Decoherence & The Measurement Problem

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

Victor Elgersma

May 13th, 2026

Contents

1. Which measurement problem?
2. Classical decoherence
3. (Adler, 2003, p.9): Why does $\langle \phi^A(t) | \phi^B(t) \rangle \approx 0$ imply "interference effects disappear" ?
4. How does Adler's counter-argument differ from Bell, Maudlin?
5. Discussion Questions

What measurement problem?

(Maudlin, 1995) :

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'

$\Psi \to P\Psi$

Unitary Time-Evolution*

*Except when a measurement occurs

+

Ψ completeness

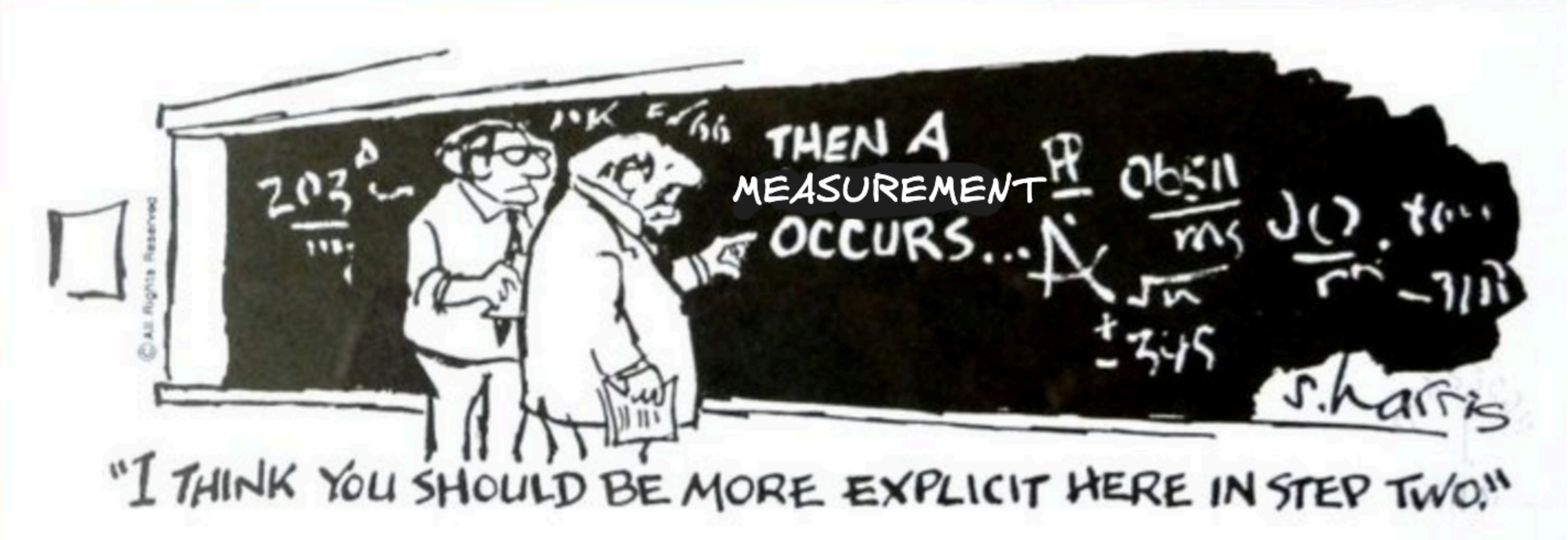
'...any result of a measurement of a real dynamical variable is one of its eigenvalues' (Dirac, 1930)

'... 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, emphasis added)



"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' $\Psi \rightarrow P\Psi$

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, emphasis added

[…] 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, emphasis added

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

Claim: 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)

Claim: 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

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

Question

Is it a problem for Adler's argument that we do not *see* wavefunctions (Adler, 2003, p. 8)?

What we *see* are experimental traces which we predict using probabilities and expectation values, and we use the post-collapse wavefunction to calculate these.

Question

Is it a problem for Adler's argument that we do not *see* wavefunctions (Adler, 2003, p. 8)?

What we *see* are experimental traces which we predict using probabilities and expectation values, and we use the post-collapse wavefunction to calculate these.

No, Adler's *see* is simply a **shorthand** for, "in calculating future expectation values, we use $|\psi^A\rangle|\phi^A\rangle$ OR $|\psi^B\rangle\ |\phi^B\rangle$, rather than the entangled superposition.

- **Claim**: Adler is tacitly assuming that decoherence must explain why ideal measurements are reproducible.

- **Claim**: Adler is tacitly assuming that decoherence must explain why ideal measurements are reproducible.

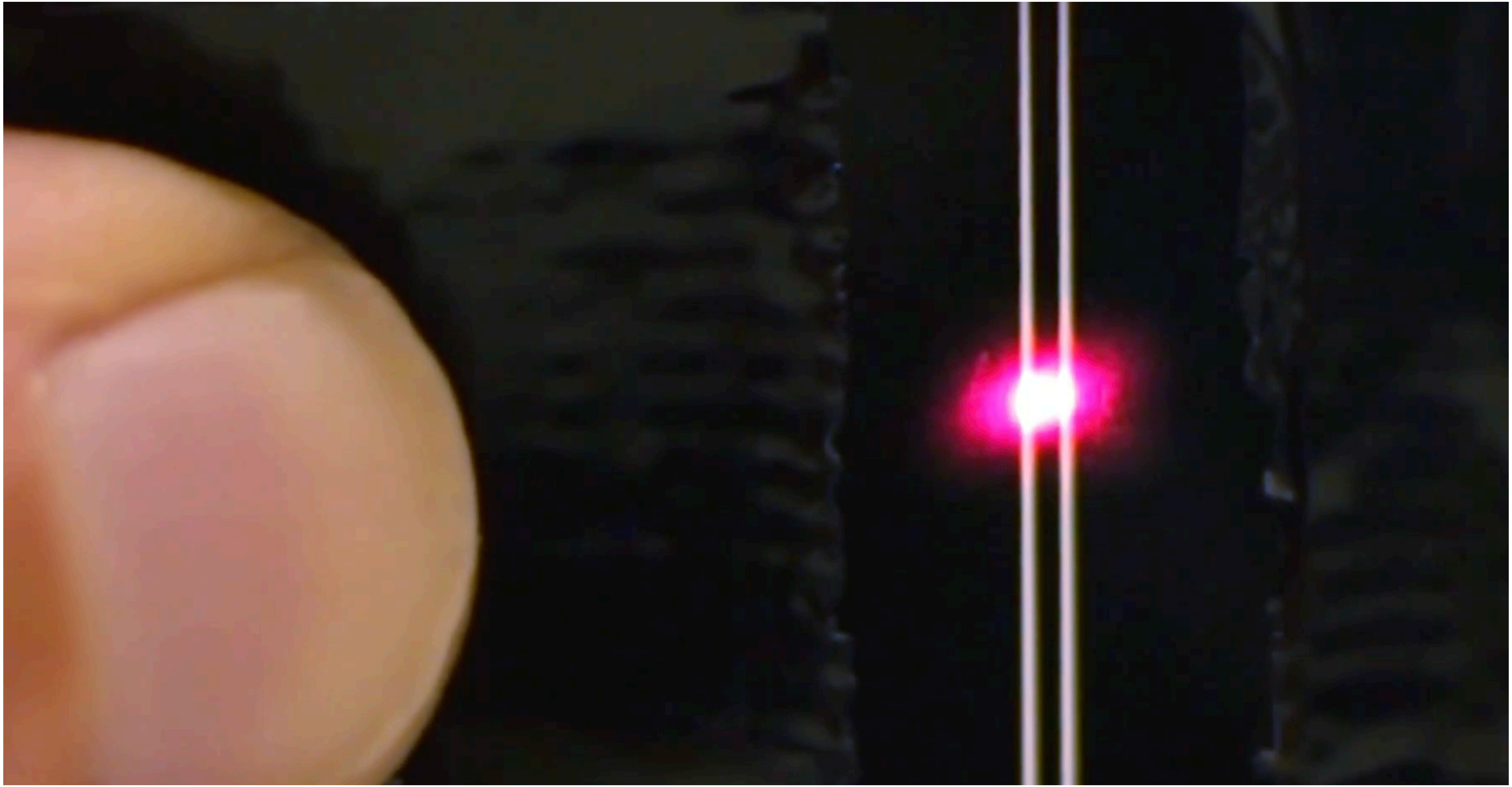
> 1. let a measurement have a definite outcome A
> 2. if this experiment is reproducible then a subsequent measurement should have outcome A with probability 100%
> 3. But this is **the definition of the eigenstate $\boldsymbol{\psi_A}$** !
> 4. Ergo we can infer $\psi \rightarrow P\psi = \psi_A$, a definite **effect**
> 5. So to explain reproducible measurements we have to solve the problem of effect

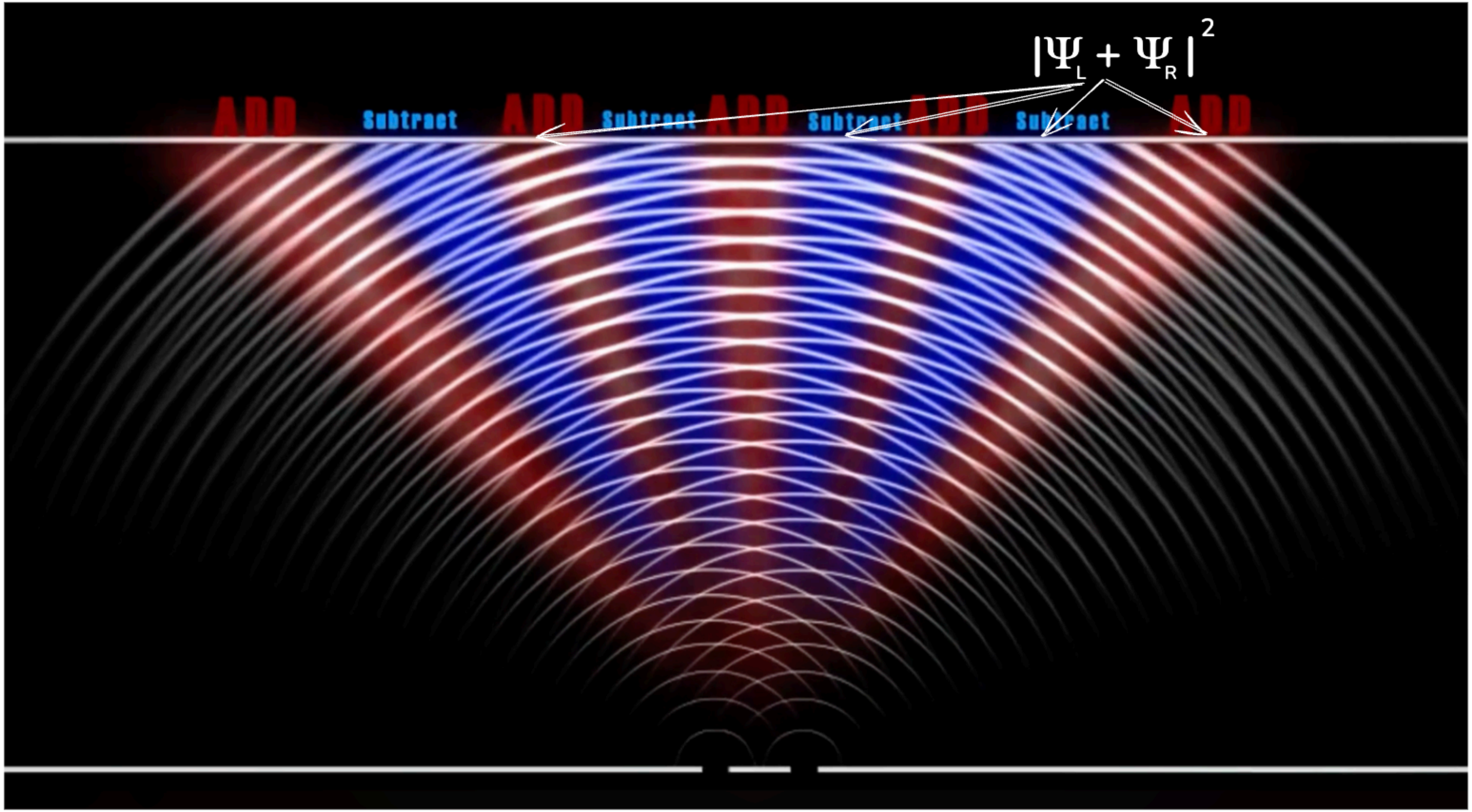
Conclusion

Adler wants decoherence to solve **both** the problem of outcomes and the problem of effect.

Contents

1. ~~Which measurement problem?~~
2. Classical decoherence
3. (Adler, 2003, p.9): Why does $\langle \phi^A(t) | \phi^B(t) \rangle \approx 0$ imply “interference effects disappear” ?
4. How does Adler's counter-argument differ from Bell, Maudlin?
5. Discussion Questions





$|\Psi_L + \Psi_R|^2$
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:

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

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

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

$$\begin{aligned} I = \langle|\psi(t)|^2\rangle &= \langle\left|\psi_R + \psi_L\right|^2\rangle \\ &= \langle\left|\psi_R\right|^2\rangle + \langle\left|\psi_L\right|^2\rangle + 2\langle\mathrm{Re}[\psi_R^*\psi_L]\rangle \\ &= 2A^2 + 2\underbrace{\langle\cos\left[\theta_{[LR]} + \xi(t)\right]\rangle}_{0} \\ &= 2A^2 \end{aligned}$$

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

$$\downarrow$$

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

$$\downarrow$$

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

No coherence ∴ No interference

This is why Newton thought light was particles!

Contents

1. ~~Which measurement problem?~~
2. ~~Classical decoherence~~
3. (Adler, 2003, p.9): Why does $\left\langle\phi^A(t)\middle|\phi^B(t)\right\rangle \approx 0$ imply “interference effects disappear” ?
4. How does Adler's counter-argument differ from Bell, Maudlin?
5. Discussion Questions

Reminder (Adler, 2002):

Product State goes to Entangled State:

$$(\alpha|\mathrm{A}\rangle + \beta|\mathrm{B}\rangle) \otimes |\phi\rangle_{\mathrm{ENV+APP}}$$

$$\alpha|\mathrm{A}\rangle \otimes |\phi\rangle_{\mathrm{ENV+APP}} + \beta|\mathrm{B}\rangle \otimes |\phi\rangle_{\mathrm{ENV+APP}}$$

Reminder (Adler, 2002):

Product State goes to Entangled State:

$$(\alpha|\mathrm{A}\rangle + \beta|\mathrm{B}\rangle) \otimes |\phi\rangle_{\mathrm{ENV+APP}}$$

$$\alpha|\mathrm{A}\rangle \otimes |\phi\rangle_{\mathrm{ENV+APP}} + \beta|\mathrm{B}\rangle \otimes |\phi\rangle_{\mathrm{ENV+APP}}$$

$$\downarrow ⌛$$

$$\alpha|\mathrm{A}\rangle \otimes \left|\phi^A\right\rangle_{\mathrm{ENV+APP}} + \beta|\mathrm{B}\rangle \otimes \left|\phi^B\right\rangle_{\mathrm{ENV+APP}}$$

This vector lives in the Hilbert space $\mathcal{H}_X \otimes \mathcal{H}_{\mathrm{APP+ENV}}$

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)

In the absence of decoherence, what would these interference effects look like?

My notation:

$$\left|\psi^A\right\rangle_X \equiv |A\rangle$$

$$\left|\psi^B\right\rangle_X \equiv |B\rangle$$

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

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

(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 $|\mathrm{A}\rangle, |\mathrm{B}\rangle$

Now treat system (X) + apparatus (APP) + environment (ENV)

$$
\begin{aligned}
|\psi\rangle_X |\phi\rangle_{\text{APP+ENV}} &= \alpha|\text{A}\rangle + \beta|\text{B}\rangle|\phi\rangle \qquad t = 0 \text{ (product state)} \\
&= \alpha|\text{A}\rangle|\phi\rangle + \beta|\text{B}\rangle|\phi\rangle \text{ coupling begins} \\
&= \alpha|\text{A}\rangle\left|\phi^A\right\rangle + \beta|\text{B}\rangle\left|\phi^B\right\rangle \quad t \text{ (entangled state)}
\end{aligned}
$$

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

$$|\psi\rangle_X|\phi\rangle_{\mathrm{APP+ENV}} = \alpha|\mathrm{A}\rangle + \beta|\mathrm{B}\rangle|\phi\rangle \qquad t = 0 \text{ (product state)}$$

$$= \alpha|\mathrm{A}\rangle|\phi\rangle + \beta|\mathrm{B}\rangle|\phi\rangle \text{ coupling begins}$$

$$= \alpha|\mathrm{A}\rangle\left|\phi^A\right\rangle + \beta|\mathrm{B}\rangle\left|\phi^B\right\rangle \qquad t \text{ (entangled state)}$$

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

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

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

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

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

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

$$\langle\psi(t)|\langle\phi(t)|O_X \otimes I|\psi(t)\rangle|\phi(t)\rangle$$

$$=$$

$$\big(\alpha^*\langle\mathrm{B}|\langle\phi^A| + \beta^*\langle\mathrm{A}|\langle\phi^B|\big)\big((|\mathrm{A}\rangle\langle\mathrm{B}| + |\mathrm{B}\rangle\langle\mathrm{A}|) \otimes I\big)\big(\alpha|\mathrm{B}\rangle|\phi^A\rangle + \beta|\mathrm{A}\rangle|\phi^B\rangle\big)$$

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

$$\langle\psi(t)|\langle\phi(t)|O_X \otimes I|\psi(t)\rangle|\phi(t)\rangle$$

$$=$$

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

$$=$$

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

$$=$$

$$\alpha^*\alpha \times 0 + \beta^*\beta \times 0 + \alpha^*\beta\langle\phi^A|\phi^B\rangle + \alpha\beta^*\langle\phi^B|\phi^A\rangle$$

$$= \underline{\alpha^*\beta\langle\phi^A|\phi^B\rangle + \alpha\beta^*\langle\phi^B|\phi^A\rangle}$$

$\therefore$ the expectation value depends on interference between macroscopically distinguishable states

$$\langle\psi(t)|\langle\phi(t)|O_X \otimes I|\psi(t)\rangle|\phi(t)\rangle = \alpha^*\beta\langle\phi^A|\phi^B\rangle + \alpha\beta^*\langle\phi^B|\phi^A\rangle$$

unless we can show $\langle\phi^B|\phi^A\rangle \approx 0$

This is exactly what decoherence tells us.

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

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

Why don't we observe the classical apparatus "interfere with itself?" when it becomes entangled with the system?

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

I have just shown that this is true for an illustrative observable with corresponding Hermitian operator O_X

In principle, you need ρ to show that this is true for an arbitrary observable:

$(\langle O \rangle = Tr[\rho O])$

Contents

(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 of observables, and the negligible contribution of certain complex.

Adler:

decoherence is a statement about expectation values of observables, and the negligible contribution of certain complex.

but this doesn’t explain why only one outcome is observed!

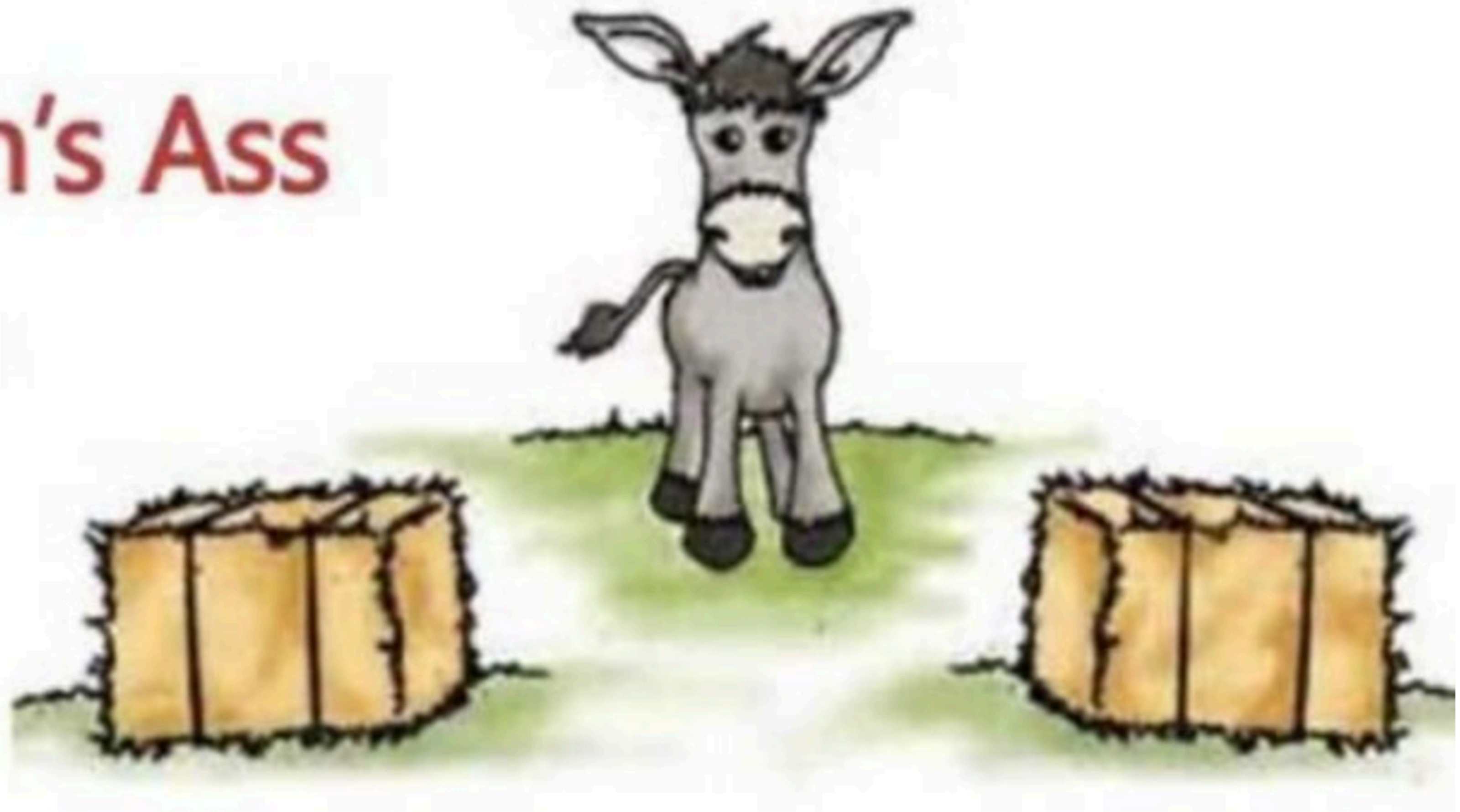
(Maudlin, 1995, p. 9)

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: $|\text{z-up}\rangle|\text{UP}\rangle + |\text{z-down}\rangle|\text{DOWN}\rangle$
Adler: $\left|\psi^A\right\rangle \left|\phi^A\right\rangle + \left|\psi^B\right\rangle \left|\phi^B\right\rangle$

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

Buridan's Ass



… but we are also **affirming the consequent** (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-

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

… but we are also **affirming the consequent** (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-

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

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

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 $\psi_X / \phi_{\mathrm{APP+ENV}}$ 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 . . .'

Decoherence explains why K.G can "drop interference terms involving pairs of macroscopically different states" (Bell, 1990, p. 36)

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* . . .

Contents

1. ~~Which measurement problem?~~
2. ~~Classical decoherence~~
3. ~~(Adler, 2003, p.9): Why does~~ $\langle\phi^A(t)|\phi^B(t)\rangle \approx 0$ ~~imply "interference effects disappear" ?~~
4. ~~How does Adler's counter-argument differ from Bell, Maudlin?~~
5. Discussion Questions

Question (1)

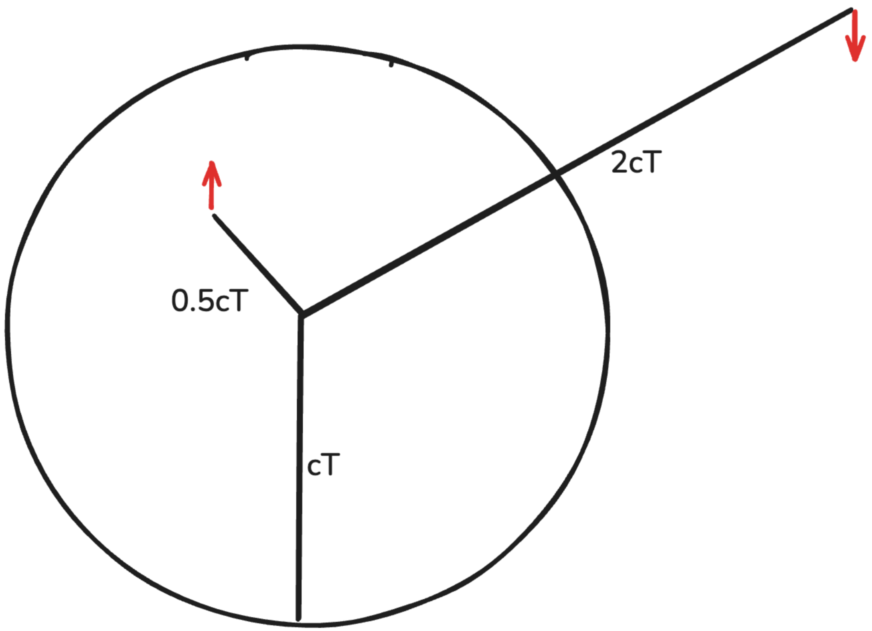
Is Adler *confusing* the problems of 'effect' and 'outcome'? Or is he simply tacitly assuming *decoherence* must solve both because it must explain reproducible measurements?

Question (2)

Is it correct to act on $|\psi(t)\rangle_X \, |\phi(t)\rangle_{\mathrm{APP+ENV}}$ with the operator $O_X \otimes I$? 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 (3):

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?



Question (4)

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 (5)

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?

Bibliography

Adler, S. L. (2003). Why Decoherence has not Solved the Measurement Problem: A Response to P. W. Anderson. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics*, *34*(1), 135–142. https://doi.org/10.1016/S1355-2198(02)00086-2

Bell, J. (1990). *Against Measurement*.

Binney, J., & Skinner. (2008). *Quantum Mechanics*. https://www-thphys.physics.ox.ac.uk/people/JamesBinney/qb.pdf

Maudlin, T. (1995). Three measurement problems. *Topoi*, *14*(1), 7–15. https://doi.org/10.1007/BF00763473

Schlosshauer, M. (2005). Decoherence, the measurement problem, and interpretations of quantum mechanics. *Reviews of Modern Physics*, *76*(4), 1267–1305. https://doi.org/10.1103/RevModPhys.76.1267

Zurek, W. H. (1991). Decoherence and the Transition from Quantum to Classical. *Physics Today*, *44*(10), 36–44. https://doi.org/10.1063/1.881293