Decoherence & The Measurement Problem

Reading "*Why Decoherence has not Solved the Measurement Problem: A Response to P.W Anderson (Adler, 2002)*"

Victor Elgersma

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Menu 🍽️

1. Which measurement problem?
2. Classical decoherence
3. Why does $\langle\varphi^A(t)|\varphi^B(t)\rangle \approx 0$ imply “interference effects disappear” (Adler, p.9)?
4. How does Adler's counter-argument differ from Bell, Maudlin?
5. Connection to Ehrenfest’s theorem and classical mechanics
6. Seven Questions

Which Measurement Problem?

Maudlin:

1. outcomes
2. statistics
3. effect

Unitary Time-Evolution + Ψ completeness

'LL' jump	'...any result of a measurement of a real dynamical variable is one of its eigenvalues' (Dirac, 1930)	'outcomes'
Born Rule	'... if the measurement of the observable .... is made a large number of times the average of all the results obtained will be...' (Dirac, 1930)	'statistics'
von Neumann Jump	'...a measurement always causes the system to jump into an eigenstate of the dynamical variable that is being measured....' (Dirac, 1930)	'effect' $\Psi \rightarrow P\Psi$

Unitary Time-Evolution*

*Except when a measurement occurs

+

Ψ completeness

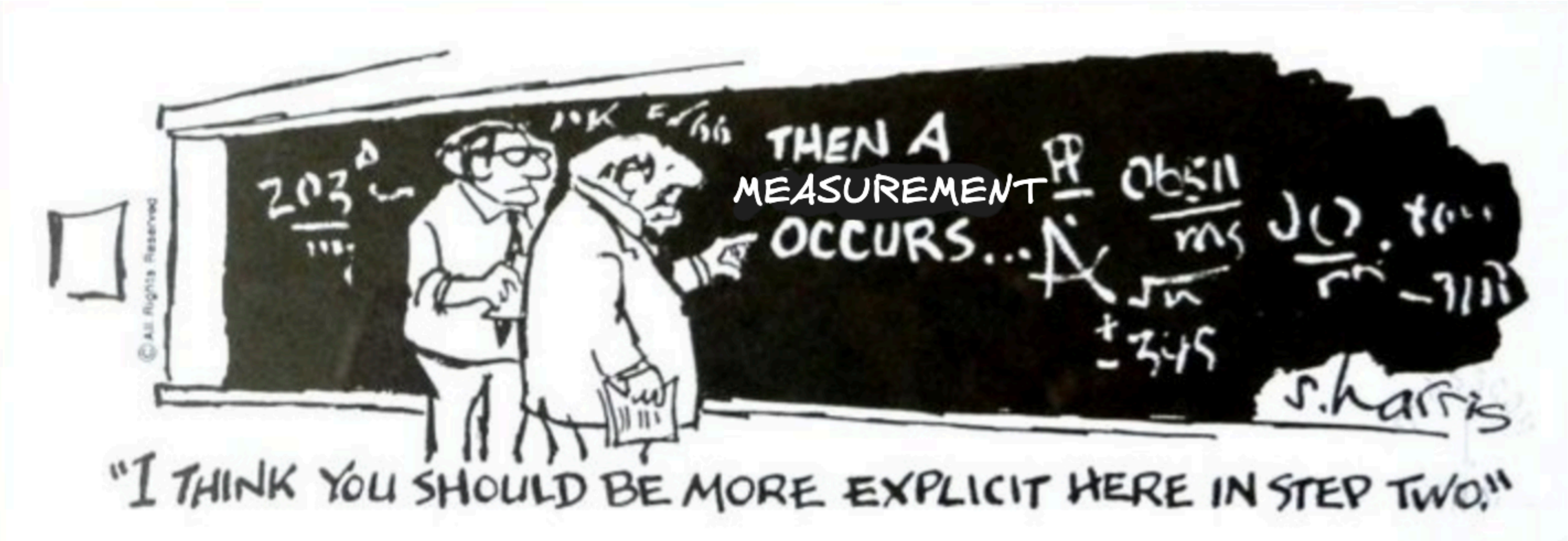
'...any result of a measurement of a real dynamical variable is one of its eigenvalues' (Dirac, 1930)

'... if the measurement of the observable .... is made a large number of times the average of all the results obtained will be...' (Dirac, 1930)

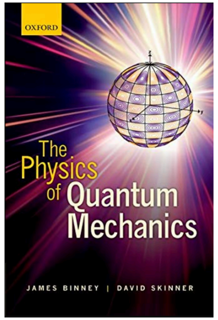
'...a measurement always causes the system to jump into an eigenstate of the dynamical variable that is being measured....' (Dirac, 1930)

'Collapse Hypothesis'

“the theory should be fully formulated in mathematical terms, with nothing left to the discretion of the theoretical physicist” (Bell, 1990, p. 33)


THEN A
MEASUREMENT
OCCURS...
s.harris
"I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO."

“Notice that the evolution from $|\psi\rangle$ to $|q_j\rangle$ has not been derived from the **TDSE**, which we have stated to be the equation that governs the time-evolution of $|\psi\rangle$. So this […] implies that **every measurement leads to a momentary suspension of the equations of motion, so the system can be steered, by forces unspecified, into a randomly chosen state!** This is *not* serious physics. We need to consider more realistically what is involved in making a measurement “ (Binney & Skinner, 2008, p. 133)



Unitary Time-Evolution + Ψ completeness

'LL' jump — '...any result of a measurement of a real dynamical variable is one of its eigenvalues' (Dirac, 1930) — 'outcomes'

Born Rule — '... if the measurement of the observable .... is made a large number of times the average of all the results obtained will be...' (Dirac, 1930) — 'statistics'

von Neumann Jump — '...a measurement always causes the system to jump into an eigenstate of the dynamical variable that is being measured....' (Dirac, 1930) — 'effect' $\Psi \to P\Psi$

Macroscopic systems are never isolated from their environments. Therefore […] they should not be expected to follow Schrödinger's equation, which is applicable only to a closed system.

— (Zurek, 1991), p. 3

[…] decoherence arises from a direct application of the quantum mechanical formalism to a description of the interaction of a physical system with its environment. By itself, decoherence is therefore **neither an interpretation nor a modification** of quantum mechanics.

— (Schlosshauer, 2005), p. 8

Which measurement problem?

(Adler, 2003, p. 9)

Note also that to see this contradiction we do not need an infinite sequence of repetitions of the experiment, as would be needed to discuss the probabilities of the outcomes (A) and

,

(B), since only enough repetitions are needed to achieve an outcome (A) and an outcome (B) at least once.[1]

Which Measurement Problem?

1. outcomes
2. ~~statistics~~
3. effect

- Adler demands decoherence solve both the **problem of *outcomes*** and the problem of effect (p.8)

(B), since only enough repetitions are needed to achieve an outcome (A) and an outcome (B) at least once.[1]

(p.9)

- Adler demands decoherence solve both the problem of outcomes and the **problem of effect** (p. 8)

ment! What is seen is not the superposition of Eq. (3), but rather *either* the unit normalized state

$$|\psi^{(A)}\rangle_X |\phi^{(A)}(t)\rangle_{APP+ENV} \quad , \tag{6a}$$

or the unit normalized state

$$|\psi^{(B)}\rangle_X |\phi^{(B)}(t)\rangle_{APP+ENV} \quad . \tag{6b}$$

- **Claim**: as soon as we recognize that ideal measurements are reproducible, then our problem of ‘outcomes’ becomes the ‘problem of effect’:

> 1. let a measurement have a definite outcome A
> 2. if this experiment is reproducible then a subsequent measurement should have outcome A with probability 100%
> 4. But this is **the definition of the eigenstate $\boldsymbol{\Psi_A}$** !
> 5. Ergo we can infer $\Psi \to P\Psi = \Psi_A$
> 6. Which is the *effect* we sought. QED.

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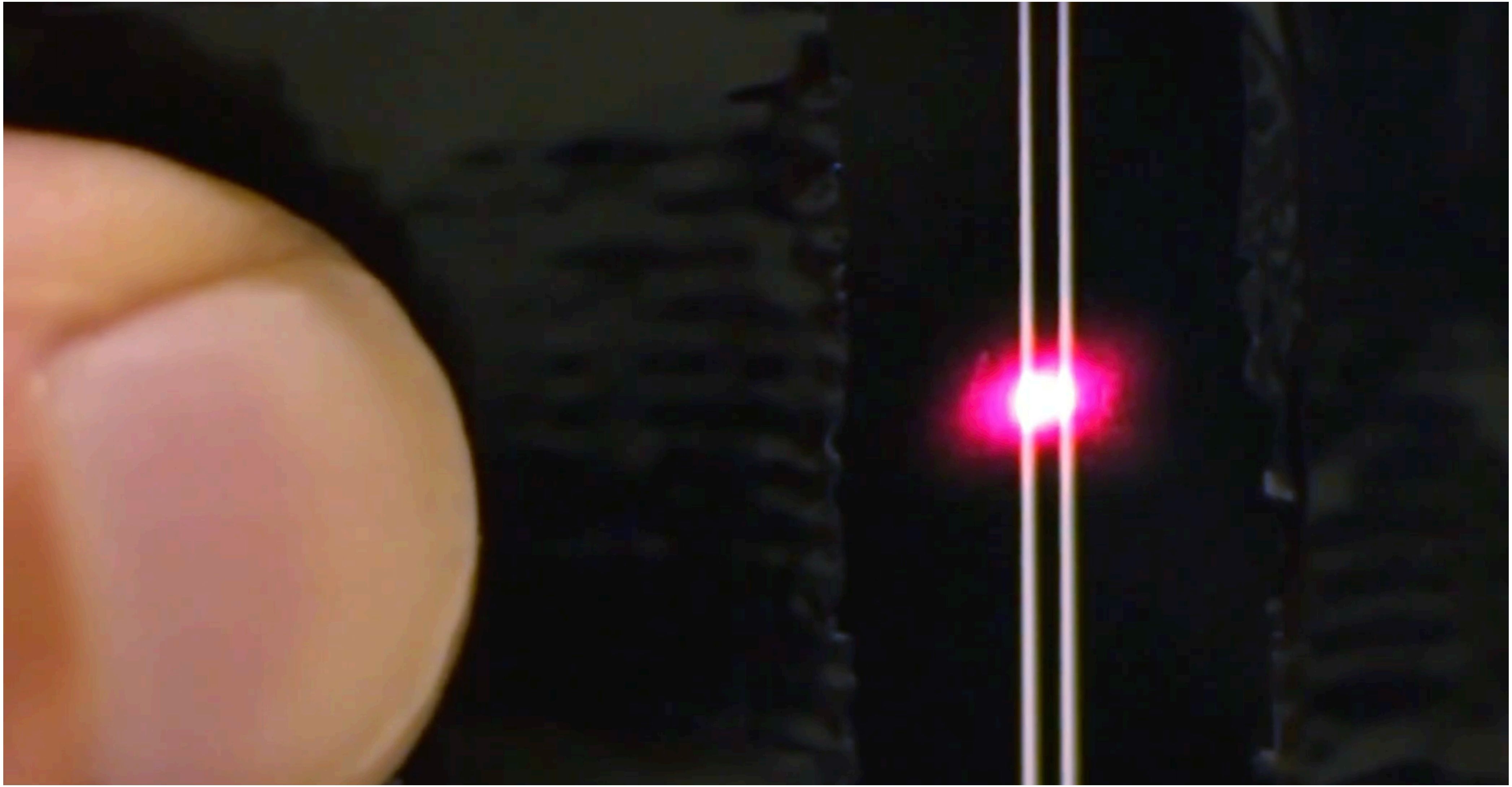
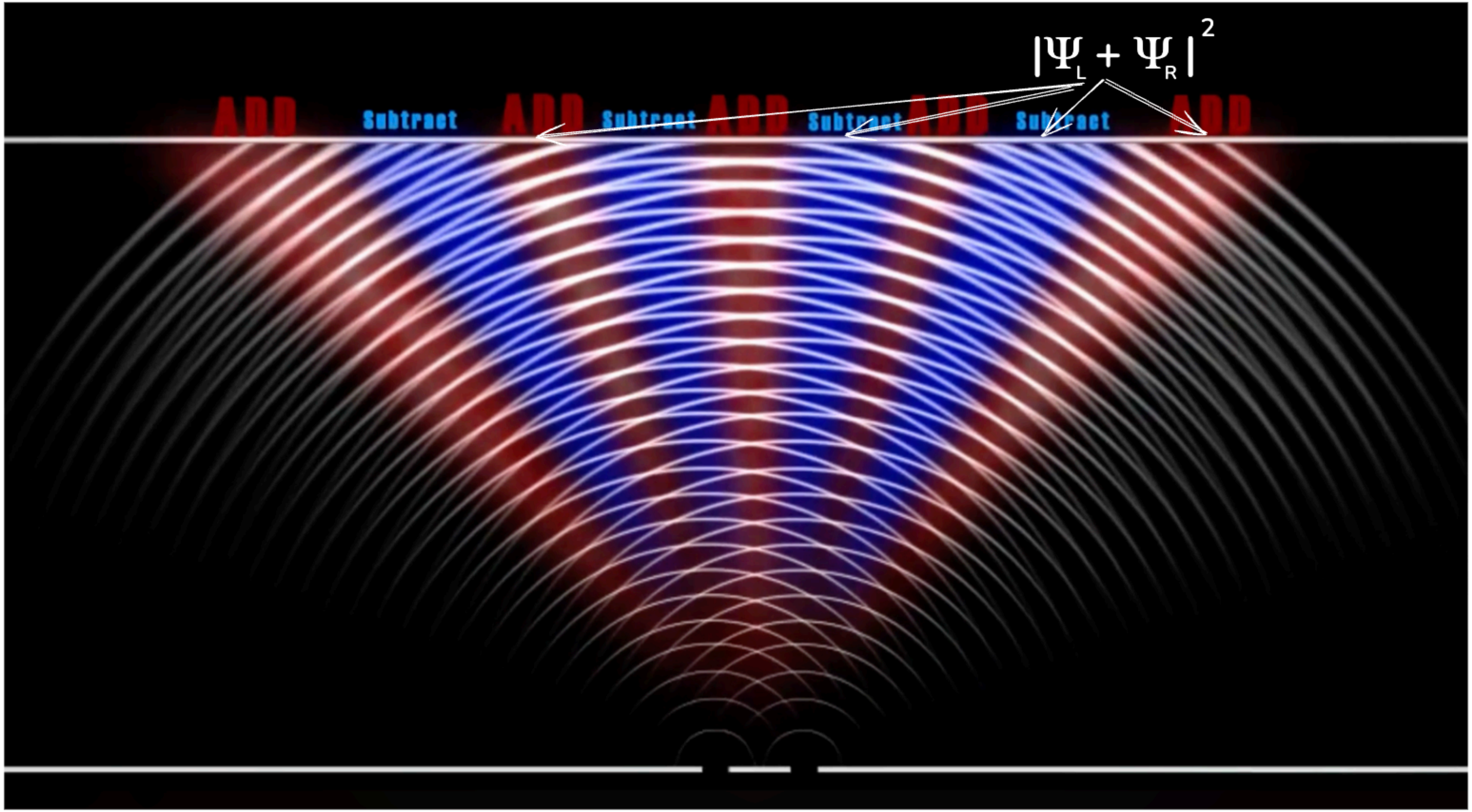



$|\Psi_L + \Psi_R|^2$
ADD
Subtract
ADD
Subtract
ADD
Subtract
ADD
Subtract
ADD

We need *coherent light* to see an interference pattern:

Why? Intensity is a time-averaged quantity:

$$\Psi_L = Ae^{iwt}$$

$$\Psi_R = Ae^{i\left(wt+\varphi_{[LR]}+\xi(t)\right)}$$

$(\text{constant } \varphi_{[LR]}; \text{ fluctuating } \xi(t))$

$$\begin{aligned} I = \langle|\Psi(t)|^2\rangle &= \langle|\Psi_R + \Psi_L|^2\rangle \\ &= \langle|\Psi_R|^2\rangle + \langle|\Psi_L|^2\rangle + 2\langle\mathrm{Re}[\Psi_R^*\Psi_L]\rangle \\ &= 2A^2 + 2\langle\cos\left[\varphi_{[LR]} + \xi(t)\right]\rangle \\ &= 2A^2 \end{aligned}$$

$$\langle x \rangle = 0 \text{ for } x \text{ uniform over } [-1,\ 1]$$

$$\downarrow$$

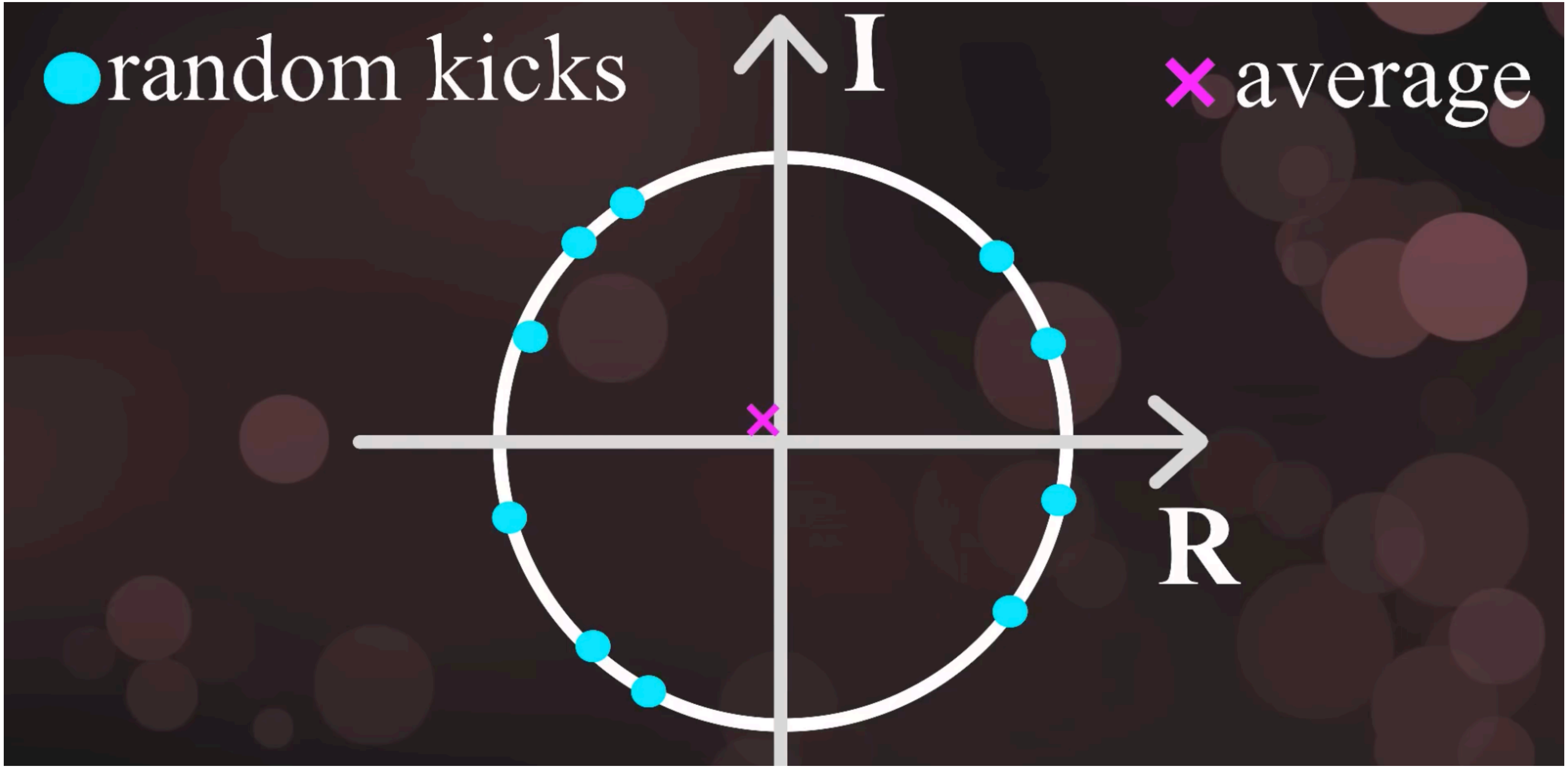
$$\langle \cos\theta \rangle = 0 \text{ for } \theta \text{ uniform over } [0,\ 2\pi]$$

$$\downarrow$$

$$\langle \cos\Big(\varphi_{[LR]} + \xi(t)\Big)\rangle = 0 \text{ for } \xi(t) \text{ uniform over } [0,\ 2\pi]$$

No coherence ∴ No interference

This may be why Newton thought light was made up of particles!



(Hossenfelder, 2020)

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Reminder (Adler, 2002):

1. Product State goes to Entangled State:

$$(\alpha|\mathrm{A}\rangle + \beta|\mathrm{B}\rangle) \otimes (|\Phi\rangle)$$

$$\alpha|\mathrm{A}\rangle \otimes |\Phi\rangle + \beta|\mathrm{B}\rangle \otimes |\Phi\rangle$$

$$\downarrow ⌛$$

$$\alpha|\mathrm{A}\rangle \otimes \left|\Phi^A\right\rangle + \beta|\mathrm{B}\rangle \otimes \left|\Phi^B\right\rangle$$

2. This vector lives in the Hilbert space $\mathcal{H}_{\mathcal{S}} \otimes \mathcal{H}_{\mathrm{APP+ENV}}$
3. $\left|\Phi^A\right\rangle$ and $\left|\Phi^B\right\rangle$ are macroscopically distinguishable (different 'pointer' positions)

of decoherence. What decoherence does is to cause the rapid decay with time of the inner product

$$_{APP+ENV}\langle\phi^{(A)}(t)|\phi^{(B)}(t)\rangle_{APP+ENV} \quad , \tag{4}$$

which at time $t = 0$ was unity. As a consequence, interference effects between the system states $|\psi^{(A)}\rangle_X$ and $|\psi^{(B)}\rangle_X$, which are initially present, rapidly disappear as time evolves. A

(Adler, 2003, p. 7)

What are these interference effects, exactly?

$$\left|\Psi^{A}\right\rangle_{X} \equiv |A\rangle$$

$$\left|\Psi^{B}\right\rangle_{X} \equiv |B\rangle$$

Coherence in an isolated system

$$|\Psi\rangle = \alpha|\mathrm{A}\rangle + \beta|\mathrm{B}\rangle$$

$$|\langle \mathrm{A}|\Psi\rangle|^2 = |\alpha|^2$$

$$|\langle \mathrm{B}|\Psi\rangle|^2 = |\beta|^2$$

$\rightarrow$ coherence, but no interference

Act with an (illustrative) Hermitian operator:

$$\begin{aligned} O|\Psi\rangle &= (|\mathrm{A}\rangle\langle\mathrm{B}| + |\mathrm{B}\rangle\langle\mathrm{A}|)|\Psi\rangle \\ &= (|\mathrm{A}\rangle\langle\mathrm{B}| + |\mathrm{B}\rangle\langle\mathrm{A}|)(\alpha|\mathrm{A}\rangle + \beta|\mathrm{B}\rangle) \\ &= \alpha|\mathrm{B}\rangle + \beta|\mathrm{A}\rangle \end{aligned}$$

(using $\langle\mathrm{A}|\mathrm{B}\rangle = 0$)

$$\begin{aligned} \langle\Psi|O|\Psi\rangle &= (\beta^*\langle\mathrm{B}| + \alpha^*\langle\mathrm{A}|)(\alpha|\mathrm{B}\rangle + \beta|\mathrm{A}\rangle) \\ &= \alpha\beta^* + \alpha^*\beta \end{aligned}$$

interference between ‘mutually exclusive’ states $|\mathrm{A}\rangle, |\mathrm{B}\rangle$

which at time $t = 0$ was unity. As a consequence, interference effects between the system states $|\psi^{(A)}\rangle_X$ and $|\psi^{(B)}\rangle_X$, which are initially present, rapidly disappear as time evolves. A

reminder:

$$\left|\Psi^{A}\right\rangle_{X} \equiv |A\rangle$$

$$\left|\Psi^{B}\right\rangle_{X} \equiv |B\rangle$$

Why don’t we observe the classical apparatus “interfere with itself?” when it becomes entangled with the system?

Answer: ~~Wave-function collapse postulate~~ Decoherence

$$
\begin{aligned}
|\Psi\rangle|\Phi\rangle &= \alpha|\mathrm{A}\rangle + \beta|\mathrm{B}\rangle|\Phi\rangle \qquad t = 0 \text{ (product state)} \\
&= \alpha|\mathrm{A}\rangle|\Phi\rangle + \beta|\mathrm{B}\rangle|\Phi\rangle \text{ coupling begins} \\
&= \alpha|\mathrm{A}\rangle\left|\Phi^A\right\rangle + \beta|\mathrm{B}\rangle\left|\Phi^B\right\rangle \quad t \text{ (entangled state)}
\end{aligned}
$$

Hermitian operator $O_s \otimes I$ (now over $\mathcal{H}_s \otimes \mathcal{H}_{\mathrm{APP+ENV}}$)

$$(|\mathrm{A}\rangle\langle\mathrm{B}| + |\mathrm{B}\rangle\langle\mathrm{A}| \otimes I)(|\Psi(t)\rangle|\Phi(t)\rangle)$$

$$(|\mathrm{A}\rangle\langle\mathrm{B}| + |\mathrm{B}\rangle\langle\mathrm{A}| \otimes I)\left(\alpha|\mathrm{A}\rangle\left|\Phi^A\right\rangle + \beta|\mathrm{B}\rangle\left|\Phi^B\right\rangle\right)$$

$$= \underline{\alpha|\mathrm{B}\rangle\left|\Phi^A\right\rangle + \beta|\mathrm{A}\rangle\left|\Phi^B\right\rangle}$$

where we used $\langle\mathrm{A}|\mathrm{B}\rangle = 0$ and $I\left|\Phi^l\right\rangle = \left|\Phi^l\right\rangle$

Q) Will we see interference effects between macroscopically distinguishable states when we bra with $\langle\Psi(t)|\langle\Phi(t)|$?

$$\langle\Psi(t)|\langle\Phi(t)|O_s \otimes I|\Psi(t)\rangle|\Phi(t)\rangle$$

$$=$$

$$\left(\alpha^*\langle\mathrm{B}|\left\langle\Phi^A\right| + \beta^*\langle\mathrm{A}|\left\langle\Phi^B\right|\right)((|\mathrm{A}\rangle\langle\mathrm{B}| + |\mathrm{B}\rangle\langle\mathrm{A}|) \otimes I)\left(\alpha|\mathrm{B}\rangle\left|\Phi^A\right\rangle + \beta|\mathrm{A}\rangle\left|\Phi^B\right\rangle\right)$$

$$=$$

$$\left(\alpha^*\langle\mathrm{B}|\left\langle\Phi^A\right| + \beta^*\langle\mathrm{A}|\left\langle\Phi^B\right|\right)\left(\alpha|\mathrm{B}\rangle\left|\Phi^A\right\rangle + \beta|\mathrm{A}\rangle\left|\Phi^B\right\rangle\right)$$

$$=$$

$$\alpha^*\alpha \times 0 + \beta^*\beta \times 0 + \alpha^*\beta\left\langle\Phi^A\middle|\Phi^B\right\rangle + \alpha\beta^*\left\langle\Phi^B\middle|\Phi^A\right\rangle$$

$$= \underline{\alpha^*\beta\left\langle\Phi^A\middle|\Phi^B\right\rangle + \alpha\beta^*\left\langle\Phi^B\middle|\Phi^A\right\rangle}$$

$$\langle\Psi(t)|\langle\Phi(t)|O_s \otimes I|\Psi(t)\rangle|\Phi(t)\rangle = \alpha^*\beta\langle\Phi^A|\Phi^B\rangle + \alpha\beta^*\langle\Phi^B|\Phi^A\rangle$$

$\therefore$ Interference terms negligible iff $\langle\Phi^B|\Phi^A\rangle \approx 0$

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(Adler, 2003, p 6-8)

$$|\Phi(t)\rangle = \alpha|\psi^{(A)}\rangle_X|\phi^{(A)}(t)\rangle_{APP+ENV} + \beta|\psi^{(B)}\rangle_X|\phi^{(B)}(t)\rangle_{APP+ENV} \quad , \tag{3}$$

Returning to the general formula of Eq. (3), the quantum measurement problem consists in the observation that Eq. (3) is *not* what is observed as the outcome of a measurement! What is seen is not the superposition of Eq. (3), but rather *either* the unit normalized state

$$|\psi^{(A)}\rangle_X|\phi^{(A)}(t)\rangle_{APP+ENV} \quad , \tag{6a}$$

or the unit normalized state

$$|\psi^{(B)}\rangle_X|\phi^{(B)}(t)\rangle_{APP+ENV} \quad . \tag{6b}$$

Adler:

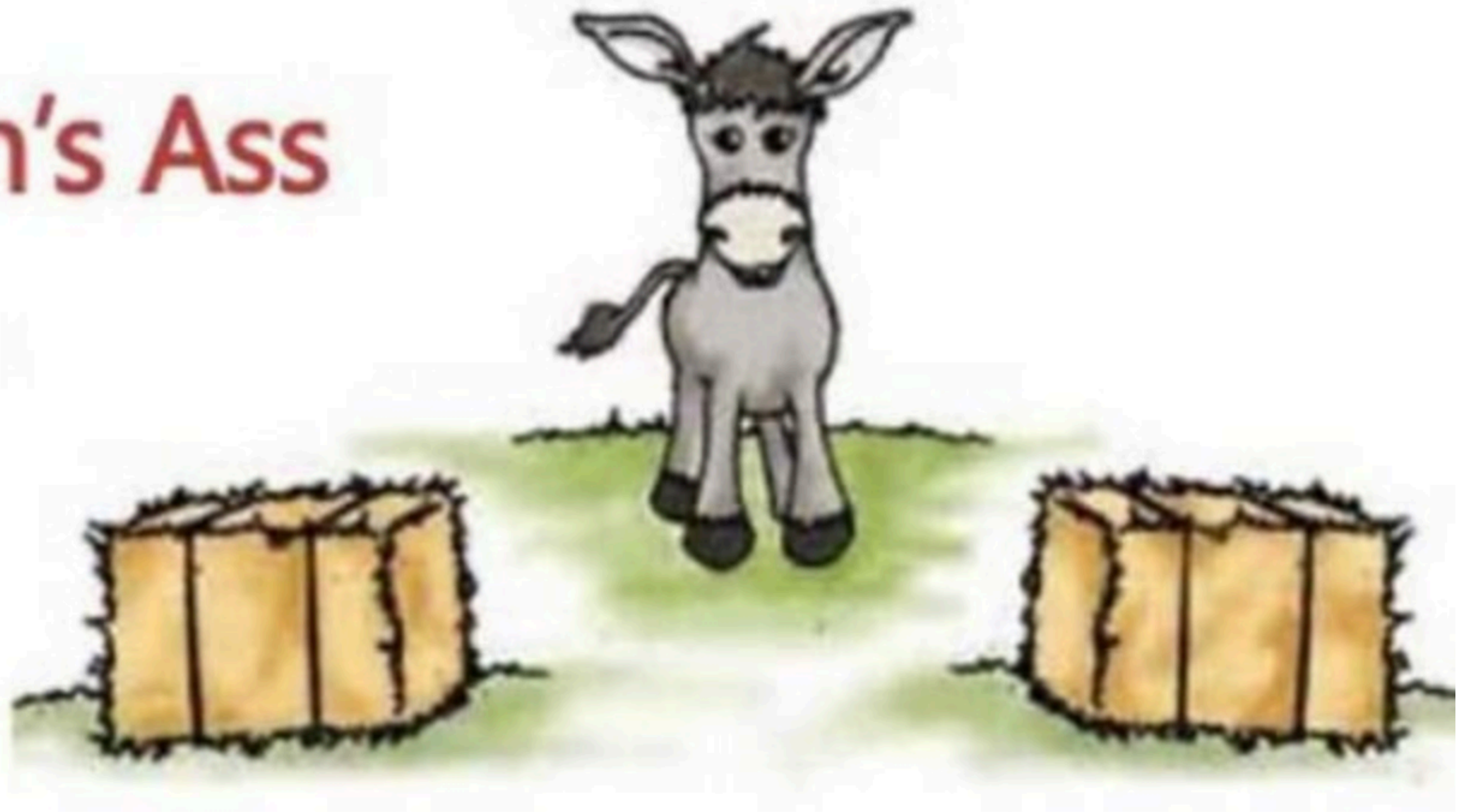
- *decoherence* is a statement about expectation values, and the negligible contribution of certain complex numbers in them.
- but this doesn't explain why only one outcome is observed!

(Maudlin, 1995, p. 9)

The most widespread misunderstanding arises from the claim that the measurement problem has to do with *superpositions* versus *mixed states*. The state S^* is a superposition of the states $|z\text{-up}\rangle_e \otimes |\text{"UP"}\rangle_d$ and $|z\text{-down}\rangle_e \otimes |\text{"DOWN"}\rangle_d$. There is another state (which one can construct using statistical operators) which is called a *mixed* state, and which we can write $50\%[|z\text{-up}\rangle_e \otimes |\text{"UP"}\rangle_d] + 50\%[|z\text{-down}\rangle_e \otimes |\text{"DOWN"}\rangle_d]$. Let us call this state M^*. This state has slightly different mathematical properties from S^*, in that the so-called interference terms are eliminated. It is also the state we would use to make predictions if we knew that the whole system was *either* in $|z\text{-up}\rangle_e \otimes |\text{"UP"}\rangle_d$ *or* in $|z\text{-down}\rangle_e \otimes |\text{"DOWN"}\rangle_d$, and ascribed a 50% likelihood to each. It has often been claimed that the measurement problem is just the problem of explaining how the measuring device gets from the state S^* to the state M^* (see, e.g., Redhead, 1987, p. 56).

- Maudlin first uses symmetry to argue that M^* still doesn't represent *one outcome occuring*

Buridan's Ass



(Maudlin, 1995, p. 10)

That is, if we get M^*, why can't we use the so-called *ignorance interpretation* and say that the system is *really* in either $|z\text{-up}\rangle_e \otimes |\text{“UP”}\rangle_d$ *or* in $|z\text{-down}\rangle_e \otimes |\text{“DOWN”}\rangle_d$, with a 50% chance of each? The short answer is that this is affirming the consequent. Just because being ignorant justifies the use of M^*, it doesn't follow that if M^* is the state of the system, we can regard ourselves as ignorant of anything (i.e. of the real state). More bluntly, in order to use the ignorance inter-

Affirming the Consequent:

$$P \Rightarrow Q \neq Q \Rightarrow P$$

$\boldsymbol{P}$ “The system *really is* in one of the eigenstates, and we are simply ignorant of it”

$\boldsymbol{Q}$ “We can represent the system by a mixed state for the purposes of calculating expectation values”

(Bell, 1990, p. 36)

- 1. explicit use of ρ
- 2. one Ψ_n for system+surroundings (no Φ/Ψ distinction)

Quoting Gottfried:

Neglecting the interaction of A with R', the joint system $S' = S + A$ is found to end, in virtue of the Schrödinger equation, after the 'measurement' on S by A, in a state

$$\Psi = \sum_n c_n \Psi_n$$

where the states Ψ_n are supposed each to have a definite apparatus pointer reading g_n. The corresponding density matrix is

$$\rho = \sum_n \sum_m c_n c_m^* \Psi_n \Psi_m^*$$

At this point KG insists very much on the fact that A, and so S', is a macroscopic system. For macroscopic systems, he says, (KG186) '. . . $trA\hat{\rho} = trA\rho$ for all observables A known to occur in nature . . .' where

$$\hat{\rho} = \sum_n |c_n|^2 \Psi_n \Psi_n^*$$

i.e. $\hat{\rho}$ is obtained from ρ by dropping interference terms involving pairs of macroscopically different states. Then (KG188) '. . . we are free to replace ρ by $\hat{\rho}$ after the measurement, safe in the knowledge that the error will never be found . . .'

Back to Bell:

I am quite puzzled by this. If one were not actually on the lookout for probabilities, I think the obvious interpretation of even $\hat{\rho}$ would be that the system is in a state in which the various Ψs somehow coexist: $\Psi_1\Psi_1^*$ *and* $\Psi_2\Psi_2^*$ *and* . . .

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What is the point of decoherence?

1. Quantum Computing!
2. a. It proves what K. Gottfried assumes by the woolly argument "for macroscopic systems we can drop interference terms in the density matrix" $\rho \rightarrow \hat{\rho}$ (Bell, 1990, p. 36)
   b. It shows that $\langle O \rangle$ in QM and $\langle O \rangle$ calculated using classical statistical mechanics looks the same.
3. It **does not solve the problem of outcomes or the problem of effect**

Relation To Ehrenfest's theorem

1. Ehrenfest's Theorem allows you to derive NII from TDSE (Binney & Skinner, 2008)

$$\frac{\mathrm{d}\langle\hat{p}\rangle}{\mathrm{d}t} = -\left\langle\frac{\mathrm{d}V}{\mathrm{d}\hat{x}}\right\rangle.$$

2. decoherence shows that QM averages and classical averages are the same **not** because of cancellation between interference terms, but because all interference terms vanish.

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Question (1)

Is it a problem for Adler's argument that we do not *see* wavefunctions ((Adler, 2003, p. 8)? (It is more accurate from an operational physics POV that we *see* probabilities and expectation values, and infer what the wavefunction must have looked like.)

Or, is Adler's '*see*' simply a shorthand for, "in calculating future expectation values, we use $\left|\Psi^A\right\rangle\left|\Phi^A\right\rangle$ OR $\left|\Psi^B\right\rangle\ \left|\Phi^B\right\rangle$, rather than the entangled superposition?

Question (2)

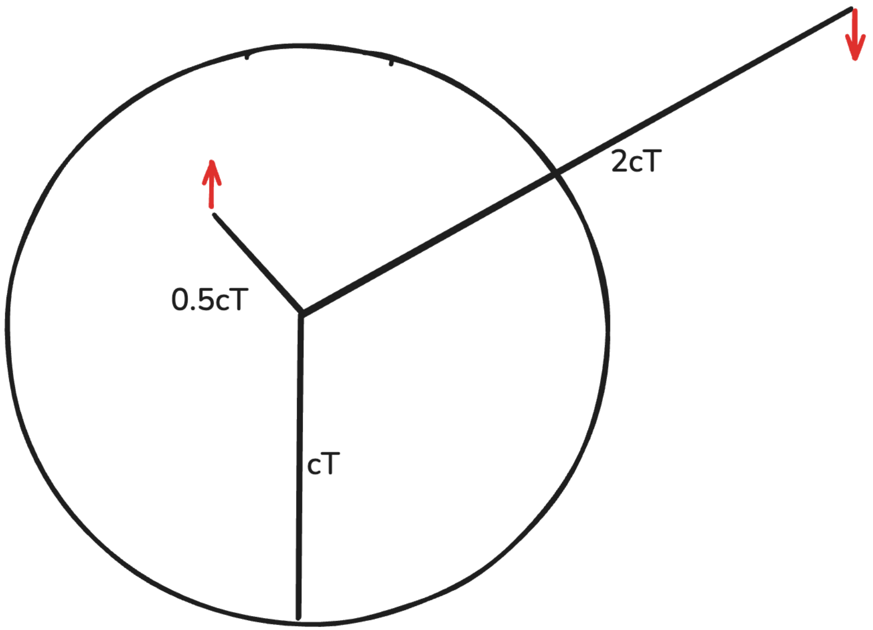
Is Adler *confusing* the problems of ‘effect’ and ‘outcome’? Or is he simply tacitly assuming *decoherence* must solve both?

Question (3)

Do I understand correctly that we are acting on $|\Psi(t)\rangle_S \, |\Phi(t)\rangle_{\mathrm{APP+ENV}}$ with the operator $O_s \otimes I$? Is it problematic that we are acting on the apparatus with the identity? Don’t we need something **more** since we are making an observation *of the apparatus*, after all!

Question (4):

Adler assumes that we are dealing with an isolated system by treating all particles within radius cT, but surely the non-locality of QM doesn't allow you to do this? i.e a particle $c\frac{T}{2}$ away might be entangled with a particle $2cT$ away? So do we even have a closed system?


2cT
0.5cT
cT

Question (5)

Do you agree/disagree that the problem of outcomes reduces to the problem of effect if we admit *repeatability*? Why/Why not?

Question (6)

Are we allowed to even assume that we know the exact eigenstate the Apparatus + Environment wavefunction is in when we begin? (Bell, Maudlin, Adler all make this assumption)

Question (7)

The justification for using eigenstates ("states in which a particular measurement […] is certain to yield a specified value." (Binney & Skinner, 2008, p. 15) seems to be predicated on the existence of ideal, reproducible measurements. But this relies on the problem of *effect* being solved! So isn't any attempt to solve the "problem of effect" from the quantum formalism doomed to circularity?

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