Title: Nonlocality via Constrained Colliders

Speakers: Huw Price

Series: Quantum Foundations, Quantum Information

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Abstract: We propose that Bell correlations are explicable as a combination of (i) collider bias and (ii) a boundary constraint on the collider variable. We show that the proposal is valid for a special class of ('W-shaped') Bell experiments involving delayed-choice entanglement swapping, and argue that it can be extended to the ordinary ('V-shaped') case. The proposal requires no direct causal influence outside lightcones, and may hence offer a way to reconcile Bell nonlocality and relativity.

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Entanglement via Constrained Colliders

Huw Price & Ken Wharton*

CausalWorlds 2024

* Based on ‘A mechanism for entanglement?’ – arXiv:2406.04571

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Penrose (2004) on ‘the mysteries of quantum entang

> “The first mystery is the phenomenon itself. How are we to come to terms with quantum entanglement and to make sense of it in terms of ideas that we can comprehend, so that we can manage to accept it as something that forms an important part of the workings of our actual universe?”

Our aim: To throw some light on this.

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Main proposal

Bell correlations can be explained as a special sort of **selection artefact**, or **‘collider bias’**.

Contents

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1. Colliders, collider bias, and constrained colliders
2. Constrained colliders in QM – special cases
3. Constrained colliders in QM – ordinary cases (I)
4. The Unpinned Regime
5. Constrained colliders in QM – ordinary cases (II)

Colliders and collider bias

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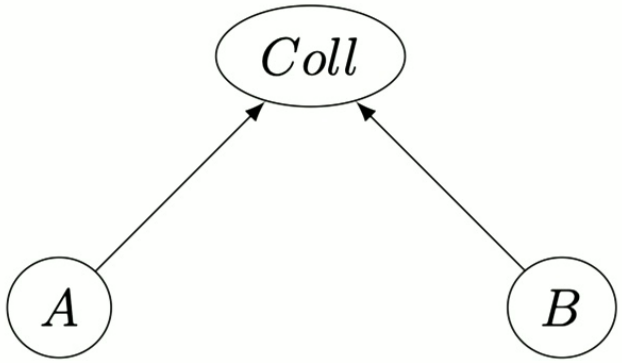
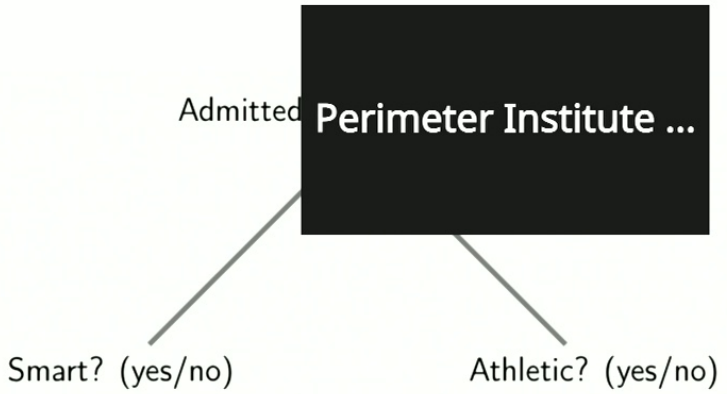


1. A **collider** is a variable with more than one contributing cause (depicted in DAGs by converging arrows).
2. If we **postselect** ("condition on") the cases in which this variable takes a particular value, we often find a correlation between the causes **A** and **B**.
3. This can look like a **causal** correlation, but it's a **causal artefact** – the result of **selection bias**, or **collider bias**.

Example: Ivy College*

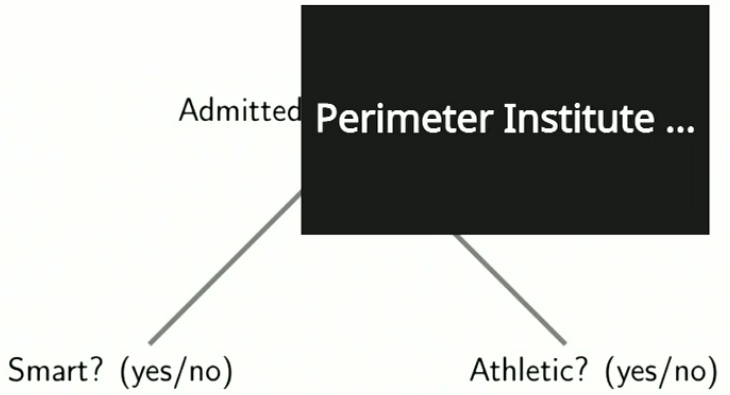
1. Suppose Ivy College selects students for academic ability and athletic ability, not requiring both – and that these are independent in the general population.
2. The admission test looks like this. Kids need a yes on at least one of the lower questions, to get a yes at the top.



* Example borrowed from George Davey Smith.

Example: Ivy College*

1. Suppose Ivy College selects students for academic ability and athletic ability, not requiring both – and that these are independent in the general population.
2. The admission test looks like this. Kids need a yes on at least one of the lower questions, to get a yes at the top.
3. Imagine you're on campus at Ivy, and you throw a ball to a random student.
4. It hits them on the head and they fall over. They're not athletic, so they must be smart.
5. Among Ivy students, then, there's a correlation between the two kinds of ability. If they don't have one, they must have the other.
6. This might look like a causal correlation, but it's selection bias, or collider bias.



* Example borrowed from George Davey Smith.

Collider bias doesn't support counterfactu

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1. Suppose that Holly is an Ivy track star, who struggles to get As.
2. Would she have been smarter if she had been less athletic?
3. **No.** If she'd been less athletic, she wouldn't have made the cut for admission to Ivy in the first place.

Constrained colliders

1. Now imagine that Holly has a Fairy Godmother.
2. Fairy Godmother (FG) has decreed that Holly **shall** be admitted to Ivy, one way or the other.
3. So FG has **constrained** the collider variable, setting it to the positive value.
4. FG can't change the admission rules. All she can do is to make sure that Holly qualifies.
5. So now it's **true** that if Holly had been less athletic, she would have been smarter – FG would have taken care of it.
6. In other words: **constrained colliders do support counterfactuals.**

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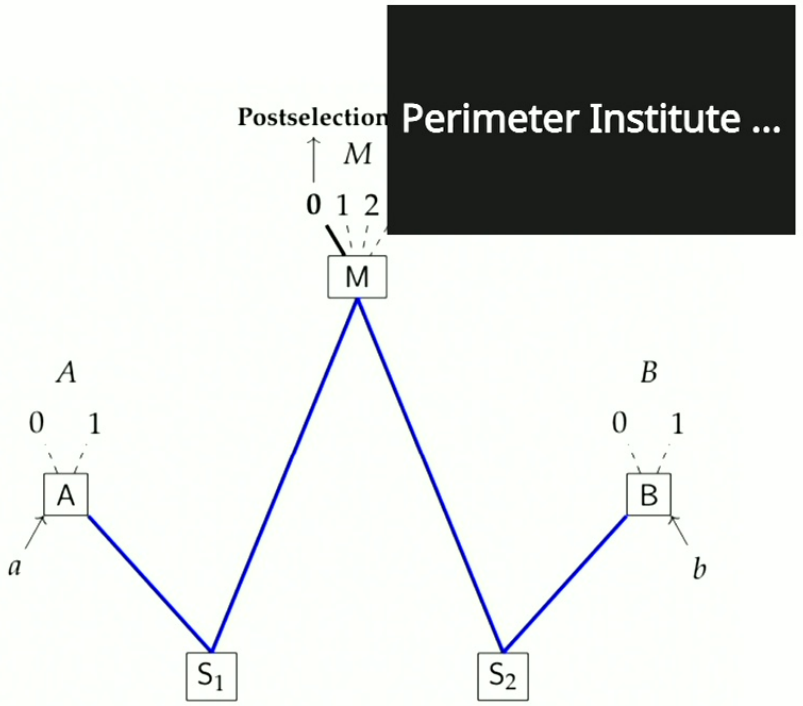
Delayed choice ‘W-shaped’ Bell experiments

1. Two sources, at S_1 and S_2, each produce a pair of entangled particles.
2. The inner particles from each pair go to a measurement at **M**, which has four possible results.
3. If we **postselect** the cases where this result is the same – say, all the **0** cases – then the outer pair of particles behave as though they are entangled. This is **entanglement swapping**.



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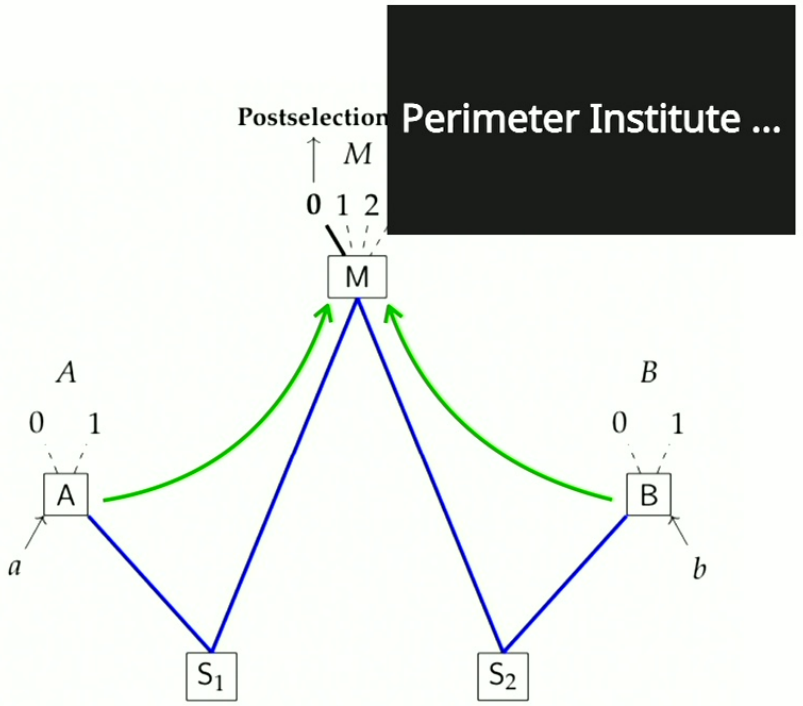
Delayed choice W-shaped Bell experiments

1. We can do Bell experiments in this format, and find Bell correlations between A and B.
2. Does that mean, in Bell's words, that the outcome at B can be affected by the measurement choice at A?
3. **Not necessarily!** As long as the result at M can be influenced by the settings choices at A and B, then it's a collider, and the Bell correlations between A and B can be collider bias.
4. As we saw in Holly's case, collider artefacts don't support counterfactuals. If changes at A can make a difference at M, there's no need for them to make a difference at B.



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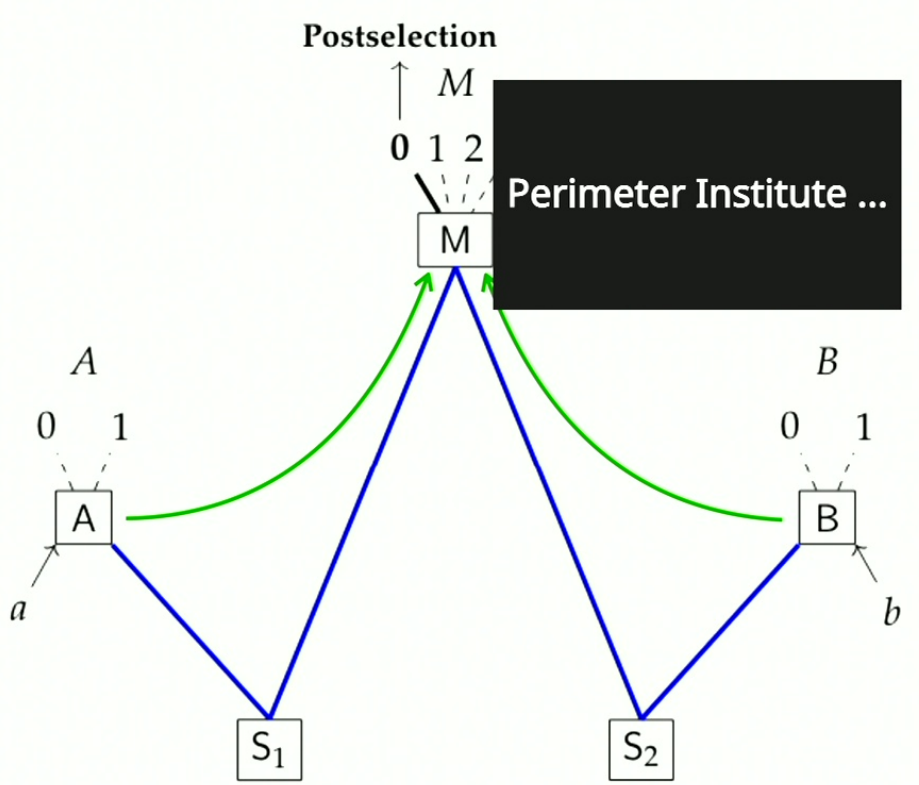
A toy model

1. Imagine you have these materials.
2. You could build a W so that a small movement on one side produced a small movement on the other.
3. But if you loosen the joint in the middle a little, you could make this connection go away.
4. The freedom of movement in the middle acts as a kind of **safety valve**, so that changes on the left needn't produce changes on the right.
5. That's what the options at M give us – a **safety valve**, so that changes to the measurement at A needn't affect the measurement result at B.
6. So in this special kind of Bell experiment, Bell correlations between A and B needn't imply nonlocality **across the W**.



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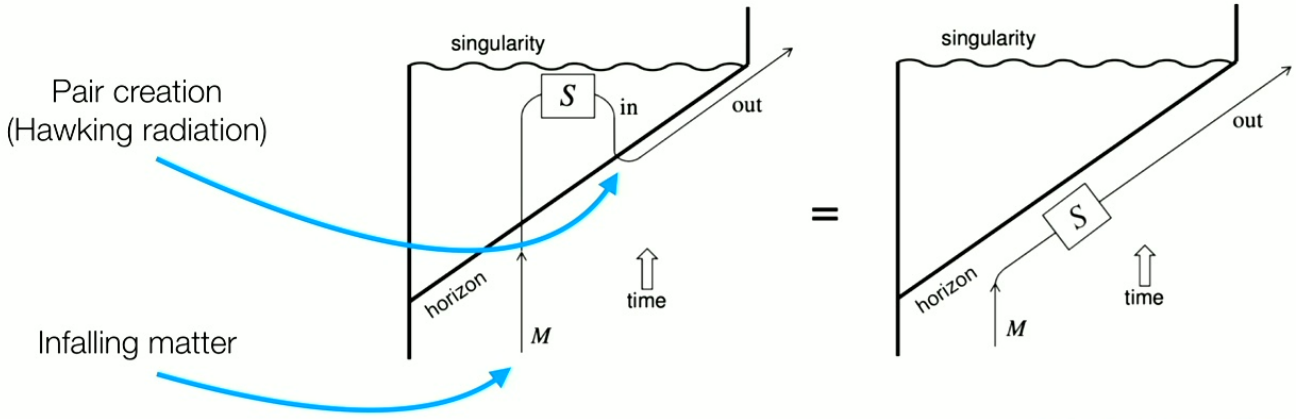
Delayed-choice entanglement swapping experiments: No evidence for timelike entanglement

Jørn Kløvfjell Mjelva

The Horowitz-Maldacena hypothesis



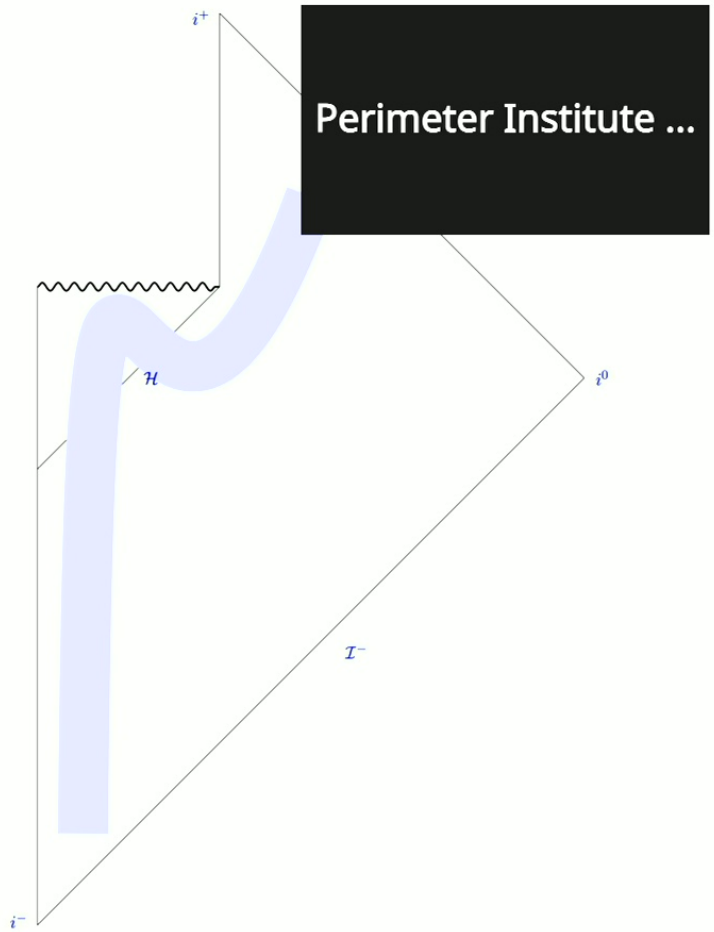
The Horowitz–Maldacena proposal (from [Lloyd & Preskill 2014])

"In the process of black hole evaporation, particles are created in correlated pairs with one falling into the black hole and the other radiated to infinity. The correlations remain even when the particles are widely separated. The final state boundary condition at the black hole singularity acts like a measurement that collapses the state into one associated with the infalling matter. This transfers the information to the outgoing Hawking radiation in a process similar to quantum teleportation." [Horowitz & Maldacena 2004]

Perry's zigzag 'flow of quantum information'

"Penrose diagram of a black hole that evaporates completely together with a river showing the expected flow of quantum information. … The interior of the black hole is therefore a strange place where one's classical notions of causality … are violated. This does not matter as long as outside the black hole such pathologies do not bother us." [Perry 2021]

Our claim: Such pathologies have been actually been bothering us for almost a century, because entanglement is much the same thing – though it relies on something much more common than black holes.



Horowitz-Maldacena meets delayed choice entanglemen

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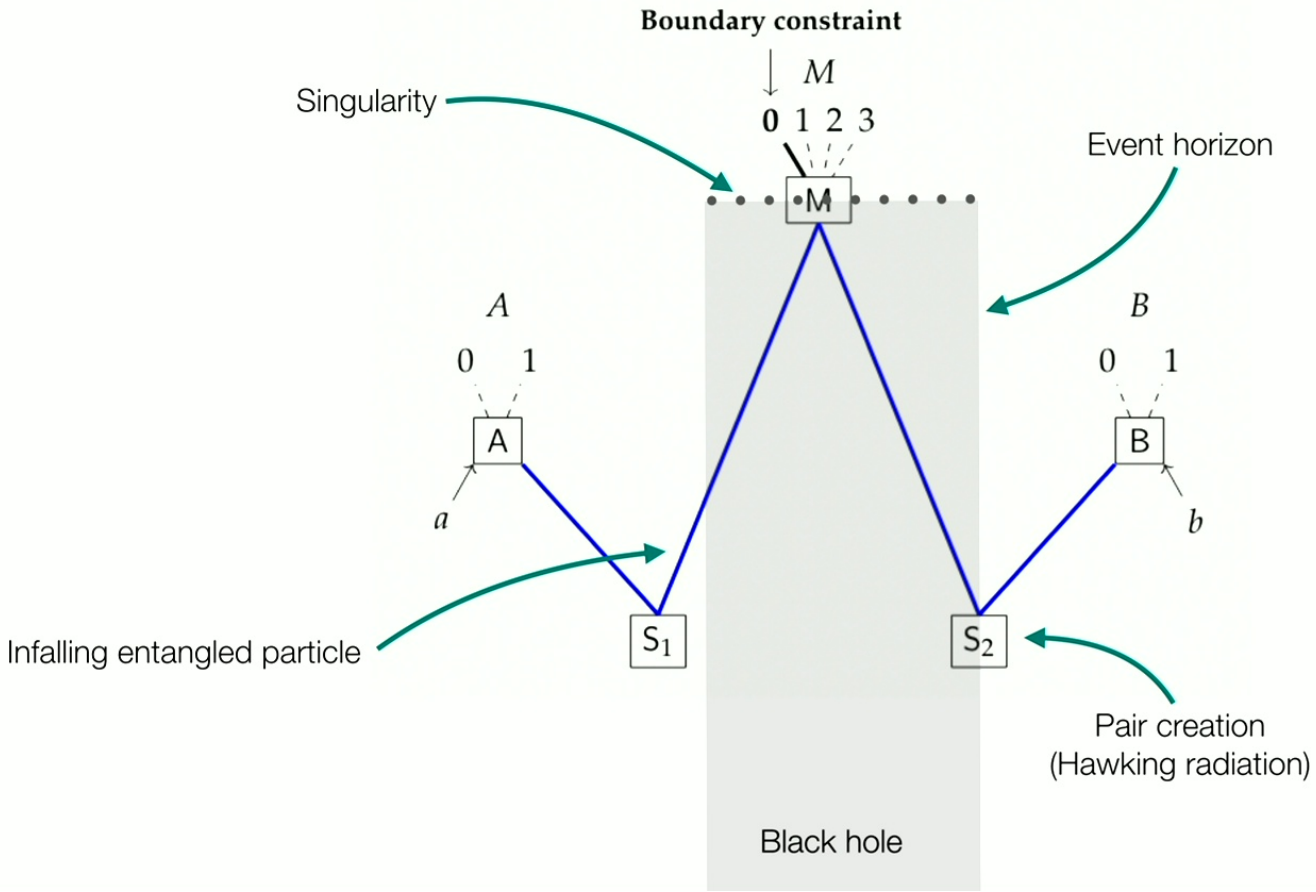

Where we are

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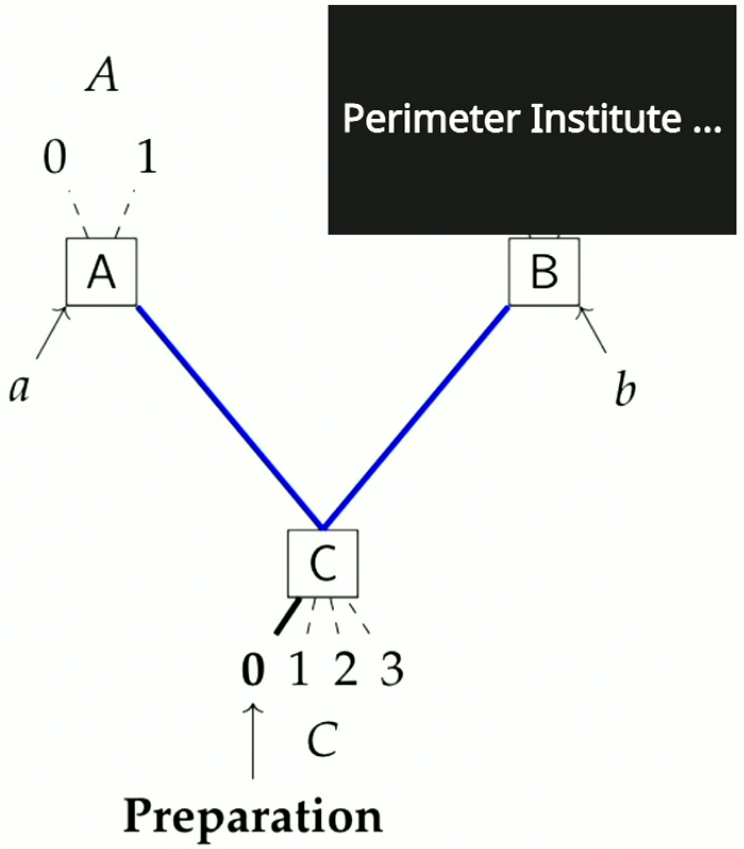
We have seen how in a very special kind of case – a W-shaped delayed-choice Bell experiment, with the central measurement inside a Horowitz-Maldacena black hole – Bell nonlocality can be a combination of two things:

1. Collider bias
2. A constraint on the collider, locking it to one value.

The last step is to show that the same explanation works in much more ordinary cases.

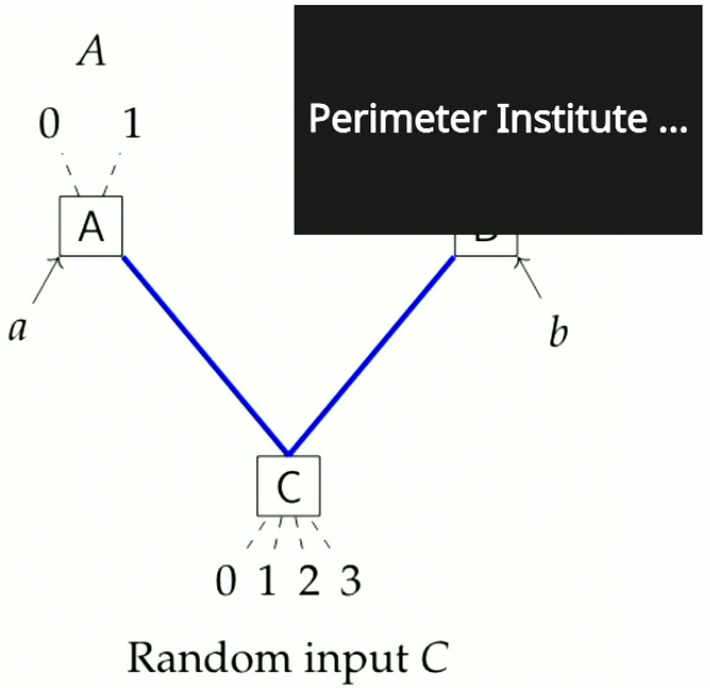
‘V-shaped’ Bell experiments

1. The source at **C** produces pairs of entangled particles in one of four possible states (0, 1, 2 or 3), chosen by the experimenter. (In the case shown it is state **0**.)
2. The two entangled particles go to measurements at **A** and **B**, where the experimenters choose a setting (*a* and *b*), and record an outcome (*A* and *B*).
3. As long as we keep the initial state *C* constant, we’ll find Bell correlations in the results.
4. These Bell correlations disappear if the initial state is allowed to vary at random, but we can recover them by ‘pre-selecting’ – i.e., throwing away all the cases except those in which the initial state has one particular value.



V-shaped Bell experiments

1. In other words, we can start with this version of the experiment, in which the initial state *C* is chosen at random.
2. We get no Bell correlations in the experiment as a whole, but we can find them again if we **pre-select** on just one of the initial values – i.e., discard all the other cases.
3. Does this mean we can regard the Bell correlations as mere selection artefacts, just as in the W case?
4. **No, or at least, not yet.** There's still an important difference.



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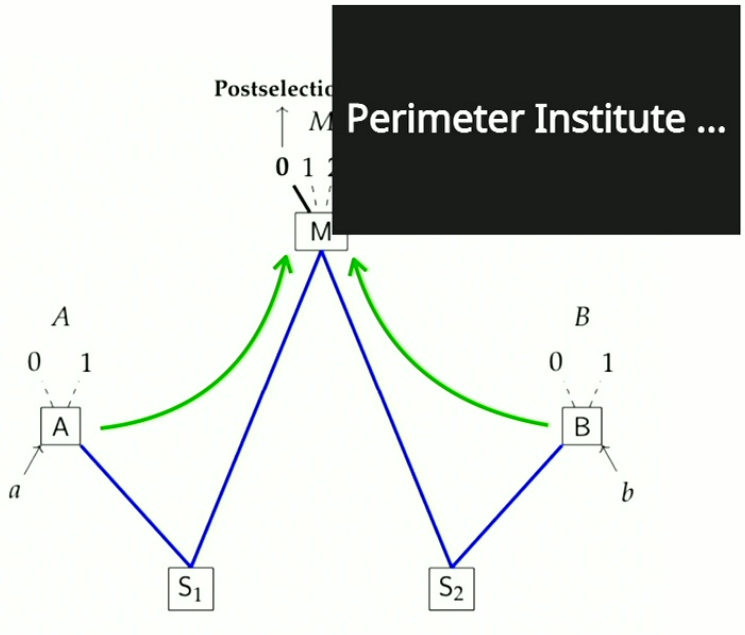
V-shaped Bell experiments

1. In the W case the result at **M** is a collider, influenced by the measurement settings on both sides.
2. That's why it can act as a safety valve, absorbing the effects of changes to the settings (so that there's no need for Bell nonlocality between **A** and **B**).
3. To get the same thing working in the V case, we'd need a causal structure like this.



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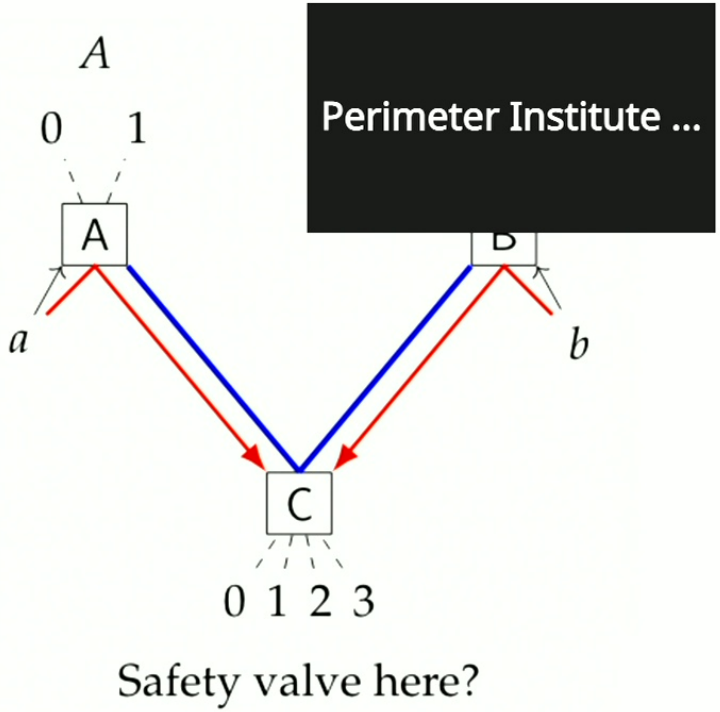
3. To get the same thing working in the V case, we'd need a causal structure like this.
4. But that seems crazy, in the real world. Quantum measurement choices **in the future** don't influence ordinary coin tosses, right?
5. **Right!** And without that, we don't have a collider at **C**, and can't use our story about Bell correlations being collider artefacts.



Safety valve here?

What to do next? (I)

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Think about perspective

What to do next? (II)

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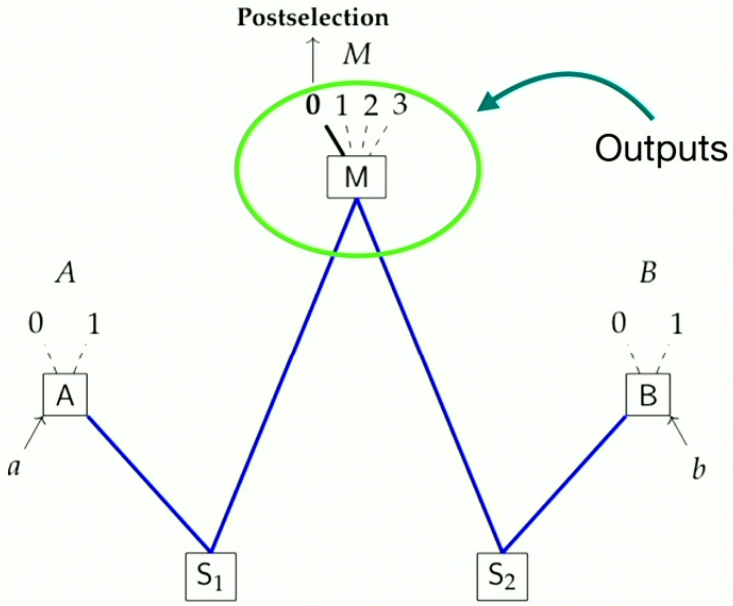

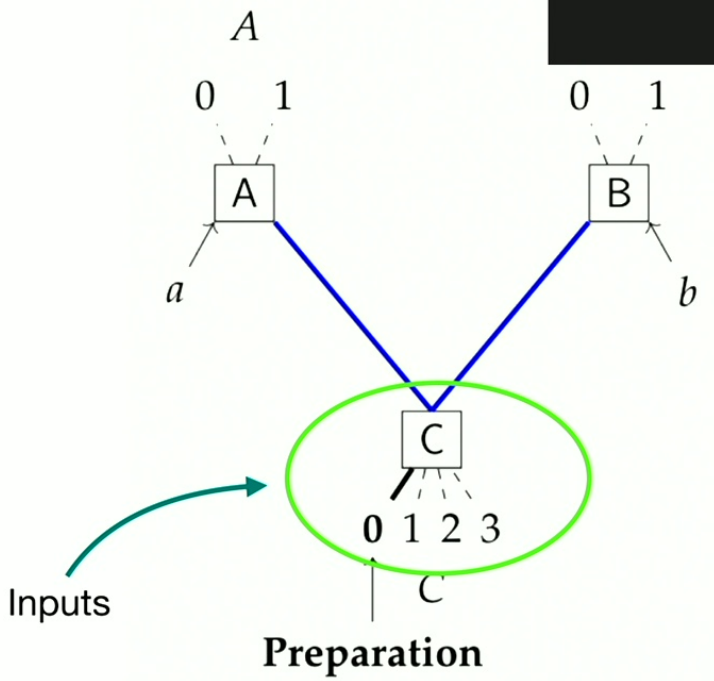

Think about the difference between inputs and outputs

Ordinary time-asymmetries

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- Here are some time-asymmetric features of the world as we encounter it.
  1. The future is **open** but the past is **fixed**.
  2. In ordinary means–end reasoning, our ends are typically **later** in time than our means for achieving those ends.
  3. We typically control the **initial** conditions of experiments, and only indirectly their **final** conditions.
  4. Causation runs **from past to future**, and not vice versa.
- Brushing aside many subtle issues about such asymmetries, let's lump them together under one heading: **Initial Control.**

Whence Initial Control?

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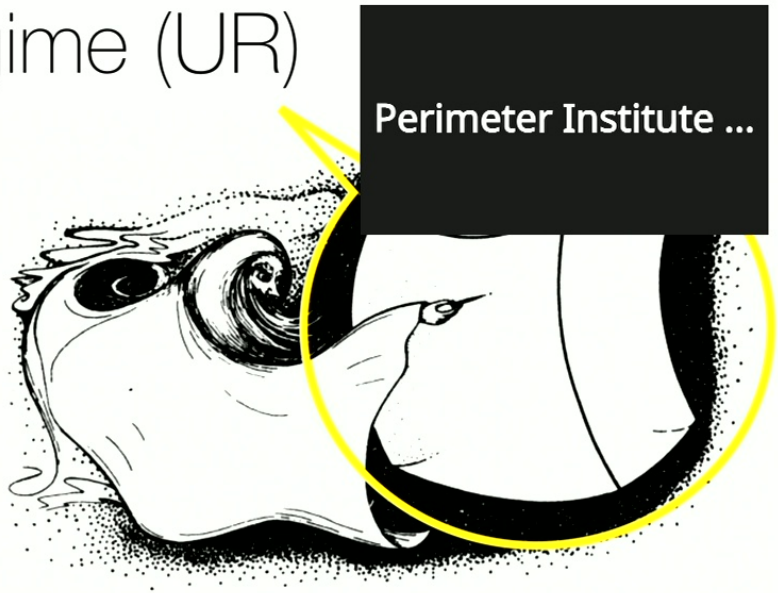
1. Where does Initial Control come from? Why is our universe time-asymmetric in this way?
2. Again, there's a lot of room for disagreement about details, but a lot of agreement about the big picture.
3. This is Penrose's version of the big picture – his depiction of the fact that our universe seems to have begun in an extremely special low entropy state (*aka* the Past Hypothesis).

Fig. 7.19. In order to produce a universe resembling the one in which we live, the Creator would have to aim for an absurdly tiny volume of the phase space of possible universes – about $1/10^{10^{123}}$ of the entire volume, for the situation under consideration. (The pin, and the spot aimed for, are not drawn to scale!)

The Unpinned Regime (UR)

1. Let's focus on the **entire** collection of possible universes, from which Penrose's Creator is making Their choice.
2. By definition, this collection does not have the time-asymmetries that result, in our actual world, from the special initial choice.



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Causation in the Unpinned Regim

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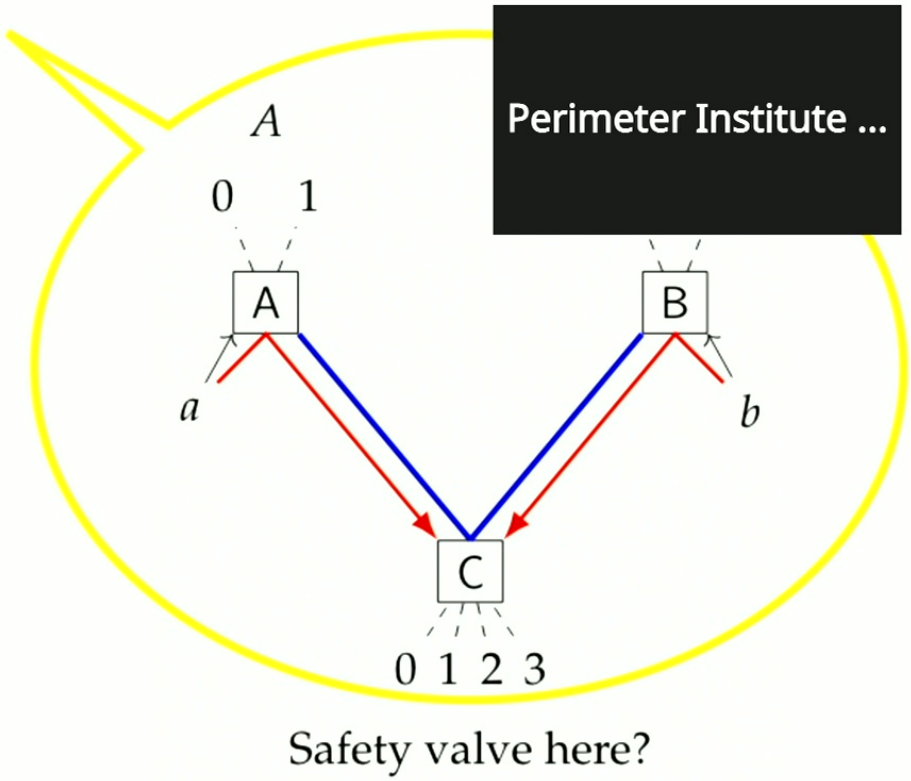
- Can we talk about causation in the UR?
- Yes, apparently, so long as we restrict ourselves to what some physicists think is the only respectable notion, in any case.

> "[I]n physics we believe that there are laws that determine the evolution of the universe uniquely. So if state A evolved into state B, one could say that A caused B. But one could equally well look at it in the other direction of time, and say that B caused A. So causality does not define a direction of time." (Hawking 1994)

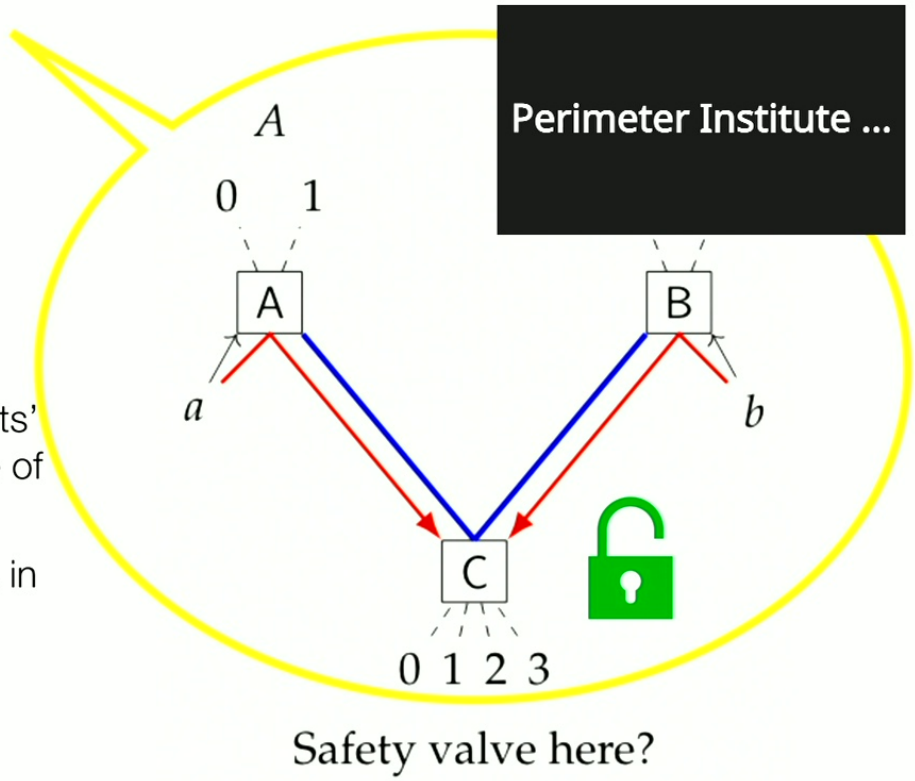
V-shaped Bell experiments in UR-physics

1. Let's go back to this case, but now imagine that it is depicting an 'experiment' happening at random, somewhere in the vast space of possibilities that is UR.



V-shaped Bell experiments in UR-physics

1. Let's go back to this case, but now imagine that it is depicting an 'experiment' happening at random, somewhere in the vast space of possibilities that is UR.
2. Do we have any reason to **deny** that we have the 'effects' shown in red, in Hawking's weak time-symmetric sense of causation?
3. No, because we have explicitly turned off Initial Control, in describing the case.
4. So now the safety valve is open, and everything works just as in the W case: Bell correlations in pre-selected ensembles can be explained as collider artefacts.



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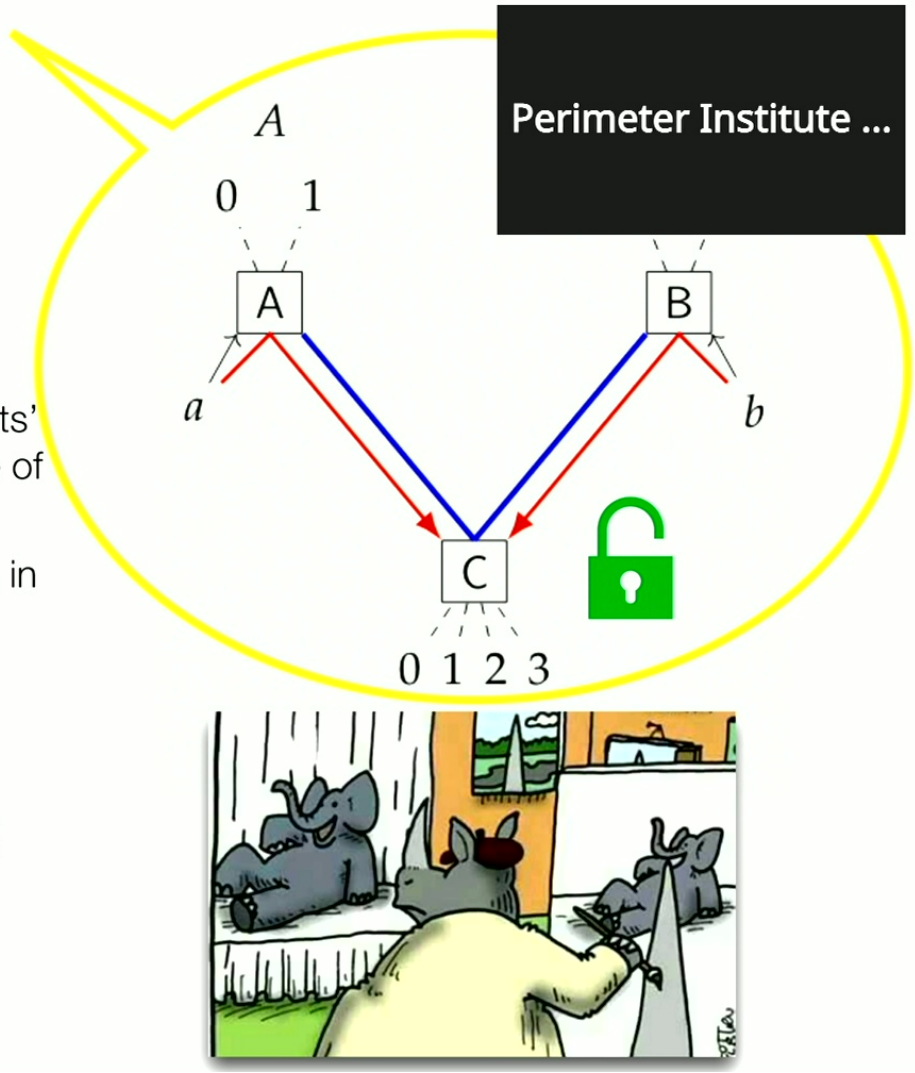
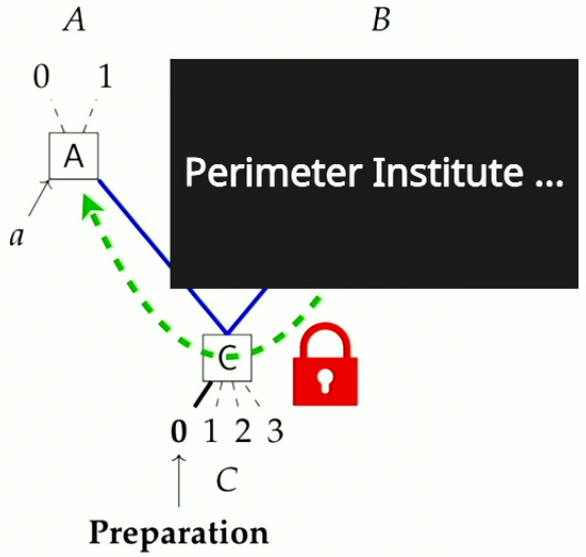
3. No, because we have explicitly turned off Initial Control, in describing the case.
4. So now the safety valve is open, and everything works just as in the W case: Bell correlations in pre-selected ensembles can be explained as collider artefacts.
5. If this seems implausible, you're still stuck in the Pinned Regime.

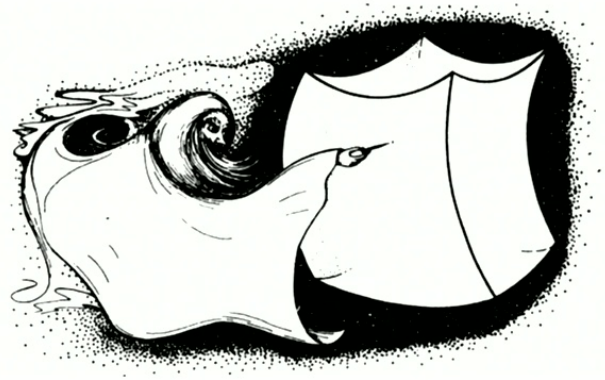


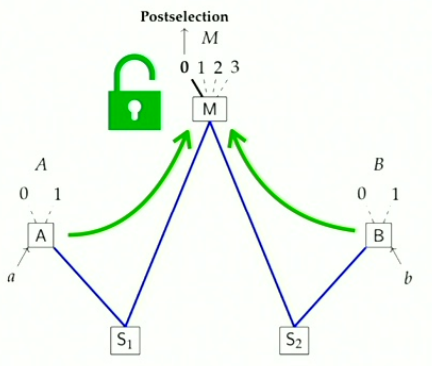
Back to the real world



- Back in the real world, of course, we **are** stuck in the Pinned Regime – downstream from Penrose's Creator's absurdly sharp pin.
- So in the real world, the collider at **C** is (almost always?) constrained.
- This closes the safety valve, so that changes at **A** have to show up at **B**, and vice versa. That's Bell nonlocality.
- But the detour via UR-physics shows us that in this case, like in the constrained W case, nonlocality can be the result of two things:

    1. Collider bias
    2. A boundary constraint on the collider, locking it to one value.





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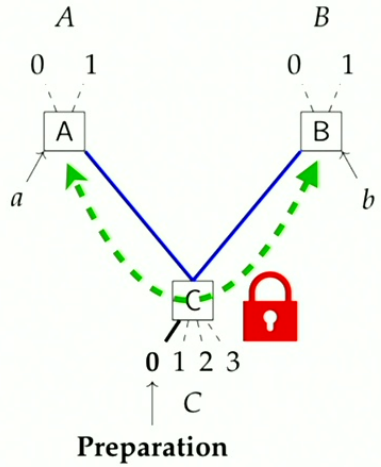
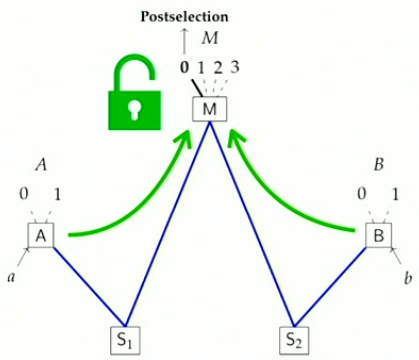
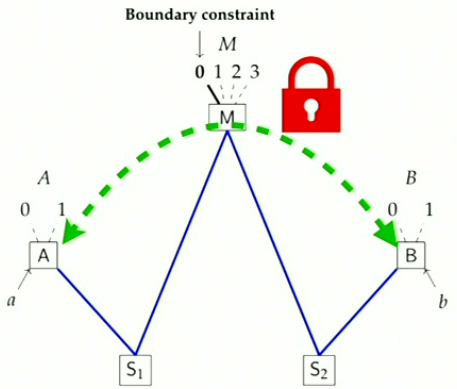
	Unconstrained colliders	Constrained colliders
W	Normal	Exceptional (only in black holes?)
V	Exceptional (only in the UR?)	Normal







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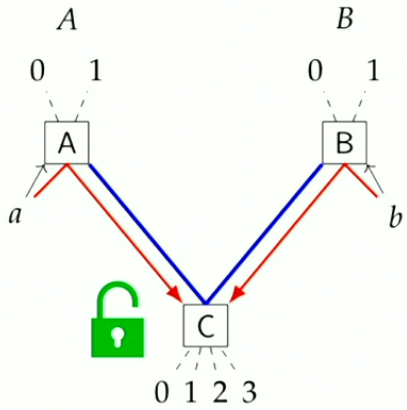

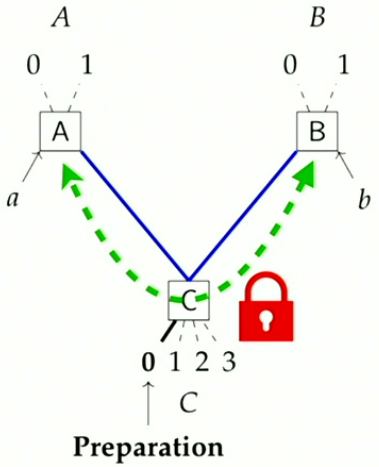

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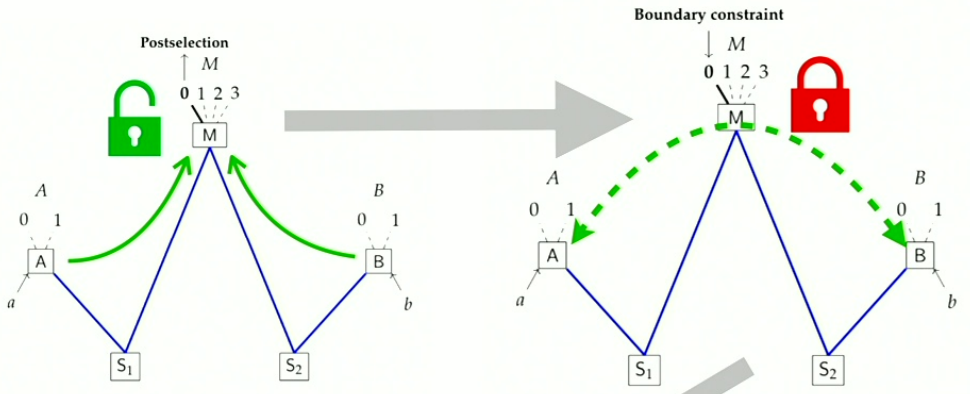
Step 1



	Unconstrained colliders	Constrained colliders
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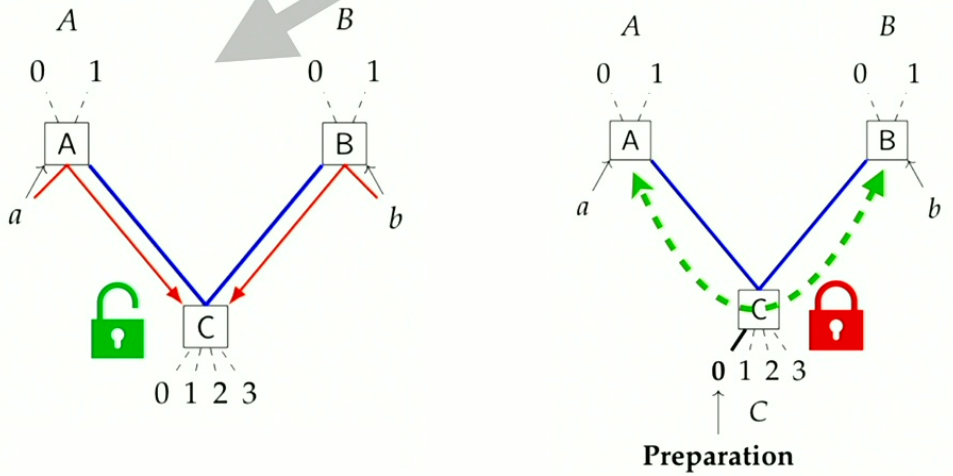
Step 3



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Payoff

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- Penrose on the 'first mystery' of quantum entanglement:

  "How are we to come to terms with quantum entanglement and to make sense of it in terms of ideas that we can comprehend …"

- Colliders and collider bias are familiar – not mysterious at all.
- **Constrained** colliders are not familiar – and not previously named, so far as we know – but they are:
  1. Easy to understand; and

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- **Constrained** colliders are not familiar – and not previously named, so far as we know – but they are:
  1. Easy to understand; and
  2. Staggeringly ubiquitous, once we understand the significance of Penrose's own point about the Creator's pin.

However

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- Penrose on the 'second mystery' of entanglement:

  "[W]hy is it something that we barely notice in our direct experience of the world? Why do these ubiquitous effects of entanglement not confront us at every turn?"

  "I do not believe that this second mystery has received nearly the attention that it deserves, people's puzzlement having been almost entirely concentrated on the first."

- We haven't said anything about that. Suggestions?

A bonus?

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- Bell on the tension between **nonlocality** and **relativity**.

  "[W]e have an apparent incompatibility, at the deepest level, between the two fundamental pillars of contemporary theory …"(Bell 1984)

- If we can explain Bell correlations as a combination of (i) **dependency relations within light cones**, and (ii) **boundary conditions**, then we don't seem to be using any ingredients in tension with relativity.
- It has long been noted that zigzag processes might provide a relativity-friendly key to the issues identified by EPR in 1935.

Thank you*

‘A mechanism for entanglement?’
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