large there will be tiny deviations between the actual number of particles and the recorded number of particles. They, and I, fail to see what the problem is here; I leave readers to reach their own conclusions.* (Wallace 2008, p. 47)

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- This is unattractive—better to view the links as "perspicacious ways if picking out certain properties of [the] wavefunction"; that is, as linguistic tools.
- But then they are not going to be sufficient to help with tails problems, and one worries that GRW is just 'Everett in denial'.

More on ‘Everett-in-denial’

Consider a post-GRW collapsed state, such as

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- On Everettian ontology, a low amplitude cat is still a cat.
- So, there are still two cats (one alive and one dead!) in the above state.
- So is GRW just (some messy version of) Everett, in disguise?

Objection 2: Probability in GRW

In some ways, GRW collapse provides but the perfect example of objective chance. But what does τ *mean*? Is it only analysable in terms of propensities, or are other options available?

Objection 3: New constants of nature

- GRW theorists will aver that the constants of nature are not $(\hbar, G_N, c)$, but $(\hbar, G_N, c, L, \tau)$.

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- Is the introduction of these two further constants of nature *ad hoc*?
- Some, e.g. Smolin (2013), aver that *everything* in a physics needs to have some explanation; the introduction of extra constants of nature would seem to run against this.

Objection 4: Compatibility with relativity

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> *When I saw this theory first, I thought that I could blow it out of the water, by showing that it was* grossly *in violation of Lorentz invariance. That's connected with the problem of 'quantum entanglement', the EPR paradox.* (Bell 1989, p. 1)

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- However, it is formulated only for systems containing a fixed number of noninteracting fermions.
- Extending to QFT is another matter: Wallace (2022) argues that there is (as-yet) no viable dynamical collapse theory for QFT, *so there is not even a genuine case of underdetermination between dynamical collapse theories (or hidden variable theories, for that matter) and Everett!*

Today

Dynamical collapse theories

The GRW theory

Objections to GRW

Modifications/alternatives to GRW

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Let's close by thinking about some dynamical collapse theories which are modifications/alternatives to GRW.

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(See (Esfeld & Gisin 2013) for more.)

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- The hope is that continuous localisation will be more easily reconcilable with relativity theory and QFT than the GRW-style 'hits', but there remains much to be done on this front.
- In any case, it's not completely obvious that CSL will offer a satisfactory resolution to the problem of tails.

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Next time: *hidden variable theories*.

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