Title: Interpretation of Quantum Theory: Lecture 8

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Abstract:

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The probability problem

Normally probability enters physics through either

1) indeterminism (GRW)
2) ignorance (de Broglie-Bohm; Statistical Mechanics)

Everett has neither

To sharpen the point: suppose we measure many many copies of

$$|\psi\rangle = \alpha|\uparrow\rangle + \beta|\downarrow\rangle$$

The worlds where we get spin up a fraction approximately $|\alpha|^2$ of the time can be proved to have weight very close to one…

… but the worlds with the "wrong" statistics are still real!

What is probability?

Long-run frequency?

But:

- We never see the long run
- We use probability talk even about *single events*
- It's circular: long-run frequencies converge on the probability…

…probably

How do we use probability?

- Inference:

if we see lots of repeats of an experiment and get result x 43% of the time, we conclude that $\Pr(x) = 0.43$

- Decision:

If we know something is highly probable, we'll bet on it; if we know doing x will make y (which is Bad) highly probably, we won't do x, etc.

Is that all there is to probability?

(no)

Subjectivism: probability as a measure of our beliefs

Suppose inference and decision *is* all there is to probability

i.e. "probability" is just a way of coding what agents believe and act

→ *Decision Theory*

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Decision Theory (I)

Suppose we have:

- A set ***S*** of *states*: that is, ways the world could turn out
- A set ***R*** of *rewards:* things we want (or actively don't want)
  e.g. ***R*** could contain various cash prizes

Then a *bet* ***b*** is formally a function from ***S*** to ***R***.

e.g. ***S*** = {Bush wins, Kerry wins}

b(Bush wins)= + $10
b(Kerry wins) = - $10

i.e. just represents a ten-dollar bet on the result of the election.

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Decision Theory (II)

The idea:

Suppose that some agent has a strategy for betting: that is for each pair of bets b_1, b_2 he either

a) prefers b_1 to b_2: $b_1 > b_2$; or
b) prefers b_2 to b_1: $b_1 < b_2$; or
c) is indifferent between b_1 and b_2: $b_1 \sim b_2$

And suppose his strategy obeys certain *principles of rationality:* e.g.

If $b_1 > b_2$ and $b_2 > b_3$ then $b_1 > b_3$

If $b_1(s) > b_2(s)$ for all s in S, then $b_1 > b_2$

(for a full list, see (e.g.) L. Savage, *Foundations of Statistics*)

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Decision Theory (III)

Then (in the right circumstances) we can prove a *representation theorem:*

For any strategy that does obey these principles of rationality, there must exist

- A *unique* positive-valued function Pr on ***S*** satisfying

$$\sum_{s \in S} Pr(s) = 1$$

- A function U on ***R***, unique up to affine transformations U → a U + b

such that $b_1 > b_2$ if and only if

$$\sum_{s \in S} Pr(s)\, U[b_1(s)] > \sum_{s \in S} Pr(s)\, U[b_2(s)]$$

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so…

a “rational agent” must act as if he ascribes probabilities to each event

is this sufficient?

NO

- Probabilities are *personal*: we can talk about “my probability for X” or “Joseph’s probability for X”, but not *the* probability for X

- But physics discovers *objective* probabilities: the probability of a uranium atom decaying is *not* a matter of opinion!

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The Principal Principle

We have:

- Subjective probability: a well defined, well motivated measure of our personal degree of belief… but which is *not* the probability of physics

- Objective probability: the observer-independent probability of physics… but what is it?

Link between them: the *Principal Principle:*

If a rational agent knows that the *objective* probability of X happening is P, he is rationally required to assign *subjective* probability of P to X happening.

…from which you can prove that the inference and decision aspects of objective probability are true.

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What is "objective probability"?

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It's that physical property – *whatever it is* – that makes the Principal Principle true.

Does this make objective probability a subjective, observer-dependent property?

… no

it's a physical thing – but the reason we *call* it "probability" is to do with what rational agents do.

But what could "objective probability" *be?*

i.e., why should the Principal Principle be true for *any* physical property?

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Everett and the Principal Principle

Can we prove that *mod-squared amplitude* satisfies the Principal Principle in the Everett interpretation?
… that is, can we prove that

> *if* an event has mod-squared amplitude P (relative to the agent's initial amplitude)
>
> *then* the agent must assign subjective probability P to that event occurring

If we can…

then we will have *proved* that *mod-squared amplitude is objective probability*

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The counting rule

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It seems impossible to prove this result, because there seem to be so many alternative rules we could choose.

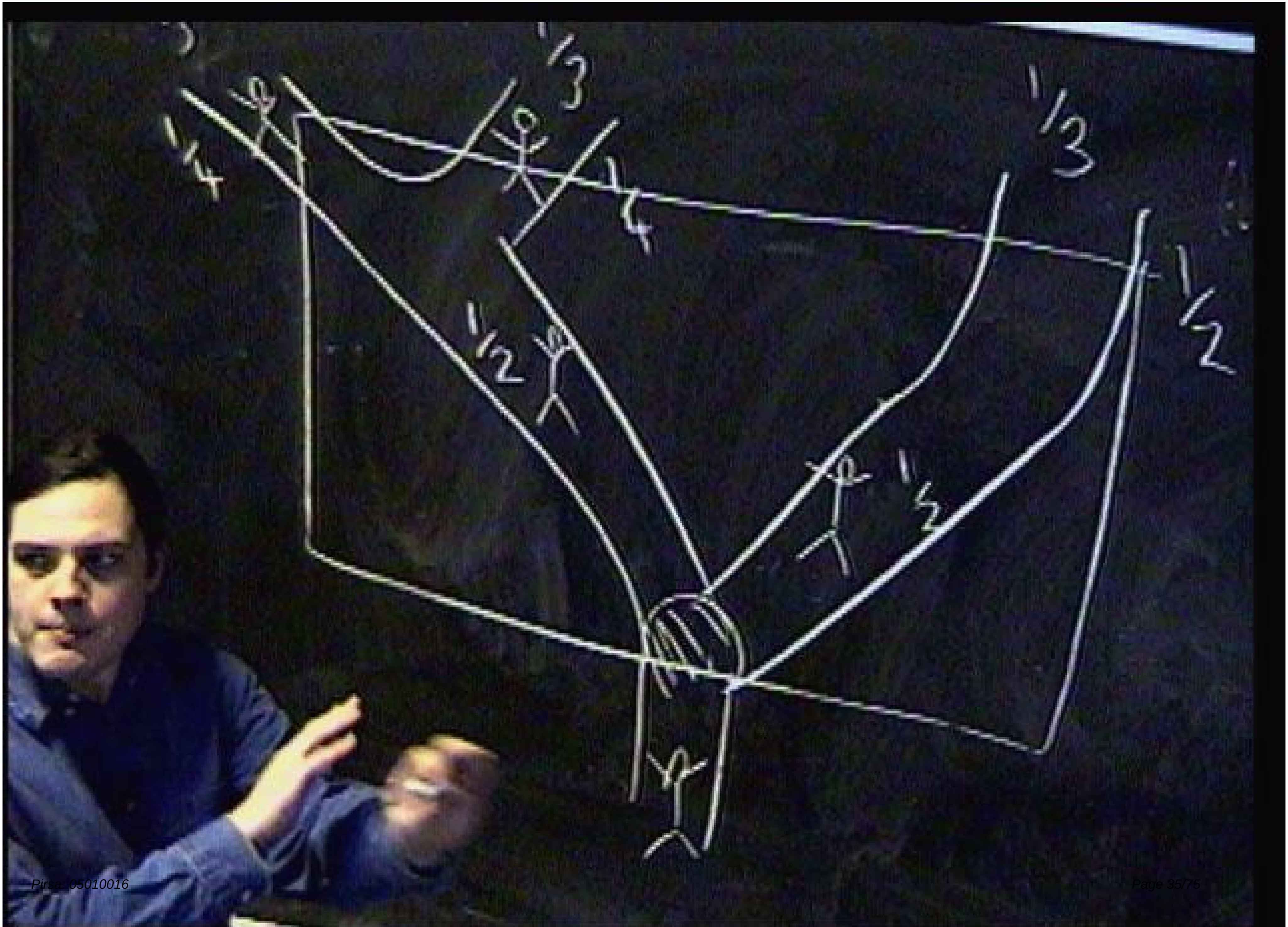
Most importantly there seems to be a much *better rule:* the "counting rule".

Counting rule: if there are n branches, ignore the amplitudes and give each branch probability 1/n.

BUT the counting rule is

- Incoherent
- Not well defined

In general: much harder to find "alternative rules" than it looks



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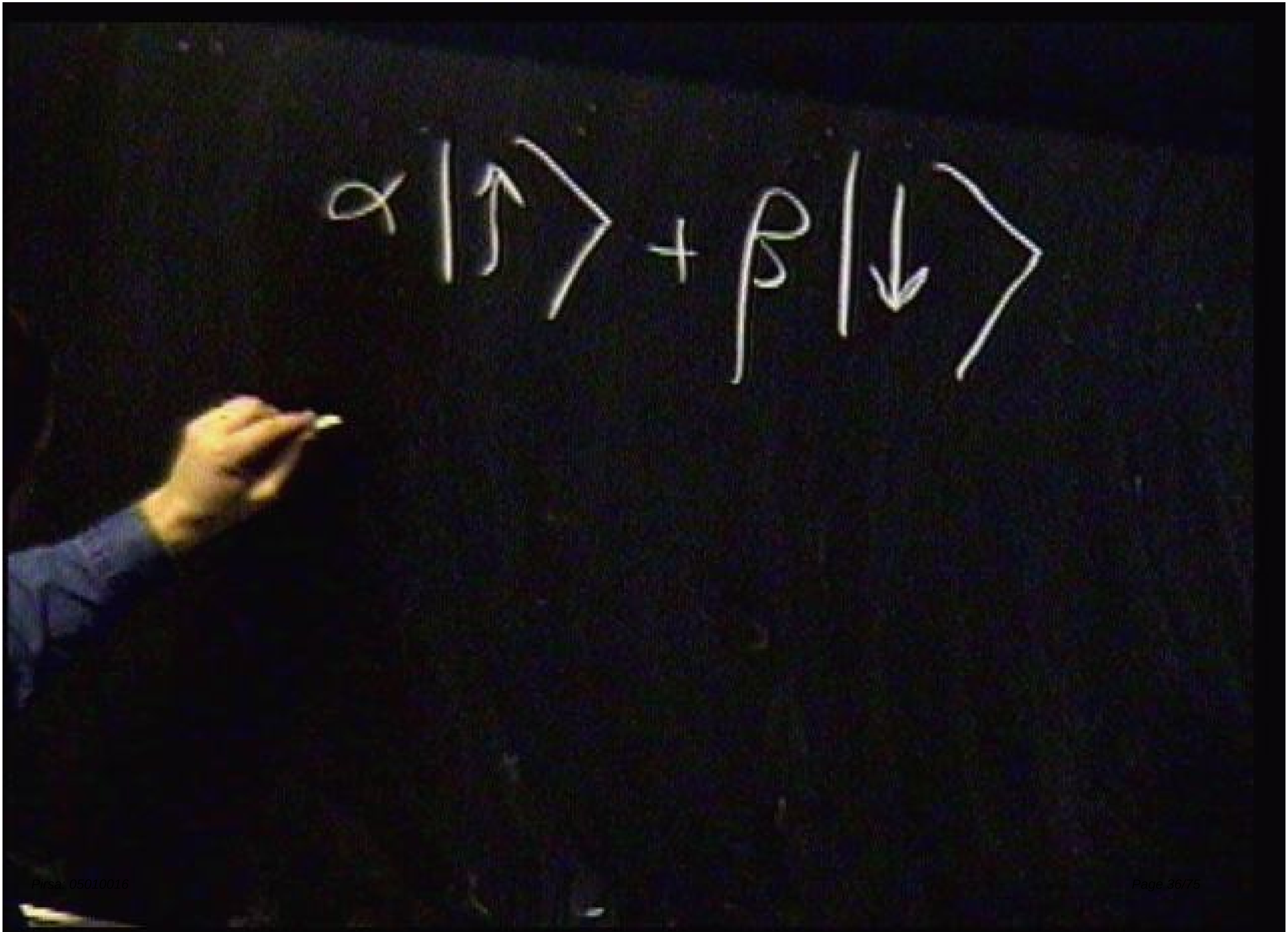
$\alpha|\uparrow\rangle + \beta|\downarrow\rangle$

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$$\rightarrow \alpha|\uparrow\rangle|\text{"up"}\rangle + \beta|\text{"down"}\rangle$$

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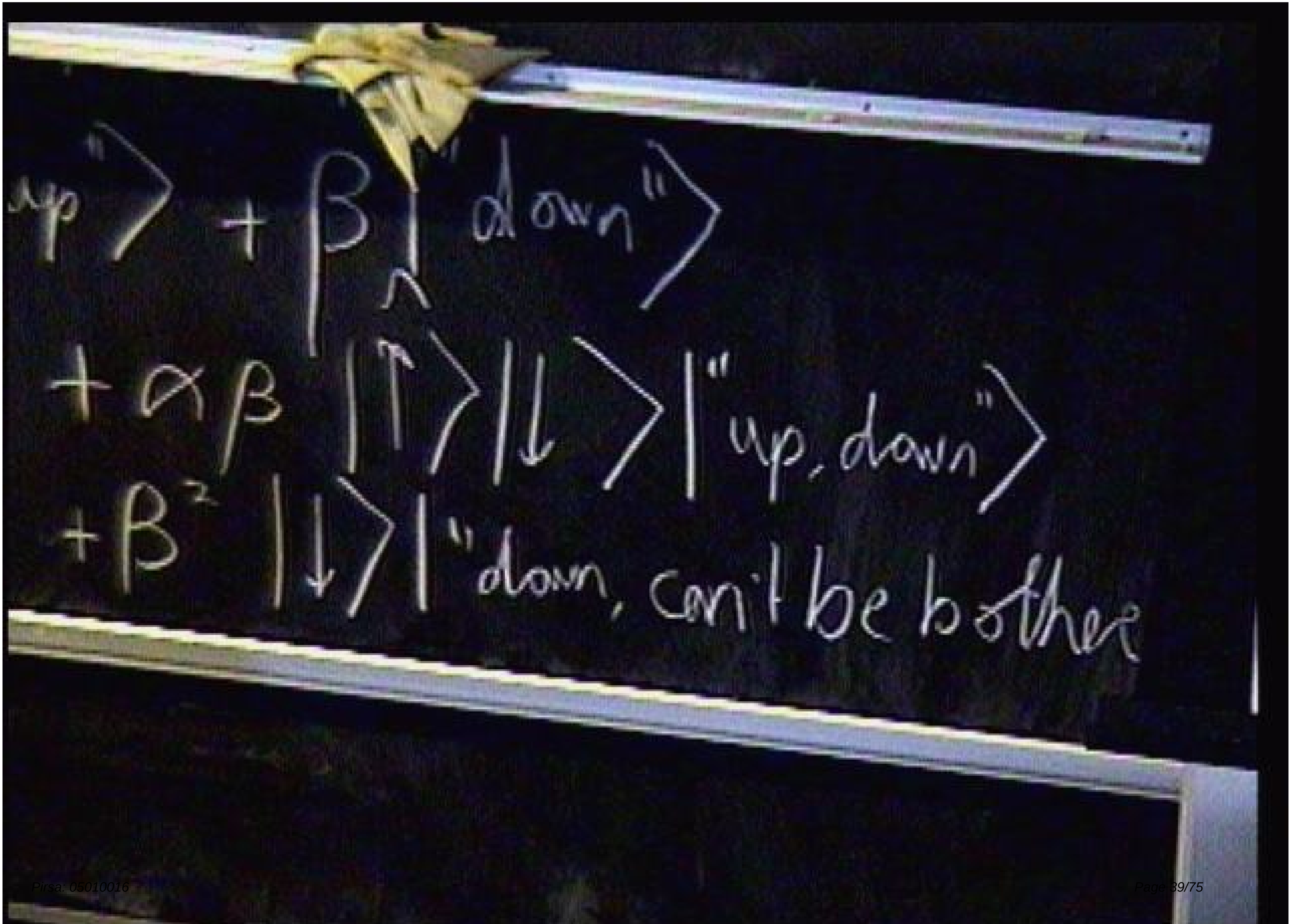
$$\rightarrow \alpha|\uparrow\rangle|\text{"up"}\rangle$$

$$\alpha^2|\uparrow\rangle|\uparrow\rangle|\text{"up", "up"}\rangle$$


up"〉 + β|"down"〉
+ αβ |↑〉|↓〉|"up, down"〉
+ β² |↓〉|"down, can't be bother

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How the proof works

1. Prove that if two events have the same weight (i.e. same mod-squared amplitude) then agents are rationally required to give them the same probability
(the *equivalence rule*)

2. Prove that if the equivalence rule is true, agents are rationally required to give probability P to an event with weight P

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A bet on "spin up"

Step 1: prepare spin-half particle in superposition of up and down

$$(\alpha|\uparrow\rangle+\beta|\downarrow\rangle)\otimes|\text{"device ready"}\rangle\otimes|\text{"agent waiting"}\rangle$$

Step 2: measure particle spin

$$|\uparrow\rangle\otimes|\text{"device ready"}\rangle \longrightarrow |\text{"spin up"}\rangle$$

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Step 3: Pay a reward iff the result is "spin up"

$$|\text{"spin up"}\rangle\otimes|\text{"agent waiting"}\rangle \longrightarrow |\text{"spin up"}\rangle\otimes|\text{"agent gets \$10"}\rangle$$

$$|\text{"spin down"}\rangle\otimes|\text{"agent waiting"}\rangle \longrightarrow |\text{"spin down"}\rangle\otimes|\text{"agent gets nothing"}\rangle$$

Step 4: Throw away the measurement result

$$|\text{"spin up"}\rangle \longrightarrow |\text{Junk}_i\rangle \in \text{set of junk states}$$

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where i and j are unknown

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state is

$$|\Psi^{0}_{up}(\alpha,\beta)\rangle = \alpha|\text{"spin up"}\rangle \otimes |\text{"agent gets \$10"}\rangle + \beta|\text{"spin down"}\rangle \otimes |\text{"agent gets nothing"}\rangle$$

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Let set of these states be $S^{up}(\alpha,\beta)$

Agent is:

Indifferent between different erasure processes, so between states in $S^{up}(\alpha,\beta)$

Indifferent as to whether erasure occurs, so between $S^{up}(\alpha,\beta)$ and $|\Psi^{0}_{up}(\alpha,\beta)\rangle$

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A bet on "spin down"

... basically the same!

Before deletion state is

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NOTE $\quad S^{down}(\alpha,\beta) = S^{up}(\beta,\alpha)$

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NOTE $S^{down}(\alpha,\beta) = S^{up}(\beta,\alpha)$

A bet on "spin down"

20

... basically the same!

Before deletion state is

$$|\psi^{0}_{down}(\alpha,\beta)\rangle = \alpha\,|\text{"spin up"}\rangle \otimes |\text{"agent gets nothing"}\rangle$$
$$+ \beta\,|\text{"spin down"}\rangle \otimes |\text{"agent gets \$10"}\rangle$$

After deletion

state is

$$|\psi^{i,j}_{down}(\alpha,\beta)\rangle = \alpha\,|\text{Junk}_i\rangle \otimes |\text{"agent gets nothing"}\rangle$$
$$+ \beta\,|\text{Junk}_j\rangle \otimes |\text{"agent gets \$10"}\rangle$$

Set of these states is $S^{down}(\alpha,\beta)$

NOTE $\quad S^{down}(\alpha,\beta) = S^{up}(\beta,\alpha)$

20

A bet on "spindown"

... basically the same!

Before deletion state is

$$|\psi^{0}_{down}(\alpha,\beta)\rangle = \alpha\,|\text{"spinup"}\rangle \otimes |\text{"agent gets nothing"}\rangle + \beta\,|\text{"spin down"}\rangle \otimes |\text{"agent gets \$10"}\rangle$$

After deletion

state is

$$|\psi^{i,j}_{down}(\alpha,\beta)\rangle = \alpha\,|\text{Junk}_i\rangle \otimes |\text{"agent gets nothing"}\rangle + \beta\,|\text{Junk}_j\rangle \otimes |\text{"agent gets \$10"}\rangle$$

Set of these states is $S^{down}(\alpha,\beta)$

NOTE $S^{down}(\alpha,\beta) = S^{up}(\beta,\alpha)$

A bet on "spin down"

20

... basically the same!

Before deletion state is

$$|\psi^{0}_{down}(\alpha,\beta)\rangle = \alpha|\text{"spin up"}\rangle \otimes |\text{"agent gets nothing"}\rangle$$
$$+ \beta|\text{"spin down"}\rangle \otimes |\text{"agent gets \$10"}\rangle$$

After deletion

state is

$$|\psi^{i,j}_{down}(\alpha,\beta)\rangle = \alpha|Junk_i\rangle \otimes |\text{"agent gets nothing"}\rangle$$
$$+ \beta|Junk_j\rangle \otimes |\text{"agent gets \$10"}\rangle$$

Set of these states is $S^{down}(\alpha,\beta)$

NOTE $S^{down}(\alpha,\beta) = S^{up}(\beta,\alpha)$

A bet on "spin down"

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... basically the same!

Before deletion state is

$$|\psi^{0}_{down}(\alpha,\beta)\rangle = \alpha|\text{"spin up"}\rangle \otimes |\text{"agent gets nothing"}\rangle + \beta|\text{"spin down"}\rangle \otimes |\text{"agent gets \$10"}\rangle$$

After deletion

state is

$$|\psi^{i,j}_{down}(\alpha,\beta)\rangle = \alpha|Junk_i\rangle \otimes |\text{"agent gets nothing"}\rangle + \beta|Junk_j\rangle \otimes |\text{"agent gets \$10"}\rangle$$

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$$+\beta\,|\text{"spin down"}\rangle \otimes |\text{"agent gets \$10"}\rangle$$

After deletion

state is

$$|\psi^{i,j}_{down}(\alpha,\beta)\rangle = \alpha\,|\text{Junk}_i\rangle \otimes |\text{"agent gets nothing"}\rangle$$
$$+\beta\,|\text{Junk}_j\rangle \otimes |\text{"agent gets \$10"}\rangle$$

Set of these states is $S^{down}(\alpha,\beta)$

NOTE $S^{down}(\alpha,\beta) = S^{up}(\beta,\alpha)$

After deletion

state is

$$|\Psi^{i,j}_{down}(\alpha,\beta)\rangle = \alpha|\text{Junk}_i\rangle \otimes |\text{"agent gets nothing"}\rangle + \beta|\text{Junk}_j\rangle \otimes |\text{"agent gets \$10"}\rangle$$

Set of these states is $S^{down}(\alpha,\beta)$

NOTE $S^{down}(\alpha,\beta) = S^{up}(\beta,\alpha)$

state is

$$|\psi^{i,j}_{down}(\alpha,\beta)\rangle = \alpha\,|\text{Junk}_i\rangle \otimes |\text{"agent gets nothing"}\rangle$$
$$+\beta\,|\text{Junk}_j\rangle \otimes |\text{"agent gets \$10"}\rangle$$

Set of these states is $S^{down}(\alpha,\beta)$

NOTE $S^{down}(\alpha,\beta) = S^{up}(\beta,\alpha)$

After deletion

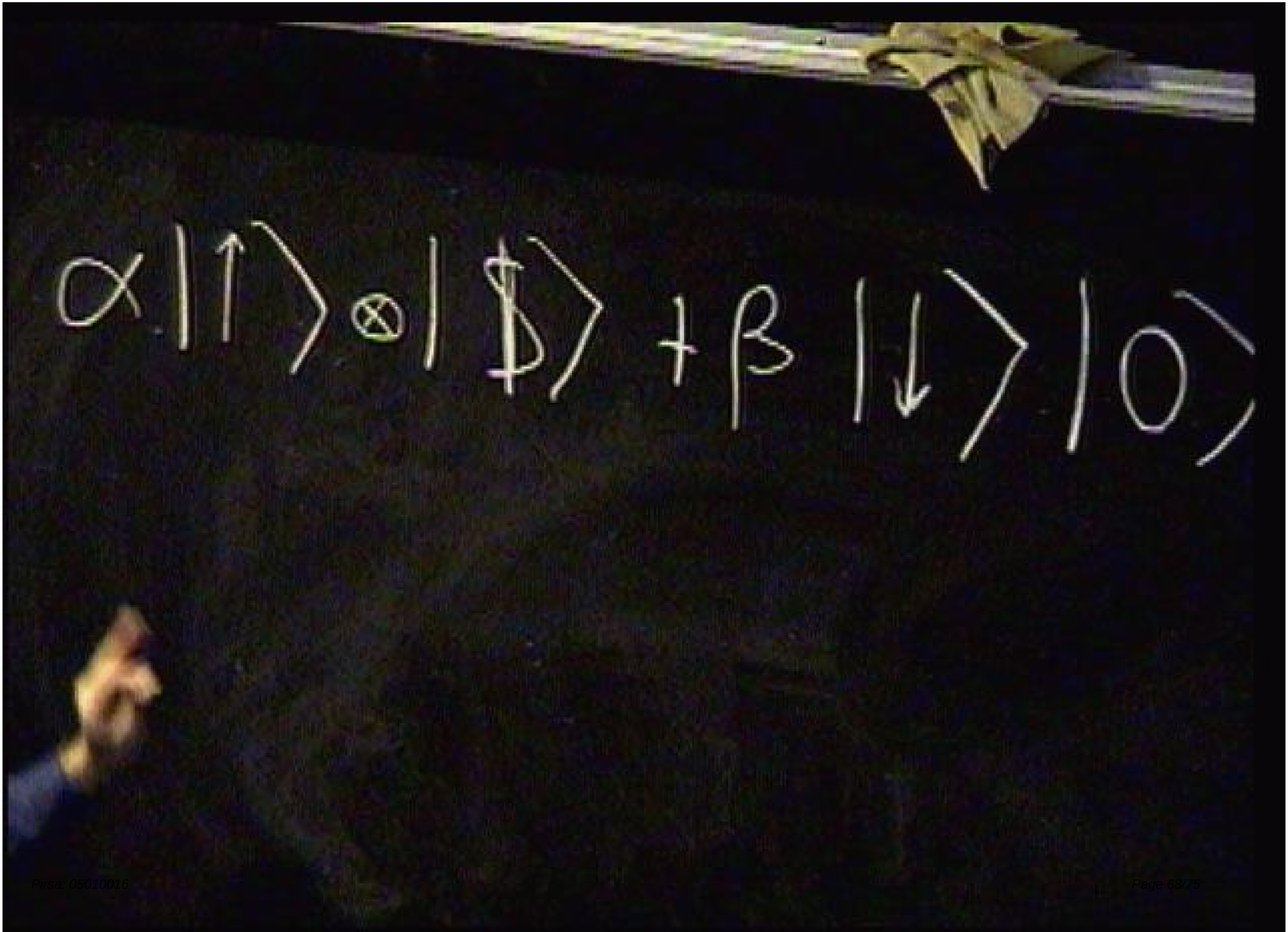
state is

$$|\psi^{i,j}_{up}(\alpha,\beta)\rangle = \alpha\,|\text{Junk}_i\rangle \otimes |\text{"agent gets \$10"}\rangle$$
$$+\beta\,|\text{Junk}_j\rangle \otimes |\text{"agent gets nothing"}\rangle$$

Let set of these states be $S^{up}(\alpha,\beta)$

Agent is:

Indifferent between different erasure processes, so between states in $S^{up}(\alpha,\beta)$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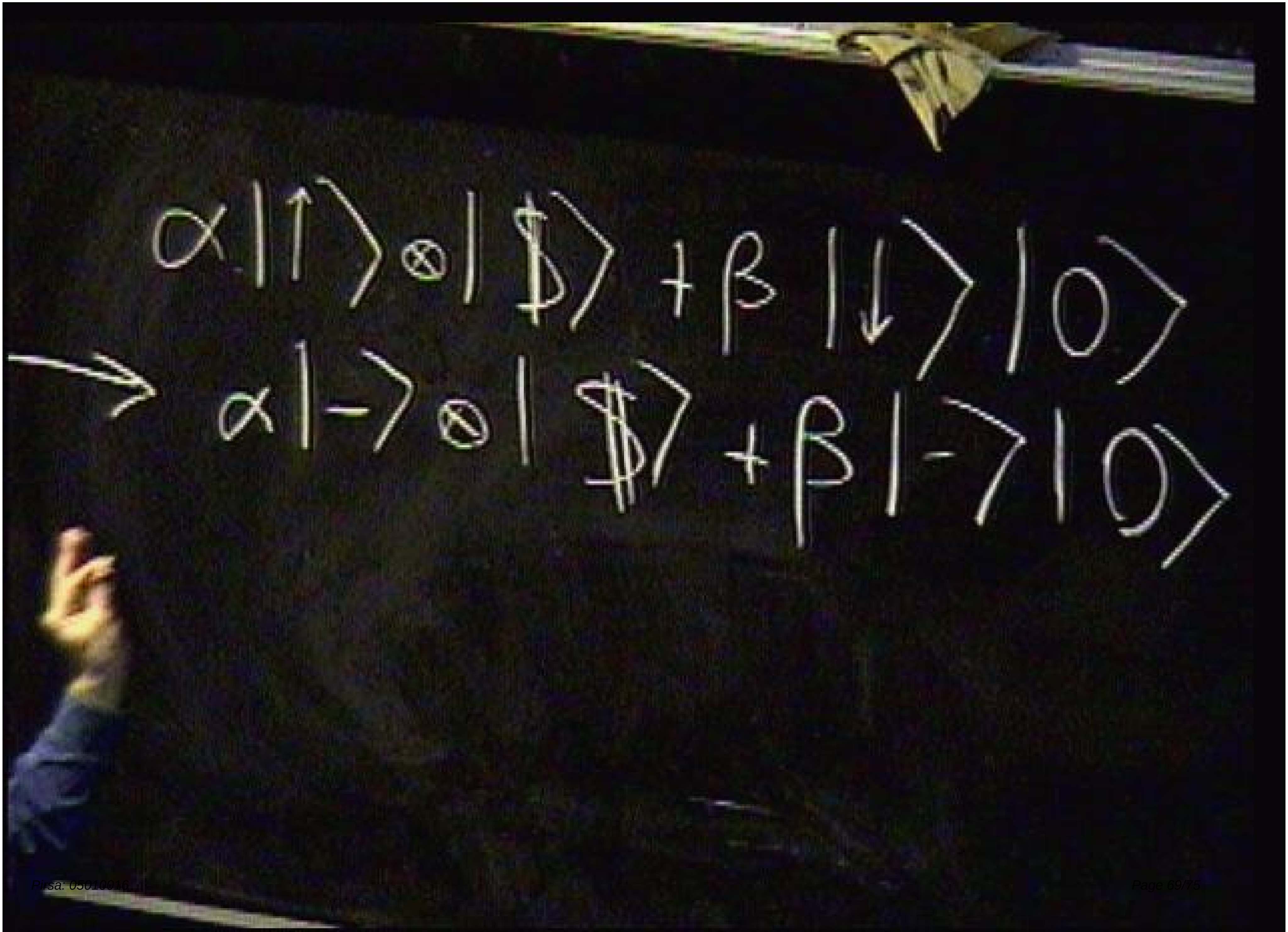
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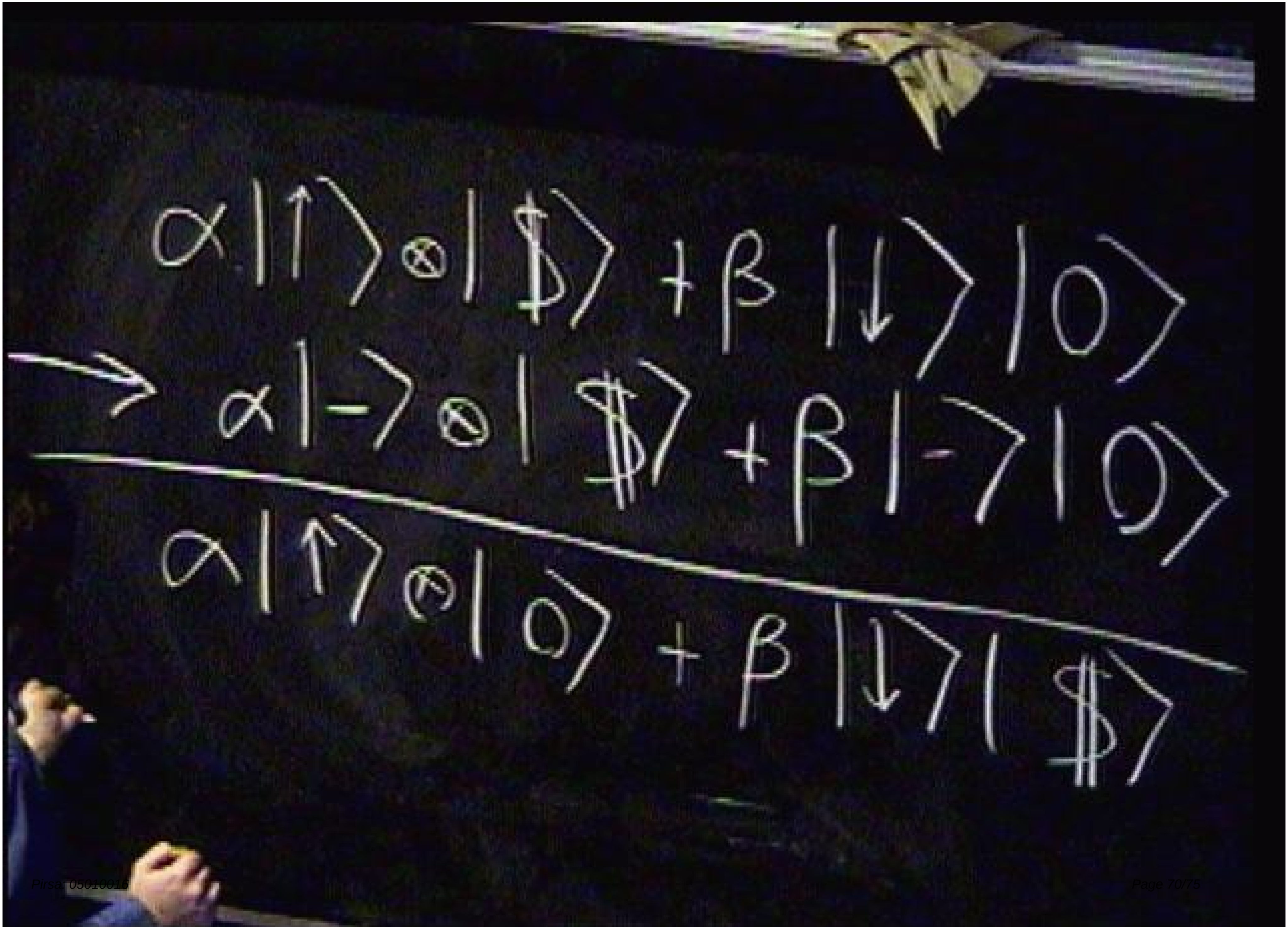
→ α|−⟩⊗|$⟩ + β|−⟩|0⟩


α|↑⟩⊗|$⟩ + β|↓⟩|0⟩
⇒ α|−⟩⊗|$⟩ + β|−⟩|0⟩
α|↑⟩⊗|0⟩ + β|↓⟩|$⟩

$$\alpha|\uparrow\rangle\otimes|\$\rangle + \beta|\downarrow\rangle|0\rangle$$

$$\rightarrow \alpha|-\rangle\otimes|\$\rangle + \beta|-\rangle|0\rangle$$

$$\alpha|\uparrow\rangle\otimes|0\rangle + \beta|\downarrow\rangle|\$\rangle$$

$$\rightarrow \alpha|-\rangle\otimes|0\rangle + \beta|-\rangle|\$\rangle$$

state is

$$|\psi^{i,j}_{down}(\alpha,\beta)\rangle = \alpha\,|Junk_i\rangle \otimes |\text{"agent gets nothing"}\rangle + \beta\,|Junk_j\rangle \otimes |\text{"agent gets \$10"}\rangle$$

Set of these states is $S^{down}(\alpha,\beta)$

NOTE $S^{down}(\alpha,\beta) = S^{up}(\beta,\alpha)$

After deletion

state is

$$|\psi^{i,j}_{up}(\alpha,\beta)\rangle = \alpha\,|Junk_i\rangle \otimes |\text{"agent gets \$10"}\rangle + \beta\,|Junk_j\rangle \otimes |\text{"agent gets nothing"}\rangle$$

Let set of these states be $S^{up}(\alpha,\beta)$

Agent is:

Indifferent between different erasure processes, so between states in $S^{up}(\alpha,\beta)$

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Nonlocality in the Everett Interpretation

The Bell inequalities *do not apply to the Everett Interpretation.*

(They assume that a measurement has a definite outcome)

Is the Everett interpretation local?

… yes and no

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Two sorts of nonlocality

- *Nonlocal interactions* – i.e action at a distance

I do something *here* and it affects the state of a system *there* instantly
(conflict with relativity)

Interactions in the Everett interpretation are local

- *Nonlocal states*

If A and B are spacetime regions then the state of A u B is not given by the states of A and B separately

States in the Everett interpretation are **non-local** (entanglement)

State nonlocality **does not conflict with relativity**

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Conclusion

Strengths of the Everett interpretation

- It is a *pure interpretation* of quantum mechanics – no need to modify the formalism or equations
- As such it is *Lorentz-covariant* at the fundamental level
- It is completely *realist* – it gives no special role to observers/measurements etc in its formulation

Questions / Problems

- Will decoherence deliver the sort of structures we need to see emergent worlds?
- Even if it does, is this the right way to think about worlds / cats / people / minds?
- Does the decision-theoretic argument satisfactorily explain the role of probability?
- **Is it too incredible to be believable?**