Philosophy of quantum mechanics

VU University Amsterdam: W_MASP_TF013 Lecture 9: 3/3/2015
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Today's lecture

- Research essays
- Recap
  - The collapse postulate.
  - Empirically testing collapse hypotheses.
- Dynamical collapse theories
  - Goals of a collapse theory.
  - Triggered versus spontaneous collapse theories.
- The GRW spontaneous collapse hypothesis
- The tails problem
  - The bare tails problem.
  - The structured tails problem.

Research essays

- Many worlds theory
  - Probability problem
    - Is Papineau's defence adequate?
    - Is Albert's critique convincing?
    - Does the Deutsch-Wallace proof work?
- Spontaneous collapse theory
  - Tails problem
    - Does Albert solve the problem?
    - Does Chalmers solve the problem?
    - Does Lewis solve the problem?
- Triggered collapse theory
  - Dynamics problem
    - Have Chalmers and I adequately responded to critics?
    - Can triggered collapse theories solve the Zeno problem?
    - Can consc-causes-collapse theory solve the tails problem?

Recap: collapse postulate

The problem of outcomes

- The following three claims are mutually inconsistent.
  - A. The wave-function of a system is complete i.e. the wave-function specifies (directly or indirectly) all of the physical properties of a system.
  - **B. The wave-function always evolves in accord with a linear dynamical equation (e.g. the Schrödinger equation).**
  - C. Measurements always (or at least usually) have determinate outcomes, i.e., at the end of the measurement the device indicates a definite physical state.

Taxonomy of solutions

- Deny A – wave function is incomplete.
  - Additional variables theories
    - E.g. Bohmian mechanics.

- Deny B – dynamics is not (always) linear.
  - **Collapse theories**
    - Triggered collapse theories.
      - Textbook theory: triggered by *measurement*
    - **Spontaneous collapse theories (today's topic).**

- Deny C – measurements don't have single outcomes.
  - Everett (many worlds theory)

Textbook: collapse on measurement

- If a physical system is not *in* an eigenstate of operator O…
  - That is, if the system's state is not *represented* by an eigenvector of O…
- And if we measure the system in the hope of finding a value for the property represented by O…
- Then the state collapses, with a certain objective probability, to some value for that property.
  - Example: the probability that a hardness measurement on a *white* electron yields hard:

$$= (< white|hard >)^2$$

$$= \left(\frac{1}{\sqrt{2}}\right)^2$$

The measurement problem

- Copenhagen interpretation is a *triggered* collapse theory.
  - John von Neumann's most precise formulation:
    - I. When *no* measurements are going on, physical systems evolve according to the linear dynamics.
    - II. When there *are* measurements going on physical systems evolve according to the collapse postulate.
- "Measurement" is the trigger for collapse.
  - But laws I and II don't determine exactly how the world behaves because "measurement" has no precise meaning.
    - So we need to consider more precise hypotheses about what (if anything) brings about collapse.

Recap: testing collapse hypotheses

Two collapse hypotheses

- Device hypothesis: measuring device causes collapse:

$$t1: |'ready'>_o |"ready">_m \left(\frac{1}{\sqrt{2}}|hard>_e + \frac{1}{\sqrt{2}}|soft>_e\right)$$

$$t2: |'ready'>_o |"hard">_m |hard>_e \text{ with } 0.5 \text{ probability OR}$$

$$|'ready'>_o |"soft">_m |soft>_e \text{ with } 0.5 \text{ probability}$$

- Brain hypothesis: observer's brain causes collapse:

$$t1: |'ready'>_o |"ready">_m \left(\frac{1}{\sqrt{2}}|hard>_e + \frac{1}{\sqrt{2}}|soft>_e\right)$$

$$t2: |'ready'>_o \left(\frac{1}{\sqrt{2}}|"hard">_m |hard>_e + \frac{1}{\sqrt{2}}|"soft">_m |soft>_e\right)$$

$$t3: |'hard'>_o |"hard">_m |hard>_e \text{ with } 0.5 \text{ probability OR}$$

$$|'soft'>_o |"soft">_m |soft>_e \text{ with } 0.5 \text{ probability}$$

To experimentally distinguish these…

- **we need to find a way to measure a state like this:**

$$t2\colon \frac{1}{\sqrt{2}}|\text{"}hard\text{"} >_m |hard >_e + \frac{1}{\sqrt{2}}|\text{"}soft\text{"} >_m |soft >_e$$

- **without collapsing it.**
  - If *we* collapse it, we can't verify that it wasn't *already* collapsed.

- For this we must:
  - Work out what operator this state is an eigenstate of.
  - Work out what property that operator represents.
  - Find a way of measuring that property.
    - If the composite system is in that eigenstate, then the device hypothesis is false, and the brain hypothesis is corroborated.

Why such experiments are difficult

- Imagine we (perhaps impossibly!) work out that this state:

$$t2\colon \frac{1}{\sqrt{2}}|"hard" >_m |hard >_e + \frac{1}{\sqrt{2}}|"soft" >_m |soft >_e$$

- ...is an eigenstate of operator O, such that O represents property P.
- We now want to measure the t2 state for property P.
- Unfortunately this is practically impossible.
  - We must prevent the m+e system from entangling with its environment.
    - If it entangles, then our measurement will collapse the state.
  - That requires that we completely isolate m+e from its environment.
  - We may never have the technology to actually do this!

How to evaluate collapse hypotheses?

- Direct experiment is not the only way we can evaluate theories.

- We can ask whether such theories can actually be precisely formulated *at all*.
  - "Device" causes collapse and "brain" causes collapse are not precisely formulated.
- Once precision is achieved we can ask whether the theory:
  - is internally coherent;
  - fits with everything else we know about the world;
  - explains what it was supposed to explain;
  - explains what it was supposed to explain better than competing (e.g. no-collapse) theories.
    - i.e. do philosophy!

Dynamical collapse theories

Triggered versus spontaneous

- Triggered collapse theories
  - The "device", "brain", and "measurement" collapse hypotheses are *triggered* collapse theories.
  - More promising hypotheses (arguably!):
    - Consciousness triggers collapse
      - We will look at this on Thursday.

- Spontaneous collapse theories
  - Collapse is not triggered by something, but happens *spontaneously*.
  - GRW theory
    - Most widely discussed collapse theory in the literature.
      - Today's topic.

Constraints on (re)formulating collapse

- Our collapse theory must meet these constraints:
  - **Constraint 1**: Guarantee that measurements have specific outcomes.
    - No superpositions of measurement devices.
  - **Constraint 2**: Guarantee that measurements have outcomes *with the right probabilities*.
    - Relative frequencies of outcomes *correspond* to Born's rule.
  - **Constraint 3**: Guarantee consistency with experiments on isolated particles.
    - Isolated particles don't collapse (often enough to be observed).

Guaranteeing measurement outcomes

- **Constraint 1**: Guarantee that measurements have specific outcomes.
  - Collapse must avoid macroscopic superpositions such as superpositions of measurement devices.
- How to satisfy this constraint?
  - Since measurement outcomes all seem to be recorded in the *positions* of things, ensure that large enough objects always have definite positions.
- How can we guarantee that?

The idea of spontaneous collapse

- Introduce a new fundamental physical property of all elementary particles:
  - **A probability per unit of time for *spontaneously* collapsing into a definite position.**

- E.g. if particle state is: $\frac{1}{\sqrt{2}}|here> + \frac{1}{\sqrt{2}}|there>$

- Then (eventually) the particle will spontaneously collapse to either *here* with probability 0.5 or *there* with probability 0.5.

- Does this proposal meet all three constraints?

Meeting constraint 3

- **Constraint 3**: Ensure consistency with experiments on isolated particles.

- Solution:
  - Set the probability per unit time (for spontaneous collapse) to be *extremely* low.
    - Low enough so that we would never expect to detect isolated particles violating the linear dynamics.
  - The theory is then consistent with the fact that we have never observed spontaneous collapse in isolated particles.

Meeting constraint 1

- **Constraint 1**: Guarantee that measurements have specific outcomes.
  - Collapse must avoid macroscopic superpositions such as superpositions of measurement devices.

- Solution:
  - Macroscopic objects (like pointers) are composed of trillions of *entangled* particles.
    - Entanglement ensures that if one collapses it will "bring down" the rest.
  - So set the probability per unit time (for spontaneous collapse) to be extremely low (as before), but still large enough that the probability that *just one* of the component particles will collapse at a given time becomes *very high*.
    - Then pointers are guaranteed definite positions!

Meeting constraint 2

- **Constraint 2**: Guarantee that measurements have outcomes *with the right probabilities*.
  - However constraint 1 is met, it must be that the relative frequencies of measurement outcomes correspond to Born's rule.

- Solution:
  - The probability that a collapse is centred on a given superposition component is given by the modulus square of that component (i.e. by Born's rule).

- Let's illustrate with an example...

Example: one particle in one dimension

- Consider a particle confined to one dimension:

$$|A> = a_1|x_1> + a_2|x_2> + a_3|x_3> + \cdots + a_N|x_N>$$

- The particle in state |A> has a very small probability per unit time for collapsing into one of the superposition components.
- The probability that the particle collapses to $|x_2>$ is:

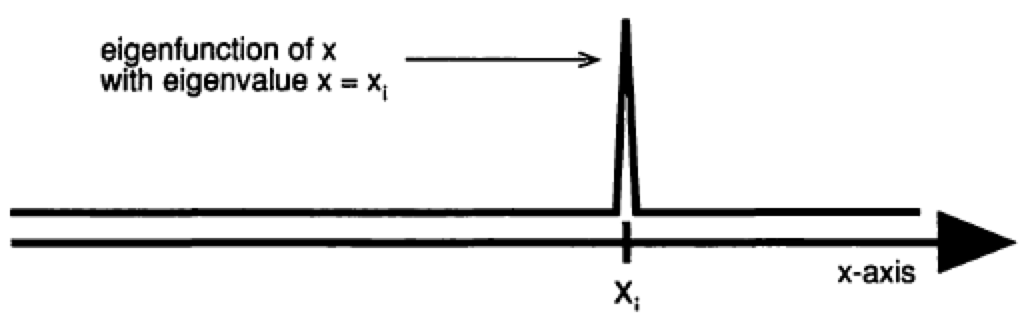
$$|a_2|^2$$

Example: one particle in one dimension

- So the collapse function takes a state like this:

$$|A> = a_1|x_1> + a_2|x_2> + a_3|x_3> + \cdots + a_N|x_N>$$

- ...selects a "collapse centre", multiplies its coefficient by some number so that it becomes one, and multiplies every other coefficient by zero.
  - As Albert (1992) puts it, the particle's wave function is multiplied by a position "eigenfunction":



The measurement situation

- Returning to this state:

$$\frac{1}{\sqrt{2}}|\text{"}hard\text{"} >_m |hard >_e + \frac{1}{\sqrt{2}}|\text{"}soft\text{"} >_m |soft >_e$$

- ...written in terms of the positions of particles that compose the pointer:

$$\frac{1}{\sqrt{2}}(|x_{h1} >_1 |x_{h2} >_2 |x_{h3} >_3 \dots)|hard >_e + \frac{1}{\sqrt{2}}(|x_{s1} >_1 |x_{s2} >_2 |x_{s3} >_3 \dots)|soft >_e$$

- This superposition will be destroyed the moment it is created; if particle 1 collapses to $|x_{h1} >_1$ then the soft component will be reduced to zero and the pointer will point to “hard”.

Summary of the basic idea

- Definite measurement outcomes guaranteed by the form of the collapse hypothesis.
- **Collapse hypothesis**: elementary particles have a small probability per unit of time for collapsing into a definite position.
- Measuring devices are composed of many entangled particles and so have a high probability per unit time for collapsing into a definite position.
- The probability that a measuring device will collapse into one of its superposition components is given by the (modulus) square of its coefficient – the theory therefore recovers Born rule predictions.

Probability and nondeterminism

- Objective probability plays *two* distinct roles:
  - 1. Probability per unit time for spontaneous collapse
  - 2. Probability that a particular superposition component will be the collapse centre.
- These are genuinely *objective* probabilities.
  - They are not subjective probabilities or degrees of belief or credences.
- Unlike in many worlds theory, nature "genuinely" plays dice.
  - The theory is not deterministic.

The GRW spontaneous collapse theory

The Ghirardi-Rimini-Weber theory

- This theory was first introduced by three physicists (Ghirardi, Rimini, and Weber) in 1985.**
  - Microscopic systems localise, on average, every hundred million years, macroscopic systems localise every 10^{-7} seconds.
- However, GRW realised that the simple collapse function just presented *can't possibly* work!
- So they proposed something slightly different...

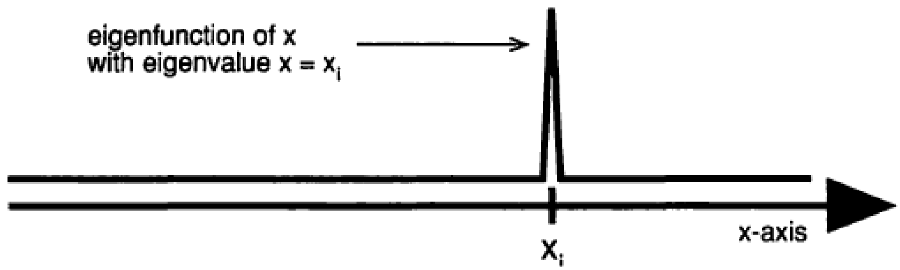
  - **Ghirardi, G.C., Rimini, A., and Weber, T.
    - (1985). "A Model for a Unified Quantum Description of Macroscopic and Microscopic Systems". *Quantum Probability and Applications*, L. Accardi et al. (eds), Springer, Berlin.
    - (1986). "Unified dynamics for microscopic and macroscopic systems". *Physical Review* D 34: 470.

Position/momentum incompatibility

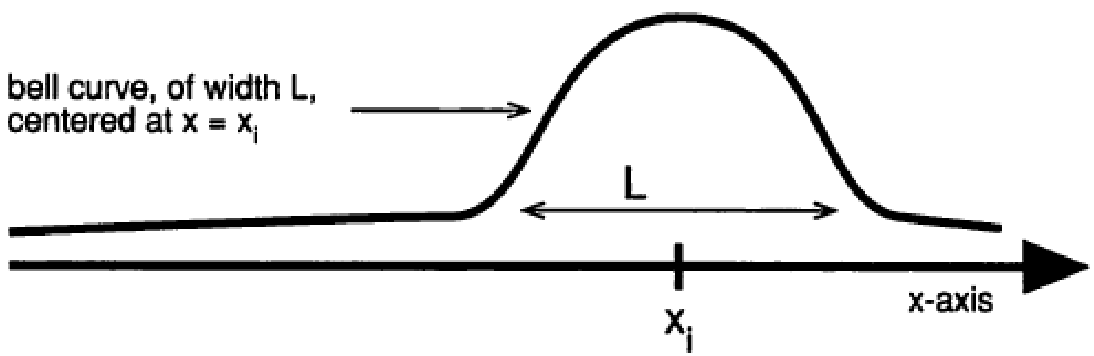
- Just as colour is incompatible with hardness, position is incompatible with momentum.
- This means that the more we localise position, the more we superpose momentum (for a given particle).
- Localising a particle to *a point* in space entails that every possible state of momentum becomes equally likely.
  - Deducible via "Fourier transformations", which give the rules for transforming position wave-functions into momentum wave-functions.
- This is ruled out by experiment.
  - Gases don't spontaneously heat up, electrons aren't spontaneously knocked out of their orbits etc.
    - Energy conservation is not violated to such high degrees.
- So GRW weakened the form of their collapse function…

The GRW collapse function

- The "delta" function that reduces all but one coefficient to zero…



- …is unphysical (position/momentum incompatibility yields experimentally disconfirmed energy increases).
- So GRW postulate a "Gaussian" function that never reduces any coefficient to zero:



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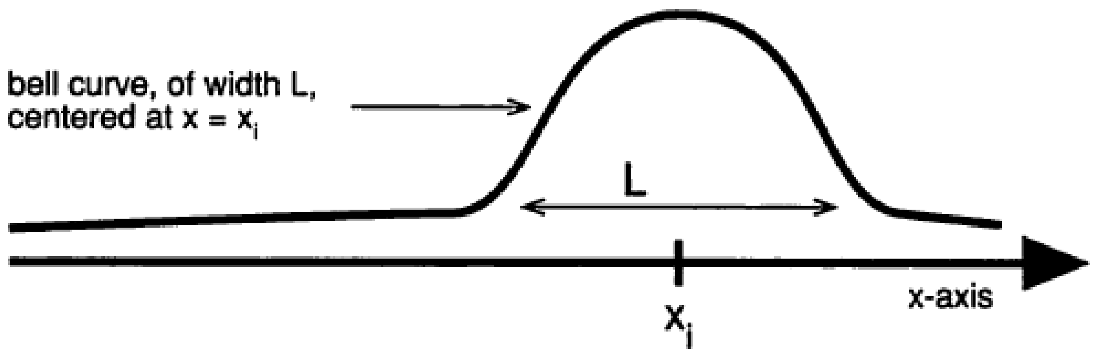
The GRW theory

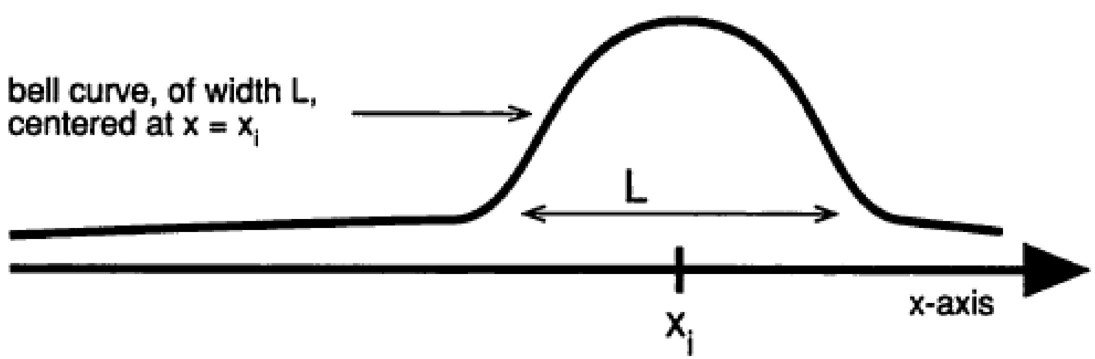
- The required collapse function involves, not a spike over the collapse centre, but a bell curve with tails extending to infinity.
  - A "Gaussian" function:



- The width L was specifically chosen to ensure that conservation of energy violations are consistent with known experiments.

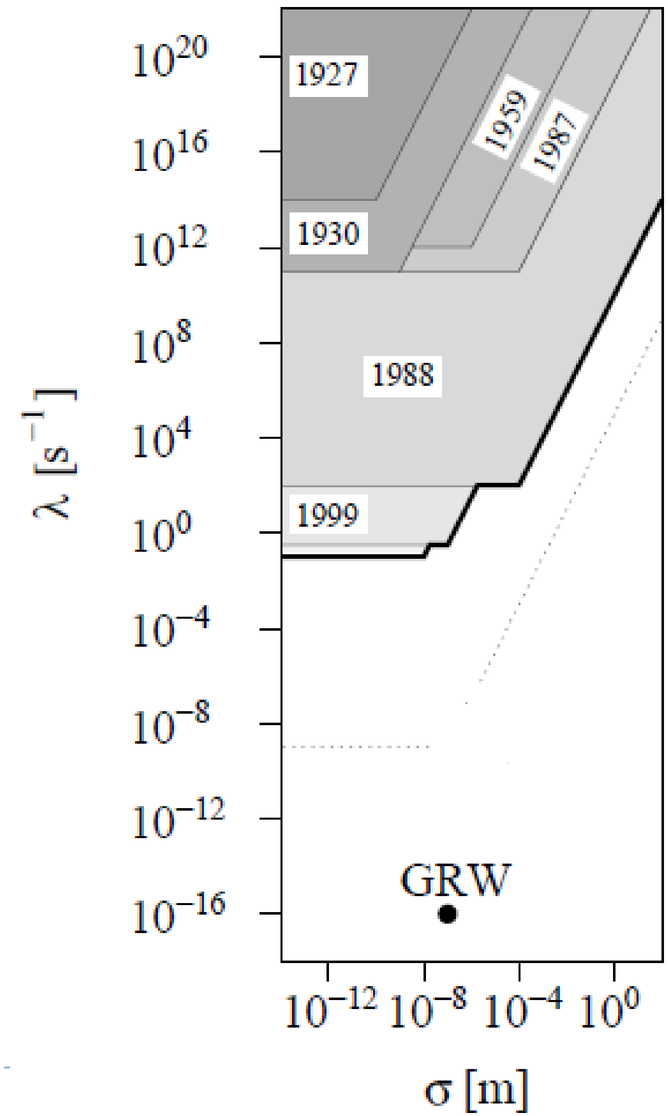
The GRW collapse function

- So GRW postulate two new fundamental constants of nature.
  - 1. The probability per unit time for spontaneous collapse.
    - Particles have a 10^{-16} probability per second for collapse.
  - 2. The width L of the bell curve:
    - $L = 10^{-5}$ meters.



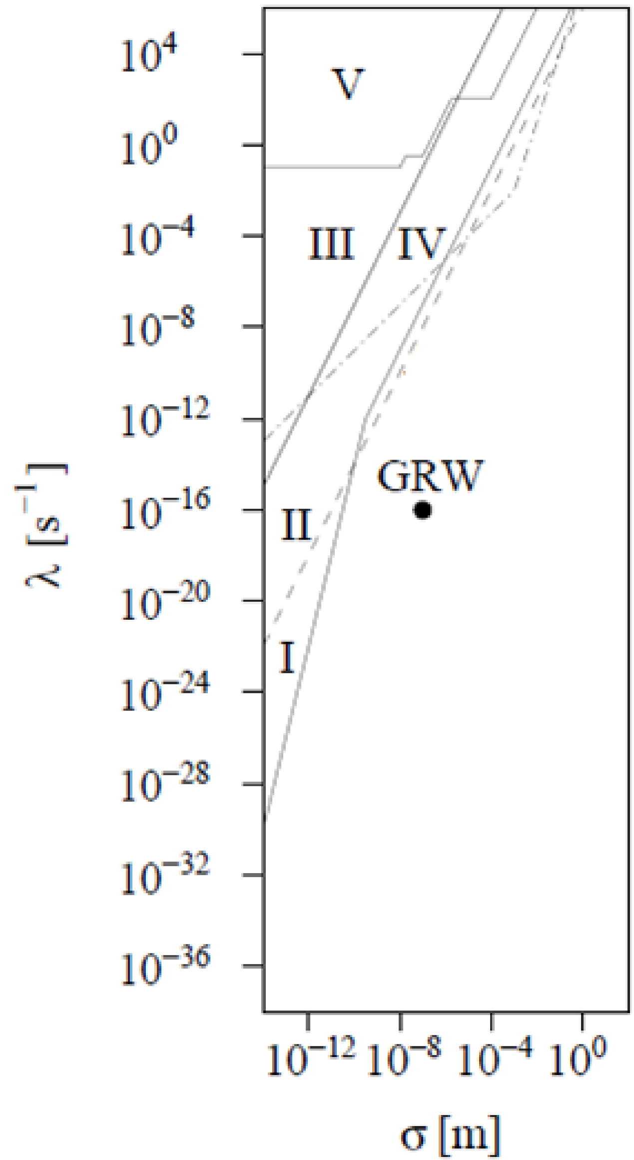
The GRW collapse function

- Growth of the "empirically refuted by diffraction experiments" region, as better data became available:
  - "A careful analysis of how the GRW dynamics affects the outcomes of a particular experiment or observation requires much research effort. We often have to resort to very rough estimates, substantial idealisations, and gross simplifications. We try to be conservative (i.e., rather draw the empirically refuted region too small than too big)."
    - Feldmann & Tumulka (2012) In "Parameter Diagrams of the GRW and CSL Theories of Wave Function Collapse".



The GRW collapse function

- The empirically refuted region broken up into regions excluded by different types of observations:
  - I: spontaneous x-ray emission,
  - II: spontaneous warming of the intergalactic medium (dashed line),
  - III: spontaneous warming of air,
  - IV: decay of supercurrents (dashed-and-dotted line),
  - V: diffraction experiments:
    - Feldmann & Tumulka (2012).



The GRW collapse function

- So the two GRW constants are chosen on the basis of empirical adequacy.
  - They must be outside the **empirically refuted region**.

- But they should also be chosen on the basis of philosophical adequacy.
  - How large is the **philosophically unacceptable region**?

- Let's start by describing more realistic collapses...

GRW illustrated

- Consider a particle confined to the x-dimension:

$$|A> = a_1|x_1> + a_2|x_2> + a_3|x_3> + \cdots + a_N|x_N>$$

- The particle in state |A> has a 10^{-16} probability per second for "collapsing" into one of the superposition components.

- But "collapsing into a component" now means something like "shifting **most** of the amplitude to that component".

GRW illustrated

- So if we were to measure the position of such a particle p (where N=3 and $a_1=a_2=a_3$):

$$t1: |\text{"ready"}>_m (a_1|x_1> + a_2|x_2> + a_3|x_3>)_p$$

- …so that the linear dynamics then leads to:

$$t2: a_1|\text{"}x_1\text{"}>_m |x_1>_p + a_2|\text{"}x_2\text{"}>_m|x_2>_p + a_3|\text{"}x_3\text{"}>_m |x_3>_p$$

- ...where $a_1=a_2=a_3$, then the state will immediately "collapse" to:

$$t3: a_1|\text{"}x_1\text{"}>_m |x_1>_p + a_2|\text{"}x_2\text{"}>_m|x_2>_p + a_3|\text{"}x_3\text{"}>_m |x_3>_p$$

- ...where $|a_1|^2 > (|a_2|^2 + |a_3|^2)$
- **OR** $|a_2|^2 > (|a_1|^2 + |a3|^2)$
- **OR** $|a_3|^2 > (|a_1|^2 + |a_2|^2)$ …the probability of which is given by Born rule.

- How should we make sense of the t3 state?

The tails problem

- Returning to this state:

$$\frac{1}{\sqrt{2}}|"hard">_m |hard>_e + \frac{1}{\sqrt{2}}|"soft">_m |soft>_e$$

- Are we guaranteed a measurement outcome just by spontaneously "collapsing" it to this state:

$$\sqrt{1-\alpha^2}|"hard">_m |hard>_e + \alpha|"soft">_m |soft>_e$$

- Where α is very small but nonzero?

The tails problem

- Problem: it is not clear that GRW guarantees measurement outcomes.

- For a start, they must abandon the eigenstate-eigenvalue link and replace it with another interpretive principle.
  - Otherwise nothing would ever have a location, since there would be no eigenstates of position.

- Whatever interpretive principle they offer will need to explain why this imperfect collapse guarantees measurement outcomes...

Four tails problems for dynamical collapse theories

Two tails problems to consider

- 1. The bare tails problem
  - Inconsistent triad:
    - (i) The eigenstate–eigenvalue link (EEL)
    - (ii) The wave-function evolves in accord with the GRW dynamics.
    - (iii) Measurements have definite outcomes
      - Most think we should deny (i) by replacing EEL.
- 2. The structured tails problem
  - If the collapse centre structure determines a particle configuration, then so do the structures in the tails. Because they are structurally isomorphic.
    - We consider a number of proposed solutions.

Two tails problems (not) to consider

- 3. The multiverse tails problem
  - Assuming the structured tails problem is unsolvable: collapse actually has distinct effects on tail-worlds: they become overwhelmed by radiation.
    - **We ignore this problem:** we want to know *whether* the structured tails problem is solvable.
- 4. The tails dilemma
  - Changing the Gaussian function into a function with compact support introduces conflict with relativity theory.
    - **We ignore this problem:** we want to know *whether* the GRW collapse function needs to be changed.

The bare tails problem

- Recall the eigenstate-eigenvalue link:
  - A system S has a measureable property P when *and only when* S's quantum state is an eigenstate of property P.

- But this state:

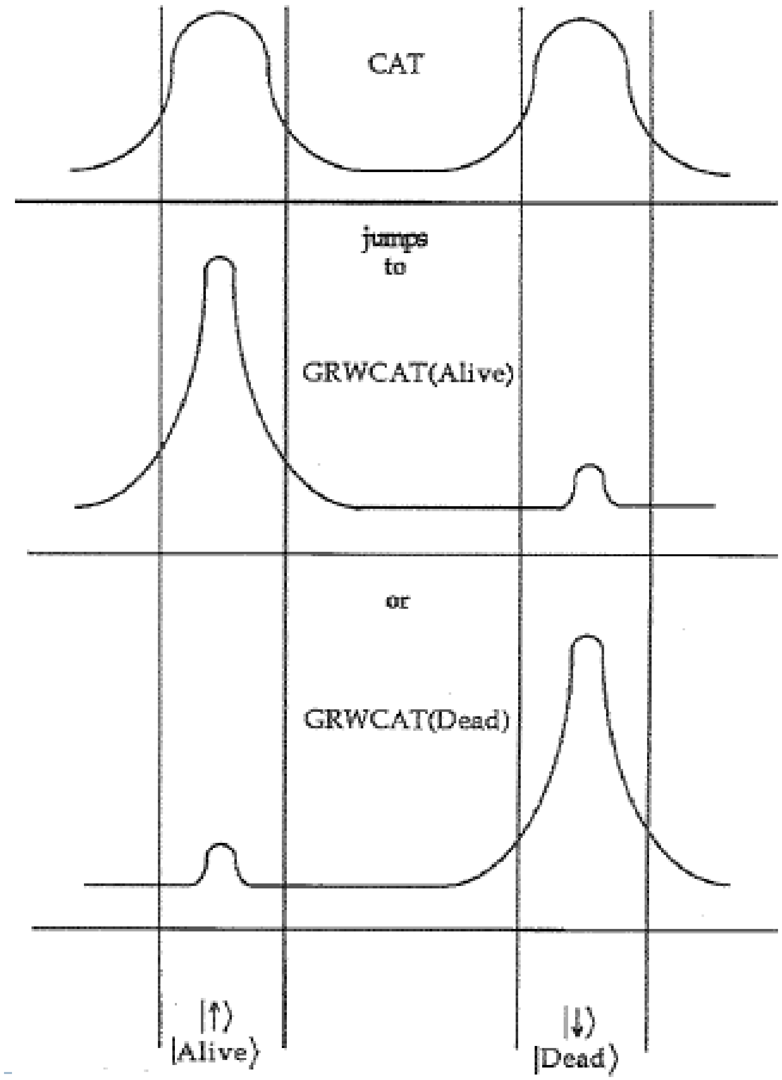
$$a_1|"x_1">_m |x_1>_p + a_2|"x_2">_m|x_2>_p + a_3|"x_3">_m |x_3>_p$$

- ...is not an eigenstate of the property "displaying a definite measurement outcome". Similarly for this state:

$$\sqrt{1-\alpha^2}|"hard">_m |hard>_e + \alpha|"soft">_m |soft>_e$$

The tails problem

- Albert and Loewer express the same point, not with measuring devices, but with the fact that GRW fails to collapse Schrödinger's cat into an eigenstate of the "aliveness" property (whose eigenstates are *alive* and *dead*).
  - In "Tails of Schrödinger's Cat" p85.



The bare tails problem

- Three incompatible propositions:
  - 1. The eigenstate-eigenvalue link.
  - 2. The wave-function evolves in accord with the GRW dynamics: usual linear dynamics + Gaussian collapse function.
  - 3. Measurements have definite outcomes.

- To solve this problem we must deny proposition 1 or proposition 2 or both.

Solving the bare tails problem

- What's involved:
  - Option 1: Deny 1: Retain the GRW collapse function, but revise the EEL interpretational principle.
  - Option 2: Deny 2: Retain the EEL interpretational but revise the GRW collapse function, .
  - Option 3: Deny 2&3: Revise both the EEL interpretational principle and the GRW collapse function.

- I will focus mainly on **option 1**.

Option 1: what's involved

- Option 1:
  - Retain the GRW collapse function.
  - Revise the EEL interpretational principle.
- EEL applied to position:
  - "Particle p is in region R" if and only if particle p is in an eigenstate of the property of being in region R.
- Equivalently:
  - "Particle p is in region R" if and only if the proportion of the total value of the (modulus) square associated with (points in) region R is equal to one.
- How should we revise this principle?

Albert and Loewer's solution

- "The thing that tugs at you, though, is that we seem to have gotten so close. The states we end up with on GRW, whatever else they are, are also undeniably almost the ones we wanted. And the intuition is that that can't have gotten us nowhere, that it must be good for something."
  - Albert & Loewer (p87).

- A&L notice that particles collapse to something like "near-eigenstates" and so base their alternative interpretational principle on this...

The "fuzzy link" principle

- Albert and Loewer's "relaxation of EEL":
  - **"Particle p is in region R" if and only if the proportion of the total mod-square value of p's quantum state associated with points in R is greater than or equal to 1-q.**

- So it doesn't matter that this state…

$$a_1|"x_1">_m|x_1>_p + a_2|"x_2">_m|x_2>_p + a_3|"x_3">_m|x_3>_p$$

- …is not a position eigenstate provided it's "near enough".
  - If the mod-square of a2 > 1-q then particle p is located at x2.

The value of q

- q must be defined so that…
  - …it is large enough to ensure that what we take to be determinate really is determinate.
    - E.g. measurements have determinate outcomes, cats are determinately alive or dead.
  - …it is small enough to ensure that what we do not take to be determinate really isn't.
    - To avoid particles being simultaneously located at two disjoint regions q must be smaller than ½.
    - E.g. we want to avoid the particles composing a pointer from being located in the region "pointing to white" *and* the region "pointing to black", in the context of a colour measurement.
- Can we narrow down the possible values of q further?

The value of q

- Could we empirically discover (i.e. by experiment) the value of q?
  - Albert & Loewer say no...
    - "q simply doesn't appear anywhere in the dynamical laws. And so there can be no initial wave function of the universe whose subsequent time evolution will in any way depend on q's value" (p90).
- This is just to say that the fuzzy-link principle is not a law of nature, but an interpretive principle.
  - "[The fuzzy link principle] is a new proposal, an alternative proposal, about the relation between position-talk and quantum talk; a new proposed supervenience rule" (p87).
  - Others have described it as "a proposal for how to use language".
    - Peter Lewis, In "GRW: A Case Study in Quantum Ontology" (2006).

The vagueness of particle-position-talk

- For A&L "there is a small continuum of precise definitions of 'located', any of which, on the GRW theory, will apparently do an excellent job of underwriting the uses we actually make of that word."
  - So there's no fact of the matter about the exact value of q!
  - Talk of particle position is irreducibly vague.
- A&L assert that this is nothing new...
  - In classical physics everyday language "supervenes vaguely" on the exact particle-language.
  - In quantum physics everyday language (still) supervenes vaguely on the micro-language, but the vague micro-language itself now supervenes vaguely on the exact language of wave functions.
- Bare tails problem solved?

The structured tails problem

Does A&L's solution work?

- David Wallace responds:
  - "If the link principles are just a matter of descriptive convenience then what prevents us regarding observers as being just as present in the dead-cat term as in the live-cat term? After all [...] the dead-cat term is as rich in complex structure as the live-cat term".
    - In "The Quantum Measurement Problem: State of Play." (2008).
- Symmetry based objection:
  - If a theory faces some anomaly, can one really just revise the way we ought to describe such things?
    - Presumably sometimes... but under what circumstances is this permissible?
  - The only difference between the dead-cat component and the live-cat component (in the exact wave-function language) is the amplitude!
    - So perhaps: if there is a cat in the high-amplitude component then there must also be a cat in the low-amplitude component due to their structural symmetry?

The structured tails problem

- If the collapse centre structure determines a particle configuration, then so do the structures in the tails.
- This is because the tails and the collapse centre are structurally isomorphic (or at least relevantly structurally similar).
- Nothing about low mod-square value can suppress this isomorphic structure.
- The consequence is an Everettian many-worlds ontology!
  - I will make the formulation of the problem more precise after considering some proposed solutions.

Proposed solutions

- 1. Clifton and Monton's response
  - We can take high objective probability to mean *existence*.
- 2. Ghirardi, Grassi and Benatti's response
  - The "matter" in the tails is inaccessible and therefore negligible.
- 3. Tumulka's and Albert's responses
  - The "matter" in the tails is noise and does not have structural credentials to compose macro-objects.
- 4. Monton's and Chalmers' responses
  - Experiences are only determined by "high weight" brains.
  - "Being located at X" means "being reliably disposed to cause experiences as of being located at X."
- 5. Lewis' response
  - GRW should reject functionalism and Dennett's criterion.

Clifton and Monton's response

- Recall Wallace's symmetry objection…
  - Why should "high amplitude" rather than "low amplitude" be existence determining?
- These amplitudes are related to objective probabilities through Born's rule. Can a solution be found there?
  - "If one is willing to entertain the thought that events in a quantum world can happen without being mandated or made overwhelmingly likely by the wavefunction, then it is no longer clear why one should need to solve the measurement problem by collapsing wavefunctions! […] one supposes there to be *a plausible intuitive connection between an event's having a high probability according to a theory, and the event actually occurring*".
    - Clifton and Monton, In "Losing your Marbles in Wavefunction Collapse Theories" 1999, p708.

Problems

- Problem 1: existence and probability don't line up?
  - Is the "plausible, intuitive" connection supposed to hold between *high probability* and *high **degree** of existence*?
  - But presumably existence does not come in degrees.
  - A connection between existence (simpliciter) and high probability seems more arbitrary than intuitive.
- Problem 2: The roles of probabilities are being confused?
  - The mod-square of a superposition component is the objective probability *for that component to become a collapse centre.*
  - It isn't *also* the objective probability for that component to have 'actually occurring' status.
  - On a realist view of GRW that component *already* exists.

Ghirardi, Grassi and Benatti's response

- The "matter" in the tails is *inaccessible* and therefore negligible.

  - Tumulka's reply:
    - What exists is not determined by what is accessible to humans.

  - My reply:
    - If the tails are structurally isomorphic to the collapse centre, then tail-matter *is* accessible to observers *in the tails*.

Tumulka's and Albert's responses

- Tumulka & Albert consider the "matter-density" version of GRW...
  - High-amplitude branches determine matter in 3D space.
  - Defined by the "matter-density function" – a function from mod-square amplitudes to matter distributions.
- Tumulka's example...
  - Take a marble in a superposition of being inside the box (with high density) and being outside the box (with low density).
    - The low density matter is analogous to "vapour" hence marble is inside the box.
- Problem:
  - But the "vapour" is structured like a marble!
    - Compare: Schrödinger's cat.

Albert's billiard balls example

- **Ball 1**: superposition of travelling to point P and to point Q, from the left.
- **Ball 2**: superposition of travelling to point P and to point Q, from the right.
  - Prior to collision:
    - **Ball 1**: $a|\rightarrow P>_1 + b|\rightarrow Q>_1$
    - **Ball 2**: $a|P\leftarrow>_2 + b|Q\leftarrow>_2$
  - After collision:
    - $a^2|\leftarrow P>_1|P\rightarrow>_2 \;+\; b^2|\leftarrow Q>_1|Q\rightarrow>_2 \;+$
    - $ab|Q\rightarrow>_1|\leftarrow P>_2 \;+\; ab|P\rightarrow>_1|\leftarrow Q>_2$
  - Here, $a^2|\leftarrow P>_1|P\rightarrow>_2$ is the high density component in which two billiard balls are travelling away from P.

Albert's billiard balls example

- After collision:
  - $a^2|\leftarrow P>_1|P\rightarrow>_2 \; + \; b^2|\leftarrow Q>_1|Q\rightarrow>_2 \; +$
  - $ab|Q\rightarrow>_1|\leftarrow P>_2 \; + \; ab|P\rightarrow>_1|\leftarrow Q>_2$
- Here, $a^2|\leftarrow P>_1|P\rightarrow>_2$ is the high density component in which two billiard balls are travelling away from P.

- "But look at the low-density sector: what happens there is that two balls converge at Q and pass right though one another – and (in the meantime) two new balls appear, which then recede in opposite directions" (2015: 154).
- So only high-density matter composes familiar stuff.

Problems

- If there is no reason to distinguish between distinct low-density sectors then Albert is right.

- But decoherence entails that in realistic circumstances there must be distinguishable sectors within the low density sector.
  - These will be (to varying degrees) dynamically isolated from each other (despite overlapping in space).

- When we make these distinctions we rediscover structured tails.

Monton's and Chalmers' solution

- "A certain assumption about psychophysical parallelism needs to be made. But the assumption is a reasonable one. […] There is no reason to suppose that mental states supervene just on particle location; instead we can suppose that mental states supervene on the distribution of [matter]. Since **the masses of particles in a brain are concentrated in the appropriate regions** of space, it is reasonable to assume that **the appropriate mental states supervene on those mass concentrations**"
  - Bradley Monton (2004:418).

Monton’s and Chalmers’ solution

- “In the case of macroscopic spatial properties, it is plausible that **spatial properties can be picked out by spatial concepts as that manifold of properties that serve as the causal basis for spatial experience** [...] To simplify, the property of being two meters away from one might be picked out as the spatial relation that normally brings about the experience of being two meters away from one. [...] One can then argue that on a collapse interpretation, **the properties and relations that normally bring about the relevant sort of spatial experiences are precisely properties and relations requiring the wavefunction’s amplitude to be largely concentrated in a certain area**.”
  - David Chalmers, In “Constructing the World” (2012: 295-296).

Problems

- Where A&L postulated that…
  - "Particle p is in region R" if and only if the mod-square value of p's quantum state associated with points in R is high."
- Chalmers adds…
  - "Particle p is in region R" if and only if **the fact that** the mod-square value of p's quantum state associated with points in R is high, **is the primary cause of experiences of particle p being in region R**.
    - For particles big enough to cause experiences, that is!
    - We can then extrapolate to smaller components.
- Is this a good analysis of our physical concepts?
- Even if so, doesn't GRW now need substantive psychophysical principles to make the causation claim come out true?

Lewis' solution

- The GRW theory requires that we reject the principle that Everettians use to derive worlds from wave-functions.
- The principle is Dennett's criterion.
  - Roughly: emergent objects can be seen as *patterns* in the underlying microphysics.

- GRW must reject this very intuitive principle.
- But Everettians have to reject the very intuitive principle that probability doesn't require uncertainty.

Problems

- Our formulation of the structured tails problem does not appeal to Dennett's criterion, or any emergence criterion. The assumptions are:
  - (i) If the collapse centre and the tails exhibit sufficient structural isomorphism then, if the collapse centre (or the tails) determines a macro-structure then the collapse centre and the tails determine structurally isomorphic macro-structures. [Supervenience principle]
  - (ii) If it is not the case that mod-square values explain differences in the macro-structures then the collapse centre and the tails exhibit sufficient structural isomorphism. [Explanation as our guide to supervenience]
  - (iii) It is not the case that mod-square values explain differences in the macro-structures. [as argued]
  - (iv) Hence, if the collapse centre (or the tails) determines a macro-structure

Problems

- (iv) Hence, if the collapse centre (or the tails) determines a macro-structure

- To derive (iv) we don't assume that GRW determines *any* macro-structure let alone a multiverse structure. For that we need a principle from GRW:
  - (v) The collapse centre determines a macro-structure. [GRW principle]
  - (vi) Hence, the collapse centre and the tails determine structurally isomorphic macro-structures. [From (iv) and (v)]

Two (further) tails problems

- 3. The multiverse tails problem
  - Assuming the structured tails problem is unsolvable: collapse actually has distinct effects on tail-worlds: they become overwhelmed by radiation.
    - **We ignore this problem:** we want to know *whether* the structured tails problem is solvable.
- 4. The tails dilemma
  - Changing the Gaussian function into a function with compact support introduces conflict with relativity theory.
    - **We ignore this problem:** we want to know *whether* the GRW collapse function needs to be changed.

For Thursday…

- Please read "In defence of quantum interactionist dualism".
  - At the end of Thursday's lecture I will ask you what you want me to focus on next Tuesday!
  - Options:
    - (i) I recap issues you find most interesting – issues you will probably write about yourself.
    - (ii) I give an overview of alternative solutions to the measurement problem (with significant emphasis on Bohmian mechanics).
  - Please think about it!