Title: The EPR Illusion: States, Counterfactuals and Elements of Reality

Date: Dec 02, 2008 04:00 PM

URL: http://pirsa.org/08120017

Abstract: We all know that the EPR argument fails, and we can all provide proofs of one sort or another that it can\'t work. But in spite of this, there\'s something curiously tempting about the reasoning, and the temptation sometimes leads to needless perplexity about other issues. This paper will do two things. It will offer a diagnosis of where the EPR argument goes wrong that shows why we should be suspicious long before we get to Bell-type results, and then use the thought behind this diagnosis to suggest an orientation toward thinking about quantum states. The proposal for understanding states will have some things in common with Bayesian approaches, but will part company with them on some crucial points.

States, Counterfactuals and Elements of Reality: The EPR Illusion

Allen Stairs, Department of Philosophy
University of Maryland

States, Counterfactuals and Elements of Reality: The EPR Illusion

Allen Stairs, Department of Philosophy
University of Maryland

Two Topics

1) The EPR Argument: banishing the illusion

2) Quantum States

Rethinking EPR helps avoid bad ways of thinking about quantum states

EPR:

The Criterion of Reality:

> If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of reality corresponding to this physical quantity.

The Argument Sketched

EPR consider a state of the (biorthogonal) form

$$\Psi = \Sigma_i c_i |a_i\rangle \otimes |p_i\rangle = \Sigma_i d_i |b_i\rangle \otimes |q_i\rangle$$

where $|a_i\rangle$ and $|p_i\rangle$ are eigenstates of A and P, $|b_i\rangle$ and $|q_i\rangle$ are eigenstates of B and Q. ($AB \neq BA$, $PQ \neq QP$)

Call A & P *parallel*; likewise B & Q.

The Argument Sketched

$$\Psi = \Sigma_i c_i|a_i\rangle \otimes |p_i\rangle = \Sigma_i d_i|b_i\rangle \otimes |q_i\rangle$$

- If Alice measures A and finds a_k, she can predict the outcome of a P-measurement.
- But her measurement on system I didn't influence II.
- Hence the value was *discovered* and not created.
- Had she measured B instead, she would have discovered a Q value.
- Hence, II has a P-value (element of reality) *and* a Q-value.
- Since no quantum state accounts for both, QM is incomplete.

Counterfactuals

Elements of reality must support measurement counterfactuals
E.g., if P *were* measured, the result *would* be p_k.

Equate *possessing an element of reality, having a value* and *satisfying the relevant measurement counterfactual.*

Thinking clearly about counterfactuals is the key to dispelling the EPR illusion.

Three Kinds of Conditionals

1) "Would" counterfactuals, as in

If X were measured, the result *would* be x.

2) "Might" counterfactuals, as in

If X were measured, the result *might* be x.

3) Indicative conditionals, as in

If X *was* measured the result was x.

Counterfactuals

1) Write $F \mathbin{\Box\!\!\rightarrow} G$ for

If F were true, G would be true.

2) Write $F \mathbin{\Diamond\!\!\rightarrow} G$ for

If F were true, G would be true.

We have: Not-($X \mathbin{\Box\!\!\rightarrow} Y$) $\equiv X \mathbin{\Diamond\!\!\rightarrow}$ not-Y.

3) Write $F \longrightarrow G$ for

If F is/was true, G is/was true.

$X \rightarrow Y$ is simply the "truth-functional" if-then.

<u>Roughly:</u>

a) $X \mathbin{\Box\!\!\rightarrow} Y$ suggests a deterministic connection

b) If $X \mathbin{\Diamond\!\!\rightarrow} Y$ and $X \mathbin{\Diamond\!\!\rightarrow}$ not-Y both hold, connection is indeterministic.

Counterfactual Excluded Middle vs. Counterfactual Definiteness

Trivially true: $F \,\square\!\!\rightarrow (G \text{ or not-}G)$

This says:

The law of excluded middle would hold if *X* were true.

For example:

If *X* were measured, either the result would be *x* or it wouldn't.

Call this *Counterfactual Excluded Middle*

Counterfactual Excluded Middle vs. Counterfactual Definiteness

Not trivially true: $(F \Box\!\!\rightarrow G)$ or $(F \Box\!\!\rightarrow \text{not-}G)$

Consider: Is it true that *either* if X were measured, the result would be x *or* if X were measured, the result would *not* be x?

- Saying *yes* suggests: the result is predetermined
- Saying *yes* and adding locality assumptions leads to an inequality.

Call the principle behind

$$(F \Box\!\!\rightarrow G) \text{ or } (F \Box\!\!\rightarrow \text{not-}G)$$

Counterfactual Definiteness

Counterfactual Excluded Middle vs. Counterfactual Definiteness

Trivially true: $F \Box\!\!\rightarrow (G \text{ or not-}G)$

This says:

The law of excluded middle would hold if *X* were true.

For example:

If *X* were measured, either the result would be *x* or it wouldn't.

Call this *Counterfactual Excluded Middle*

Counterfactual Excluded Middle vs. Counterfactual Definiteness

Not trivially true: $(F \;\square\!\!\rightarrow G)$ or $(F \;\square\!\!\rightarrow \text{not-}G)$

Consider: Is it true that *either* if X were measured, the result would be x *or* if X were measured, the result would *not* be x?

- Saying *yes* suggests: the result is predetermined
- Saying *yes* and adding locality assumptions leads to an inequality.

Call the principle behind

$$(F \;\square\!\!\rightarrow G) \text{ or } (F \;\square\!\!\rightarrow \text{not-}G)$$

Counterfactual Definiteness

Counterfactual Excluded Middle vs. Counterfactual Definiteness

Trivially true: $F \Box\!\!\rightarrow (G \text{ or not-}G)$

This says:

The law of excluded middle would hold if X were true.

For example:

If X were measured, either the result would be x or it wouldn't.

Call this *Counterfactual Excluded Middle*

Counterfactual Excluded Middle vs. Counterfactual Definiteness

Not trivially true: $(F \,\Box\!\!\rightarrow G)$ or $(F \,\Box\!\!\rightarrow \text{not-}G)$

Consider: Is it true that *either* if X were measured, the result would be x *or* if X were measured, the result would *not* be x?

- Saying *yes* suggests: the result is predetermined
- Saying *yes* and adding locality assumptions leads to an inequality.

Call the principle behind

$$(F \,\Box\!\!\rightarrow G) \text{ or } (F \,\Box\!\!\rightarrow \text{not-}G)$$

Counterfactual Definiteness

Counterfactual Excluded Middle vs. Counterfactual Definiteness

Trivially true: $F \mathrel{\Box\!\!\rightarrow} (G \text{ or not-}G)$

This says:

> The law of excluded middle would hold if X were true.

For example:

> If X were measured, either the result would be x or it wouldn't.

Call this *Counterfactual Excluded Middle*

Counterfactual Excluded Middle vs. Counterfactual Definiteness

Not trivially true: $(F \,\Box\!\!\rightarrow G)$ or $(F \,\Box\!\!\rightarrow \text{not-}G)$

Consider: Is it true that *either* if X were measured, the result would be x *or* if X were measured, the result would *not* be x?

- Saying *yes* suggests: the result is predetermined
- Saying *yes* and adding locality assumptions leads to an inequality.

Call the principle behind

$$(F \,\Box\!\!\rightarrow G) \text{ or } (F \,\Box\!\!\rightarrow \text{not-}G)$$

Counterfactual Definiteness

Counterfactual Excluded Middle vs. Counterfactual Definiteness

Trivially true: $F \,\square\!\!\rightarrow (G \text{ or not-}G)$

This says:

The law of excluded middle would hold if *X* were true.

For example:

If *X* were measured, either the result would be *x* or it wouldn't.

Call this *Counterfactual Excluded Middle*

Counterfactual Excluded Middle vs. Counterfactual Definiteness

Not trivially true: $(F \;\Box\!\!\rightarrow G)$ or $(F \;\Box\!\!\rightarrow \text{not-}G)$

Consider: Is it true that *either* if X were measured, the result would be x *or* if X were measured, the result would *not* be x?

- Saying *yes* suggests: the result is predetermined
- Saying *yes* and adding locality assumptions leads to an inequality.

Call the principle behind

$$(F \;\Box\!\!\rightarrow G) \text{ or } (F \;\Box\!\!\rightarrow \text{not-}G)$$

Counterfactual Definiteness

EPR and Counterfactual Definiteness

- EPR's opposition is indeterminist
- Indeterminists don't assume that counterfactual definiteness holds for all measurements
- EPR don't simply *assume* that counterfactual definiteness holds
- They *argue* that it holds in cases where the indeterminists who accept completeness must say it doesn't

Our question:

EPR and Counterfactual Definiteness

- EPR's opposition is indeterminist
- Indeterminists don't assume that counterfactual definiteness holds for all measurements
- EPR don't simply *assume* that counterfactual definiteness holds
- They *argue* that it holds in cases where the indeterminists who accept completeness must say it doesn't

Our question:

Do EPR give the orthodox indeterminist good reason to change her view?

A Warm-Up Case

- Single particle, outcome of A-measurement not determined
- Alice measures A at ξ and gets result a_k. For shorthand:

$$\mathbb{X} \equiv \boldsymbol{A}_\xi \;\&\; \boldsymbol{a}_k$$

- Orthodox indeterminist assumes: unless something intervenes or evolves, repeated projective measurements give identical results

A Warm-Up Case

Let ω be a point a little earlier than ξ. The indeterminist *will* say:

If A was actually measured at ω, the result was a_k:

$$A_\omega \rightarrow a_k$$

The indeterminist *won't* say:

If A *had been* measured at ω, the result *would have been* a_k.

$$A_\omega \mathrel{\Box\!\!\rightarrow} a_k$$

But...

The indeterminist will accept this conditional probability:

$$\mathrm{pr}(\boldsymbol{a}_k|\mathbb{X}\ \&\ \boldsymbol{A}) = 1$$

And so...

- We have a conditional probability of 1
- The measurement we reason *from* doesn't influence the measurement we reason *to*
- But we aren't entitled to infer an element of reality (because we can't infer the relevant measurement counterfactual)

A Warm-Up Case

Let ω be a point a little earlier than ξ. The indeterminist *will* say:

If *A* was actually measured at ω, the result was a_k:

$$A_\omega \rightarrow a_k$$

The indeterminist *won't* say:

If *A* *had been* measured at ω, the result *would have been* a_k.

$$A_\omega \;\Box\!\!\rightarrow\; a_k$$

But…

The indeterminist will accept this conditional probability:

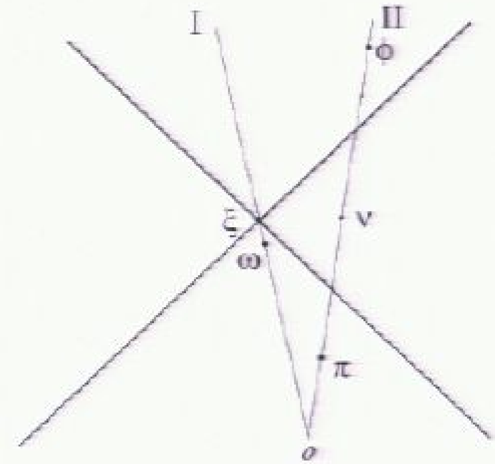
$$\mathrm{pr}(\boldsymbol{a}_k | \mathbb{X} \,\&\, \boldsymbol{A}) = 1$$

And so…

- We have a conditional probability of 1
- The measurement we reason *from* doesn't influence the measurement we reason *to*
- But we aren't entitled to infer an element of reality (because we can't infer the relevant measurement counterfactual)

Looking Backward

- Consider two particles, *I* and *II*, in the state Ψ described above.
- *I* is first measured at ξ, with result a_k.
- *II* is measured at most once.



("πast," νow," "φuture")

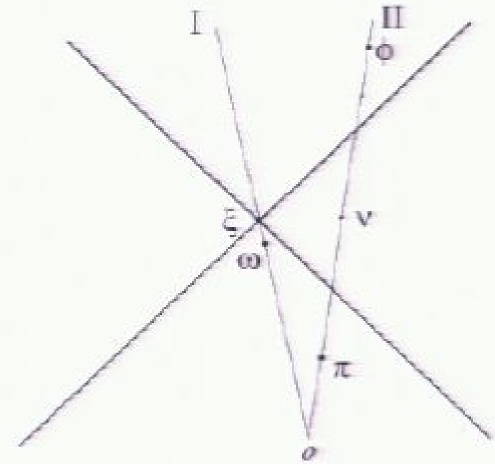
Looking Backward

- If P was actually measured at π, the result was p_k:

$$P_\pi \rightarrow \boldsymbol{p}_k$$

- The following probability holds:

$$\text{pr}(\boldsymbol{p}_k | \mathbb{X} \ \& \ P_\pi) = 1$$



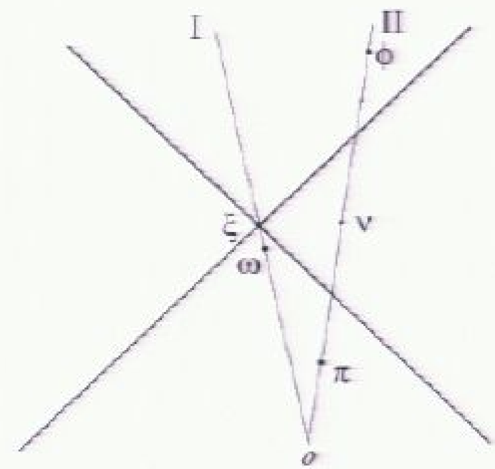
But supposing *II wasn't* measured at or before π, the indeterminist will *deny*

$$P_\pi \;\Box\!\!\rightarrow\; \boldsymbol{p}_k$$

She will assert both

$$(P_\pi \Diamond\!\!\rightarrow \boldsymbol{p}_k) \textit{ and } (P_\pi \Diamond\!\!\rightarrow \text{not-}\boldsymbol{p}_k)$$

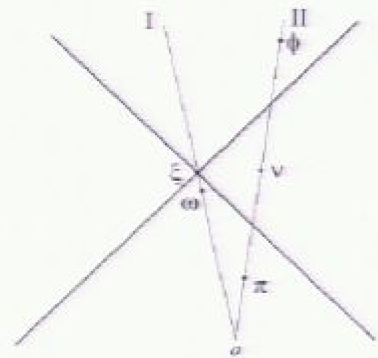
Looking Backward



- The indeterminist will say that if EPR are correct, their argument *should* work in the backward-looking case.
  - ❖ We have the relevant probability *and* no disturbance
- But she will insist that it *doesn't* work
  - ❖ Just as an actual result at ξ doesn't fix a merely possible result at ω, so an actual result at ξ doesn't fix a merely possible result in ξ's causal past.

Adobe Acrobat Professional - [Slides for Perimeter.pdf]

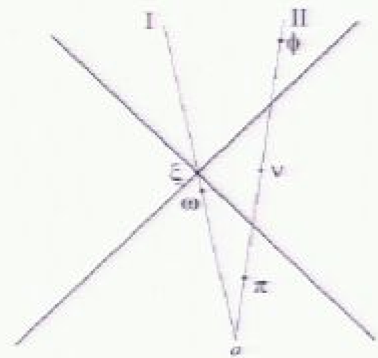
Looking Backward



- The indeterminist will say that if EPR are correct, their argument *should* work in the backward-looking case.
  - ❖ We have the relevant probability *and* no disturbance
- But she will insist that it *doesn't* work
  - ❖ Just as an actual result at ξ doesn't fix a merely possible result at ω, so an actual result at ξ doesn't fix a merely possible result in ξ's causal past.

18 of 50

Looking Forward



Suppose instead:

- A is measured at ξ with result a_k (as before)
- II is not measured before ϕ.
- We have

$$P_\phi \rightarrow p_k$$

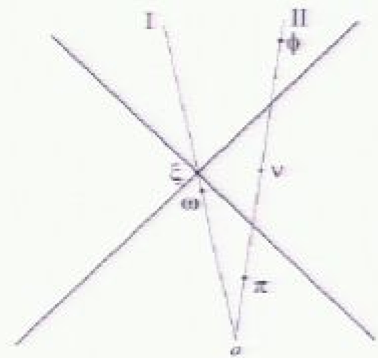
- We also have

$$\mathrm{pr}(p_k | \mathbb{X} \,\&\, P_\phi) = 1$$

QUESTION: Should we accept

$$P_\phi \;\Box\!\!\rightarrow p_k$$

Looking Forward



Suppose instead:

- A is measured at ξ with result a_k (as before)
- II is not measured before ϕ.
- We have

$$P_\phi \rightarrow p_k$$

- We also have

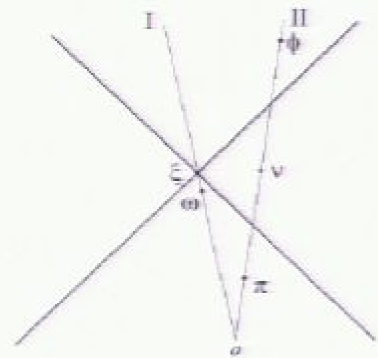
$$\mathrm{pr}(p_k | \mathbb{X} \,\&\, P_\phi) = 1$$

QUESTION: Should we accept

$$P_\phi \;\square\!\!\rightarrow p_k$$

Looking Backward

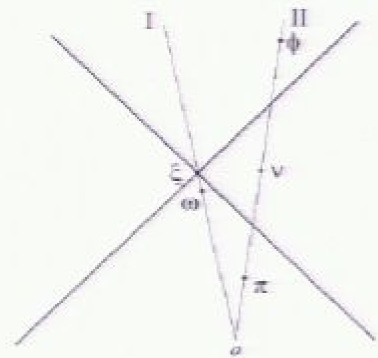
- Consider two particles, *I* and *II*, in the state Ψ described above.
- *I* is first measured at ξ, with result a_k.
- *II* is measured at most once.



("πast," νow," "ϕuture")

Looking Backward

- Consider two particles, I and II, in the state Ψ described above.
- I is first measured at ξ, with result a_k.
- II is measured at most once.



("πast," νow," "ϕuture")

Adobe Acrobat Professional - [Slides for Perimeter.pdf]

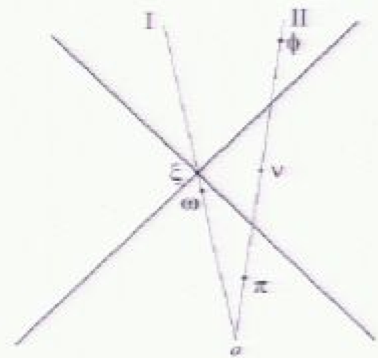
Looking Backward

- If P was actually measured at π, the result was p_k:

$$P_\pi \rightarrow p_k$$

- The following probability holds:

$$\mathrm{pr}(p_k | \mathbb{X} \;\&\; P_\pi) = 1$$



But supposing *II wasn't* measured at or before π, the indeterminist will *deny*

$$P_\pi \;\Box\!\!\rightarrow p_k$$

She will assert both

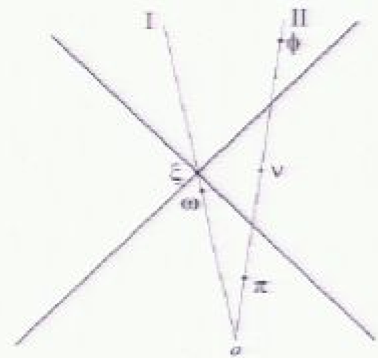
$$(P_\pi \Diamond\!\!\rightarrow p_k) \textit{ and } (P_\pi \Diamond\!\!\rightarrow \text{not-}p_k)$$

Wireless Network Connection is now connected
Connected to: GuestPass(unsecured)
Signal Strength: Very Good

17 of 50

Looking Backward

- Consider two particles, *I* and *II*, in the state Ψ described above.
- *I* is first measured at ξ, with result a_k.
- *II* is measured at most once.



("πast," νow," "ϕuture")

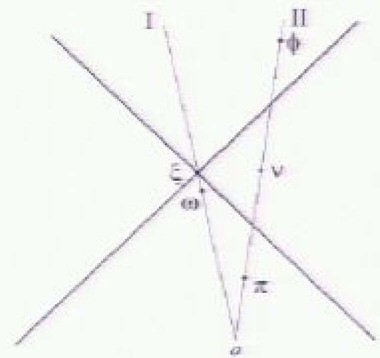
Looking Backward

- If P was actually measured at π, the result was p_k:

$$P_\pi \rightarrow p_k$$

- The following probability holds:

$$\mathrm{pr}(p_k | \mathbb{X} \,\&\, P_\pi) = 1$$



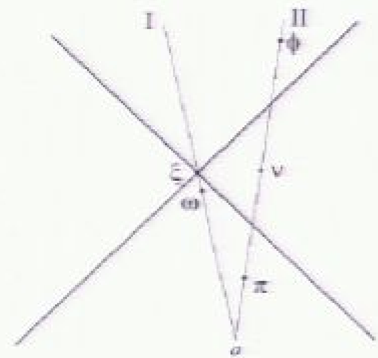
But supposing *II wasn't* measured at or before π, the indeterminist will *deny*

$$P_\pi \,\Box\!\!\rightarrow p_k$$

She will assert both

$$(P_\pi \Diamond\!\!\rightarrow p_k) \textit{ and } (P_\pi \Diamond\!\!\rightarrow \text{not-}p_k)$$

Looking Backward



- If P was actually measured at π, the result was p_k:

$$P_\pi \rightarrow p_k$$

- The following probability holds:

$$\mathrm{pr}(p_k | \mathbb{X} \,\&\, P_\pi) = 1$$

But supposing *II wasn't* measured at or before π, the indeterminist will *deny*

$$P_\pi \,\Box\!\!\rightarrow p_k$$

She will assert both

$$(P_\pi \Diamond\!\!\rightarrow p_k) \text{ } \mathit{and} \text{ } (P_\pi \Diamond\!\!\rightarrow \text{not-}p_k)$$

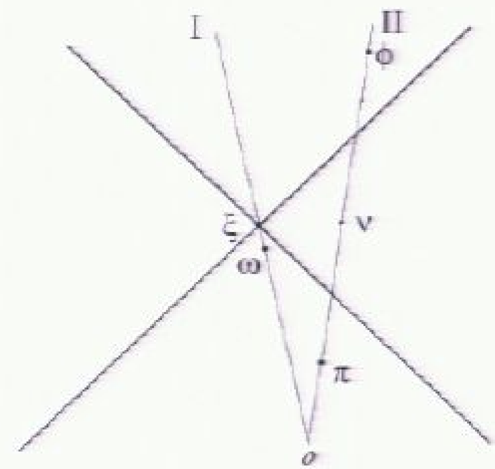
Looking Backward

- If P was actually measured at π, the result was p_k:

$$P_\pi \rightarrow \boldsymbol{p}_k$$

- The following probability holds:

$$\mathrm{pr}(\boldsymbol{p}_k | \mathbb{X}\ \&\ P_\pi) = 1$$



But supposing *II wasn't* measured at or before π, the indeterminist will *deny*

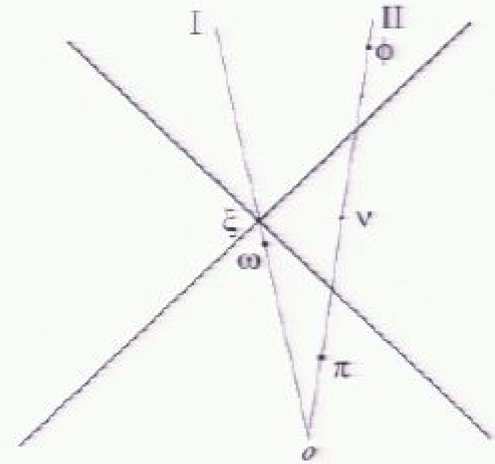
$$P_\pi \ \square\!\!\rightarrow \boldsymbol{p}_k$$

She will assert both

$$(P_\pi \Diamond\!\!\rightarrow \boldsymbol{p}_k)\ \textit{and}\ (P_\pi \Diamond\!\!\rightarrow \text{not-}\boldsymbol{p}_k)$$

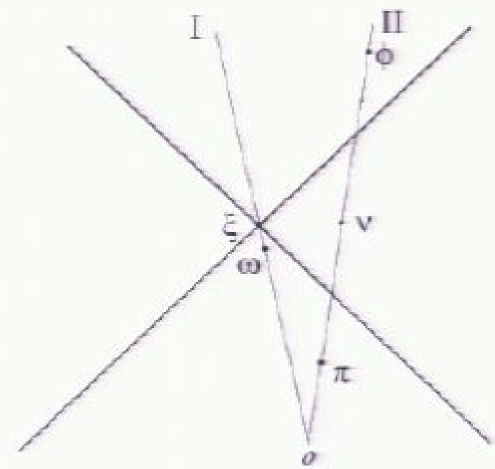
Looking Backward

- The indeterminist will say that if EPR are correct, their argument *should* work in the backward-looking case.
    - We have the relevant probability *and* no disturbance



- But she will insist that it *doesn't* work
    - Just as an actual result at ξ doesn't fix a merely possible result at ω, so an actual result at ξ doesn't fix a merely possible result in ξ's causal past.

Looking Forward



Suppose instead:

- A is measured at ξ with result a_k (as before)
- II is not measured before ϕ.
- We have

$$P_\phi \to \boldsymbol{p}_k$$

- We also have

$$\mathrm{pr}(\boldsymbol{p}_k | \mathbb{X} \,\&\, P_\phi) = 1$$

QUESTION: Should we accept

$$P_\phi \;\Box\!\!\rightarrow\; p_k$$

Looking Forward

The Indeterminist's Answer:

Quite possibly.

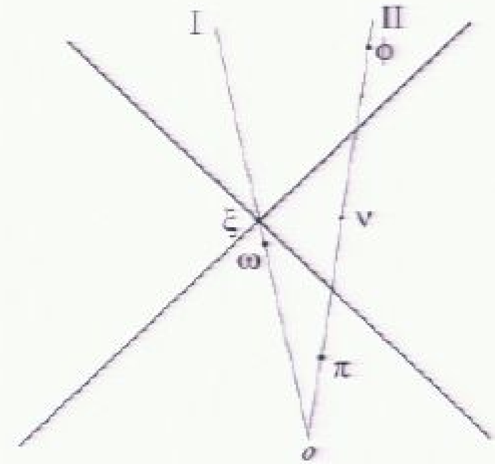
- No conflict with relativity
- Alice could phone Bob and give him useful, apparently counterfactual-supporting information about *II*.

But...

- *Does this help EPR?*

The indeterminist will say *No.*

Looking Forward



Simultaneous Values

- Suppose Alice had measured *B* instead of *A*
- The indeterminist says:

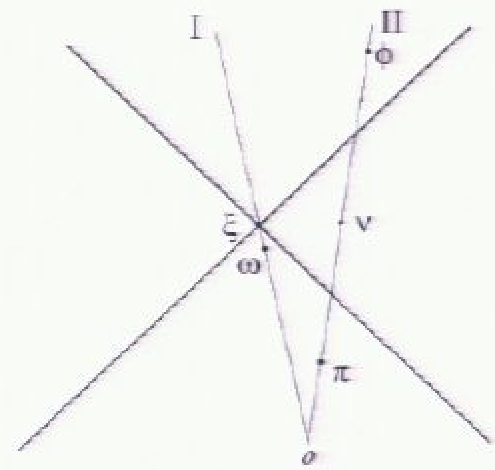
  We *don't* have

  $(B_\xi \;\square\!\!\rightarrow\; \boldsymbol{b}_1)$ or $(B_\xi \;\square\!\!\rightarrow\; \boldsymbol{b}_2)$ or...

  We only have

  $B_\xi \;\square\!\!\rightarrow\; (\boldsymbol{b}_1$ or $\boldsymbol{b}_1$ or...)
- No reason to infer a definite value for *B*, hence no reason to ascribe a parallel *Q*-element of reality to *II*.

Looking Forward



No-Disturbance

- Suppose the indeterminist accepts $P_\phi \Box\!\!\rightarrow p_k$ – hence, a *P* element of reality for *II* at ϕ.
- Had Alice made her *A*-measurement at ω, the result *might* have been a_j.
- If Alice had measured *A* at ω and found a_j, she would have inferred that $P_\phi \Box\!\!\rightarrow p_j$ rather than $P_\phi \Box\!\!\rightarrow p_k$. And so

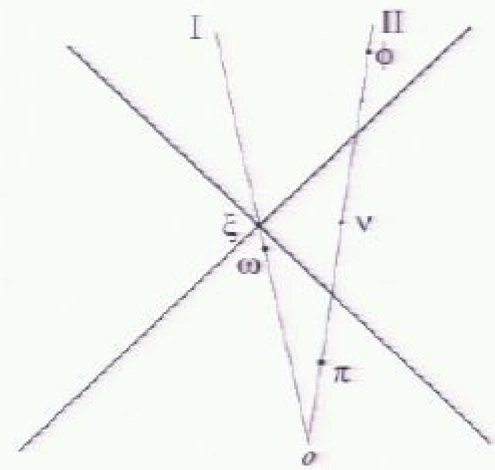
> Had Alice made her measurement at ω rather than ξ, the element of reality at ϕ might have been different.

That is, $(A_\omega \Diamond\!\!\rightarrow a_j)$, $(A_\omega \,\&\, a_j) \Box\!\!\rightarrow (P_j \Box\!\!\rightarrow p_j) \;\therefore\; A_\omega \Diamond\!\!\rightarrow (P_j \Box\!\!\rightarrow p_j)$ is valid.

Looking Forward

Don't like this conclusion?

- You can avoid it by refusing the inference from $\mathbb{X}$ to $P_{\phi} \Box\!\!\rightarrow p_k$
- In that case, however, the EPR argument doesn't get off the ground.

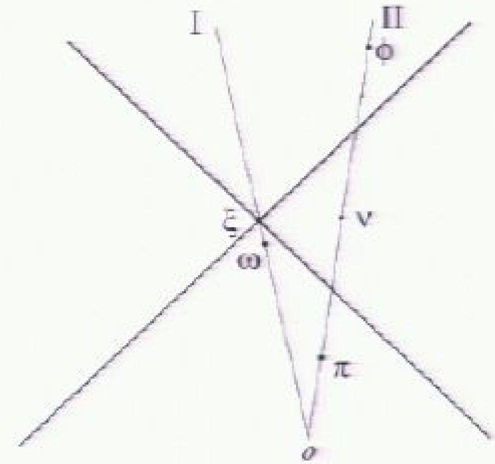


Looking Forward

Summing up:

- To infer simultaneous values in the Forward-Looking Case, you need to accept Counterfactual Definiteness in a case where the indeterminist has no reason to agree
- If you accept the inference from $\mathbb{X}$ to $P_\phi \Box\!\!\rightarrow p_k$, the No-Disturbance condition comes into doubt
- If you reject the inference from $\mathbb{X}$ to $P_\phi \Box\!\!\rightarrow p_k$, the EPR argument can't even get started.

Interlude



- The indeterminist has good reason to resist the EPR argument in the Backward-Looking *and* Forward-Looking cases.
- It would be very peculiar if the argument was somehow acceptable in the case of space-like separated measurements

Looking Elsewhere

Suppose instead:

- A is measured at ξ with result a_k (as before)
- II is not measured before ν.
- We have

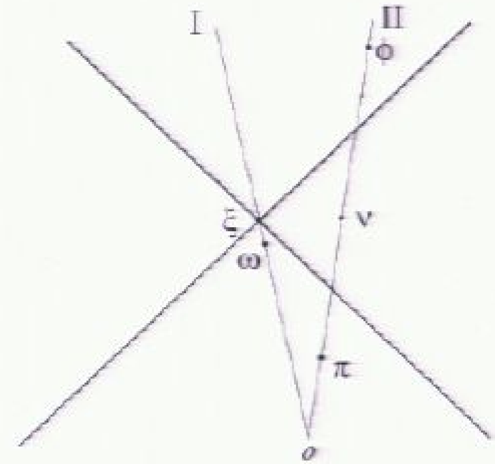
$$P_\nu \rightarrow \boldsymbol{p}_k$$

- We also have

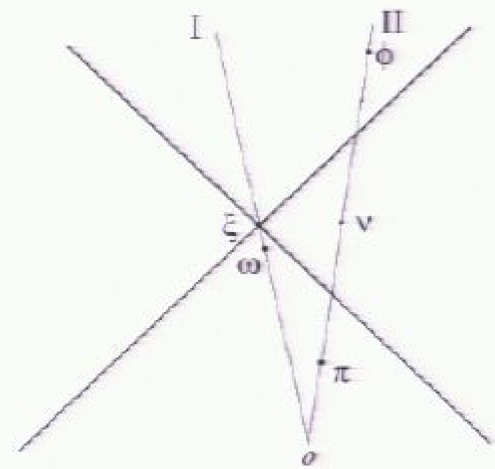
$$\mathrm{pr}(\boldsymbol{p}_k | \mathbb{X} \,\&\, P_\nu) = 1$$

QUESTION: Should we accept

$$P_\nu \;\Box\!\!\rightarrow \boldsymbol{p}_k$$



Looking Elsewhere



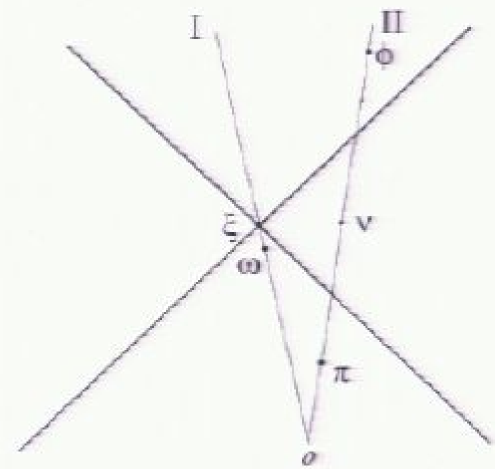
Coming at it another way…

- Suppose $\mathbb{X}$, as before
- Is P_ν □→ p_k more like P_ϕ □→ p_k?
- Or is it more like P_π □→ p_k?

No good reason to pick P_ϕ □→ p_k. But…

Suppose otherwise.

Looking Elsewhere



Inferring $\boldsymbol{P}_\nu \;\Box\!\!\rightarrow \boldsymbol{p}_k$ from $\mathbb{X}$ recreates the problems of the Forward-Looking Case.

- We have no reason to infer *simultaneous* values for P and Q

  Because the indeterminist will deny that there's a definite (though unmeasured) B-value.

- We have the same dependence of the element of reality for II on the measurement outcome for I.

  Because had Alice measured A at ω rather than ξ, the result might not have been a_k, hence the counterfactual inferred might not have been $\boldsymbol{P}_\nu \;\Box\!\!\rightarrow \boldsymbol{p}_k$.

Interim Summary:

From the point of view of Orthodox Indeterminism, EPR's argument fails long before we arrive at Bell-type results.

Bell-type results are simply the icing on the cake

- They show that what seemed intuitively to be a bad idea in the Elsewhere-Oriented Case can't be carried out anyway.

Thus:

- Accepting $\mathbb{X}$ and $\mathrm{pr}(\boldsymbol{p}_k|\mathbb{X} \,\&\, \boldsymbol{P})$ does *not* require attributing an "element of reality" to system *II*.
- The EPR illusion is a product of bad habits in thinking counterfactually.

Thinking About Correlations and States

The indeterminist accepts counterfactuals like

$$(A \,\&\, P) \;\Box\!\!\rightarrow\; [(a_1 \,\&\, p_1) \text{ or } (a_2 \,\&\, p_2) \text{ or} \ldots]$$

without accepting

$$[(A \,\&\, P) \;\Box\!\!\rightarrow\; (a_1 \,\&\, p_1)] \text{ or } [(A \,\&\, P) \;\Box\!\!\rightarrow\; (a_2 \,\&\, p_2)] \text{ or } \ldots$$

and *without* accepting

$$[A \;\Box\!\!\rightarrow\; a_1] \text{ or } [A \;\Box\!\!\rightarrow\; a_2] \text{ or } \ldots$$
$$[P \;\Box\!\!\rightarrow\; p_1] \text{ or } [P \;\Box\!\!\rightarrow\; p_2] \text{ or } \ldots$$

Thinking About Correlations and States

- We will *not* assume that quantum systems always have quantum states even if (?) they do always have some ontological state.
- We will *not* assume that there is always a best answer to the question "What is the quantum state?"
- We will *not* assume that ascribing a quantum state amounts to attributing an "element of reality."

States

The *eigenvalue-eigenstate link* holds that a quantity X has a value (element of reality) x if and only if the state ψ satisfies

$$X\psi = x\psi.$$

The indeterminist rejects the E-E link. She will claim:

- It can make good sense to assign a state $|X=x>$ *without* claiming that X has the value x. But...
- When we know that a measurement counterfactual is true, we should assign the corresponding state.

Put crudely: we can't reason from states to elements of reality, but we can sometimes reason from elements of reality to states.


LV
LX

Caveats and Comments

We have set the measurement problem aside

We have relied on idealizations.

- But idealizations are ubiquitous and, lifting them won't resuscitate EPR

The view on offer is a species of orthodoxy

But may help reframe issues such as

- Hyperplane dependence
- "Correlations without correlate"

And with luck, will contribute to "quantum metaphysical modesty."