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

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

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' $\Psi \to P\Psi$

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)

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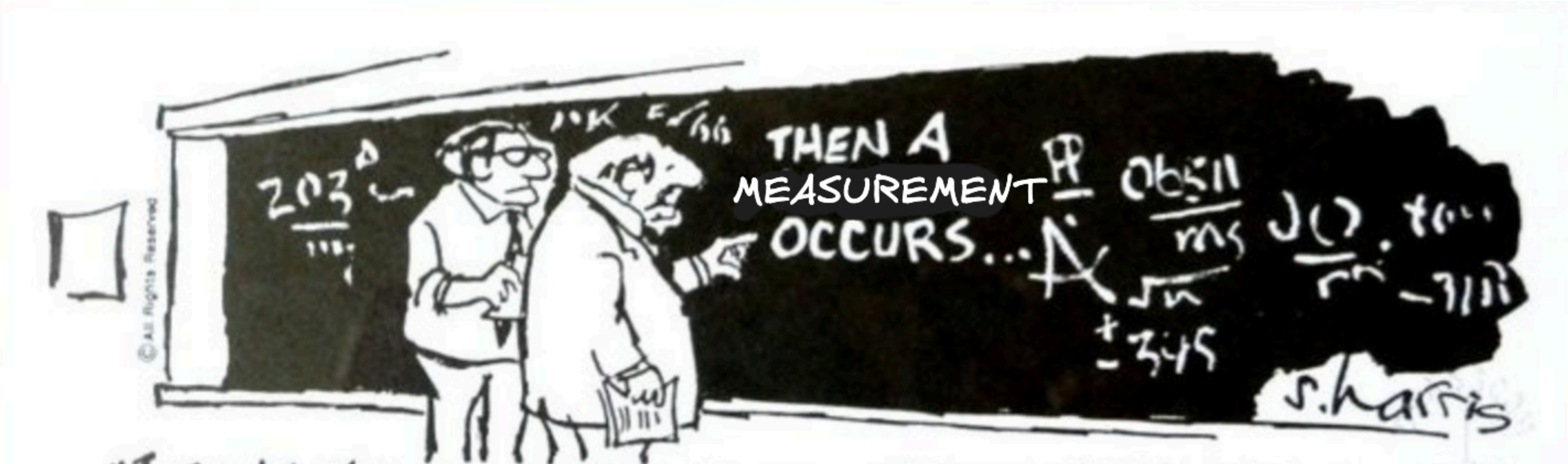
'...a measurement always causes the system to jump into an eigenstate of the dynamical variable that is being measured....' (Dirac, 1930)

'Collapse Hypothesis'



"I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO."

(Quantum Mechanics, Binney and Skinner, Ch6, p 141):

Notice that the evolution from $|\psi\rangle$ to $|qj\rangle$ has not been derived from the TDSE, which we have stated to be the equation that governs the time-evolution of $|\psi>$. So this Copenhagen interpretation of quantum mechanics 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.

Unitary Time-Evolution + Ψ completeness

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Adler, 2002 (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]

~~Born Rule~~

Which Measurement Problem?

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

- Claim: Adler demands decoherence solve both the **problem of *outcomes*** and the problem of effect:

(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

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

Q. Is it a problem for Adler's argument that we do not *see* wavefunctions? 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.

- Q) Is Adler confusing the problems of ‘effect’ and ‘outcome’?
- Claim: as soon as we admit **reproducibility of measurement**, then our problem of ‘outcomes’ becomes our ‘problem of effect’.
  - definite outcome + reproducibility = definite effect

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Proof:

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. Ergo we can infer $\Psi \to P\Psi = \Psi_A$
4. Which is the *effect* we sought. QED.

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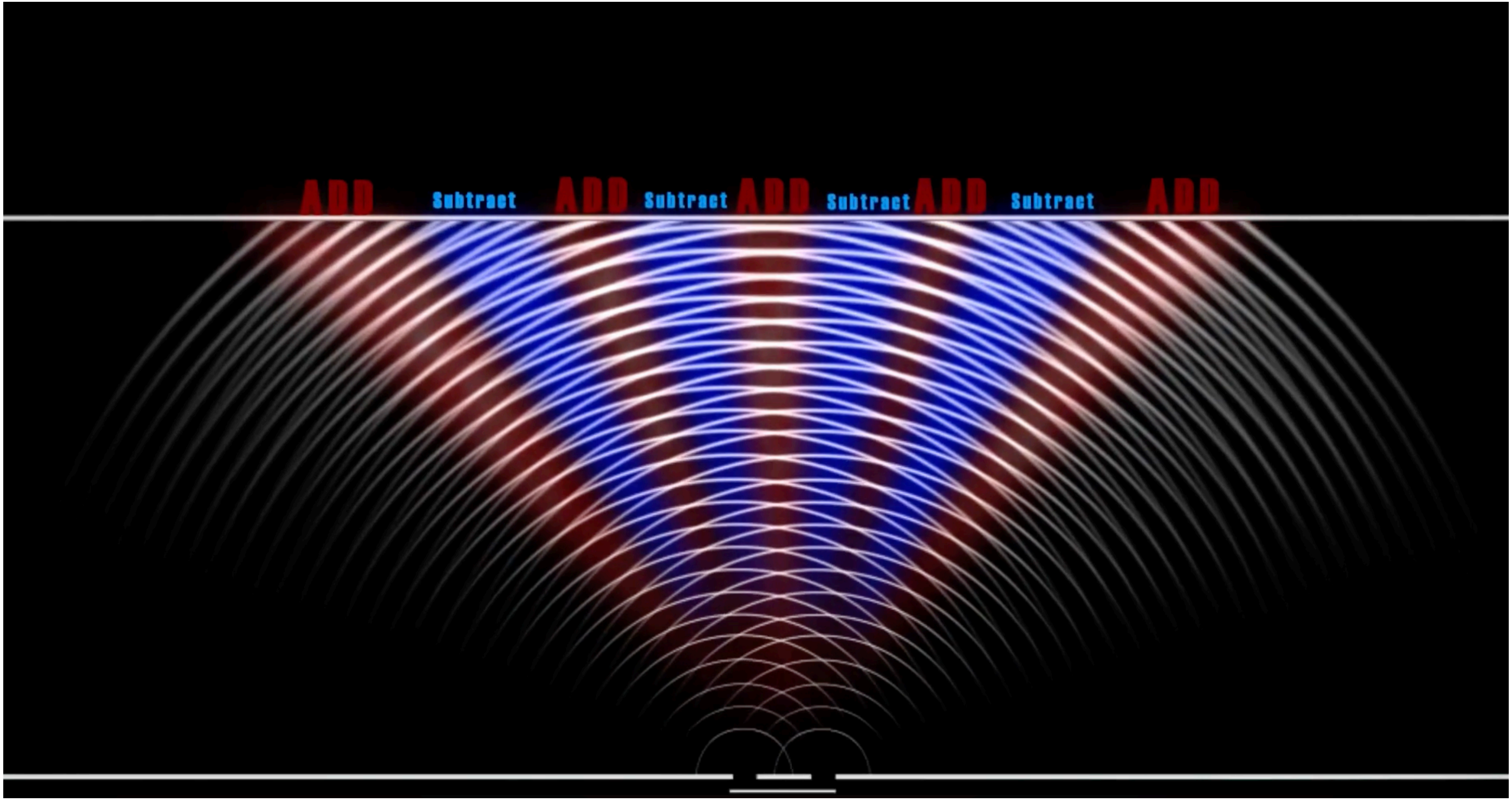
Classical Coherence / Decoherence


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

Intensity is a time-averaged quantity:

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

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

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

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

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

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

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

$\therefore$ No coherence = No interference

This is why Newton thought light was made up of particles!

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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

(p.7)

What are these interference effects, exactly?

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

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

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

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:

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

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

$$|\langle\Psi|O|\Psi\rangle|^2 = |\alpha\beta^*|^2 + |\alpha^*\beta|^2 + 2\alpha\alpha^*\beta\beta^*$$

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

$$|\Psi\rangle|\Phi\rangle = [\alpha|\mathrm{A}\rangle + \beta|\mathrm{B}\rangle]|\Phi\rangle \qquad t = 0 \text{ (product state)}$$

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

$$= \alpha|\mathrm{A}\rangle|\Phi, A\rangle + \beta|\mathrm{B}\rangle|\Phi, B\rangle \quad t \text{ (entangled state)}$$

Hermitian operator $O_s \otimes I$ (now a map in/out of $\mathcal{H}_s \otimes \mathcal{H}_{\mathrm{APP+ENV}}$)

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

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

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

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

$$=$$

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

$$=$$

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

$$=$$

$$\alpha^*\alpha \times 0 + \beta^*\beta \times 0 + a^*\beta\langle\Phi, A|\Phi, B\rangle + \alpha\beta^*\langle\Phi, B|\Phi, A\rangle$$

$$=$$

$$a^*\beta\langle\Phi, A|\Phi, B\rangle + \alpha\beta^*\langle\Phi, B|\Phi, A\rangle$$

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

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

Question: is it OK to act on the state $|\Psi(t)\rangle\, |\Phi(t)\rangle$ with the operator mapping from/to $O_s \otimes I$? If we are observing the apparatus surely we need to operate with something something other than $I \in \mathcal{B}(\mathcal{H}_{\mathrm{APP+ENV}})$

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- 1. Symmetry (Maudlin)
- ρ (v Bell)

More Questions (1)

Q) Do you agree/disagree that the problem of outcomes reduces to the problem of effect if we admit *repeatability*?

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

Q) Bell uses density matrices, Maudlin uses mixed states. Adler uses neither. Is this deliberate? Is this a disadvantage or an advantage for his argument?

More Questions (2)

Q) Isn’t the ‘problem out outcomes’ simply the statement that ideal measurements are reproducible? Can we even use linear maps and vector spaces to describe QM without the assumption of ideal, reproducible measurements?

References

- Sabine Hossenfelder on Decoherence