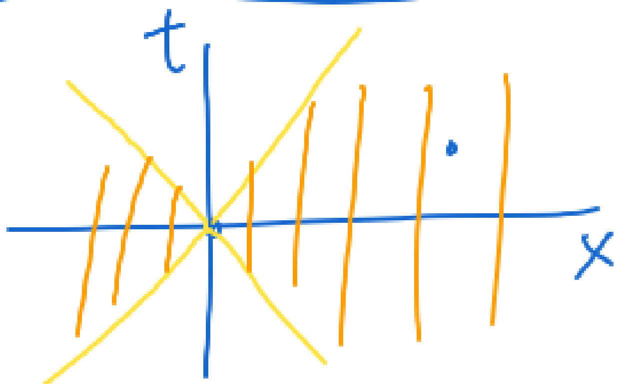
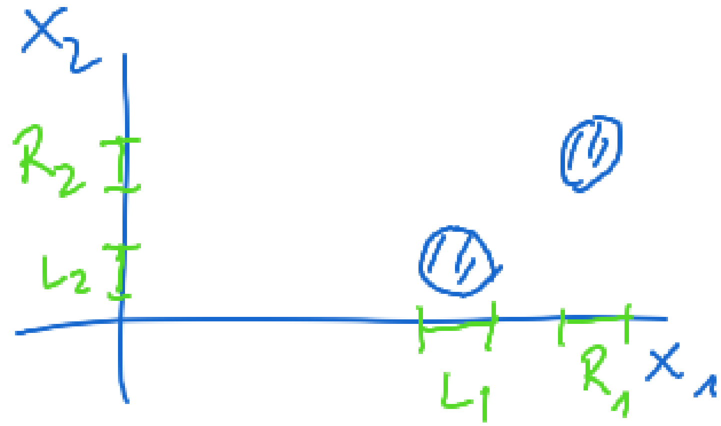
EPR's argument

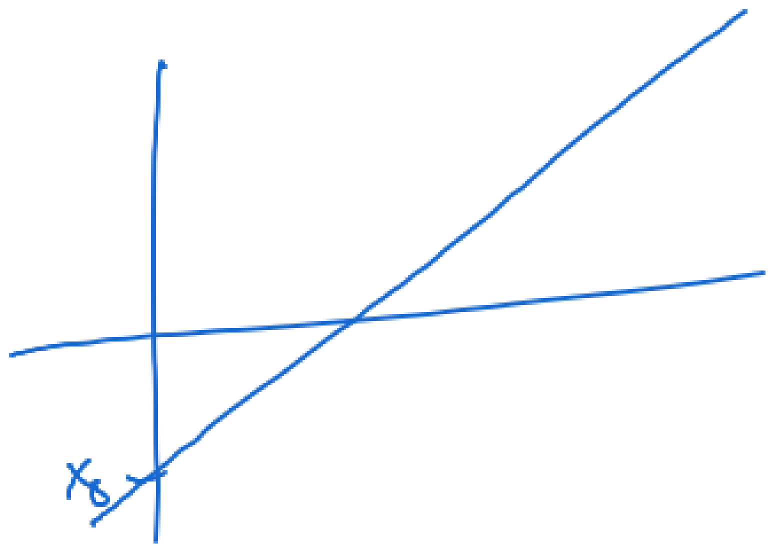




spacelike separation $(t_1, \underline{x}_1), (t_2, \underline{x}_2)$

$$|\underline{x}_1 - \underline{x}_2| > c\,|t_1 - t_2|$$

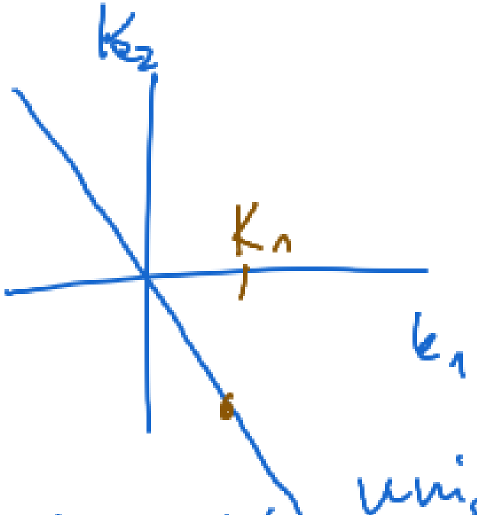
$$\Psi(x_1, x_2) = \delta(x_1 - x_2 + x_0)$$



Further conclusions

$$\hat{\Psi}(k_1, k_2) = \frac{1}{2\pi}\int dx_1 \int dx_2\, e^{-ik_1x_1}\, e^{-ik_2x_2}\, \delta(x_1 - x_2 + x_0)$$

$$= \frac{1}{2\pi}\int dx_1\, e^{-ik_1x_1}\, e^{-ik_2(x_1+x_0)}$$



$$= \frac{1}{\sqrt{2\pi}} e^{-ik_2x_0} \int dx_1 \frac{1}{\sqrt{2\pi}} e^{-i(k_1+k_2)x_1}$$

$$= \frac{1}{\sqrt{2\pi}} e^{+ik_1x_0}\, \delta(k_1 + k_2)$$

uniform

Alice K_1,

$$\hat{\Psi}'(k_1, k_2) = \frac{1}{\sqrt{2\pi}} e^{iK_1x_0}\, \delta(K_1 + k_2)\, \delta(k_1 - K_1)$$

Bob obtains $K_2 = -K_1$.

EPR arg $\Longrightarrow$ $\exists$ momentum ~~variable~~ values before any meas.

Another variant: Alice meas. pos.
Bob meas. mom.

Bohm's version 2 spin-$\frac{1}{2}$ particles, $\mathcal{H} = \mathbb{C}^2 \otimes \mathbb{C}^2$

singlet ~~sp~~ state $\phi = \frac{1}{\sqrt{2}}\big(|z\text{-up}\rangle|z\text{-down}\rangle - |z\text{-down}\rangle|z\text{-up}\rangle\big)$

Alice meas. σ_3 on particle 1, outcome $Z_1 = \pm 1$ w/ prob 1/2

z_2

If $z_1 = +1$, collapse to $\phi'_+ = |z\text{-up}\rangle|z\text{-down}\rangle$ -1

$z_1 = -1$ $\phi'_- = |z\text{-down}\rangle|z\text{-up}\rangle$ $+1$

so Bob ~~obtains~~ meas of σ_3 on part. 2, obtains z_2

(perfect anti-correlation)

Conclusion: $\exists$ values of z-spin before any meas.

x-spin, y-spin, n-spin

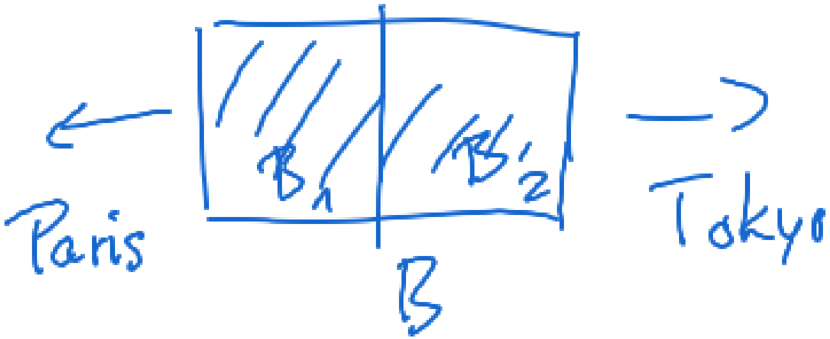
$$\phi \propto \frac{1}{\sqrt{2}}\left(|x\text{-up}\rangle|x\text{-down}\rangle - |x\text{-down}\rangle|x\text{-up}\rangle\right)$$

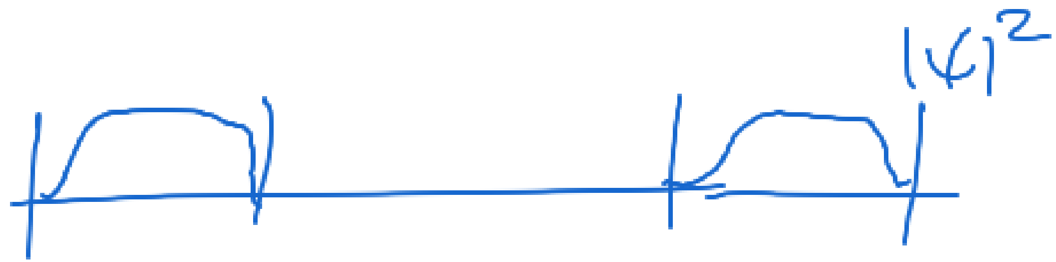
$$\propto \frac{1}{\sqrt{2}}\left(|y\text{-up}\rangle|y\text{-down}\rangle - |y\text{-down}\rangle|y\text{-up}\rangle\right)$$

$$\propto \frac{1}{\sqrt{2}}\left(|n\text{-up}\rangle|n\text{-down}\rangle - |n\text{-down}\rangle|n\text{-up}\rangle\right)$$

Einstein's boxes argument (1927)

1 part.





Assumption: no real change can immediately take place in T in conseq. of a meas. in P.

$\Rightarrow$ ψ is incomplete.

"spukhafte Fernwirkung"

Too good to be true (Bell 1964)

Proof of Nonlocality

Locality: If x and y are spacelike separated then events at x do not influence events at y.

(true in relativistic classical mechanics
electrodynamics
gravity (GR))

Bell's theorem: Locality is sometimes false if certain emp. predictions of the quantum formalism are correct.

Tests: Aspect (1982), at Sp. Sep.: 21st century.

Conclusion: Locality is wrong.

- propagation locality $\neq$ locality
- interaction locality $\neq$ locality

2 meanings of "interaction":

1) a term in H
2) any influence.

- 2 observables for x, y sp. sep., commute:
"commutation locality" $\neq$ locality

Bell's Experiment

$$\phi \propto \frac{1}{\sqrt{2}}\Big(|n\text{-up}\rangle |n\text{-down}\rangle - |n\text{-down}\rangle |n\text{-up}\rangle \Big) \quad \text{singlet}$$

Alice $\underline{n} = \underline{\alpha} \in \mathbb{R}^3$, Bob $\underline{n} = \underline{\beta} \in \mathbb{R}^3$, meas. $I \otimes \underline{\beta} \cdot \underline{\sigma}$

meas. $\underline{\alpha} \cdot \underline{\sigma} \otimes I$,

<u>Fact</u> (prediction) $\mathbb{P}_{\alpha\beta}(Z_1 = z_1, Z_2 = z_2) =: \mu_{\alpha\beta}$

$++$	$+-$	$\frac{1}{2}$ row sum $\mathbb{P}(Z_1 = +1)$
$-+$	$--$	$\frac{1}{2}$ $\mathbb{P}(Z_1 = -1)$
$\frac{1}{2}$ col sum	$\frac{1}{2}$	

$$\mu_{\alpha\beta} = \begin{pmatrix} \frac{1}{4} - \frac{1}{4}\underline{\alpha} \cdot \underline{\beta} & \frac{1}{4} + \frac{1}{4}\underline{\alpha} \cdot \underline{\beta} \\ \frac{1}{4} + \frac{1}{4}\underline{\alpha} \cdot \underline{\beta} & \frac{1}{4} - \frac{1}{4}\underline{\alpha} \cdot \underline{\beta} \end{pmatrix} = \begin{pmatrix} \frac{1}{2}\sin^2(\theta/2) & \frac{1}{2}\cos^2(\theta/2) \\ \frac{1}{2}\cos^2(\theta/2) & \frac{1}{2}\sin^2(\theta/2) \end{pmatrix}$$

θ = angle betw. $\underline{\alpha}$ and $\underline{\beta}$