Title: Quantum Foundations Lecture

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Collection: Quantum Foundations

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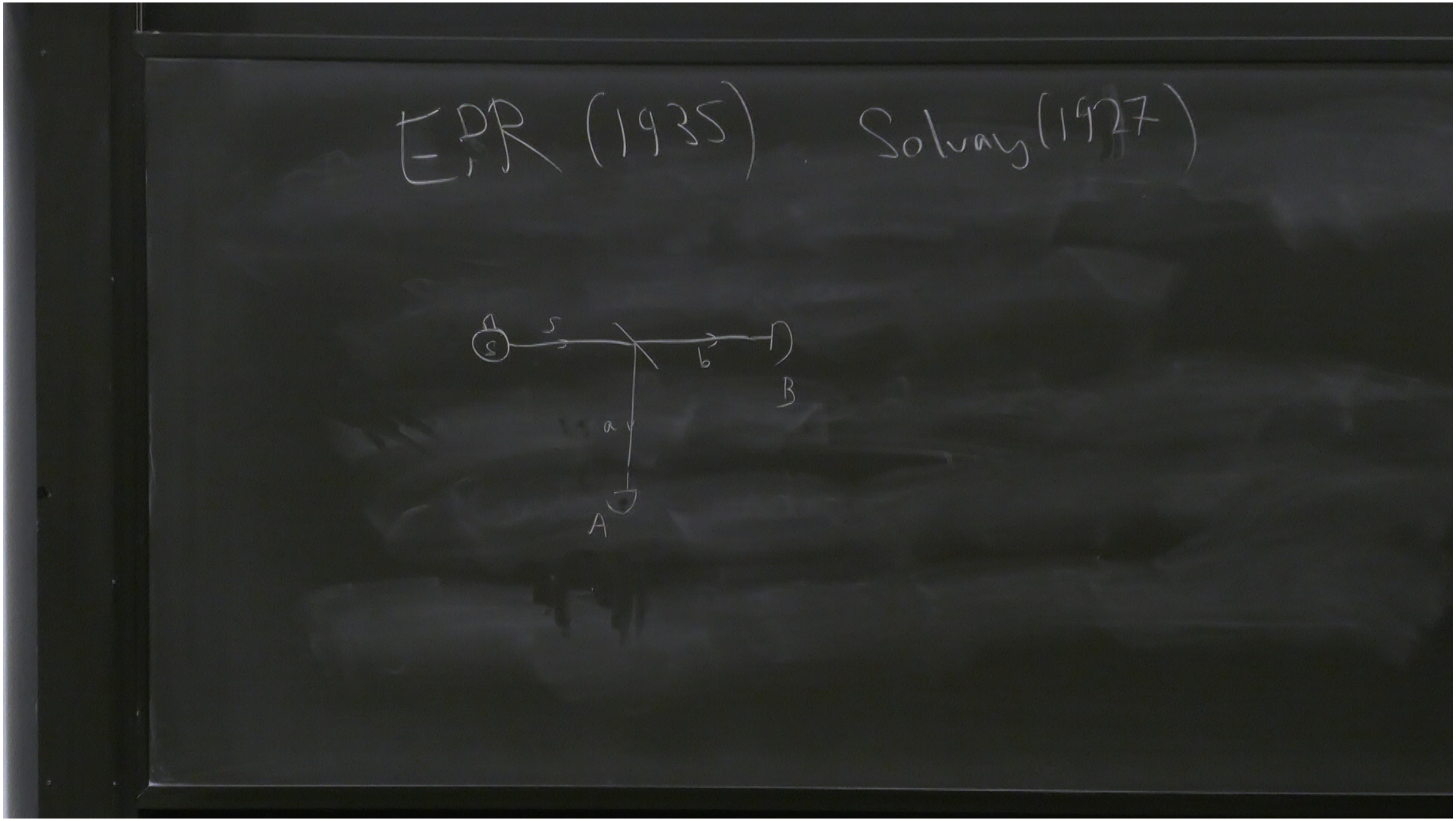

EPR (1935)
Solvay (1927)
S
s
b
B
a
A

Completeness In a complete theory every element of physical reality must have a counterpart in the physical theory.

In QT completeness $\Rightarrow$ All elements of physical reality follow from the quantum state

There is an epr, $[A=\alpha]_a$, iff $\langle\psi|\hat{P}_{A=\alpha}|\psi\rangle = 1$

Sufficient criterion for the existance of an e.p.r.

"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 physical reality corresponding to this quantity".

<u>Locality</u> A system is undisturbed by choices made at a space like separation from it.

QT $\wedge$ completeness $\wedge$ locality $\Rightarrow$ contradiction

...rion for the existence of an e.p.r.

...any way disturbing a system, we can predict
...ty (i.e. with probability equal to unity) the value
... quantity then there exists an element of
...ty corresponding to this quantity".

$$|\ldots\rangle = \frac{1}{\sqrt{2}}\left(i|a\rangle + |b\rangle\right) \qquad \hat{P}_{A=0,1}$$

Localit...

choices

QT $\wedge$ ...

We have

$$\mathrm{prob}\left(\left(A = \begin{matrix}1\\0\end{matrix}\right)_a \,\middle\|\, \left(B = \begin{matrix}0\\1\end{matrix}\right)_b \right) =$$

If we perform B and see $B = 0$

$$\left[A = 1\right]_a$$

using locality

If

$\left(B = \begin{smallmatrix}0\\1\end{smallmatrix}\right)_b \Big) = 1$ according to QT.

$B = 0$

If we perform B and see $B = 1$

ality

$\left[A = 0\right]_a$ using locality

T

nd see $B = 1$

oing locality

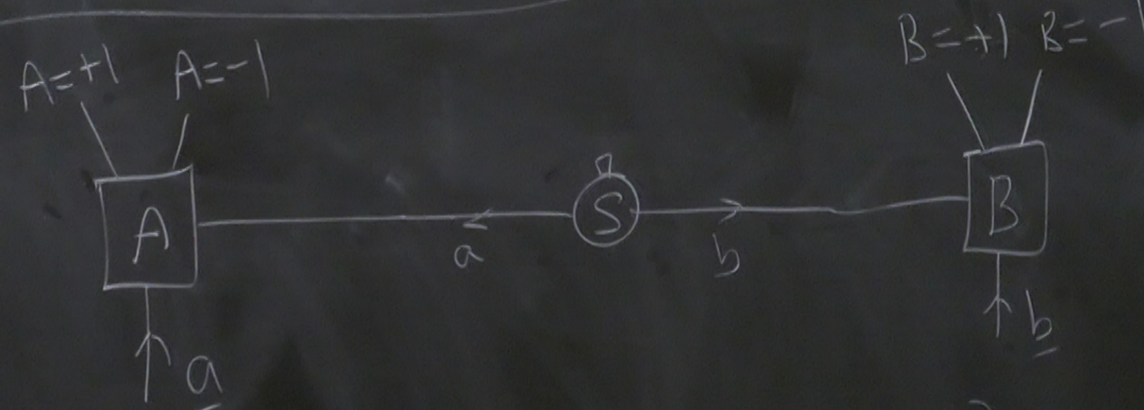
whether or not we do meas B
doesn't disturb A (by locality)

Hence we must have an epr

$$\left[A = \alpha\right]_a$$

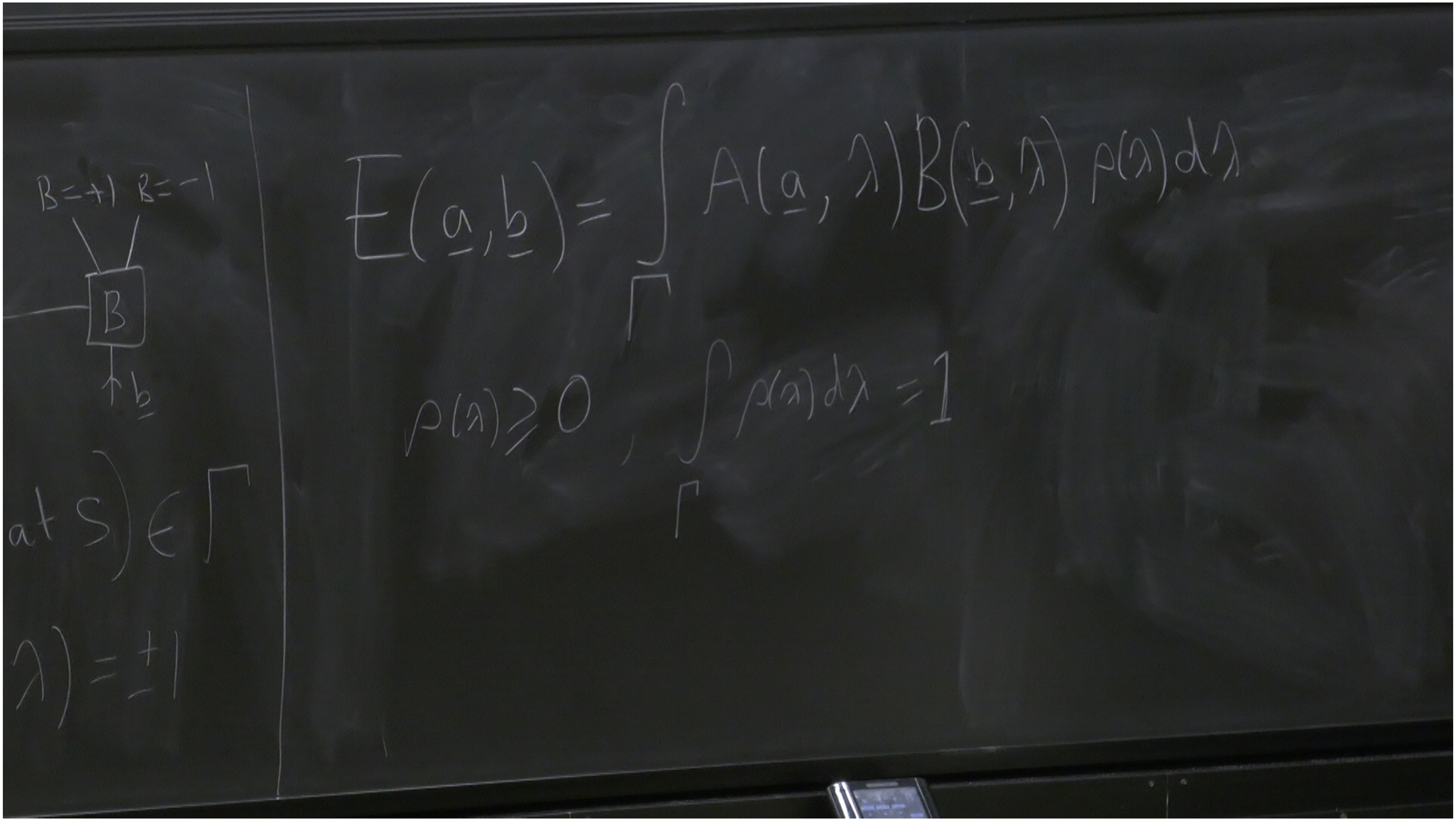
even if we don't measure B.

J.S. Bell 1964



λ (hidden variables shared at S) $\in \Gamma$

$A(\underline{a}, \lambda) = \pm 1 \qquad B(\underline{b}, \lambda) = \pm 1$


$B=+1$ $B=-1$
B
b
at S$) \in \Gamma$
$\lambda) = \pm 1$
$E(\underline{a},\underline{b}) = \int_\Gamma A(\underline{a},\lambda)B(\underline{b},\lambda)\,\rho(\lambda)\,d\lambda$
$\rho(\lambda) \geq 0, \quad \int_\Gamma \rho(\lambda)\,d\lambda = 1$

CHSH 1969

$$x, x', y, y' = \pm 1$$

$$x'y' + x'y + xy' - xy = \pm 2$$

$$x'\underbrace{(y'+y)}_{\pm 2,\, 0} + x\underbrace{(y'-y)}_{0,\, \pm 2} = \pm 2$$

$$y = \pm 2$$

$$2$$

$$x' = A(\underline{a}', \lambda), \quad x = A(\underline{a}, \lambda)$$

$$y' = B(\underline{b}', \lambda), \quad y = B(\underline{b}, \lambda)$$

$$-2 \leq E(\underline{a}', \underline{b}') + E(\underline{a}', \underline{b}) + E(\underline{a}, \underline{b}') - E(\underline{a}, \underline{b}) \leq +2$$

CHSH Bell inequality

$= A(\underline{a}, \lambda)$

$$\int N(\lambda)\rho(\lambda)d\lambda$$

$= B(\underline{b}, \lambda)$

$$\int_{\lambda\in\Gamma^+} N(\lambda)\rho(\lambda)d\lambda + \int_{\lambda\in\Gamma^-} N(\lambda)\rho(\lambda)d\lambda$$

$E(\underline{a}, \underline{b}') - E(\underline{a}, \underline{b}) \leq +2$

lity

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|+\rangle_a|-\rangle_b - |-\rangle_a|+\rangle_b\right)$$

for two spin $\frac{1}{2}$ particles.

$A \Rightarrow \sigma_{\underline{a}}$ $\qquad$ $B \Rightarrow \sigma_{\underline{b}}$

$$E(\underline{a},\underline{b}) = \langle\psi|\,\sigma_{\underline{a}} \otimes \sigma_{\underline{b}}\,|\psi\rangle = -\underline{a}\cdot\underline{b}$$

($\underline{a}$, $\underline{b}$ unit vectors)

$$E(\underline{a}',\underline{b}') + E(\underline{a}',\underline{b}) + E(\underline{a},\underline{b}') - E(\underline{a},\underline{b}) \leq +2 \quad \lambda \in$$

CHSH Bell inequality

$\vec{b}$

$$E(a',b') + E(a',b) + E(a\,b') - E(a,b)$$

$$\left(-\frac{\sqrt{2}}{2}\right) + \left(-\frac{\sqrt{2}}{2}\right) + \left(-\frac{\sqrt{2}}{2}\right) - \left(+\frac{\sqrt{2}}{2}\right) = -4\frac{\sqrt{2}}{2} = -2\sqrt{2} < -2$$