

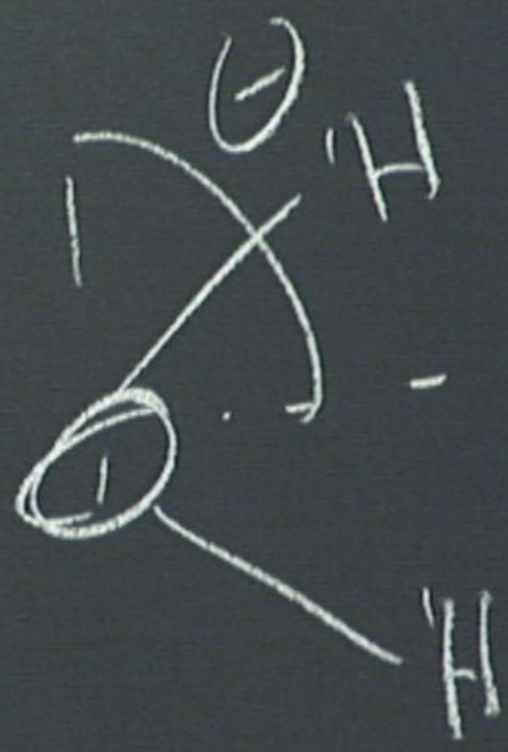
Title: Explorations in Quantum Info. (PHYS 641) - Lecture 14

Date: Mar 05, 2010 09:00 AM

URL: <http://pirsa.org/10030047>

Abstract:

\vec{B}_0



$\frac{1}{2} \pi$
 $\frac{1}{2} \pi$

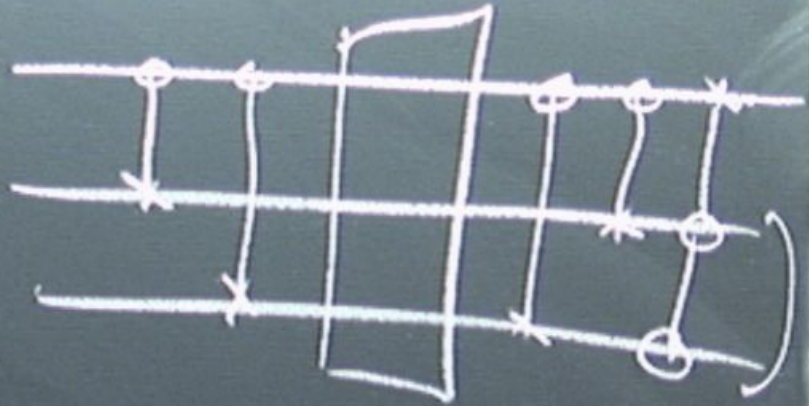
QEC

QEC

$$\alpha|0\rangle + \beta|1\rangle$$

$$|0\rangle$$

$$|0\rangle$$



$$\alpha|0\rangle$$

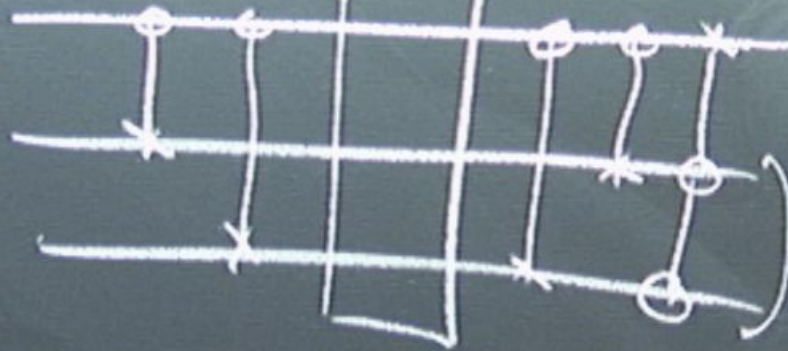


QEC

$$\alpha|0\rangle + \beta|1\rangle$$

$$|0\rangle$$

$$|0\rangle$$



$$\alpha|0\rangle + \beta|1\rangle$$

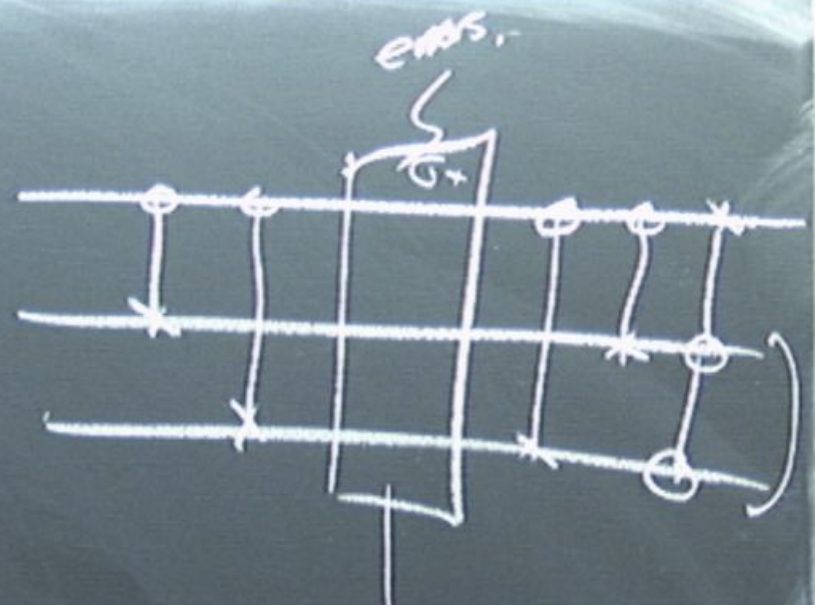


QEC

$$\alpha|0\rangle + \beta|1\rangle$$

$$|0\rangle$$

$$|0\rangle$$



$$\alpha|0\rangle + \beta|1\rangle$$

$$K_1 = \sqrt{1 - (P_1 + P_2 + P_3)} \mathbb{I} \mathbb{I} \mathbb{I}$$

$$K_2 = P_1 \sigma_x \mathbb{I} \mathbb{I}$$

$$K_3 = P_2 \mathbb{I} \sigma_x \mathbb{I}$$

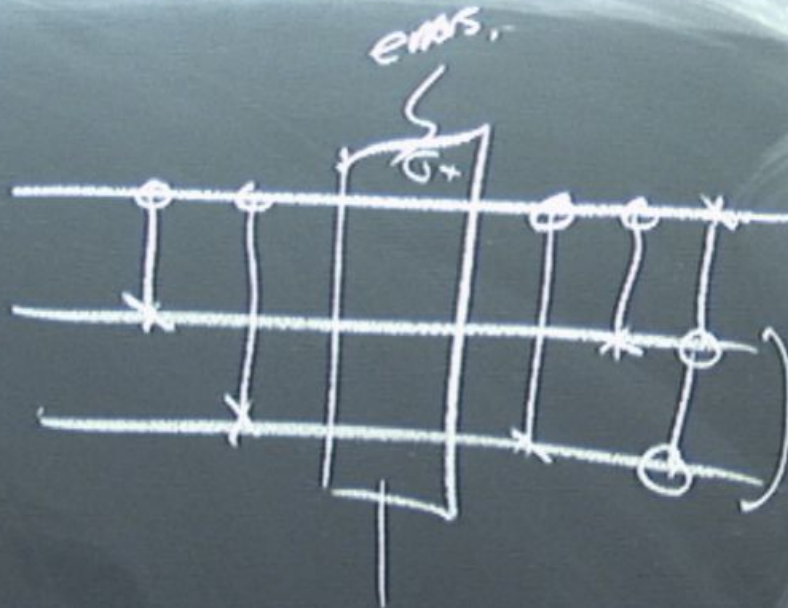
$$K_4 = P_3 \mathbb{I} \mathbb{I} \sigma_x$$

QEC

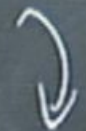
$$\alpha|0\rangle + \beta|1\rangle$$

$$|0\rangle$$

$$|0\rangle$$



$$\alpha|0\rangle + \beta|1\rangle$$



$$K_1 = \sqrt{1 - (R + P_2 + P_3)} \quad \text{II II}$$

$$K_2 = \sqrt{P_1} \quad \sigma_x \text{II II}$$

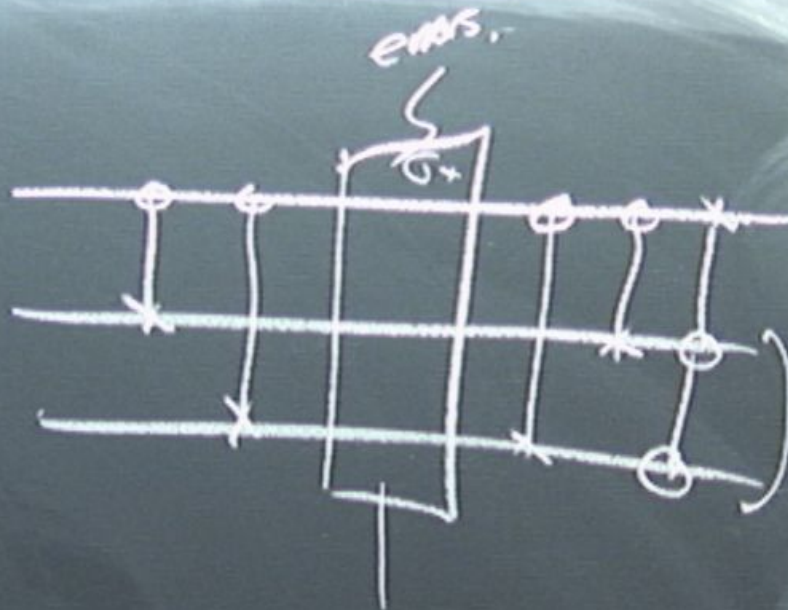
$$K_3 = \sqrt{P_2} \quad \text{II } \sigma_x \text{II}$$

$$K_4 = \sqrt{P_3} \quad \text{II II } \sigma_x$$

QEC

$$\alpha|0\rangle + \beta|1\rangle$$

$$\begin{cases} |0\rangle \\ |0\rangle \\ |0\rangle \end{cases}$$



$$\alpha|0\rangle + \beta|1\rangle$$

$$K_1 = \sqrt{1 - (P_1 + P_2 + P_3)} \quad \text{II II}$$

$$K_2 = \sqrt{P_1} \quad \sigma_x \text{II II}$$

$$K_3 = \sqrt{P_2} \quad \text{II} \sigma_x \text{II}$$

$$K_4 = \sqrt{P_3} \quad \text{II II} \sigma_x$$

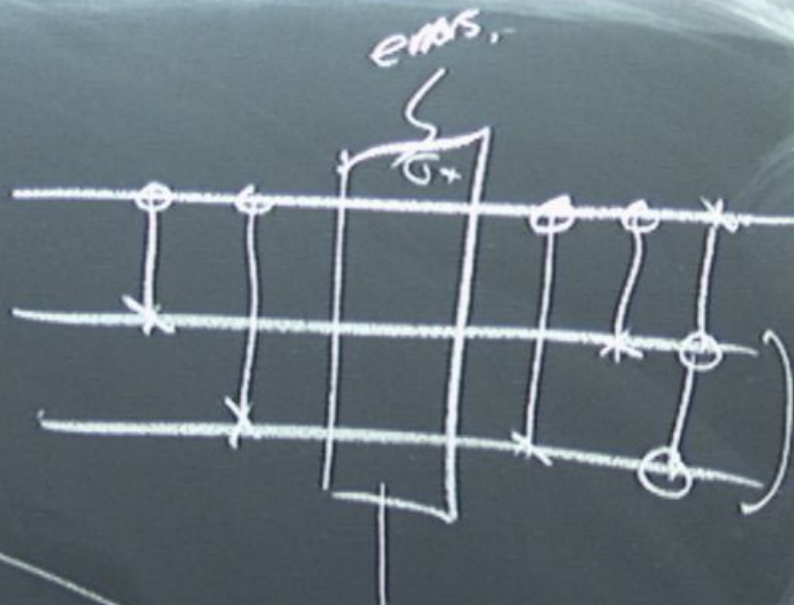
QEC

$$\alpha|0\rangle + \beta|1\rangle$$

lattice expands
H

$$\left\{ \begin{array}{l} |0\rangle \\ |1\rangle \end{array} \right\}$$

$$2^2$$

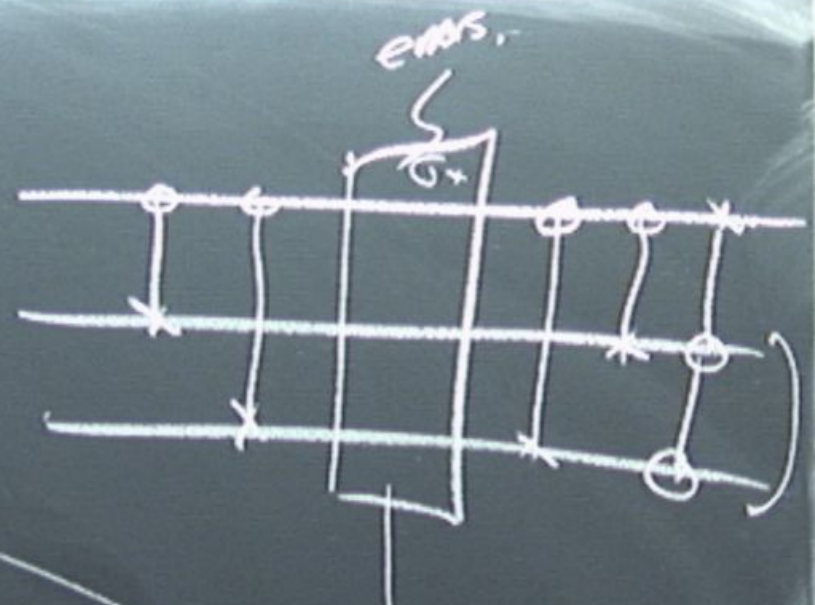


$$\alpha|0\rangle + \beta|1\rangle$$

$$\left\{ \begin{array}{l} K_1 = \sqrt{1 - (P_1 + P_2 + P_3)} \quad \mathbb{I} \mathbb{I} \mathbb{I} \\ K_2 = \sqrt{P_1} \quad \sigma_x \mathbb{I} \mathbb{I} \\ K_3 = \sqrt{P_2} \quad \mathbb{I} \sigma_x \mathbb{I} \\ K_4 = \sqrt{P_3} \quad \mathbb{I} \mathbb{I} \sigma_x \end{array} \right.$$

QEC

$\alpha|0\rangle + \beta|1\rangle$
 lattice expands
 $\{ |0\rangle, |1\rangle \}$
 2^2

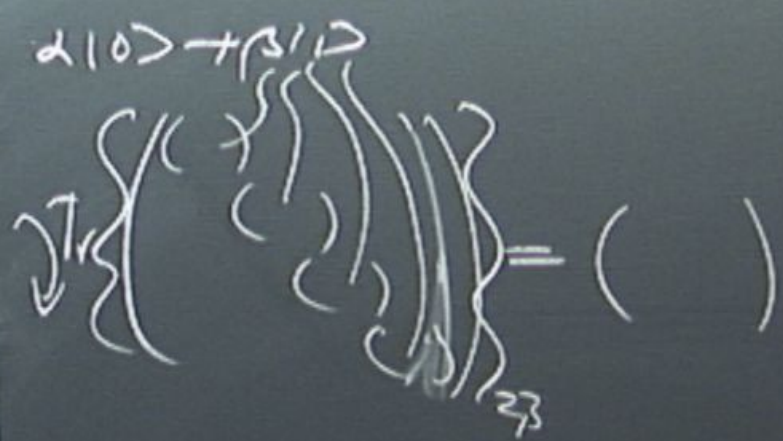
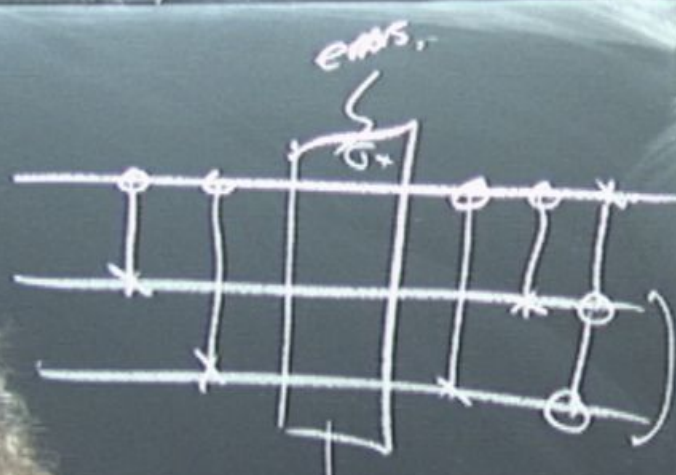


$\alpha|0\rangle + \beta|1\rangle$

$$\begin{aligned}
 K_1 &= \sqrt{1 - (P_1 + P_2 + P_3)} \quad \mathbb{I} \mathbb{I} \mathbb{I} \\
 K_2 &= \sqrt{P_1} \quad \sigma_x \mathbb{I} \mathbb{I} \\
 K_3 &= \sqrt{P_2} \quad \mathbb{I} \sigma_x \mathbb{I} \\
 K_4 &= \sqrt{P_3} \quad \mathbb{I} \mathbb{I} \sigma_x
 \end{aligned}$$

QEC

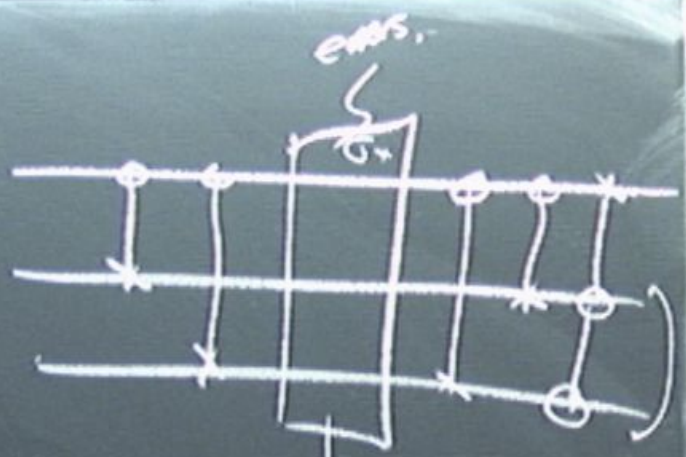
$\alpha|0\rangle + \beta|1\rangle$
 $(|0\rangle)$
 lattice expands



$$\left. \begin{aligned}
 K_1 &= \sqrt{1 - (P_1 + P_2 + P_3)} \mathbb{I} \mathbb{I} \mathbb{I} \\
 K_2 &= \sqrt{P_1} \sigma_x \mathbb{I} \mathbb{I} \\
 K_3 &= \sqrt{P_2} \mathbb{I} \sigma_x \mathbb{I} \\
 K_4 &= \sqrt{P_3} \mathbb{I} \mathbb{I} \sigma_x
 \end{aligned} \right\}$$

QEC

$\alpha|0\rangle + \beta|1\rangle$
 lattice expanded
 $\left\{ \begin{array}{l} |0\rangle \\ |1\rangle \end{array} \right\}$
 2^2

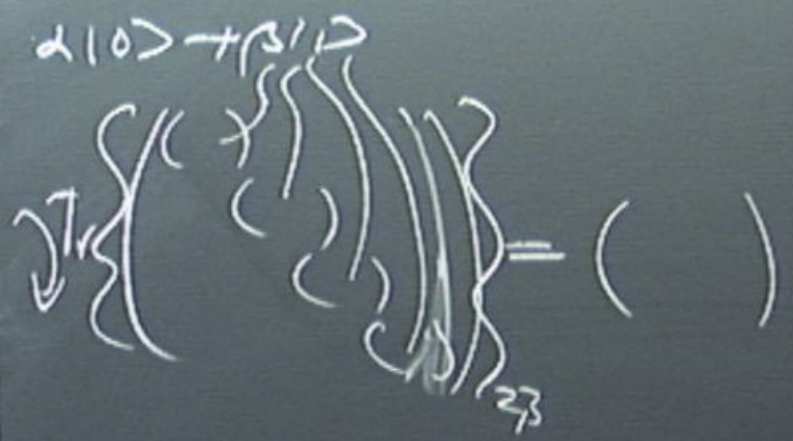
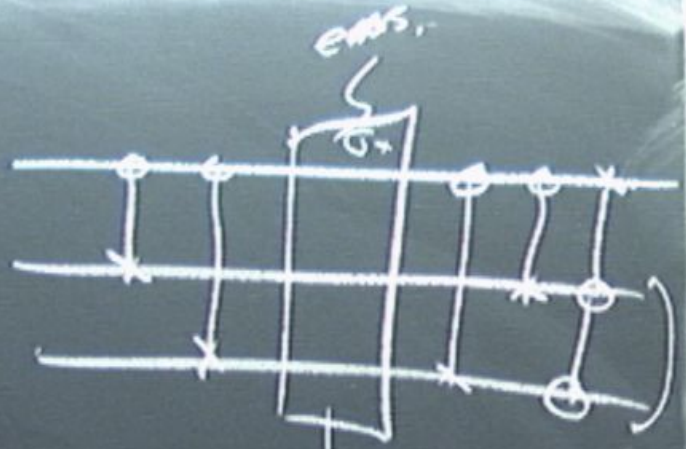


$\alpha|0\rangle + \beta|1\rangle$
 $\left\{ \begin{array}{l} () \\ () \\ () \\ () \end{array} \right\} = ()$
 2^3

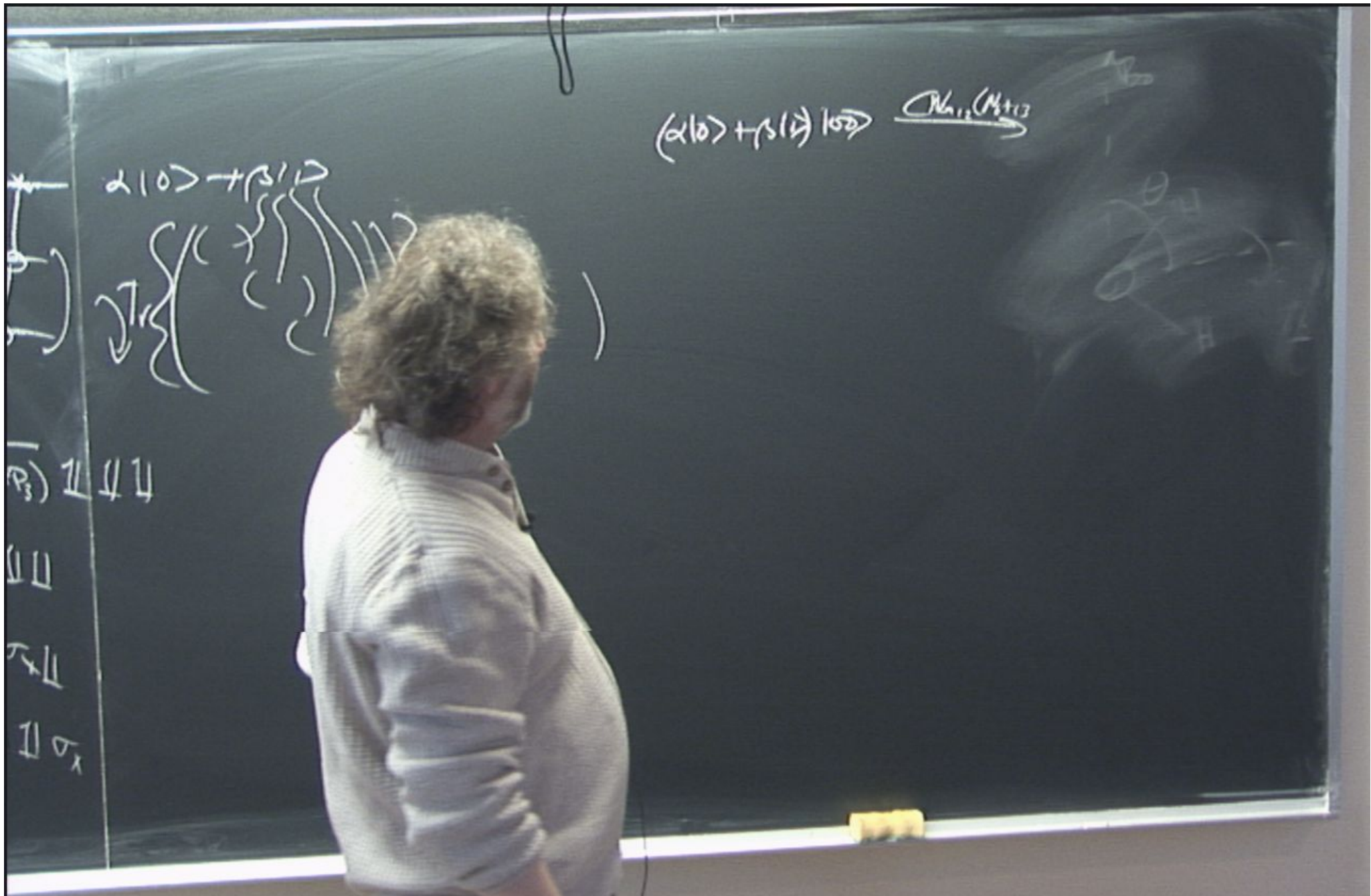
$$\left. \begin{aligned}
 K_1 &= \sqrt{1 - (R+P_2+P_3)} \mathbb{I} \mathbb{I} \mathbb{I} \\
 K_2 &= \sqrt{P_1} \sigma_x \mathbb{I} \mathbb{I} \\
 K_3 &= \sqrt{P_2} \mathbb{I} \sigma_x \mathbb{I} \\
 K_4 &= \sqrt{P_3} \mathbb{I} \mathbb{I} \sigma_x
 \end{aligned} \right\}$$

QEC

$\alpha|0\rangle + \beta|1\rangle$
 lattice expanded
 $\left\{ \begin{array}{l} |0\rangle \\ |1\rangle \end{array} \right\}$
 2^2

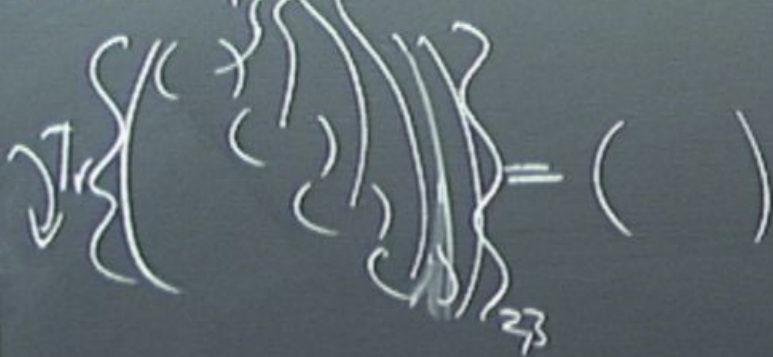


$$\left\{ \begin{array}{l}
 K_1 = \sqrt{1 - (P_1 + P_2 + P_3)} \quad \mathbb{I} \mathbb{I} \mathbb{I} \\
 K_2 = \sqrt{P_1} \sigma_x \mathbb{I} \mathbb{I} \\
 K_3 = \sqrt{P_2} \mathbb{I} \sigma_x \mathbb{I} \\
 K_4 = \sqrt{P_3} \mathbb{I} \mathbb{I} \sigma_x
 \end{array} \right.$$



$$(\alpha|0\rangle + \beta|1\rangle) |0\rangle \xrightarrow{C_{N_{12}}(N_{11})} \alpha|000\rangle + \beta|111\rangle$$

$$\alpha|10\rangle + \beta|11\rangle$$

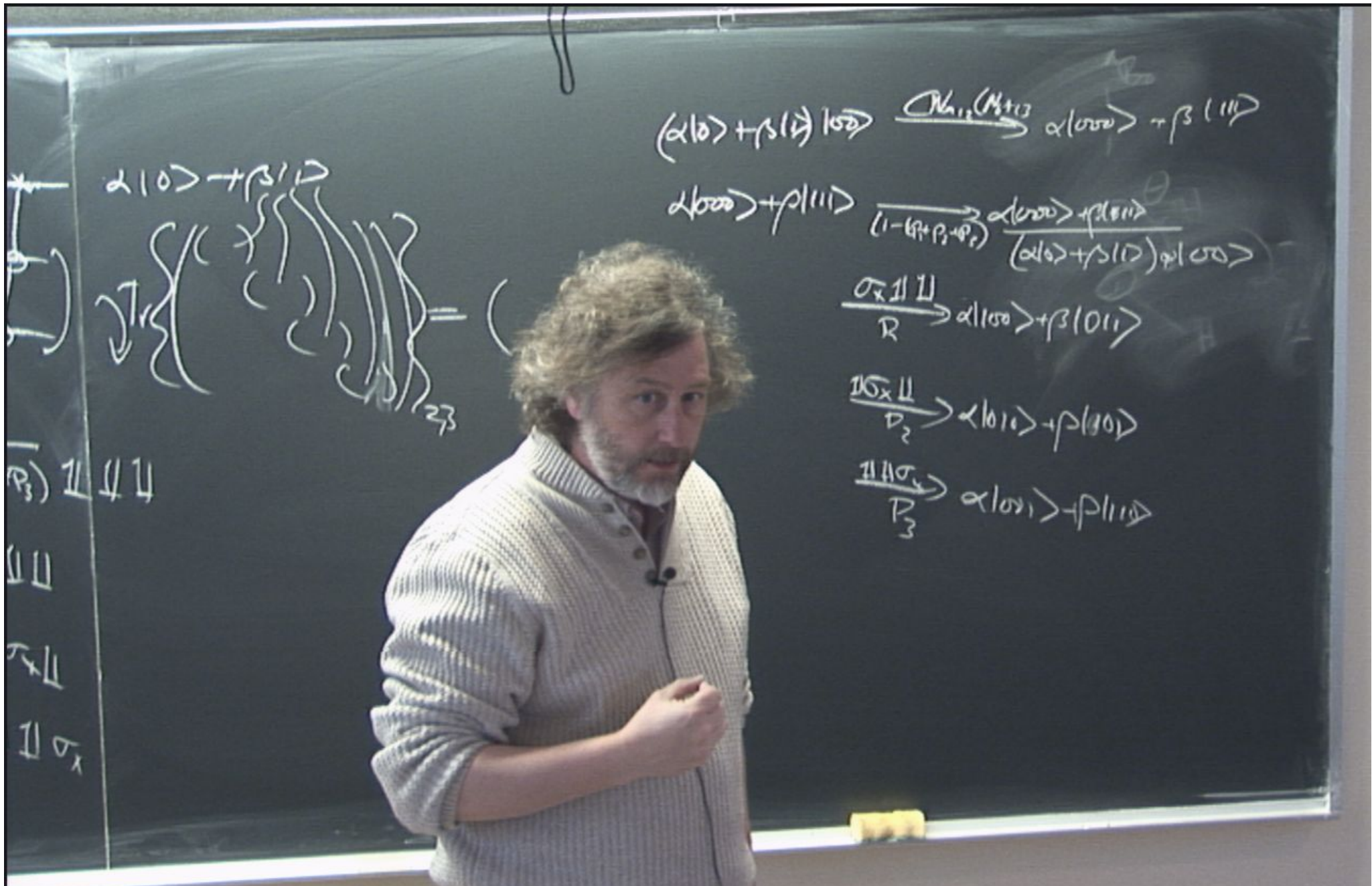


$$P_3) \perp \perp \perp$$

$$\perp \perp$$

$$\perp \perp \perp$$

$$\perp \perp \perp$$



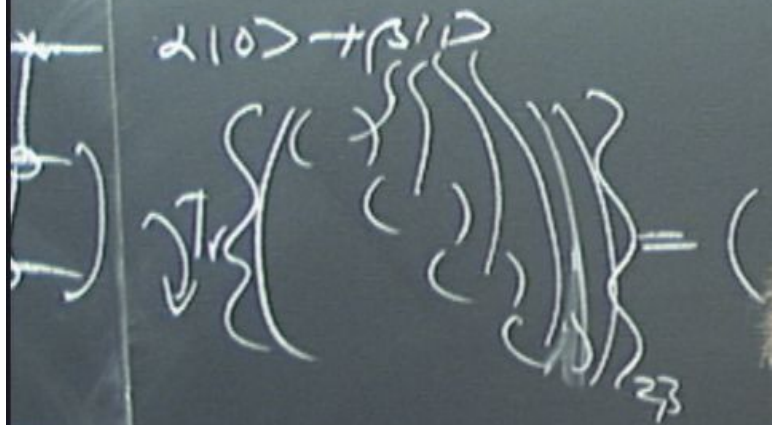
$$(\alpha|10\rangle + \beta|11\rangle) |100\rangle \xrightarrow{M_{112} (M_{113})} \alpha|1000\rangle + \beta|1111\rangle$$

$$\alpha|1000\rangle + \beta|1111\rangle \xrightarrow{(1 - P_1 + P_2 + P_3)} \frac{\alpha|1000\rangle + \beta|1111\rangle}{(\alpha|10\rangle + \beta|11\rangle) |100\rangle}$$

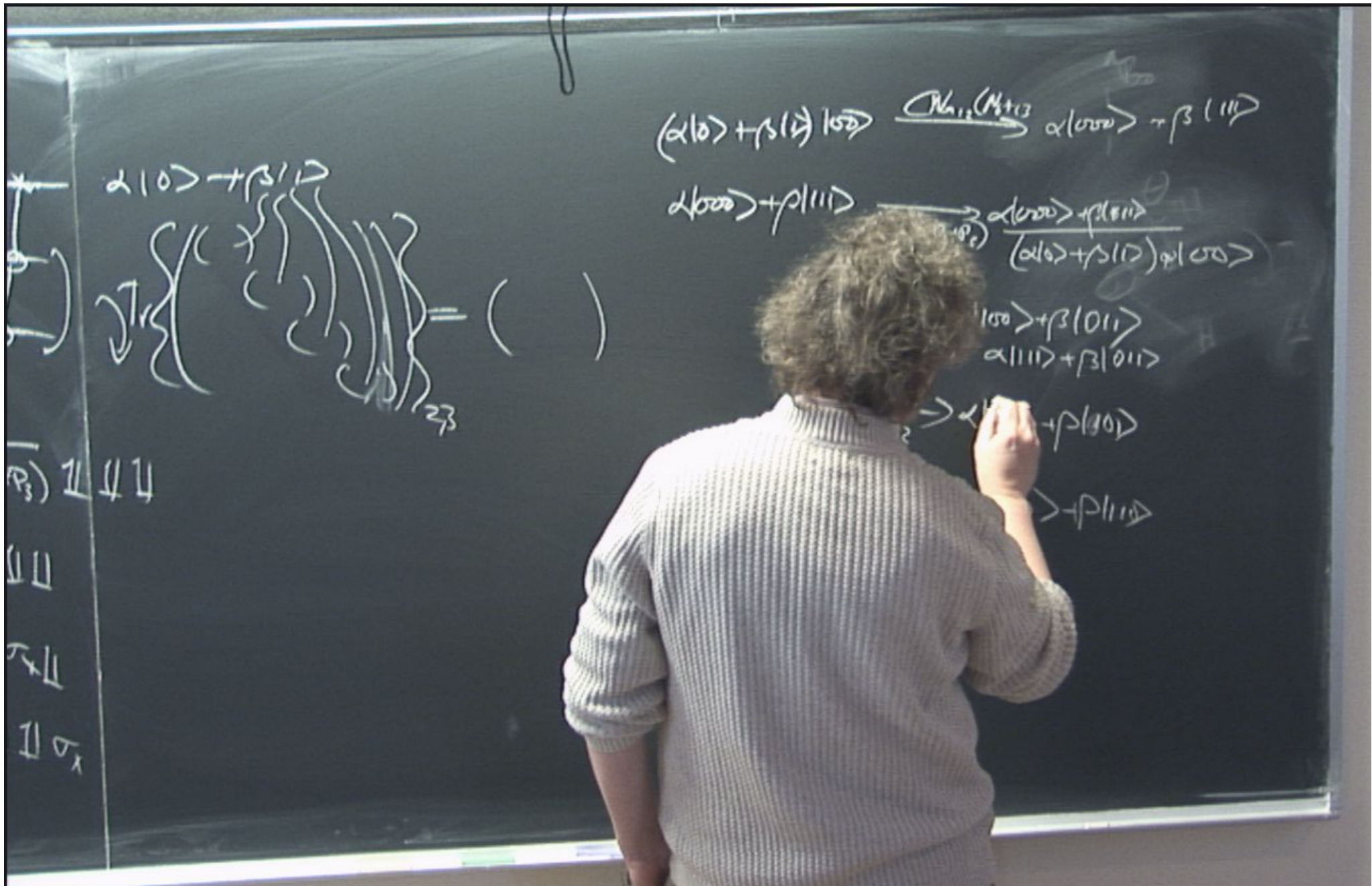
$$\frac{\sigma_x \otimes I \otimes I}{P} \rightarrow \alpha|1100\rangle + \beta|1011\rangle$$

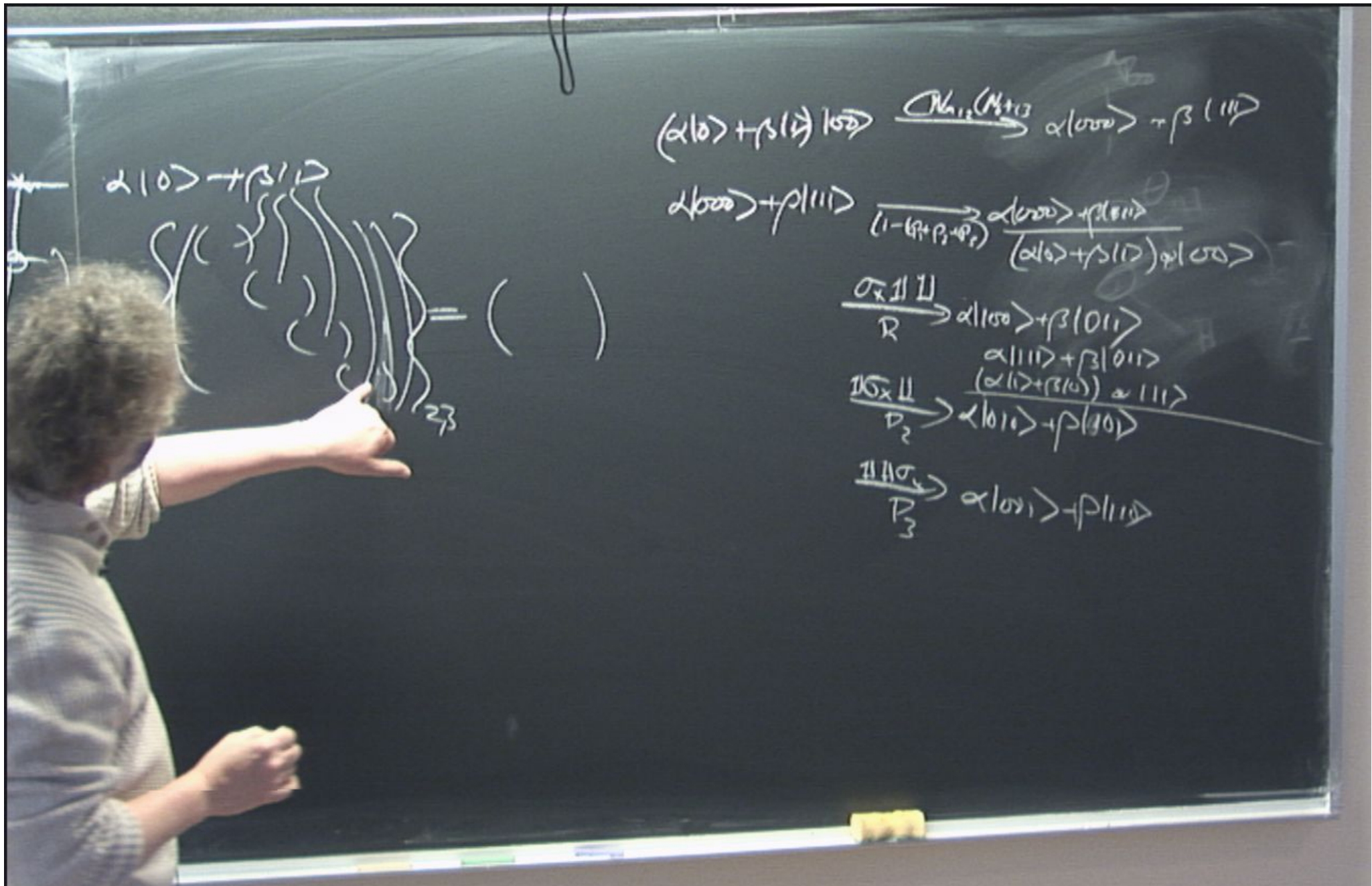
$$\frac{I \otimes \sigma_x \otimes I}{P_2} \rightarrow \alpha|1010\rangle + \beta|1101\rangle$$

$$\frac{I \otimes I \otimes \sigma_x}{P_3} \rightarrow \alpha|1001\rangle + \beta|1110\rangle$$

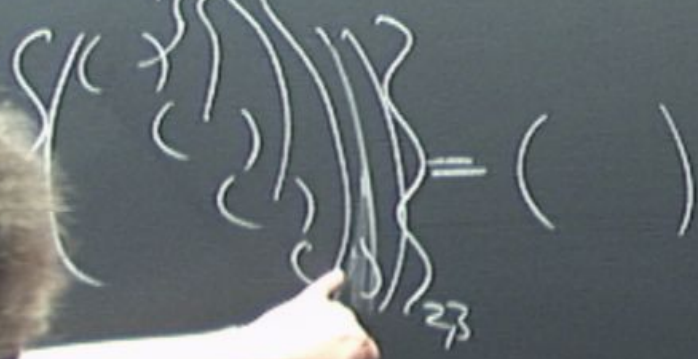


$(P_3) \perp \perp \perp$
 $\perp \perp$
 $\perp \perp$
 $\perp \perp$
 $\perp \perp$





$$\alpha|10\rangle + \beta|11\rangle$$



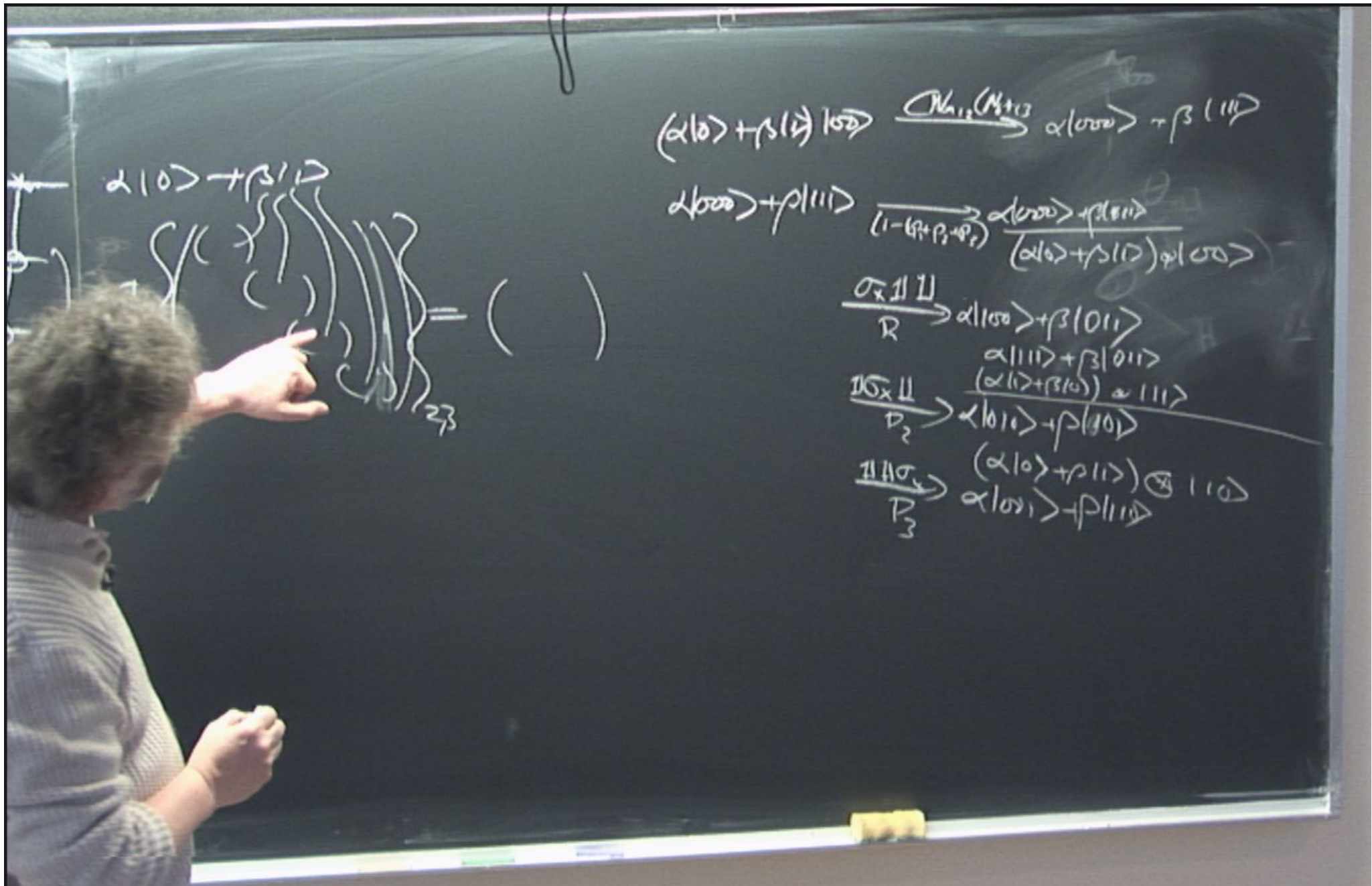
$$(\alpha|10\rangle + \beta|11\rangle) |100\rangle \xrightarrow{P_{112}(N_1+1)} \alpha|1000\rangle + \beta|111\rangle$$

$$\alpha|1000\rangle + \beta|111\rangle \xrightarrow{(1-P_1+P_2+P_3)} \frac{\alpha|1000\rangle + \beta|111\rangle}{(\alpha|10\rangle + \beta|11\rangle) |100\rangle}$$

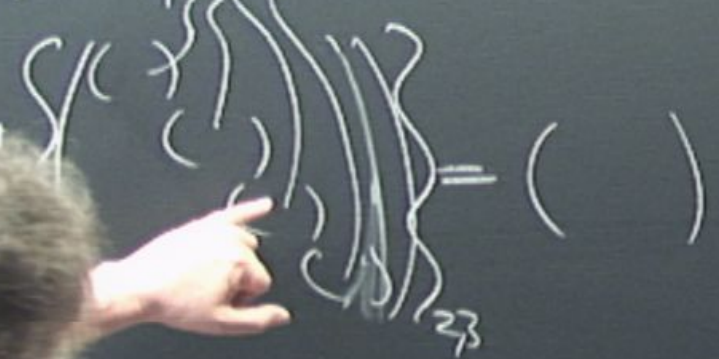
$$\frac{\sigma_x \otimes 1 \otimes 1}{P_1} \rightarrow \alpha|1100\rangle + \beta|1011\rangle$$

$$\frac{1 \otimes \sigma_x \otimes 1}{P_2} \rightarrow \frac{\alpha|1111\rangle + \beta|1011\rangle}{(\alpha|11\rangle + \beta|10\rangle) |111\rangle} \rightarrow \alpha|1011\rangle + \beta|1101\rangle$$

$$\frac{1 \otimes 1 \otimes \sigma_x}{P_3} \rightarrow \alpha|1001\rangle + \beta|1110\rangle$$



$$\alpha|10\rangle + \beta|11\rangle$$



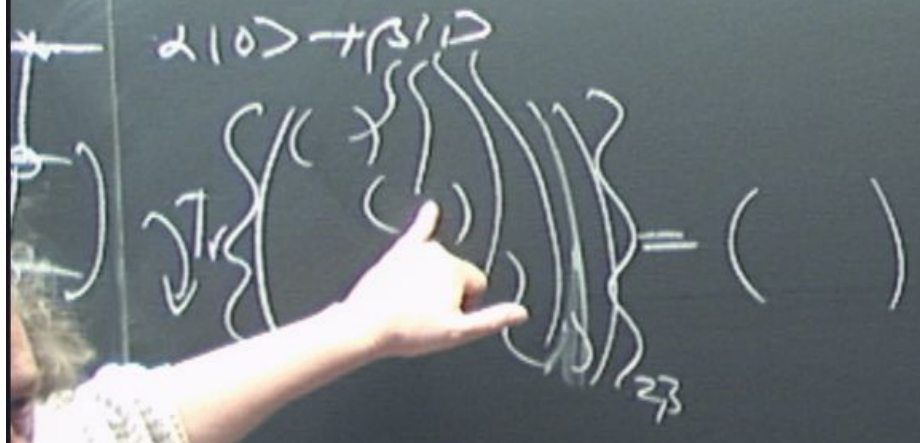
$$(\alpha|10\rangle + \beta|11\rangle) |00\rangle \xrightarrow{CN_{12}(N_{13})} \alpha|1000\rangle + \beta|1111\rangle$$

$$\alpha|1000\rangle + \beta|1111\rangle \xrightarrow{(1 - P_1 + P_2 + P_3)} \frac{\alpha|1000\rangle + \beta|1111\rangle}{(\alpha|10\rangle + \beta|11\rangle) \otimes |00\rangle}$$

$$\frac{\sigma_x \otimes I \otimes I}{R} \rightarrow \alpha|1100\rangle + \beta|1011\rangle$$

$$\frac{I \otimes \sigma_x \otimes I}{P_2} \rightarrow \frac{\alpha|1111\rangle + \beta|1011\rangle}{(\alpha|11\rangle + \beta|10\rangle) \otimes |11\rangle}$$

$$\frac{I \otimes I \otimes \sigma_x}{P_3} \rightarrow \frac{(\alpha|10\rangle + \beta|11\rangle) \otimes |110\rangle}{\alpha|1011\rangle + \beta|1111\rangle}$$



$$(\alpha|10\rangle + \beta|11\rangle) |00\rangle \xrightarrow{CNOT_{12}} \alpha|1000\rangle + \beta|1111\rangle$$

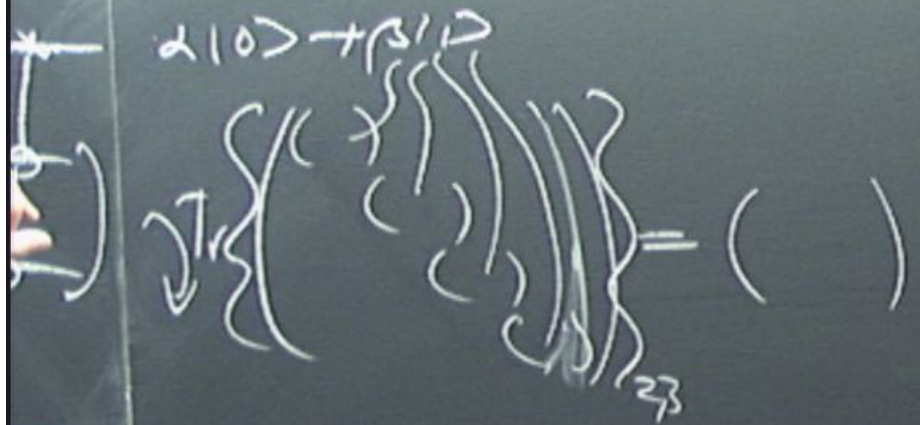
$$\alpha|1000\rangle + \beta|1111\rangle \xrightarrow{(I - P_1 + P_2 + P_3)} \frac{\alpha|1000\rangle + \beta|1111\rangle}{(\alpha|10\rangle + \beta|11\rangle) |00\rangle}$$

$$\frac{\sigma_x \otimes I \otimes I}{R} \rightarrow \alpha|1100\rangle + \beta|1011\rangle$$

$$\frac{I \otimes \sigma_x \otimes I}{P_2} \rightarrow \frac{\alpha|1111\rangle + \beta|1011\rangle}{(\alpha|11\rangle + \beta|10\rangle) |111\rangle}$$

$$\frac{I \otimes I \otimes \sigma_x}{P_3} \rightarrow \frac{(\alpha|10\rangle + \beta|11\rangle) \otimes |110\rangle}{\alpha|1001\rangle + \beta|1110\rangle}$$

$$(\alpha|10\rangle + \beta|11\rangle) \otimes |011\rangle$$



$P_3 \parallel \parallel \parallel$
 $\parallel \parallel$
 $\parallel \parallel$
 $\parallel \sigma_x$

$$(\alpha|10\rangle + \beta|11\rangle) |00\rangle \xrightarrow{CN_{12}(N_{12})} \alpha|1000\rangle + \beta|1111\rangle$$

$$\alpha|1000\rangle + \beta|1111\rangle \xrightarrow{(1-P_1+P_2+P_3)} \frac{\alpha|1000\rangle + \beta|1111\rangle}{(\alpha|10\rangle + \beta|11\rangle) \otimes |00\rangle}$$

$$\frac{\sigma_x \parallel \parallel}{P} \rightarrow \alpha|1100\rangle + \beta|1011\rangle$$

$$\frac{10 \times \parallel}{P_2} \rightarrow \frac{\alpha|1111\rangle + \beta|1011\rangle}{(\alpha|11\rangle + \beta|10\rangle) \otimes |11\rangle}$$

$$\frac{\parallel \parallel \sigma_x}{P_3} \rightarrow \frac{(\alpha|10\rangle + \beta|11\rangle) \otimes |110\rangle}{\alpha|1001\rangle + \beta|1110\rangle}$$

$$(\alpha|10\rangle + \beta|11\rangle) \otimes |101\rangle$$

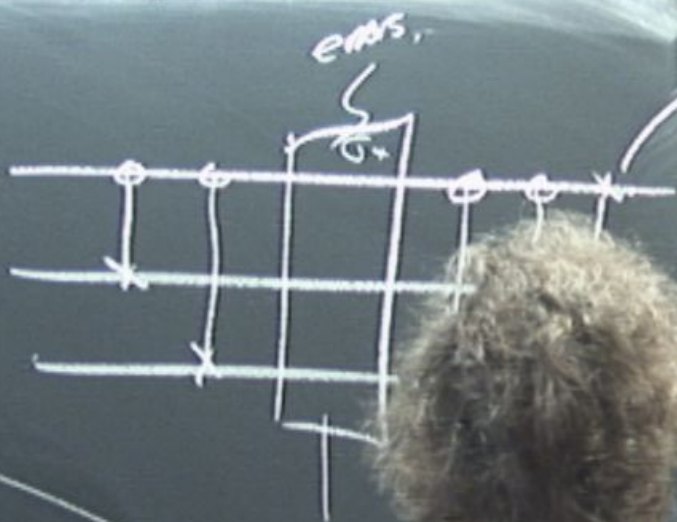
QEC

$$\alpha|0\rangle + \beta|1\rangle$$

lattice expands

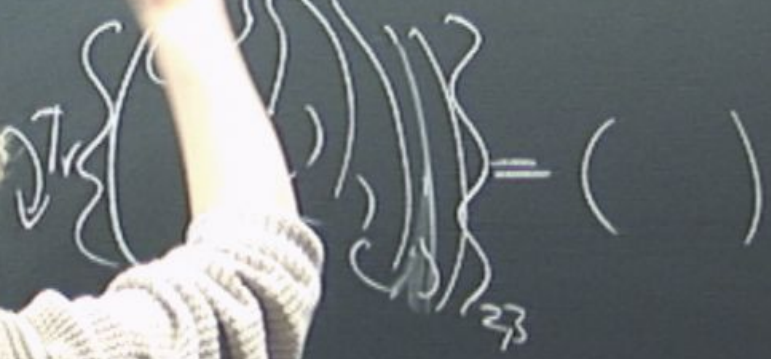
$$\begin{cases} |0\rangle \\ |1\rangle \end{cases}$$

$$2^2$$



$T_{SPK} =$

$$\alpha|0\rangle + \beta|1\rangle$$



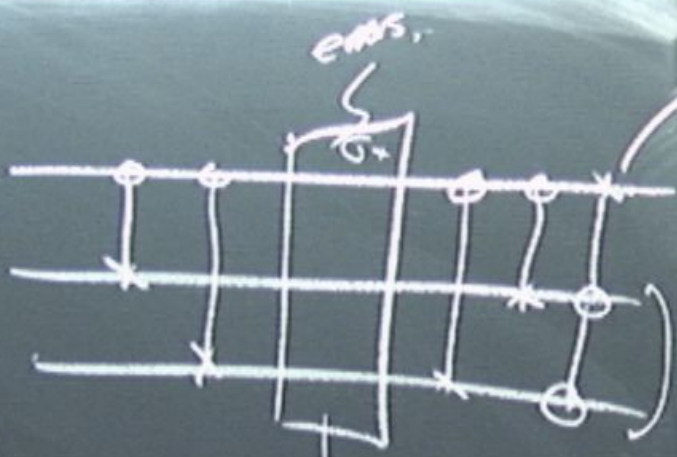
QEC

$$\alpha|0\rangle + \beta|1\rangle$$

lattice expands
+

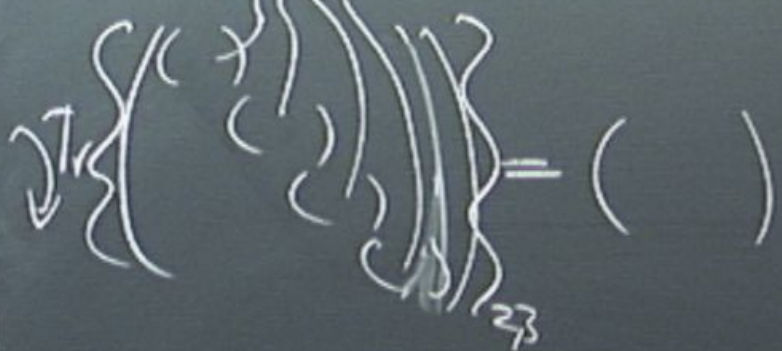
$$\left\{ \begin{array}{l} |0\rangle \\ |1\rangle \end{array} \right\}$$

2^2



$$TSPH = \sigma_x E_+ E_+ + \mathbb{1} E_- E_- + \mathbb{1} E_+ E_- + \mathbb{1} E_- E_+$$

$$\alpha|0\rangle + \beta|1\rangle$$



$$\left\{ \begin{array}{l} K_1 = \sqrt{\frac{1}{2}} (\mathbb{1} \otimes \mathbb{1} \otimes \mathbb{1}) \\ K_2 = \sqrt{\frac{1}{2}} (\sigma_x \otimes \mathbb{1} \otimes \mathbb{1}) \\ K_3 = \sqrt{\frac{1}{2}} (\mathbb{1} \otimes \sigma_x \otimes \mathbb{1}) \\ K_4 = \sqrt{\frac{1}{2}} (\mathbb{1} \otimes \mathbb{1} \otimes \sigma_x) \end{array} \right.$$

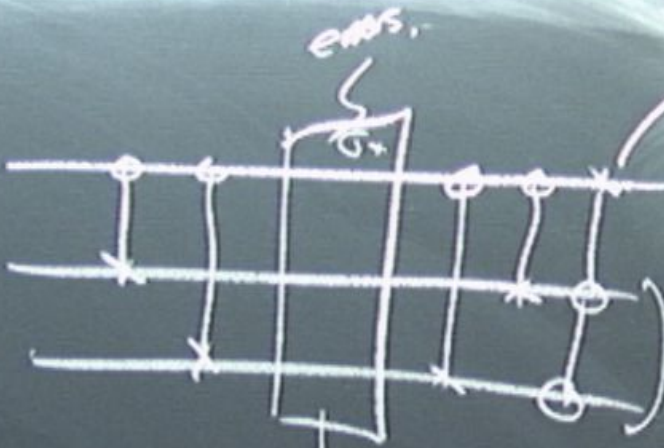
QEC

$$\alpha|0\rangle + \beta|1\rangle$$

lattice expands

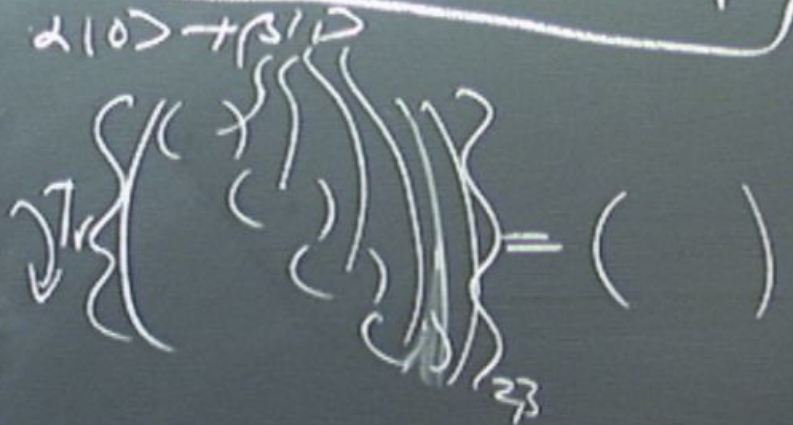
$$\left\{ \begin{array}{l} |0\rangle \\ |1\rangle \end{array} \right\}$$

$$2^2$$



$$\left\{ \begin{array}{l} K_1 = \sqrt{I - (R_1 + R_2 + R_3)} \quad \text{II II} \\ K_2 = \sqrt{R_1} \quad \text{IX II} \\ K_3 = \sqrt{R_2} \quad \text{II IX} \\ K_4 = \sqrt{R_3} \quad \text{II II IX} \end{array} \right.$$

$$T_{SPK} = \alpha_+ E_+ E_+ + \beta_- E_- E_- + \gamma E_+ E_- + \delta E_- E_+$$

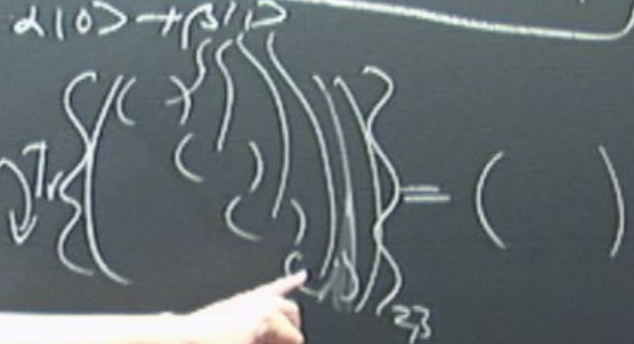


QEC

$\alpha|10\rangle + \beta|11\rangle$
 lattice expanded
 $\left\{ \begin{array}{l} |10\rangle \\ |11\rangle \end{array} \right\}$
 2^2



$$T_{SPR} = \sigma_x E_+ E_+ + \mathbb{1} E_- E_- + \mathbb{1} E_+ E_- + \mathbb{1} E_- E_+$$



$(\alpha|10\rangle + \beta|11\rangle)$
 $(\alpha|000\rangle + \dots)$

$\sigma_x \mathbb{1} \mathbb{1}$
 $\mathbb{1} \sigma_x \mathbb{1}$
 $\mathbb{1} \mathbb{1} \sigma_x$

$$\langle N_{\pm} e_{\pm} \rangle = E_{\pm} \sigma_{\pm} \mathbb{1} + E_{\pm} \mathbb{1} \mathbb{1}$$

$$CN_{\hat{e}_{12}} = E_+ \sigma_x \mathbb{1} + E_- \mathbb{1} \mathbb{1}$$

$$CN_{\hat{e}_{13}} = E_+ \mathbb{1} \sigma_x + E_- \mathbb{1} \mathbb{1}$$

$$CN_{\mathbb{R}^2} = E_+ \oplus \mathbb{I} \oplus \mathbb{I}$$

$$CN_{\mathbb{R}^3} = E_+ \oplus \mathbb{I} \oplus \mathbb{I}$$

$$\sigma_x \sigma_x \rightarrow 1$$

$$E_{\pm} E_{\pm} \rightarrow E_{\pm}$$

$$CN_{\vec{e}_{12}} = E_+ \sigma_x \mathbb{1} + E_- \mathbb{1} \sigma_x$$

$$CN_{\vec{e}_{13}} = E_+ \mathbb{1} \sigma_x + E_- \sigma_x \mathbb{1}$$

$$\sigma_x \sigma_x \rightarrow \mathbb{1}$$

$$E_+ E_+ \rightarrow E_+$$

$$E_+ E_- \rightarrow 0$$

$$\hat{\sigma}_{12} = E_+ \sigma_x \mathbb{1} + E_- \mathbb{1} \sigma_x$$

$$\hat{\sigma}_{13} = E_+ \mathbb{1} \sigma_x + E_- \mathbb{1} \sigma_x$$

$$\sigma_x \sigma_x \rightarrow \mathbb{1}$$

$$E_+ E_+ \rightarrow E_+$$

$$E_+ E_- \rightarrow 0$$

$$E_+ \sigma_x E_- = \frac{\sigma_x - i\sigma_y}{2}$$

$$E_- \sigma_x E_+ = \frac{\sigma_x + i\sigma_y}{2}$$

$$CN_{\hat{e}_{12}} = E_+ \sigma_x \mathbb{1} + E_- \mathbb{1} \mathbb{1}$$

$$CN_{\hat{e}_{13}} = E_+ \mathbb{1} \sigma_x + E_- \mathbb{1} \mathbb{1}$$

$$\sigma_x \sigma_x \rightarrow \mathbb{1}$$

$$E_+ E_+ \rightarrow E_+$$

$$E_+ E_- \rightarrow 0$$

$$E_+ \sigma_x E_- = \frac{\sigma_x - i\sigma_y}{2}$$

$$E_- \sigma_x E_+ = \frac{\sigma_x + i\sigma_y}{2}$$

$$E_{\pm} = \frac{1}{2} (\mathbb{1} \pm \sigma_z)$$

$$CN_{12} = E_+ \sigma_x \mathbb{1} + E_- \mathbb{1} \mathbb{1}$$

$$CN_{13} = E_+ \mathbb{1} \sigma_x + E_- \mathbb{1} \mathbb{1}$$

$$\sigma_x \sigma_x \rightarrow \mathbb{1}$$

$$E_+ E_+ \rightarrow E_+$$

$$E_+ E_- \rightarrow 0$$

$$E_+ \sigma_x E_- = \frac{\sigma_x - i\sigma_y}{2}$$

$$E_- \sigma_x E_+ = \frac{\sigma_x + i\sigma_y}{2}$$

$$E_{\pm} = \frac{1}{2}(\mathbb{1} \pm \sigma_z)$$

$$CN_{\hat{e}_{12}} = E_+ \sigma_x \mathbb{1}$$

$$CN_{\hat{e}_{13}} = E_+ \mathbb{1}$$

$$\sigma_x \sigma_x \rightarrow \mathbb{1}$$

$$E_+ E_+ \rightarrow E_+$$

$$E_+ E_- \rightarrow 0$$

$$E_+ \sigma_x E_- = \frac{\sigma_x - i\sigma_y}{2}$$

$$E_- \sigma_x E_+ = \frac{\sigma_x + i\sigma_y}{2}$$

$$E_+ = \frac{1}{2}(\mathbb{1} + \sigma_z)$$

$$CN_{\hat{e}_{12}} = E_+ \sigma_x \mathbb{1} + E_- \mathbb{1} \mathbb{1}$$

$$CN_{\hat{e}_{13}} = E_+ \mathbb{1} \sigma_x + E_- \mathbb{1} \mathbb{1}$$

$$\sigma_x \sigma_x \rightarrow \mathbb{1}$$

$$E_+ E_+ \rightarrow E_+$$

$$E_+ E_- \rightarrow 0$$

$$E_+ \sigma_x E_- = \frac{\sigma_x - i\sigma_y}{2}$$

$$E_- \sigma_x E_+ = \frac{\sigma_x + i\sigma_y}{2}$$

$$E_{\pm} = \frac{1}{2} (\mathbb{1} \pm \sigma_z)$$

$$N_{\hat{e}_{12}} = E_+ \sigma_x \mathbb{1} + E_- \mathbb{1} \mathbb{1}$$

$$N_{\hat{e}_{13}} = E_+ \mathbb{1} \sigma_x + E_- \mathbb{1} \mathbb{1}$$

$$N_{\hat{e}_{12}} N_{\hat{e}_{13}} = E_+ \sigma_x \sigma_x + E_- \mathbb{1} \mathbb{1}$$

$$\sigma_x \sigma_x \rightarrow \mathbb{1}$$

$$E_+ E_+ \rightarrow E_+$$

$$E_+ E_- \rightarrow 0$$

$$E_+ \sigma_x E_- = \frac{\sigma_x - i\sigma_y}{2}$$

$$E_- \sigma_x E_+ = \frac{\sigma_x + i\sigma_y}{2}$$

$$E_{\pm} = \frac{1}{2} (\mathbb{1} \pm \sigma_z)$$

$$CN_{\uparrow\downarrow 12} = E_+ \sigma_x \mathbb{1} + E_- \mathbb{1} \mathbb{1}$$

$$CN_{\uparrow\downarrow 13} = E_+ \mathbb{1} \sigma_x + E_- \mathbb{1} \mathbb{1}$$

$$CN_{\uparrow\downarrow 23} = E_+ \sigma_x \sigma_x + E_- \mathbb{1} \mathbb{1}$$

$$\sigma_x \sigma_x \rightarrow \mathbb{1}$$

$$E_+ E_+ \rightarrow E_+$$

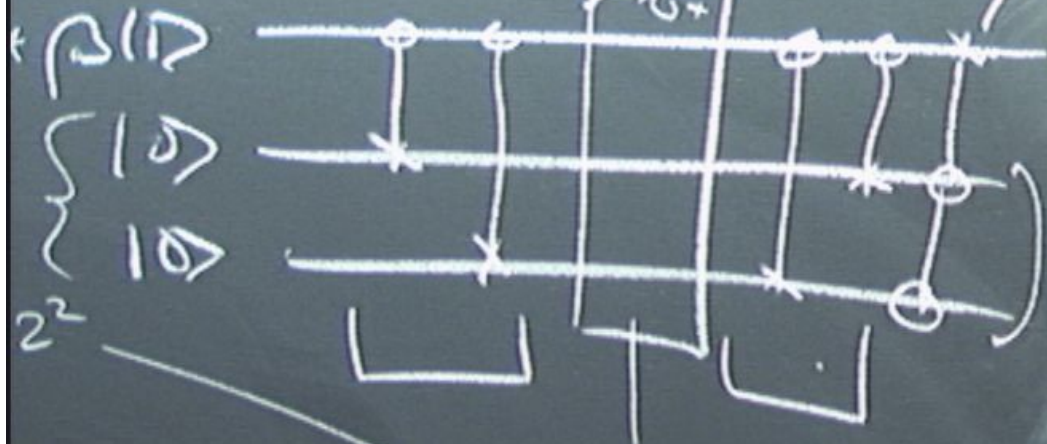
$$E_+ E_- \rightarrow 0$$

$$E_+ \sigma_x E_- = \frac{\sigma_x - i\sigma_y}{2}$$

$$E_- \sigma_x E_+ = \frac{\sigma_x + i\sigma_y}{2}$$

$$E_{\pm} = \frac{1}{2}(\mathbb{1} \pm \sigma_z)$$

EC



$$\begin{aligned}
 K_1 &= \sqrt{1 - (R_1 + R_2 + R_3)} \quad \parallel \parallel \parallel \\
 K_2 &= \sqrt{\frac{R_1}{R_2}} \quad \parallel \times \parallel \parallel \\
 K_3 &= \sqrt{\frac{R_1}{R_2}} \quad \parallel \parallel \times \parallel \\
 K_4 &= \sqrt{\frac{R_2}{R_3}} \quad \parallel \parallel \parallel \times
 \end{aligned}$$

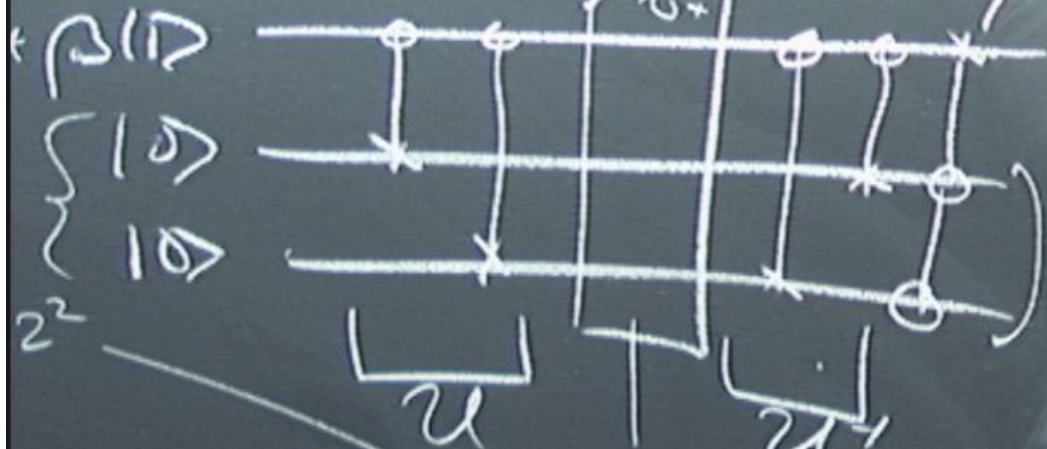
$$\begin{aligned}
 TSPR_1 &= \sigma_x E_+ E_+ + \mathbb{1} E_- E_- \\
 &+ \mathbb{1} E_+ E_- + \mathbb{1} E_- E_+
 \end{aligned}$$

$\langle 10 \rangle + \langle \beta | \rangle$

$$\text{Tr} \left(\begin{pmatrix} \times & & & \\ & \times & & \\ & & \times & \\ & & & \times \end{pmatrix} \right) = ()$$

23

EC



2^2

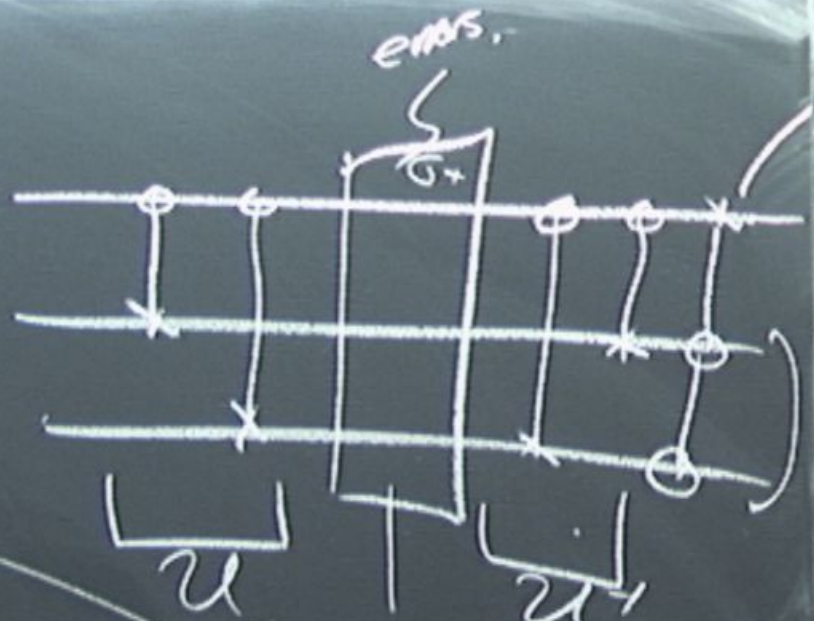
$$\begin{aligned}
 K_1 &= \sqrt{1 - (R_1 + R_2 + R_3)} \quad \text{II II II} \\
 K_2 &= \sqrt{R_1} \quad \sigma_x \text{II II} \\
 K_3 &= \sqrt{R_2} \quad \text{II } \sigma_x \text{II} \\
 K_4 &= \sqrt{R_3} \quad \text{II II } \sigma_x
 \end{aligned}$$

$$\text{Tr} \rho_1 = \sigma_x E_+ E_+ + \text{II } E_- E_- + \text{II } E_+ E_- + \text{II } E_- E_+$$

$$\text{Tr} \left(\begin{matrix} \text{II} \\ \text{II} \\ \text{II} \end{matrix} \right) = \left(\begin{matrix} \text{II} \\ \text{II} \\ \text{II} \end{matrix} \right)$$

EC

$\beta | \uparrow \downarrow \rangle$
 $\{ | \uparrow \rangle$
 $\{ | \downarrow \rangle$
 2^2



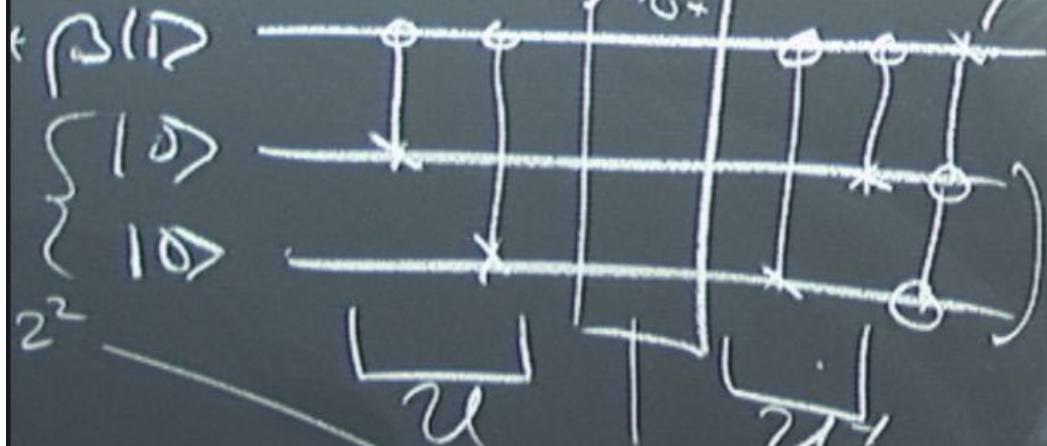
$$\begin{aligned}
 K_1 &= \sqrt{1 - (R_1 + R_2 + R_3)} \mathbb{I} \otimes \mathbb{I} \otimes \mathbb{I} \\
 K_2 &= \sqrt{R_1} \sigma_x \otimes \mathbb{I} \otimes \mathbb{I} \\
 K_3 &= \sqrt{R_2} \mathbb{I} \otimes \sigma_x \otimes \mathbb{I} \\
 K_4 &= \sqrt{R_3} \mathbb{I} \otimes \mathbb{I} \otimes \sigma_x
 \end{aligned}$$

$$\text{Tr} \rho_1 = \sigma_x E_+ E_+ + \mathbb{I} E_- E_- + \mathbb{I} E_+ E_- + \mathbb{I} E_- E_+$$

$$\text{Tr} \left(\left(\begin{matrix} \times \\ \times \\ \times \end{matrix} \right) \right) = ()$$

$$K_1 = U K_1 U^\dagger$$

EC



$$TSPR = \sigma_x E_+ E_+ + \mathbb{1} E_- E_- + \mathbb{1} E_+ E_- + \mathbb{1} E_- E_+$$

$\alpha|10\rangle + \beta|11\rangle$

$\text{Tr} \left(\begin{pmatrix} \times & & & \\ & & & \\ & & & \\ & & & \end{pmatrix} \right)$

$$K_1 = \sqrt{1 - (R + P_2 + P_3)}$$

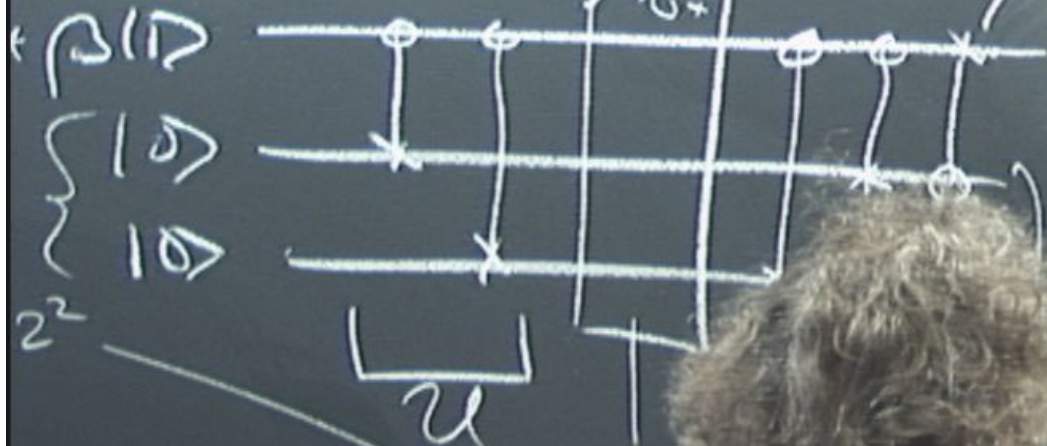
$$K_2 = \sqrt{\dots}$$

$$K_3 = \sqrt{\dots}$$

$$K_4 = \sqrt{\dots}$$

$$K^T = \mathbb{1} \mathbb{1} \mathbb{1}$$

EC



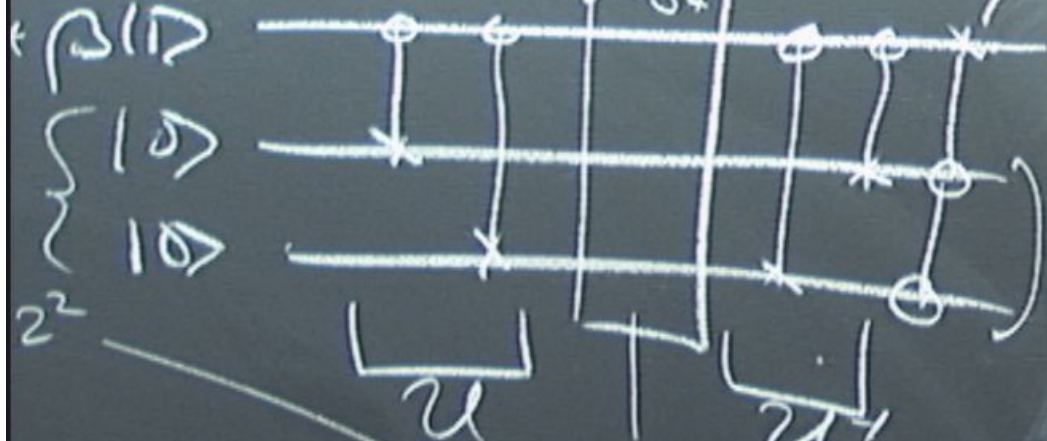
$$TSPR = \sigma_x E_+ E_+ + \mathbb{1} E_- E_- + \mathbb{1} E_+ E_- + \mathbb{1} E_- E_+$$

$\alpha|10\rangle + |\beta_1\rangle$

$$\text{Tr} \left(\begin{matrix} \text{---} \\ \text{---} \\ \text{---} \end{matrix} \right) = (\quad)$$

$$\mathbb{1} \mathbb{1} \mathbb{1}; K_1 = U K U^\dagger = \mathbb{1} \mathbb{1} \mathbb{1}$$

EC



$$TSPR = \sigma_x E_+ E_+ + \mathbb{1} E_- E_- + \mathbb{1} E_+ E_- + \mathbb{1} E_- E_+$$

$\alpha | 10 \rangle + \beta | 11 \rangle$

$$\text{Tr} \left(\begin{matrix} \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \end{matrix} \right) = (\quad)$$

23

$$K_1 = \sqrt{1 - (R_1 + R_2 + R_3)} \mathbb{1} \mathbb{1} \mathbb{1} \mathbb{1} ; K_1 = U K_1 U^T = \mathbb{1} \mathbb{1} \mathbb{1} \mathbb{1}$$

$$K_2 = \sqrt{\frac{R_1}{2}} \sigma_x \mathbb{1} \mathbb{1}$$

$$K_3 = \sqrt{\frac{R_2}{2}} \mathbb{1} \sigma_x \mathbb{1}$$

$$K_4 = \sqrt{\frac{R_3}{2}} \mathbb{1} \mathbb{1} \sigma_x$$

$$CN_{\hat{e}_{12}} = E_+ \sigma_x \mathbb{1} + E_- \mathbb{1} \mathbb{1}$$

$$CN_{\hat{e}_{13}} = E_+ \mathbb{1} \sigma_x + E_- \mathbb{1} \mathbb{1}$$

$$CN_{\hat{e}_{12}} CN_{\hat{e}_{13}} = E_+ \sigma_x \sigma_x + E_- \mathbb{1} \mathbb{1} = \mathcal{U} = \mathcal{U}^{-1}$$

$$\sigma_x \sigma_x \rightarrow$$

$$E_+ E_+ \rightarrow$$

$$E_+ E_- \rightarrow$$

$$E_+ \sigma_x E_- = \sigma_x$$

$$E_- \sigma_x E_+ = \sigma_x$$

$$E_+ = \frac{1}{2} (\mathbb{1} + \sigma_x)$$

$$CN_{st,2} = E_+ \sigma_x \mathbb{1} + E_- \mathbb{1} \mathbb{1}$$

$$CN_{st,3} = E_+ \mathbb{1} \sigma_x + E_- \mathbb{1} \mathbb{1}$$

$$CN_{st,2} CN_{st,3} = E_+ \sigma_x \sigma_x + E_- \mathbb{1} \mathbb{1} = \mathcal{U} = \mathcal{U}^{-1}$$

$$\sigma_x \sigma_x \rightarrow \mathbb{1}$$

$$E_+ E_+ \rightarrow E_+$$

$$E_+ E_- \rightarrow 0$$

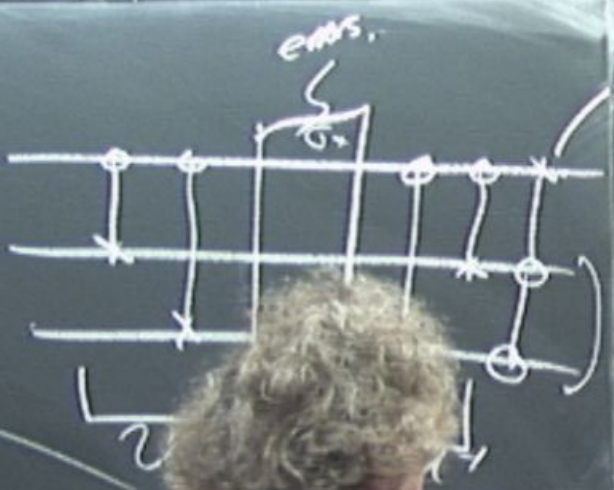
$$E_+ \sigma_x E_- = \frac{\sigma_x - i\sigma_y}{2}$$

$$E_- \sigma_x E_+ = \frac{\sigma_x + i\sigma_y}{2}$$

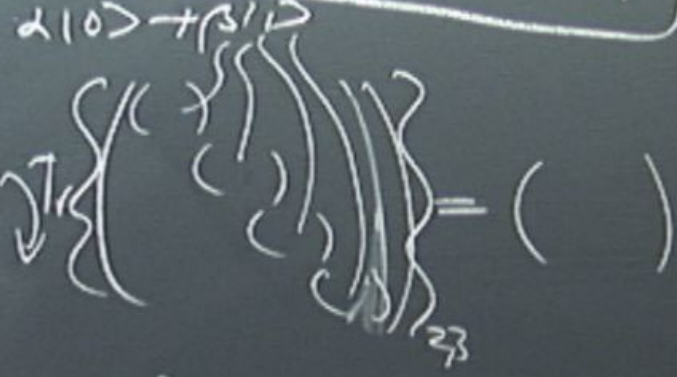
$$E_{\pm} = \frac{1}{2}(\mathbb{1} \pm \sigma_z)$$

QEC

$\alpha|0\rangle + \beta|1\rangle$
 $\begin{cases} |0\rangle \\ |0\rangle \end{cases}$
 2^2



$$TSPR = \sigma_x E_+ E_+ + \mathbb{1} E_- E_- + \mathbb{1} E_+ E_- + \mathbb{1} E_- E_+$$



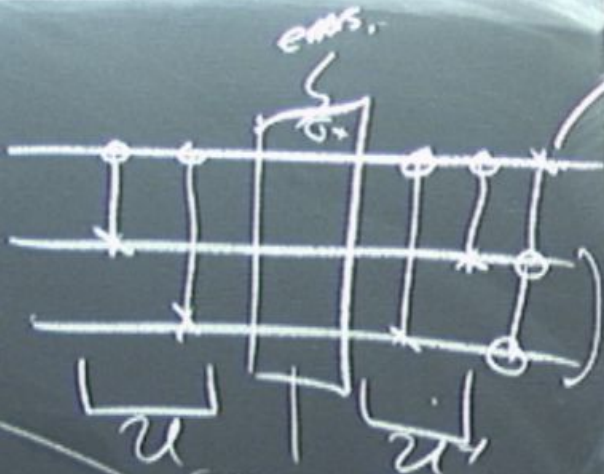
$(\alpha|0\rangle + \beta|1\rangle)|00\rangle$
 $(\alpha|000\rangle + \beta|111\rangle)$

$(R+P_2+P_3) \mathbb{1} \mathbb{1} \mathbb{1} ; K_1 = \mathcal{U} K, \mathcal{U}^\dagger = \mathbb{1} \mathbb{1} \mathbb{1}$

$\frac{\sigma_x \mathbb{1}}{R}$
 $\frac{\mathbb{1} \sigma_x \mathbb{1}}{P_2}$
 $\frac{\mathbb{1} \mathbb{1} \sigma_x}{P_3}$

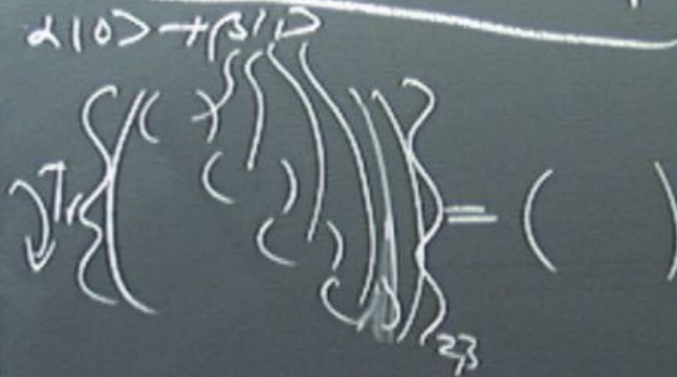
QEC

$\alpha|0\rangle + \beta|1\rangle$
 $\left\{ \begin{array}{l} |0\rangle \\ |1\rangle \end{array} \right\}$
 2^2



$$\left\{ \begin{array}{l} K_1 = \sqrt{I - (R_1 + P_2 + P_3)} \quad \mathbb{1} \quad \mathbb{1} \quad \mathbb{1} \\ K_2 = \sqrt{P_1} \quad \sigma_x \mathbb{1} \mathbb{1} \\ K_3 = \sqrt{P_2} \quad \mathbb{1} \sigma_y \mathbb{1} \\ K_4 = \sqrt{P_3} \quad \mathbb{1} \mathbb{1} \sigma_x \end{array} \right.$$

$$T_{SPR} = \sigma_x E_+ E_+ + \mathbb{1} E_- E_- + \mathbb{1} E_+ E_- + \mathbb{1} E_- E_+$$



$$K_1 = U K_1 U^\dagger = \mathbb{1} \mathbb{1} \mathbb{1}$$

$(\alpha|0\rangle + \beta|1\rangle) |00\rangle$
 $\alpha|000\rangle + \beta|111\rangle$

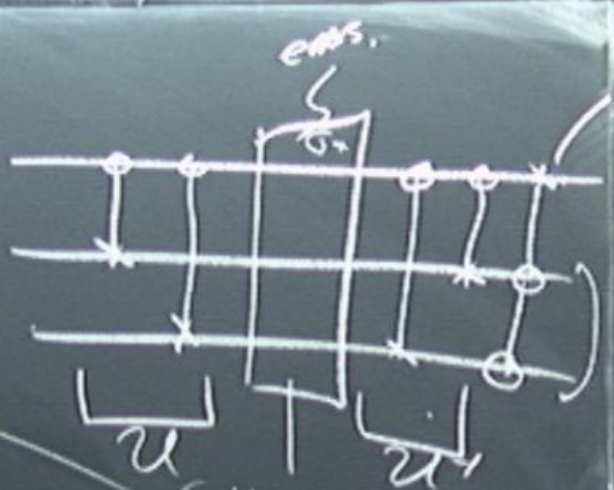
$$\frac{\sigma_x \mathbb{1}}{R}$$

$$\frac{\mathbb{1} \sigma_y \mathbb{1}}{P_2}$$

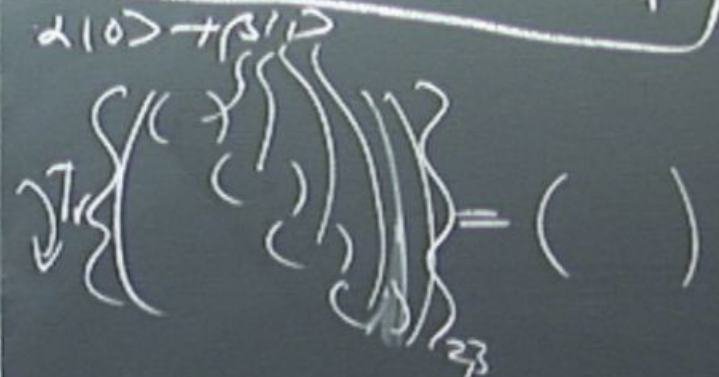
$$\frac{\mathbb{1} \mathbb{1} \sigma_x}{P_3}$$

QEC

$\alpha|0\rangle + \beta|1\rangle$
 lattice expanded
 $\left\{ \begin{array}{l} |0\rangle \\ |1\rangle \end{array} \right\}$
 2^2



$$\mathcal{H}_{\text{code}} = \sigma_x E_+ E_- + \mathbb{1} E_- E_- + \mathbb{1} E_+ E_- + \mathbb{1} E_- E_+$$



$$E_+ \sigma_x \sigma_x \quad \sigma_x \mathbb{1} \mathbb{1} \quad E_- \mathbb{1} \mathbb{1}$$

$$\left\{ \begin{array}{l} K_1 = \sqrt{\frac{1}{2}} (\mathbb{1} + P_1 P_2 P_3) \\ K_2 = \sqrt{\frac{1}{2}} P_1 \sigma_x \mathbb{1} \mathbb{1} \\ K_3 = \sqrt{\frac{1}{2}} \mathbb{1} P_2 \sigma_x \mathbb{1} \\ K_4 = \sqrt{\frac{1}{2}} \mathbb{1} \mathbb{1} P_3 \sigma_x \end{array} \right.$$

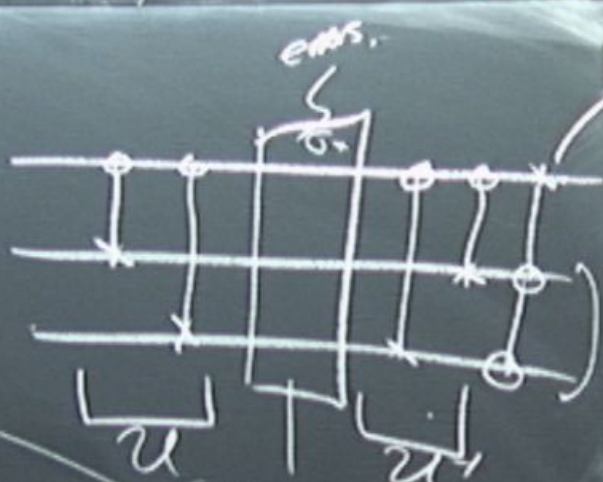
$$K_1 = \mathbb{1} \mathbb{1} \mathbb{1} \mathbb{1} ; K_1 = U K_1 U^\dagger = \mathbb{1} \mathbb{1} \mathbb{1} \mathbb{1} ; K_2$$

QEC

$$\alpha|0\rangle + \beta|1\rangle$$

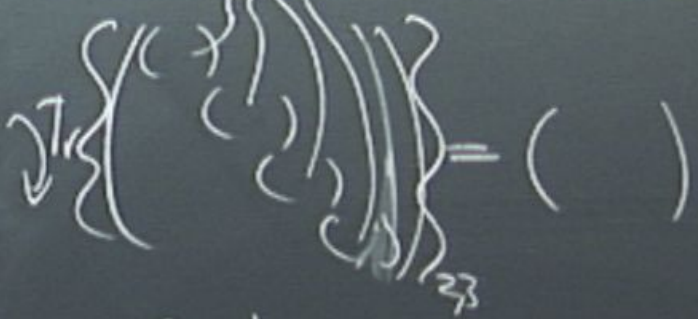
lattice expanded

$$\begin{cases} |0\rangle \\ |1\rangle \end{cases} 2^2$$



$$TSPR = \sigma_x E_+ E_+ + \mathbb{1} E_- E_- + \mathbb{1} E_+ E_- + \mathbb{1} E_- E_+$$

$$\alpha|0\rangle + \beta|1\rangle$$



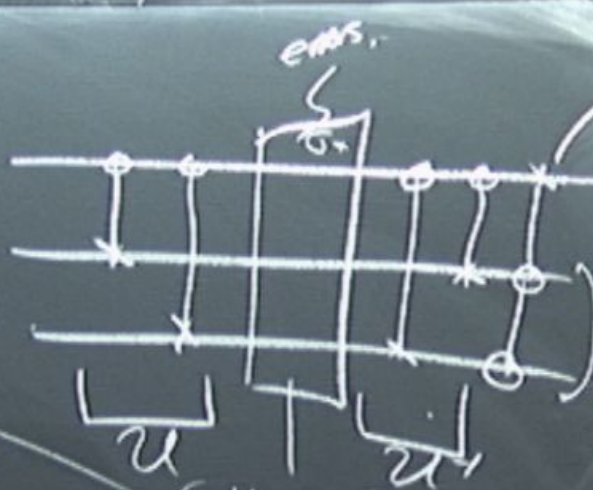
$$\begin{matrix} E_+ \sigma_x \sigma_x & \sigma_x \mathbb{1} \mathbb{1} & E_- \mathbb{1} \mathbb{1} \\ E_- \mathbb{1} \mathbb{1} & \sigma_x \mathbb{1} \mathbb{1} & E_+ \sigma_x \sigma_x \end{matrix}$$

$$\begin{cases} K_1 = \sqrt{\frac{1}{2}} (\mathbb{1} + P_1 + P_2 + P_3) \\ K_2 = \sqrt{\frac{1}{2}} P_1 \sigma_x \mathbb{1} \mathbb{1} \\ K_3 = \sqrt{\frac{1}{2}} P_2 \mathbb{1} \sigma_x \mathbb{1} \\ K_4 = \sqrt{\frac{1}{2}} P_3 \mathbb{1} \mathbb{1} \sigma_x \end{cases}$$

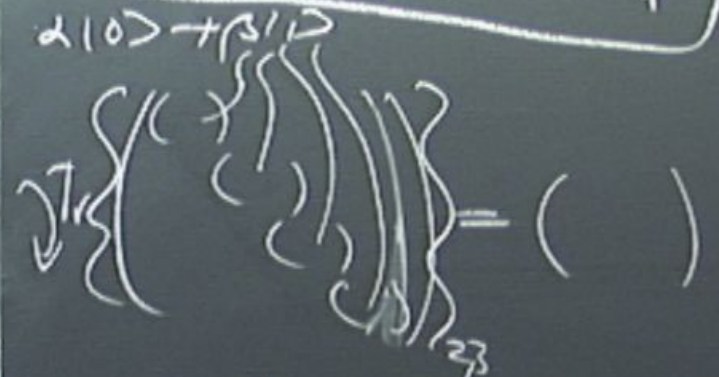
$$\begin{aligned} \tilde{K}_1 &= \mathcal{U} K_1 \mathcal{U}^\dagger = \mathbb{1} \mathbb{1} \mathbb{1} \\ \tilde{K}_2 &= \sigma_x \sigma_x \sigma_x \end{aligned}$$

QEC

$\alpha|0\rangle + \beta|1\rangle$
 lattice expanded
 $\left\{ \begin{array}{l} |0\rangle \\ |1\rangle \end{array} \right\}$
 2^2



$$TSPR = \sigma_x E_+ E_+ + \mathbb{1} E_- E_- + \mathbb{1} E_+ E_- + \mathbb{1} E_- E_+$$



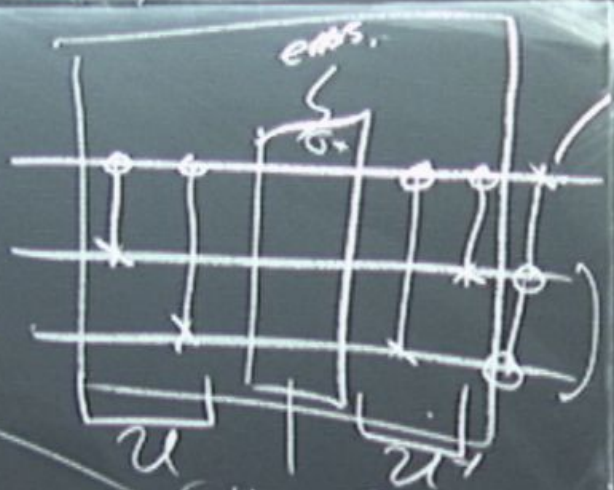
$$\begin{array}{l}
 E_+ \sigma_x \sigma_x \quad \sigma_x \mathbb{1} \mathbb{1} \quad E_- \mathbb{1} \mathbb{1} \\
 E_- \mathbb{1} \mathbb{1} \quad \sigma_x \mathbb{1} \mathbb{1} \quad E_+ \sigma_x \sigma_x
 \end{array}$$

$$\begin{cases}
 K_1 = \sqrt{1 - (P_1 + P_2 + P_3)} \mathbb{1} \mathbb{1} \mathbb{1} \\
 K_2 = \sqrt{P_1} \sigma_x \mathbb{1} \mathbb{1} \\
 K_3 = \sqrt{P_2} \mathbb{1} \sigma_x \mathbb{1} \\
 K_4 = \sqrt{P_3} \mathbb{1} \mathbb{1} \sigma_x
 \end{cases}$$

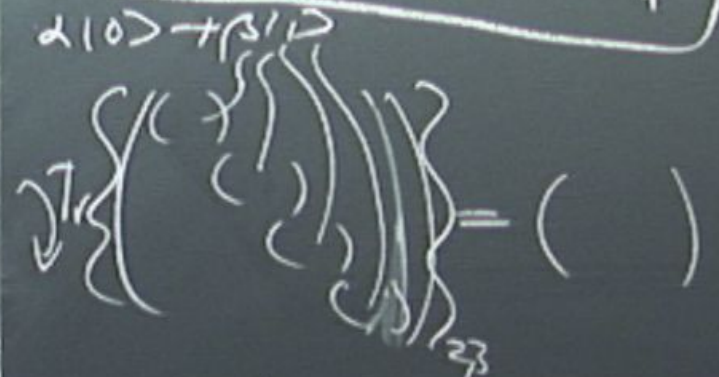
$$\begin{aligned}
 K_1 &= \mathbb{1} \mathbb{1} \mathbb{1} \\
 K_1 &= \mathcal{U} K_1 \mathcal{U}^\dagger = \mathbb{1} \mathbb{1} \mathbb{1} \\
 K_2 &= \sigma_x \sigma_x \sigma_x \\
 &\mathbb{1} \sigma_x \mathbb{1} \\
 &\mathbb{1} \mathbb{1} \sigma_x
 \end{aligned}$$

QEC

$\alpha|0\rangle + \beta|1\rangle$
 lattice expanded
 \uparrow
 $\left\{ \begin{array}{l} |0\rangle \\ |1\rangle \end{array} \right\}$
 2^2



$$\mathcal{H}_{\text{code}} = \sigma_x E_+ E_- + \mathbb{1} E_- E_- + \mathbb{1} E_+ E_- + \mathbb{1} E_- E_+$$



$$\mathbb{1} \mathbb{1} E_- \mathbb{1} \mathbb{1} \\
 E_+ \sigma_x \sigma_x$$

$$\left\{ \begin{array}{l} K_1 = \sqrt{\frac{1}{2}} (\mathbb{1} + P_1 P_2 P_3) \mathbb{1} \mathbb{1} \\ K_2 = \sqrt{\frac{1}{2}} P_1 \sigma_x \mathbb{1} \mathbb{1} \\ K_3 = \sqrt{\frac{1}{2}} \mathbb{1} P_2 \sigma_x \mathbb{1} \\ K_4 = \sqrt{\frac{1}{2}} \mathbb{1} \mathbb{1} P_3 \sigma_x \end{array} \right.$$

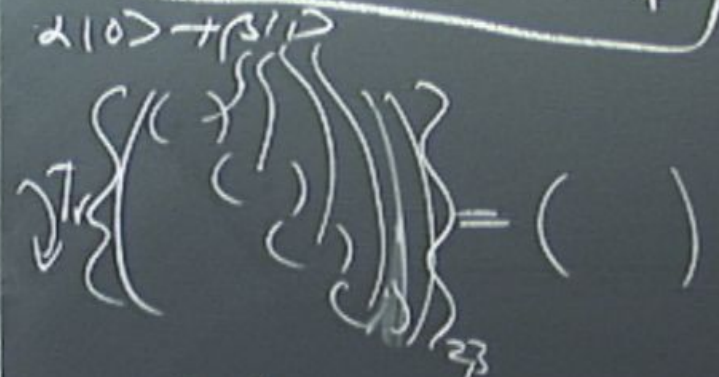
$$\begin{aligned}
 & \mathbb{1} \mathbb{1} \mathbb{1} \mathbb{1} ; \tilde{K}_1 = U K_1 U^\dagger = \mathbb{1} \mathbb{1} \mathbb{1} \mathbb{1} \\
 & ; \tilde{K}_2 = \sigma_x \sigma_x \sigma_x \\
 & ; \mathbb{1} \sigma_x \mathbb{1} \\
 & ; \mathbb{1} \mathbb{1} \sigma_x
 \end{aligned}$$

QEC

$\alpha|0\rangle + \beta|1\rangle$
 lattice expanded
 $\left\{ \begin{array}{l} |0\rangle \\ |1\rangle \end{array} \right\}$
 2^2



$$TSPR = \sigma_x E_+ E_+ + \mathbb{1} E_- E_- + \mathbb{1} E_+ E_- + \mathbb{1} E_- E_+$$

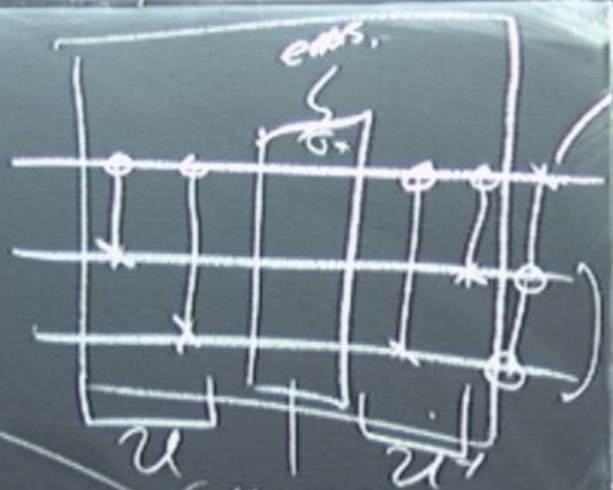


$$\begin{array}{l}
 E_+ \sigma_x \sigma_x \quad \sigma_x \mathbb{1} \mathbb{1} \quad E_- \mathbb{1} \mathbb{1} \\
 E_- \mathbb{1} \mathbb{1} \quad \sigma_x \mathbb{1} \mathbb{1} \quad E_+ \mathbb{1} \mathbb{1}
 \end{array}$$

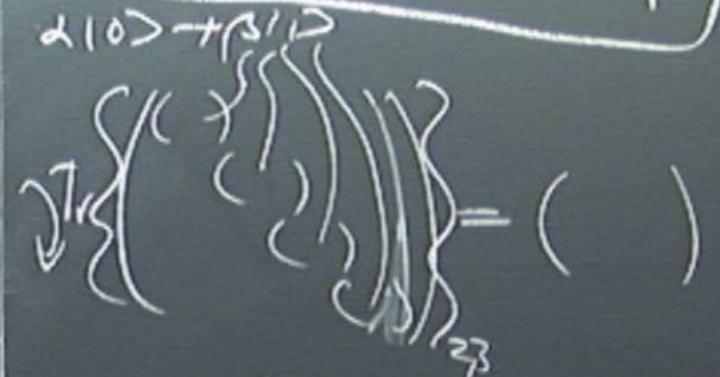
$$\begin{array}{l}
 K_1 = \mathbb{1} \mathbb{1} \mathbb{1} \mathbb{1}; \quad K_2 = \mathbb{1} \mathbb{1} \mathbb{1} \mathbb{1}; \quad K_3 = \sigma_x \sigma_x \sigma_x \\
 K_4 = \sigma_x \mathbb{1} \mathbb{1} \mathbb{1} \\
 K_5 = \mathbb{1} \mathbb{1} \sigma_x \mathbb{1} \\
 K_6 = \mathbb{1} \mathbb{1} \mathbb{1} \sigma_x
 \end{array}$$

QEC

$\alpha|0\rangle + \beta|1\rangle$
 lattice expanded
 $\left\{ \begin{array}{l} |0\rangle \\ |1\rangle \end{array} \right\}$
 2^2



$$\begin{aligned}
 \mathcal{H}_{\text{stabilizer}} = & \sigma_x E_+ E_+ + \mathbb{1} E_- E_- \\
 & + \mathbb{1} E_+ E_- + \mathbb{1} E_- E_+
 \end{aligned}$$



$$\begin{array}{l}
 E_+ \sigma_x \sigma_x \quad \sigma_x \mathbb{1} \mathbb{1} \quad E_- \mathbb{1} \mathbb{1} \\
 E_- \mathbb{1} \mathbb{1} \quad \sigma_x \mathbb{1} \mathbb{1} \quad E_+ \sigma_x \sigma_x
 \end{array}$$

$$\begin{cases}
 K_1 = \sqrt{\mathbb{1} - (R_1 + R_2 + R_3)} \mathbb{1} \mathbb{1} \mathbb{1} \\
 K_2 = \sqrt{P_1} \sigma_x \mathbb{1} \mathbb{1} \\
 K_3 = \sqrt{P_2} \mathbb{1} \sigma_x \mathbb{1} \\
 K_4 = \sqrt{P_3} \mathbb{1} \mathbb{1} \sigma_x
 \end{cases}$$

$$\begin{aligned}
 \tilde{K}_1 &= \mathcal{U} K_1 \mathcal{U}^\dagger = \mathbb{1} \mathbb{1} \mathbb{1} \\
 \tilde{K}_2 &= \sigma_x \sigma_x \sigma_x \xrightarrow{\mathcal{H}_f} \mathbb{1} \sigma_x \sigma_x \\
 & \mathbb{1} \sigma_x \mathbb{1} \\
 & \mathbb{1} \mathbb{1} \sigma_x
 \end{aligned}$$

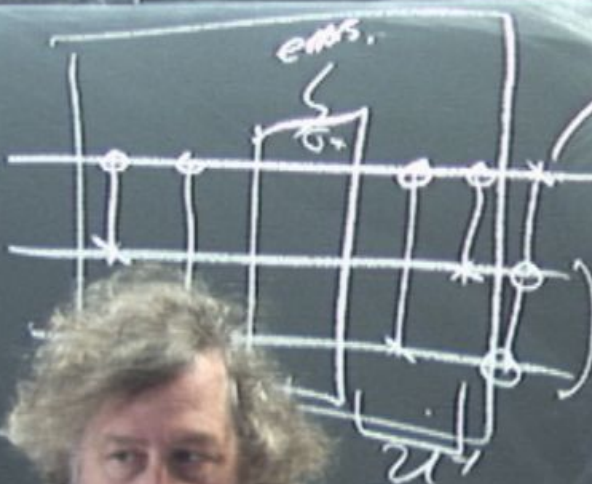
QEC

$$\alpha|0\rangle + \beta|1\rangle$$

lattice expanded

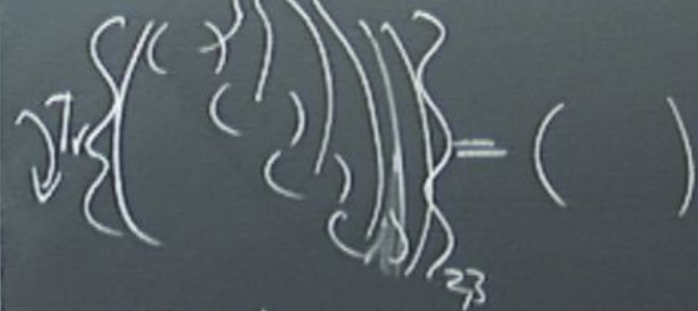
$$\begin{cases} |0\rangle \\ |1\rangle \end{cases}$$

$$2^2$$



$$TSPH = \sigma_x E_+ E_+ + \mathbb{1} E_- E_- + \mathbb{1} E_+ E_- + \mathbb{1} E_- E_+$$

$$\alpha|0\rangle + \beta|1\rangle$$



$$E_+ \sigma_x \sigma_x \quad \sigma_x \mathbb{1} \mathbb{1} \quad E_-$$

$$E_- \mathbb{1} \mathbb{1} \quad \sigma_x \mathbb{1} \mathbb{1}$$

$$\sqrt{1 - (R_1 + R_2 + R_3)} \quad \mathbb{1} \mathbb{1} \mathbb{1} ; K_1 = \mathbb{1} \mathbb{1} K, U^\dagger = \mathbb{1} \mathbb{1} \mathbb{1}$$

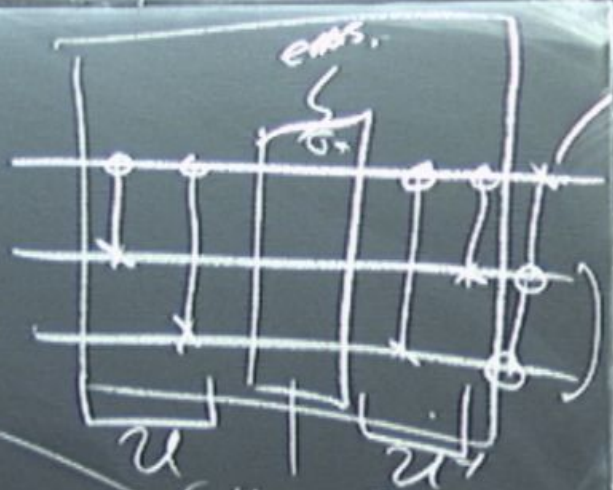
$$; K_2 = \sigma_x \sigma_x \sigma_x \xrightarrow{Tof} \mathbb{1} \sigma_x \sigma_x$$

$$\mathbb{1} \sigma_x \mathbb{1}$$

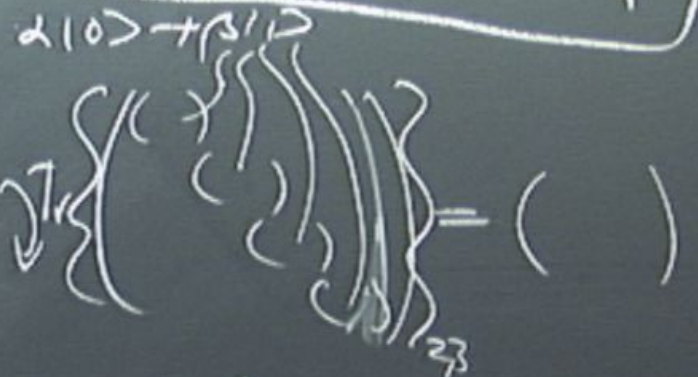
$$\mathbb{1} \mathbb{1} \sigma_x$$

QEC

$\alpha|0\rangle + \beta|1\rangle$
 lattice expanded
 $\left\{ \begin{array}{l} |0\rangle \\ |1\rangle \end{array} \right\}$
 2^2



$$TSPH = \sigma_x E_+ E_+ + \mathbb{1} E_- E_- + \mathbb{1} E_+ E_- + \mathbb{1} E_- E_+$$



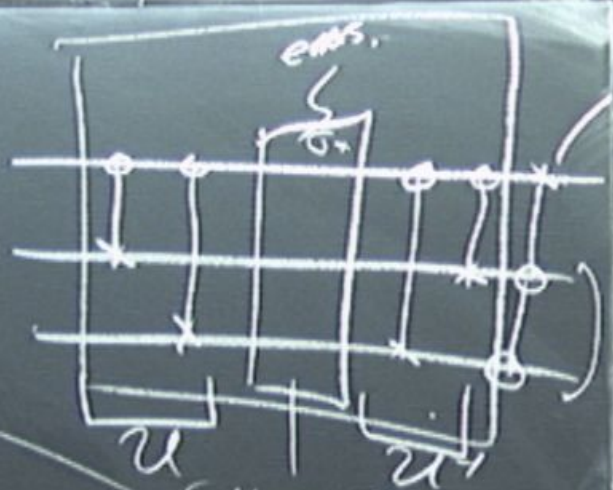
$$\begin{array}{l}
 E_+ \sigma_x \sigma_x \quad \sigma_x \mathbb{1} \mathbb{1} \quad E_- \mathbb{1} \mathbb{1} \\
 E_- \mathbb{1} \mathbb{1} \quad \sigma_x \mathbb{1} \mathbb{1} \quad E_+ \sigma_x \sigma_x
 \end{array}$$

$$\left\{ \begin{array}{l}
 K_1 = \sqrt{\frac{1}{2}} (\mathbb{1} + P_1 P_2 P_3) \\
 K_2 = \sqrt{\frac{1}{2}} P_1 \sigma_x \mathbb{1} \mathbb{1} \\
 K_3 = \sqrt{\frac{1}{2}} \mathbb{1} \sigma_x \mathbb{1} \mathbb{1} \\
 K_4 = \sqrt{\frac{1}{2}} \mathbb{1} \mathbb{1} \sigma_x
 \end{array} \right.$$

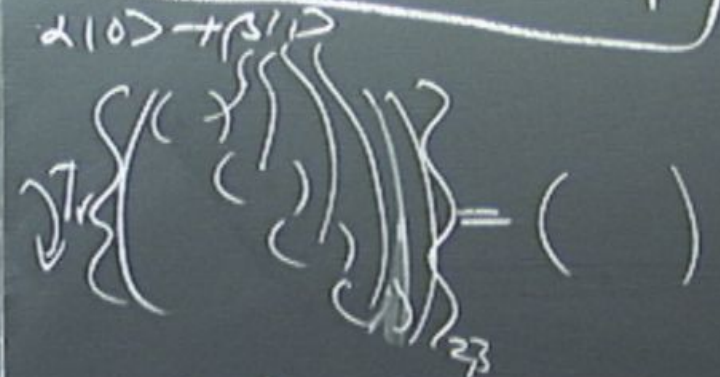
$$\begin{array}{l}
 K_1 = \sqrt{\frac{1}{2}} (\mathbb{1} + P_1 P_2 P_3) \mathbb{1} \mathbb{1} \mathbb{1} ; K_1 = \mathcal{U} K_1 \mathcal{U}^\dagger = \mathbb{1} \mathbb{1} \mathbb{1} \\
 ; K_2 = \sigma_x \sigma_x \sigma_x \xrightarrow{T_{sf}} \mathbb{1} \sigma_x \sigma_x \\
 ; \mathbb{1} \sigma_x \mathbb{1} \\
 ; \mathbb{1} \mathbb{1} \sigma_x
 \end{array}$$

QEC

$\alpha|0\rangle + \beta|1\rangle$
 lattice expanded
 $\left\{ \begin{array}{l} |0\rangle \\ |1\rangle \end{array} \right\}$
 2^2



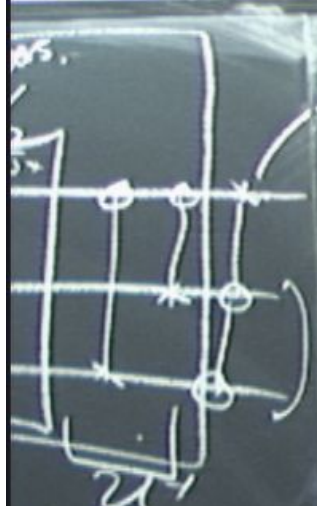
$$\begin{aligned}
 \mathcal{H}_{\text{stabilizer}} = & \sigma_x E_+ E_+ + \mathbb{1} E_- E_- \\
 & + \mathbb{1} E_+ E_- + \mathbb{1} E_- E_+
 \end{aligned}$$



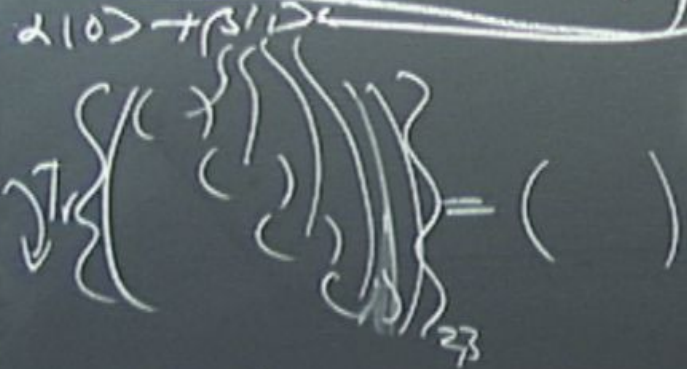
$$\begin{array}{l}
 E_+ \sigma_x \sigma_x \quad \sigma_x \mathbb{1} \mathbb{1} \quad E_- \mathbb{1} \mathbb{1} \\
 E_- \mathbb{1} \mathbb{1} \quad \sigma_x \mathbb{1} \mathbb{1} \quad E_+ \sigma_x \sigma_x
 \end{array}$$

$$\begin{aligned}
 K_1 &= \sqrt{\frac{1}{2}} \frac{1}{\sqrt{1-(P_1+P_2+P_3)}} \mathbb{1} \mathbb{1} \mathbb{1} \\
 K_2 &= \sqrt{\frac{1}{2}} \frac{1}{\sqrt{P_1}} \sigma_x \mathbb{1} \mathbb{1} \\
 K_3 &= \sqrt{\frac{1}{2}} \frac{1}{\sqrt{P_2}} \mathbb{1} \sigma_x \mathbb{1} \\
 K_4 &= \sqrt{\frac{1}{2}} \frac{1}{\sqrt{P_3}} \mathbb{1} \mathbb{1} \sigma_x
 \end{aligned}$$

$$\begin{aligned}
 \tilde{K}_1 &= \mathcal{U} K_1 \mathcal{U}^\dagger = \mathbb{1} \mathbb{1} \mathbb{1} \\
 \tilde{K}_2 &= \sigma_x \sigma_x \sigma_x \xrightarrow{\mathcal{H}_f} \mathbb{1} \sigma_x \sigma_x \\
 & \mathbb{1} \sigma_x \mathbb{1} \\
 & \mathbb{1} \mathbb{1} \sigma_x
 \end{aligned}$$



$$TSPH = \sigma_x E_+ E_+ + \mathbb{1} E_- E_- + \mathbb{1} E_+ E_- + \mathbb{1} E_- E_+$$



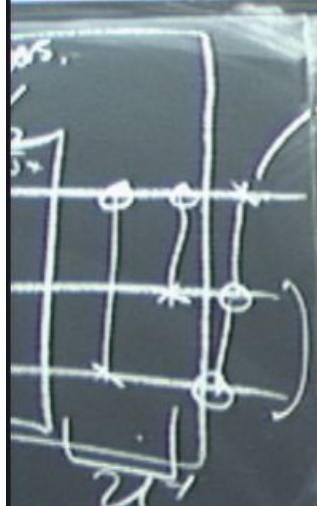
$$S(\theta) = \frac{1}{2} \begin{pmatrix} e^{-i\theta} & -e^{-3i\theta} \\ 3e^{-i\theta} & -e^{-3i\theta} \end{pmatrix}$$

$$\sqrt{1-(R_1 R_2 R_3)} \mathbb{1} \mathbb{1} \mathbb{1} ; \tilde{K}_1 = \mathcal{U} K_1 \mathcal{U}^\dagger = \mathbb{1} \mathbb{1} \mathbb{1}$$

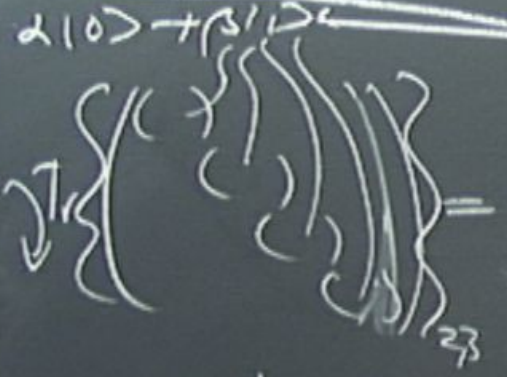
$$\sqrt{1} \sigma_x \mathbb{1} \mathbb{1} ; \tilde{K}_2 = \sigma_x \sigma_x \sigma_x \xrightarrow{Kf} \mathbb{1} \sigma_x \sigma_x$$

$$= \sqrt{1} \mathbb{1} \sigma_x \mathbb{1} ; \mathbb{1} \sigma_x \mathbb{1}$$

$$= \sqrt{1} \mathbb{1} \mathbb{1} \sigma_x ; \mathbb{1} \mathbb{1} \sigma_x$$



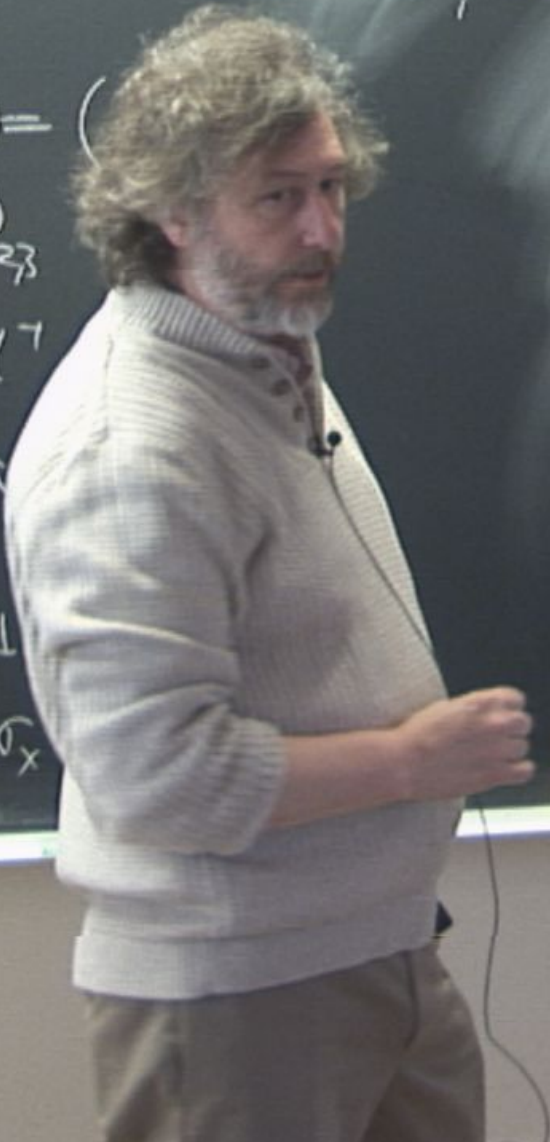
$$TSPR = \sigma_x E_+ E_+ + \mathbb{1} E_- E_- + \mathbb{1} E_+ E_- + \mathbb{1} E_- E_+$$

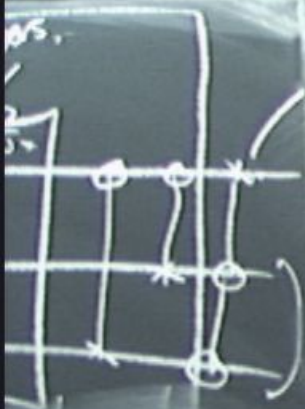


$$S(\theta) = \frac{1}{2} \begin{pmatrix} e^{-i\theta} & -e^{-3i\theta} \\ 3e^{i\theta} & -e^{3i\theta} \end{pmatrix}$$

$$\begin{matrix} \sigma_2 \mathbb{1} \mathbb{1} & \sigma_2 \sigma_2 \sigma_2 \\ \mathbb{1} \sigma_2 \mathbb{1} \\ \mathbb{1} \mathbb{1} \sigma_2 \end{matrix}$$

$$\begin{aligned} & \sqrt{1-(R_1 R_2 R_3)} \mathbb{1} \mathbb{1} \mathbb{1}; \tilde{K}_1 = \mathbb{1} K_1 \mathbb{1} \\ & \sqrt{1-R_1} \sigma_x \mathbb{1} \mathbb{1}; \tilde{K}_2 = \sigma_x \sigma_x \sigma_x \\ & \sqrt{1-R_2} \mathbb{1} \sigma_x \mathbb{1}; \\ & \sqrt{1-R_3} \mathbb{1} \mathbb{1} \sigma_x \end{aligned}$$





$$TSPH = \sigma_x E_+ E_+ + \mathbb{1} E_- E_- + \mathbb{1} E_+ E_- + \mathbb{1} E_- E_+$$

$\alpha|00\rangle + \beta|11\rangle$

$$\mathcal{H} = DW(\sigma_z^1 \sigma_z^2) + R J \sigma_z^1 \sigma_z^2$$

$$CN_{\hat{e}_{12}} = E_+ \sigma_x \mathbb{1} + E_- \mathbb{1} \mathbb{1}$$

$$CN_{\hat{e}_{13}} = E_+ \mathbb{1} \sigma_x + E_- \mathbb{1} \mathbb{1}$$

$$CN_{\hat{e}_{12}} CN_{\hat{e}_{13}} = E_+ \sigma_x \sigma_x + E_- \mathbb{1} \mathbb{1} = \mathcal{U} = \mathcal{U}^{-1}$$

$$AE_+ = \rho E_+ + \mathbb{1} E_-$$

$$\sigma_x \sigma_x \rightarrow$$

$$E_+ E_+ \rightarrow$$

$$E_+ E_- \rightarrow$$

$$E_+ \sigma_x E_- = \sigma_x$$

$$E_- \sigma_x E_+ = \sigma_x$$

$$E_+ = \frac{1}{2} (\mathbb{1} + \sigma_x)$$

$$CN_{st_{12}} = E_+ \sigma_x \mathbb{1} + E_- \mathbb{1} \mathbb{1}$$

$$CN_{st_{13}} = E_+ \mathbb{1} \sigma_x + E_- \mathbb{1} \mathbb{1}$$

$$CN_{st_{12}} CN_{st_{13}} = E_+ \sigma_x \sigma_x + E_- \mathbb{1} \mathbb{1} = \mathcal{U} = \mathcal{U}^{-1}$$

$$e^{A E_+} = e^A E_+ + \mathbb{1} E_-$$

$$\sigma_x \sigma_x \rightarrow$$

$$E_+ E_+ \rightarrow$$

$$E_+ E_- \rightarrow$$

$$E_+ \sigma_x E_- = \sigma_x$$

$$E_- \sigma_x E_+ = \sigma_x$$

$$E_{\pm} = \frac{1}{2} (\mathbb{1} \pm \sigma_x)$$

$$\begin{array}{l}
 + E_+ + 1 E_- E_- \\
 + E_- + 1 E_- E_+
 \end{array}$$

$$\mathcal{H} = DW(\sigma_z^1 - \sigma_z^2) + J\sigma_z^1 \sigma_z^2$$

$$CN\sigma_y$$

$$CN\sigma_x - 1 E_+ 1 + E_- \sigma_y$$

$$\begin{array}{l} + E_+ + \mathbb{1} E_- E_- \\ + E_- + \mathbb{1} E_- E_+ \end{array}$$

$$\mathcal{H} = DW(\sigma_z^1 - \sigma_z^2) + RJS\sigma_z^1\sigma_z^2$$

CNBT

$$CNBT = \mathbb{1} E_+ \mathbb{1} + E_- \sigma_x$$

$$\begin{pmatrix} \mathbb{B} & A \\ i\sigma_x E_- + E_+ & \mathbb{A} \end{pmatrix} \begin{pmatrix} iE_-^A + E_+^A \\ \mathbb{A} \end{pmatrix}$$

$$\begin{pmatrix} E_+ + \frac{1}{2} E_- \\ E_- + \frac{1}{2} E_+ \end{pmatrix}$$

$$\mathcal{H} = DW(\sigma_z^1 - \sigma_z^2) + RJS\sigma_z^1\sigma_z^2$$

CNOT

$$CNOT = |E_+\rangle\langle E_+| + |E_-\rangle\sigma_x$$

$$\begin{pmatrix} \sigma_x^B E_-^A + E_+^A \\ \sigma_x^B E_+^A + E_-^A \end{pmatrix} \begin{pmatrix} |E_-^A\rangle + |E_+^A\rangle \\ |E_-^A\rangle - |E_+^A\rangle \end{pmatrix}$$

$$\rho \rightarrow \sigma_x^B E_+^A \frac{1}{\sqrt{2}}$$

$$\begin{array}{l}
 + E_+ + 1 E_- E_- \\
 + E_- + 1 E_- E_+
 \end{array}$$

$$\mathcal{H} = DW(\sigma_2^1 - \sigma_2^2) + R J \sigma_2^1 \sigma_2^2$$

CNOT

$$CNOT = |E_+\rangle\langle E_+| + |E_-\rangle\langle E_-| \sigma_x$$

$$\begin{pmatrix}
 \sigma_x^B E_-^A + E_+^A \\
 \sigma_x^B E_+^A + E_-^A
 \end{pmatrix}
 \begin{pmatrix}
 i E_-^A + E_+^A \\
 i E_+^A + E_-^A
 \end{pmatrix}$$

$$e^{-i \sigma_x^B E_+^A \pi/2} \quad e^{-i E_-^A \pi/2}$$

$$\begin{array}{l}
 + E_+ + 11 E_- E_- \\
 + E_- + 11 E_- E_+
 \end{array}$$

$$\mathcal{H} = DW(\sigma_2^1 - \sigma_2^2) + R J \sigma_2^1 \sigma_2^2$$

CNOT

$$CNOT = |E_+\rangle\langle E_+| + |E_-\rangle\langle E_-| \sigma_x$$

$$\left(\begin{array}{c} \sigma_x^B E_-^A + E_+^A \\ \sigma_x^B E_+^A \end{array} \right) \left(\begin{array}{c} i E_-^A + E_+^A \\ E_-^A \end{array} \right)$$

$$\rightarrow \sigma_x^B E_+^A \pi/2 \quad e^{-i E_-^A \pi/2}$$

$$\begin{array}{l}
 \pi/4 \rightarrow \sigma_x^B \pi/4 \quad e \\
 \pi/4 \rightarrow \sigma_2^A \pi/4 \quad e \\
 \pi/4 \rightarrow \sigma_2^A \sigma_x^B \pi/4 \quad e
 \end{array}$$

$$\begin{array}{l}
 + E_+ + 1 E_- E_- \\
 + E_- + 1 E_- E_+
 \end{array}$$

$$\mathcal{H} = DW(\sigma_z^1 - \sigma_z^2) + R J \sigma_z^1 \sigma_z^2$$

CNOT

$$CNOT = |E_+\rangle\langle E_+| + |E_-\rangle\langle E_-| \sigma_x$$

$$\begin{pmatrix}
 \sigma_x^B E_-^A + E_+^A \\
 \sigma_x^B E_+^A
 \end{pmatrix}
 \begin{pmatrix}
 i E_-^A + E_+^A \\
 i E_+^A
 \end{pmatrix}$$

$$e^{-i \sigma_x^B E_+^A \pi/2} \quad e^{-i E_+^A \pi/2}$$

$$e^{-i \pi/4} \quad e^{-i \sigma_x^B \pi/4} \quad e^{-i \sigma_z^A \pi/4} \quad e^{-i \sigma_z^A \sigma_x^B \pi/4}$$

$$\begin{array}{l} +E_+ + 11E_- E_- \\ +E_- + 11E_- E_+ \end{array}$$

$$\mathcal{H} = DW(\sigma_2^1 - \sigma_2^2) + RJS\sigma_2^1\sigma_2^2$$

CNOT

$$CNOT = |E_+\rangle\langle E_+| + |E_-\rangle\sigma_x$$

$$\begin{pmatrix} \sigma_x^B E_-^A + E_+^A \\ iE_-^A + E_+^A \end{pmatrix}$$

$$e^{-i\sigma_x^B E_+^A \pi/2} \quad e^{-iE_-^A \pi/2}$$

$$e^{+i\pi/4} \rightarrow i\sigma_x^B \pi/4 \quad e^{-i\sigma_2^A \pi/4} \rightarrow i\sigma_2^A \pi/4 \rightarrow i\sigma_2^A \sigma_x^B \pi/4$$



$$\begin{array}{l} + E_+ + 1 E_- E_- \\ + E_- + 1 E_- E_+ \end{array}$$

$$\mathcal{H} = DW(\sigma_z^1 - \sigma_z^2) + RJS\sigma_z^1\sigma_z^2$$

CNOT

$$CNOT = |E_+\rangle\langle E_+| + |E_-\rangle\sigma_x$$

$$\begin{pmatrix} \sigma_x^B E_-^A + E_+^A \\ i\sigma_x^B E_-^A - E_+^A \end{pmatrix} \begin{pmatrix} iE_-^A + E_+^A \\ iE_-^A - E_+^A \end{pmatrix}$$

$$e^{-i\sigma_x^B E_+^A \pi/2} \quad e^{-iE_-^A \pi/2}$$

$$e^{+i\pi/4} \quad e^{-i\sigma_x^B \pi/4} \quad e^{-i\sigma_z^A \pi/4} \quad e^{-i\sigma_z^A \sigma_x^B \pi/4}$$



$$\begin{array}{c} \pi/2 \quad \pi/2 \quad \pi/2 \\ x \quad y \quad z \end{array}$$

$$\begin{array}{l}
 + E_+ + 1 E_- \\
 + E_- + 1 E_+
 \end{array}$$

$$\mathcal{H} = DW(\sigma_2^1 - \sigma_2^2) + R J \sigma_2^1 \sigma_2^2$$

CNOT

$$CNOT = |E_+\rangle\langle E_+| + |E_-\rangle\langle E_-| \sigma_x$$

$$\begin{pmatrix} \sigma_x^B E_-^A + E_+^A \\ \sigma_x^B E_+^A + E_-^A \end{pmatrix} \begin{pmatrix} i E_-^A + E_+^A \\ i E_+^A + E_-^A \end{pmatrix}$$

$$e^{-i \sigma_x^B E_+^A \pi/2} \quad e^{-i E_-^A \pi/2}$$

$$e^{+i \pi/4} \quad e^{-i \sigma_x^B \pi/4} \quad e^{-i \sigma_2^A \pi/4} \quad e^{-i \sigma_2^A \sigma_x^B \pi/4}$$

$$\begin{array}{c}
 \pi/2 \quad \pi/2 \quad \pi/2 \\
 x \quad y \quad z
 \end{array}$$

$$\begin{pmatrix} E_+ + \mathbb{1} & E_- \\ E_- + \mathbb{1} & E_+ \end{pmatrix}$$

$$\mathcal{H} = DW(\sigma_z^1 - \sigma_z^2) + R \int \sigma_z^1 \sigma_z^2$$

CNOT

$$\mathbb{1} + E_- \sigma_x$$

$$\begin{pmatrix} iE_-^A & E_+^A \\ E_-^A & E_+^A \end{pmatrix}$$

$$e^{iE_-^A \pi/2}$$

$$e^{-i\sigma_z^A \sigma_x^B \pi/4}$$

$$\begin{matrix} + E_+ + 1 E_- & E_- \\ + E_- + 1 E_+ & E_+ \end{matrix}$$

$$\mathcal{H} = DW(\sigma_z^1 - \sigma_z^2) + R J \sigma_z^1 \sigma_z^2$$

CNOT

$$CNOT = |E_+\rangle\langle E_+| + |E_-\rangle\langle E_-| \sigma_x$$

$$\begin{pmatrix} \sigma_x^B E_-^A + E_+^A \\ \sigma_x^B E_+^A \end{pmatrix} \begin{pmatrix} i E_-^A + E_+^A \\ -i E_-^A + E_+^A \end{pmatrix}$$

$$e^{-i \sigma_x^B E_+^A \pi/2} \quad e^{-i E_-^A \pi/2}$$

$$e^{+i \pi/4} \rightarrow \sigma_x^B \pi/4 \quad e^{-i \sigma_z^A \pi/4} \rightarrow \sigma_z^A \pi/4 \quad e^{-i \sigma_z^A \sigma_x^B \pi/4}$$

$$\begin{pmatrix} \pi/2 & \pi/2 \\ x & y \end{pmatrix} \begin{pmatrix} \pi/2 \\ 2 \end{pmatrix} \begin{pmatrix} \pi/2 \\ 1 \end{pmatrix} \begin{pmatrix} \pi/2 \\ 1 \end{pmatrix}$$

$$\begin{matrix} + E_+ + 1 E_- \\ + E_- + 1 E_+ \end{matrix}$$

$$\mathcal{H} = DW(\sigma_z^1 - \sigma_z^2) + R \int \sigma_z^1 \sigma_z^2$$

CNOT

$$CNOT = |E_+\rangle\langle E_+| + |E_-\rangle\sigma_x$$

$$\begin{pmatrix} \sigma_x^B E_-^A + E_+^A \\ \sigma_x^B E_+^A + E_-^A \end{pmatrix} \begin{pmatrix} i E_-^A + E_+^A \\ i E_+^A + E_-^A \end{pmatrix}$$

$$e^{-i \sigma_x^B E_+^A \pi/2}$$

$$e^{i E_-^A \pi/2}$$

$$e^{-i \sigma_x^B \pi/4}$$

$$e^{-i \sigma_z^A \sigma_x^B \pi/4}$$

$$\begin{matrix} \pi/2 & \pi/2 & \pi/4 \\ x & y & z \end{matrix} \quad \begin{matrix} \pi/2 & \pi/4 \\ x & y \end{matrix}$$

$$\begin{array}{l} + E_+ + 1 E_- E_- \\ + E_- + 1 E_- E_+ \end{array}$$

$$\mathcal{H} = DW(\sigma_z^1 - \sigma_z^2) + R J \sigma_z^1 \sigma_z^2$$

CNOT

$$CNOT = |E_+\rangle\langle E_+| + |E_-\rangle\langle E_-| \sigma_x$$

$$\left(i \sigma_x^B E_-^A + |E_+\rangle\langle E_+|^A \right) \left(i |E_-\rangle\langle E_-|^A + |E_+\rangle\langle E_+|^A \right)$$

$$e^{-i \sigma_x^B E_+^A \pi/2}$$

$$e^{i E_-^A \pi/2}$$

$$e^{+i \pi/4}$$

$$e^{-i \sigma_x^B \pi/4}$$

$$e^{-i \sigma_z^A \pi/4}$$

$$e^{i \sigma_z^A \sigma_x^B \pi/4}$$



$$\begin{array}{c} \pi/2 \\ x \end{array} \begin{array}{c} \pi/2 \\ y \end{array} \begin{array}{c} \pi/2 \\ z \end{array} \begin{array}{c} \pi/2 \\ x \end{array} \begin{array}{c} \pi/2 \\ y \end{array} \begin{array}{c} \pi/2 \\ z \end{array}$$

$$\begin{array}{l}
 + E_+ + 1 E_- \\
 + E_- + 1 E_+
 \end{array}$$

$$\mathcal{H} = DW(\sigma_2^1 - \sigma_2^2) + R J \sigma_2^1 \sigma_2^2$$

CNOT

$$CNOT = |E_+\rangle\langle E_+| + |E_-\rangle\sigma_x$$

$$\begin{pmatrix}
 \sigma_x^B E_-^A + E_+^A \\
 \sigma_x^B E_+^A
 \end{pmatrix}
 \begin{pmatrix}
 i E_-^A + E_+^A
 \end{pmatrix}$$

$$e^{-i \sigma_x^B E_+^A \pi/2} \quad e^{-i E_-^A \pi/2}$$

$$e^{+i \pi/4} \quad e^{-i \sigma_x^B \pi/4} \quad e^{-i \sigma_2^A \pi/4} \quad e^{-i \sigma_2^A \sigma_x^B \pi/4}$$



$$\begin{array}{c}
 \pi/2 \\
 x \\
 \pi/2 \\
 y \\
 \pi/2 \\
 x \\
 \pi/2 \\
 y \\
 \pi/2 \\
 x \\
 \pi/2 \\
 y \\
 \pi/2 \\
 x
 \end{array}$$

$$\begin{matrix} +E_+ + \frac{1}{2}E_- \\ +E_- + \frac{1}{2}E_+ \end{matrix}$$

$$\mathcal{H} = DW(\sigma_2^1 - \sigma_2^2) + RJS \underbrace{\sigma_2^1 \sigma_2^2}$$

CNOT

$$CNOT = |E_+\rangle\langle E_+| + |E_-\rangle\sigma_x$$

$$\left(\begin{matrix} B & A \\ i\sigma_x E_-^A + E_+^A \end{matrix} \right) \left(\begin{matrix} A \\ iE_-^A + E_+^A \end{matrix} \right)$$

$$e^{-i\sigma_x^B E_+^A \pi/2} \quad e^{iE_-^A \pi/2}$$

$$e^{+i\pi/4} \quad e^{-i\sigma_x^B \pi/4} \quad e^{-i\sigma_2^A \pi/4} \quad e^{i\sigma_2^A \sigma_x^B \pi/4}$$



$$\begin{matrix} \pi/2 & \pi/2 & \pi/2 & \pi/2 \\ x & y & x & x \end{matrix} \quad \begin{matrix} \pi/2 & \pi/2 \\ y & x \end{matrix}$$

$$TSPR = \sigma_x E_+ E_+ + \frac{1}{2} E_- E_- + \frac{1}{2} E_+ E_- + \frac{1}{2} E_- E_+$$

$$2|0\rangle + \beta|1\rangle$$

$$\mathcal{H} = DW(\sigma_z^2 - \sigma_z)$$

$$CNST$$

$$CNST = \frac{1}{2} E_+ \frac{1}{2}$$

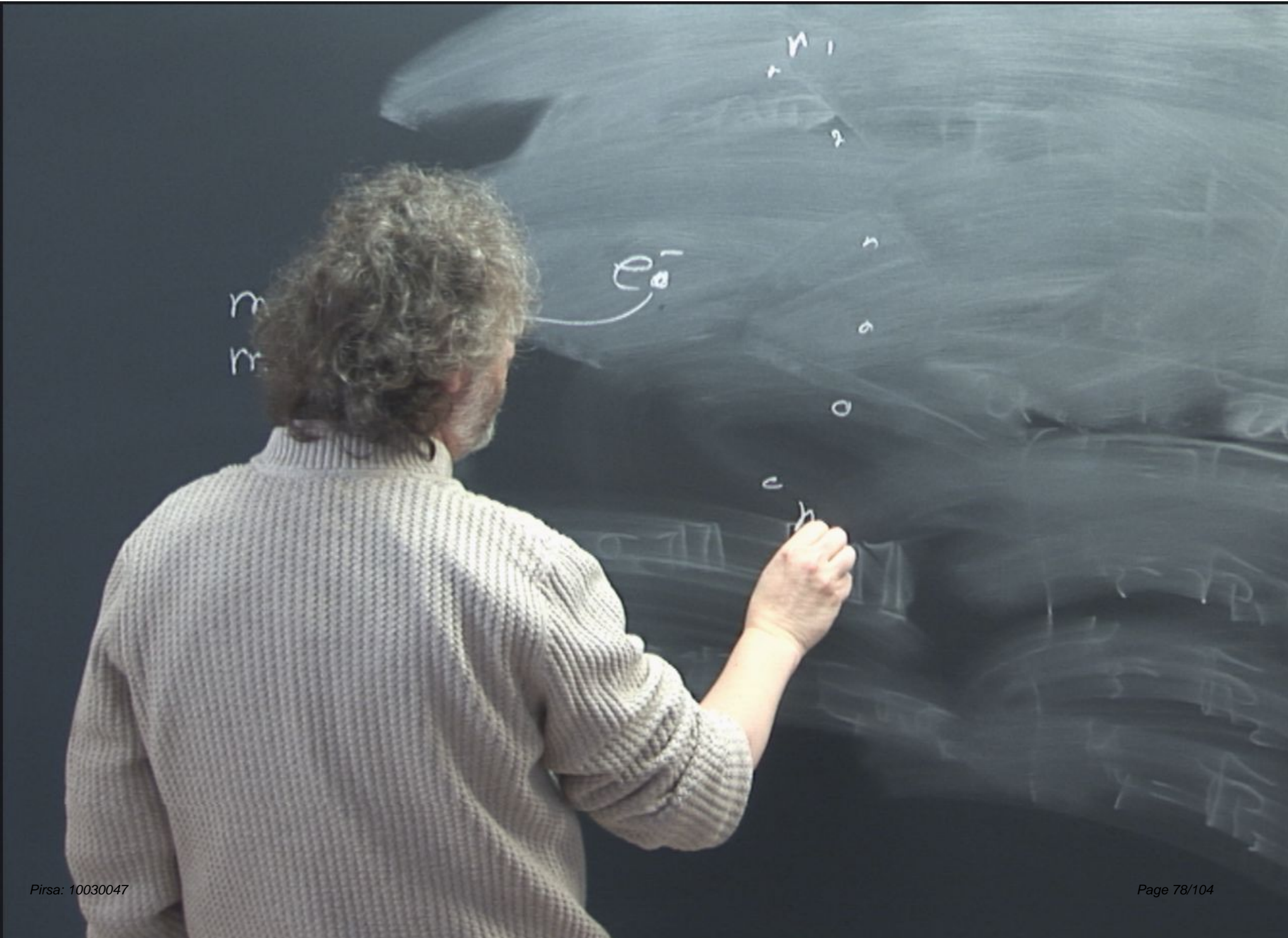
$$\left(\frac{1}{2} \sigma_x^B E_-^A + \frac{1}{2} E_+^A \right)$$

$$\rightarrow \frac{1}{2} \sigma_x^B E_+^A \frac{1}{2}$$

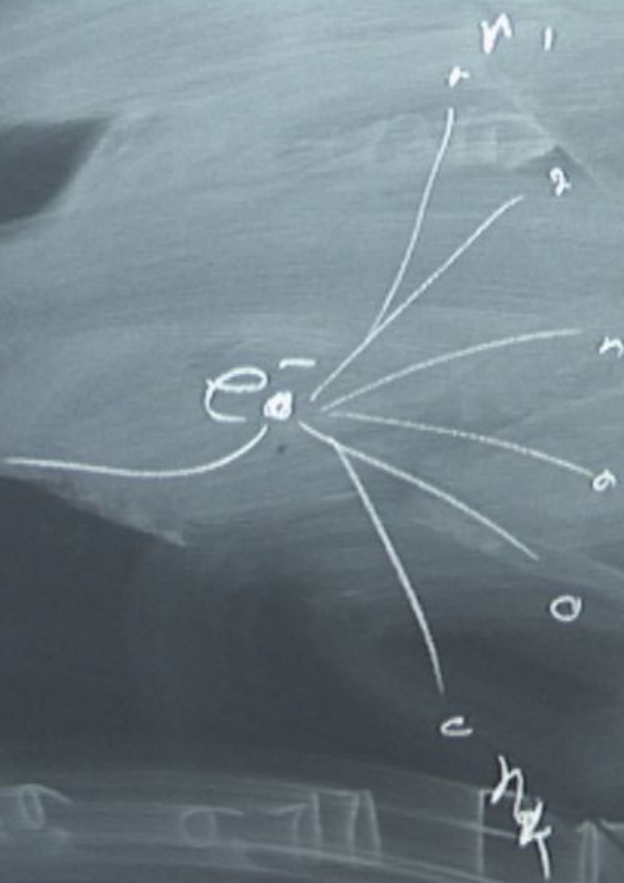
$$\frac{1}{2} \sigma_x^B \frac{1}{2} \rightarrow \frac{1}{2} \sigma_x^B \frac{1}{2}$$

$$\rightarrow \frac{1}{2} \sigma_x^B \frac{1}{2}$$

$$\frac{1}{2} \sigma_x^B \frac{1}{2} \frac{1}{2}$$



modest field
modest T



$$\mathcal{H} = w_e \sigma_{z^p}^2 + \sum_i w_h \sigma_z^{i'} + \sum_i w_h \sigma_z^p \sigma_z^{i'}$$

$$\mathcal{H} = w_c \sigma_z^c + \sum_i w_{H^i} \sigma_z^i + \sum_i w_A^i \sigma_z^c \sigma_z^i + \sum_i w_B^i \sigma_z^c \sigma_x^i$$

$$\omega_H = \underbrace{\omega_c \sigma_z^e}_{210 \text{ GHz}} + \sum_i \omega_{H_i} \sigma_z^i + \sum_i \omega_{H_i} \sigma_z^e \sigma_z^i + \sum_i \omega_B^i \sigma_z^e \sigma_x^i$$

\uparrow 10 MHz \uparrow 30 MHz

$$\omega_c = \gamma B_0$$



$$\mathcal{H} = \underbrace{\omega_c \sigma_z^p}_{210 \text{ GHz}} + \sum_i \underbrace{\omega_{H_i}}_{10 \text{ MHz}} \sigma_z^i + \sum_i \underbrace{\omega_{H_i}^p}_{30 \text{ MHz}} \sigma_z^p \sigma_z^i + \sum_i \omega_{B_i}^p \sigma_z^p \sigma_x^i$$

$$\sum_i \omega_n^i \sigma_z^i + \sum_i \omega_A^i \sigma_z^i \sigma_z^i + \sum_i \omega_B^i \sigma_z^i \sigma_x^i$$

\uparrow 10 MHz \uparrow 30 MHz

$$\sum_i \omega_i^i \sigma_z^i + \sum_i \omega_A^i \sigma_z^i \sigma_z^i + \sum_i \omega_B^i \sigma_z^i \sigma_x^i$$

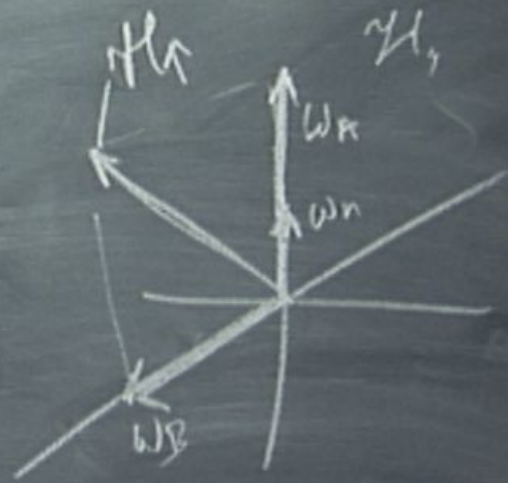
\uparrow 10 MHz \uparrow 30 MHz

30

$$\sum_i \omega_n^i \sigma_z^i + \sum_i \omega_A^i \sigma_x^i + \sum_i \omega_B^i \sigma_z^i \sigma_x^i$$

↑
10 MHz

↑
3

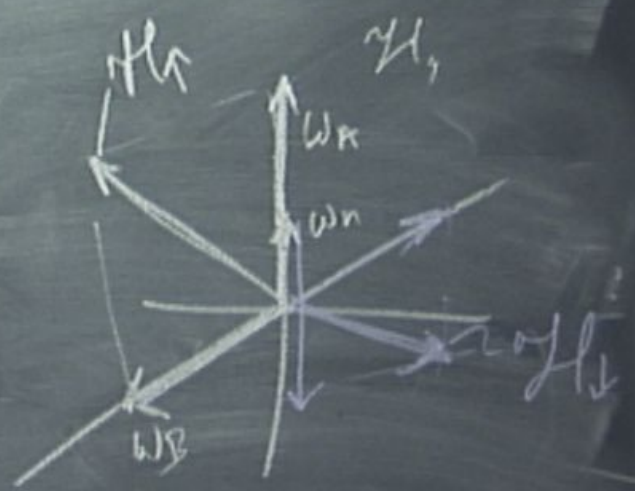


30

$$\sum_i \omega_n^i \sigma_z^i \quad \omega_A^i \sigma_z^i \sigma_z^i + \sum_i \omega_B^i \sigma_z^i \sigma_x^i$$

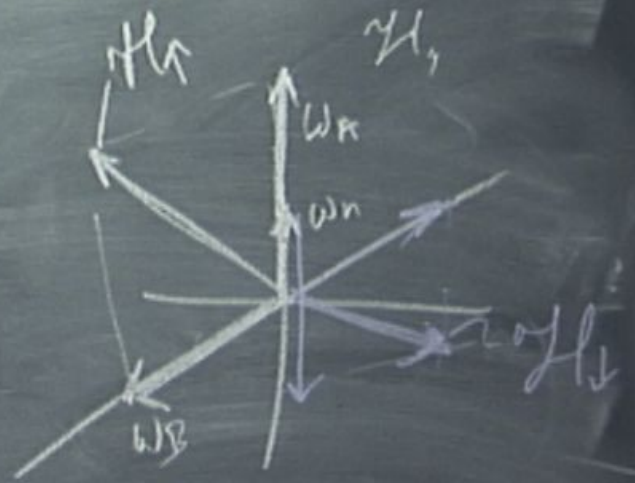
10 MHz

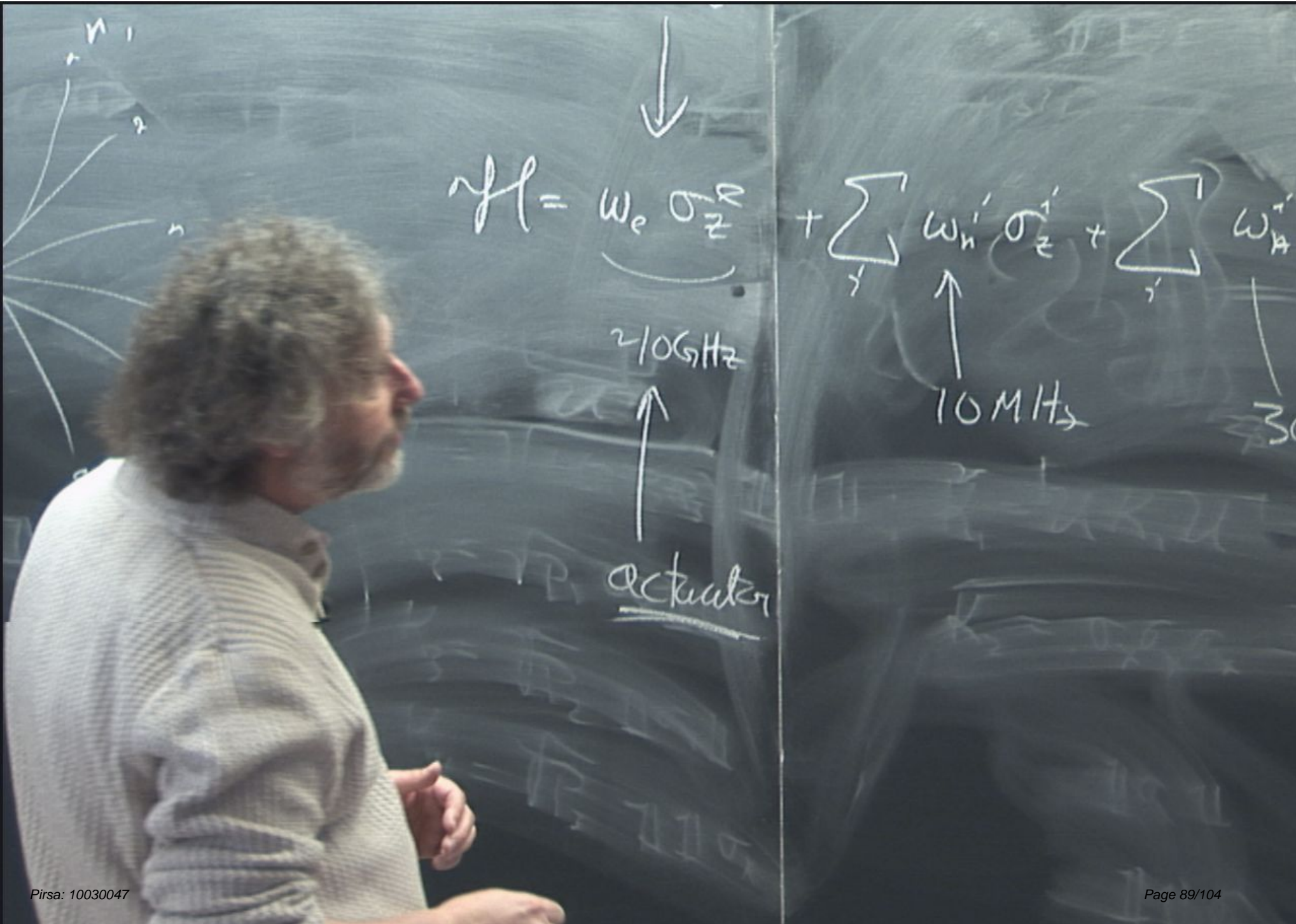
MHz



$$\sum_i \omega_n^i \sigma_z^i + \sum_i \omega_A^i \sigma_z^i \sigma_z^i + \sum_i \omega_B^i \sigma_z^i \sigma_x^i$$

\uparrow 10 MHz \uparrow 30 MHz





$$\Delta H = \omega_e \sigma_z^e$$

2/06 Hz



actuator

$$+ \sum_i \omega_{n_i} \sigma_z^{n_i} + \sum_i \omega_{h_i} \sigma_z^{h_i}$$

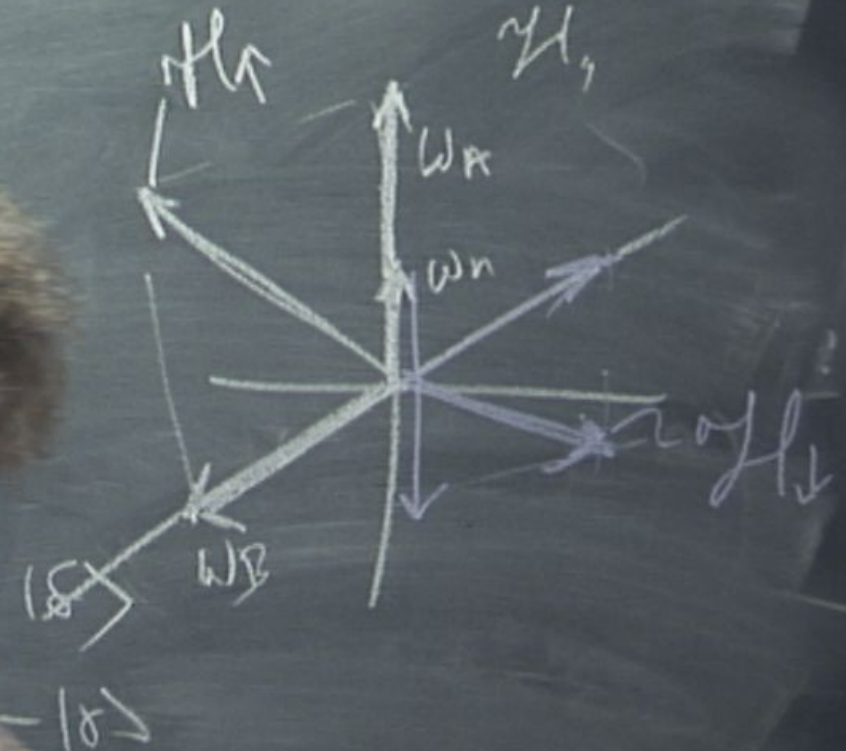


10 MHz

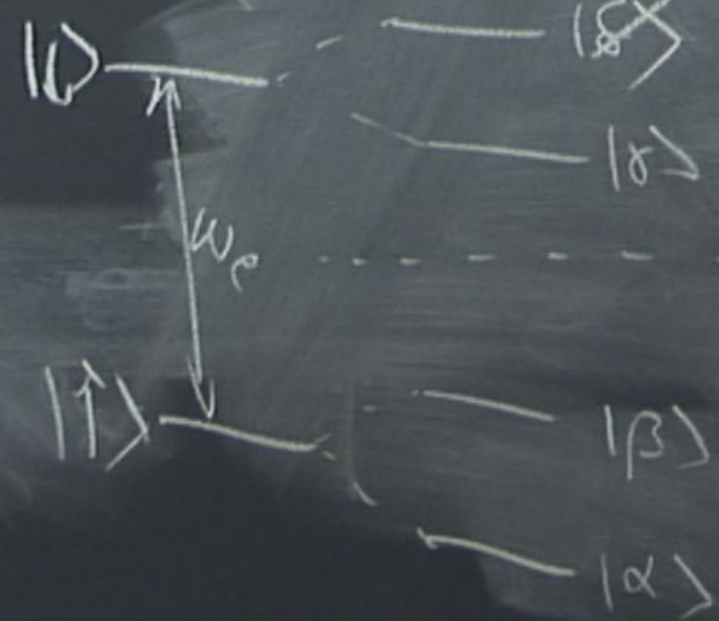
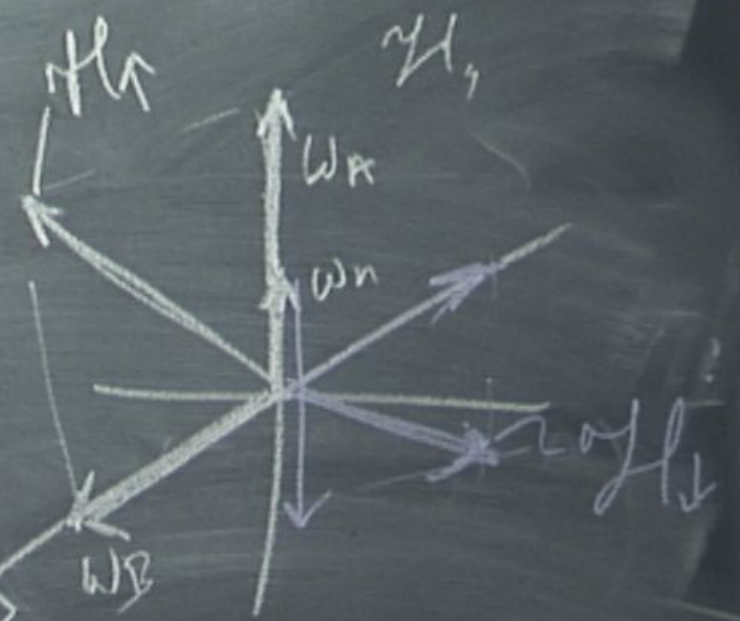
30 MHz

$$\sum_i \omega_A^i \sigma_z^i \sigma_z^i + \sum_i \omega_B^i$$

30 MHz



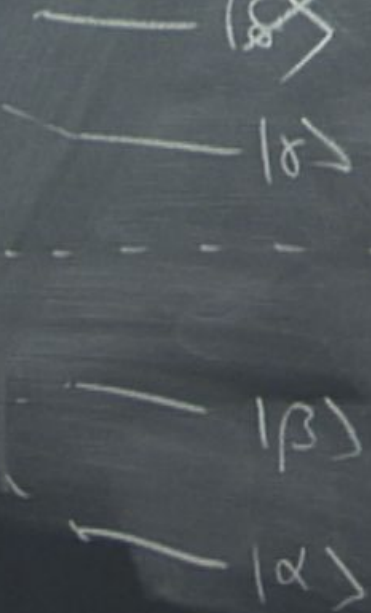
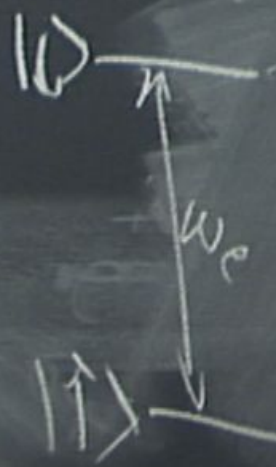
$$\frac{\omega_0}{2} \sigma_z + \sum_i \omega_i \sigma_z^i \sigma_x^i$$



$$\langle \alpha | \beta \rangle = 0$$

$$\sum_i \omega_A^i \sigma_z^e \sigma_z^i + \sum_i \omega_B^i \sigma_z^e \sigma_x^i$$

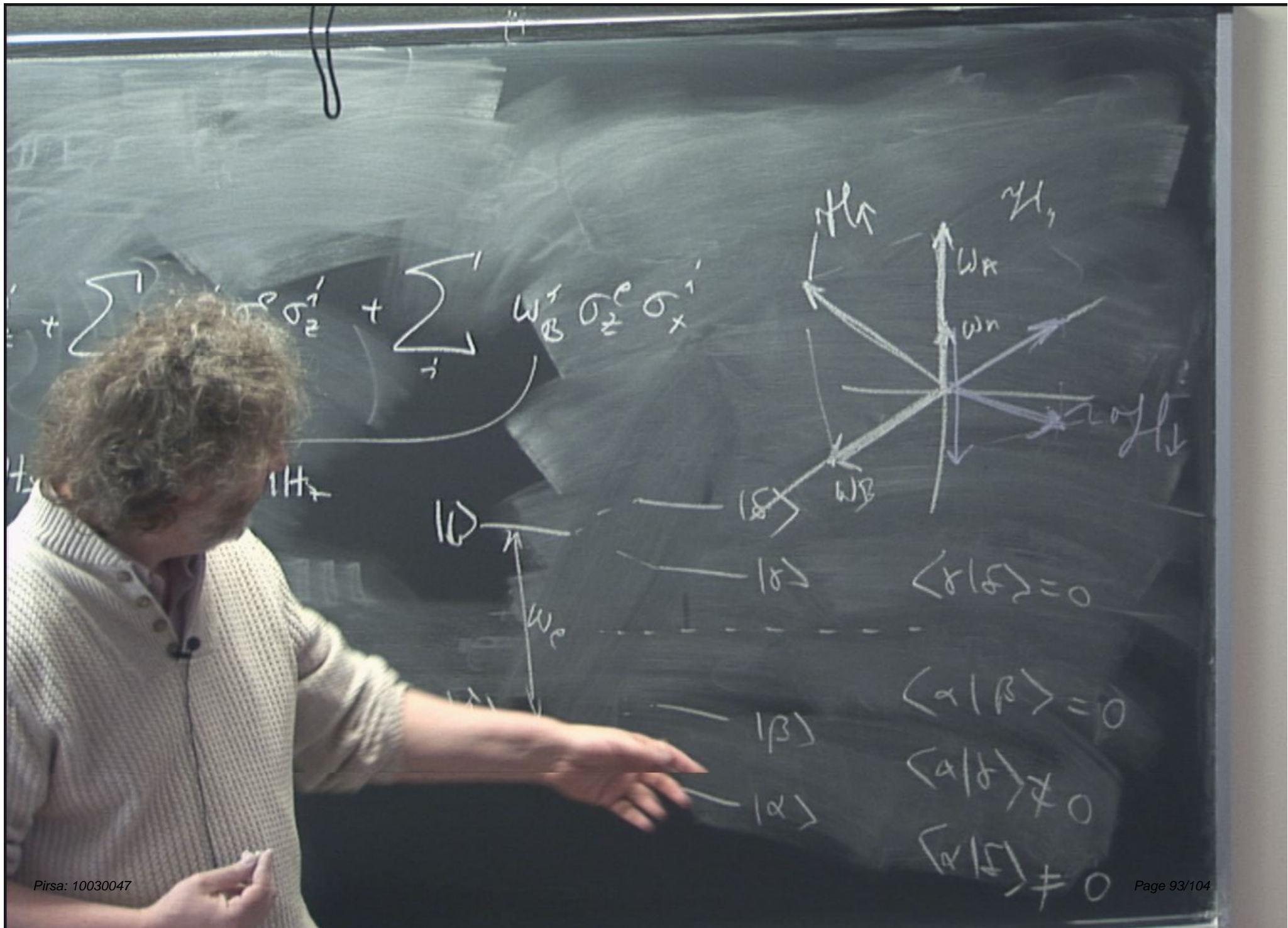
30 MHz



$$\langle \gamma | \beta \rangle = 0$$

$$\langle \alpha | \beta \rangle = 0$$

$$\langle \alpha | \gamma \rangle \neq 0$$



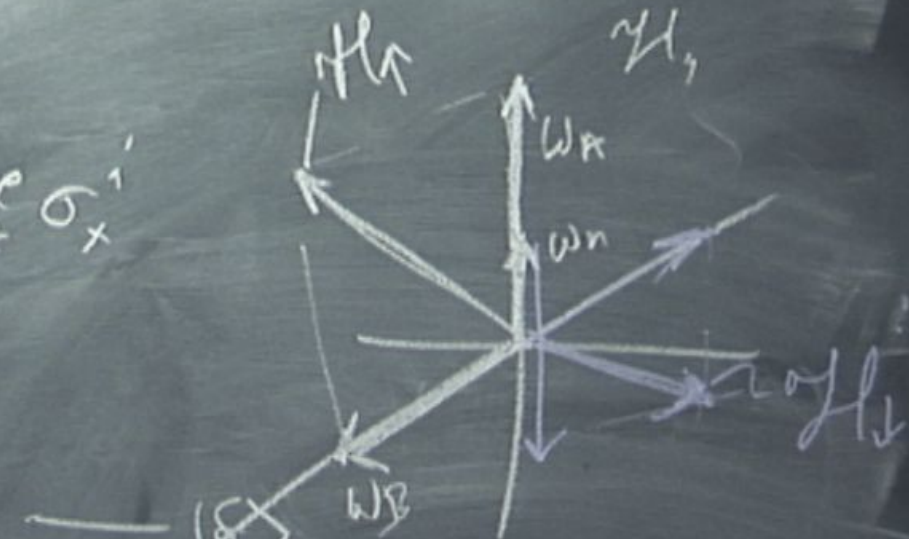
$$+ \sum_i \omega_A^i \sigma_z^p \sigma_z^i + \sum_i \omega_B^i \sigma_z^p \sigma_x^i$$

H_s
30 MHz

$|0\rangle$

$|1\rangle$

ω_p



$|\delta\rangle$

$|\delta\rangle$

$|\beta\rangle$

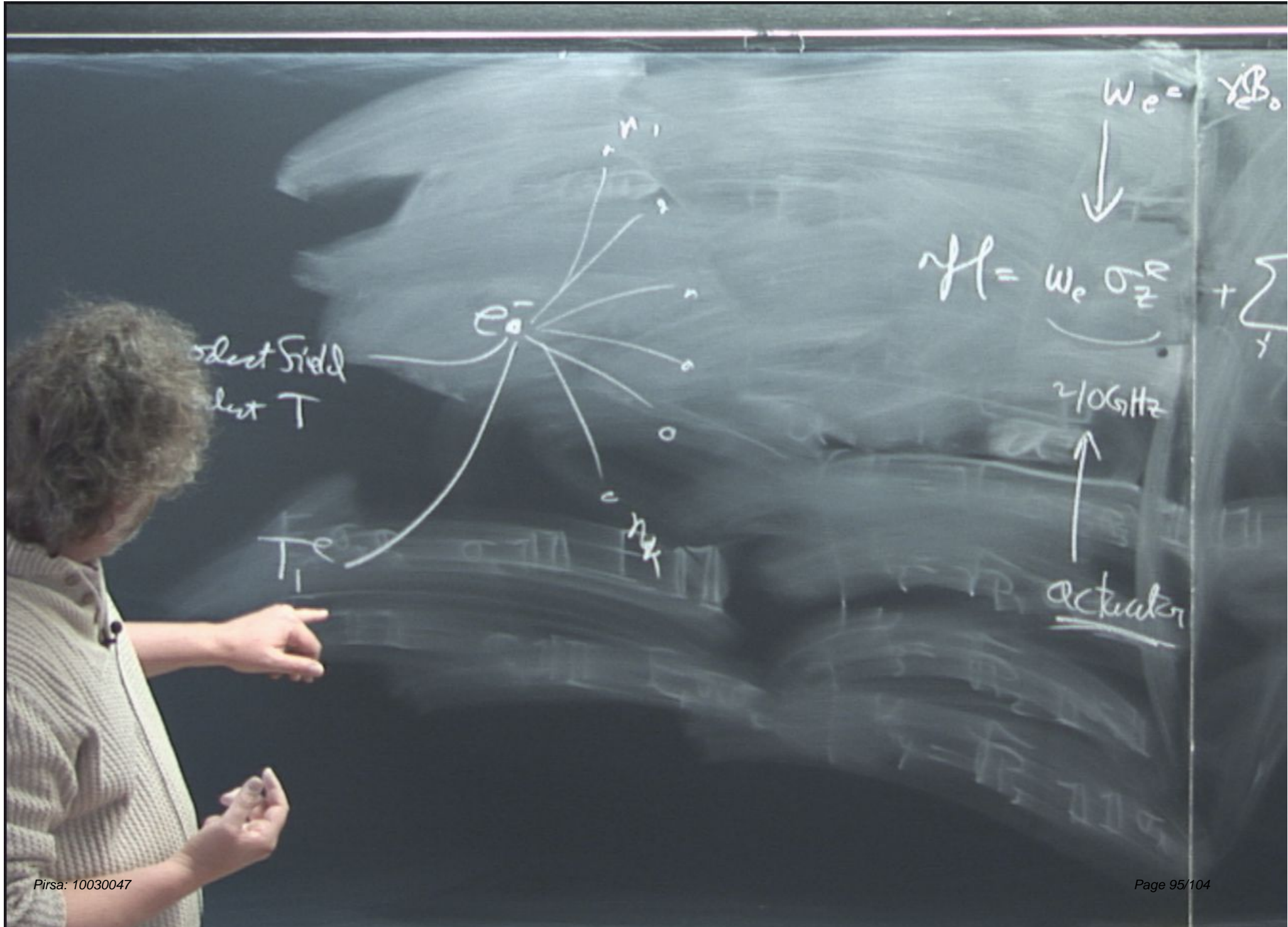
$|\alpha\rangle$

$$\langle \delta | \delta \rangle = 0$$

$$\langle \alpha | \beta \rangle = 0$$

$$\langle \alpha | \delta \rangle \neq 0$$

$$\langle \alpha | \delta \rangle \neq 0$$



odest field
est T



$$W_e = \gamma B_0$$

↓

$$H = W_e \sigma_z^R + \sum_j$$

↑

210 GHz

actuator

$$\omega_c = \gamma B_0$$



$$\mathcal{H} = \underbrace{\omega_c \sigma_z^R}_{210 \text{ GHz}} + \sum_i \omega_{H_i} \sigma_z^i + \sum_i \omega_{H_i} \sigma_z^R \sigma_z^i + \sum_i \omega_B \sigma_z^R \sigma_x^i$$

210 GHz



actuator

10 MHz

30 MHz

10

ω_c

11

$$\omega_c = \gamma B_0$$



$$\mathcal{H} = \underbrace{\omega_c \sigma_z^p}_{2106 \text{ Hz}} + \sum_i \omega_{H_i} \sigma_z^i + \sum_i \omega_{H_i} \sigma_z^p \sigma_z^i + \sum_i \omega_B \sigma_z^p \sigma_x^i$$

2106 Hz



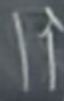
actuator

10 MHz

30 MHz

10

ω_c



$$\omega_e = \gamma B_0$$



$$\mathcal{H} = \underbrace{\omega_e \sigma_z^R}_{210 \text{ GHz}} + \sum_i \omega_{H_i} \sigma_z^i + \sum_i \omega_{H_i} \sigma_z^e \sigma_z^i + \sum_i \omega_B^i \sigma_z^e \sigma_x^i$$

210 GHz



actuator

10 MHz

30 MHz



10

ω_e

11

$$\omega_c = \gamma B_0$$



$$\mathcal{H} = \underbrace{\omega_c \sigma_z^R}_{210 \text{ GHz}} + \sum_i \omega_{H_i} \sigma_z^i + \sum_i \omega_{H_i} \sigma_z^R \sigma_z^i + \sum_i \omega_B \sigma_z^R \sigma_x^i$$

210 GHz

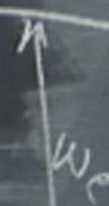


actuator

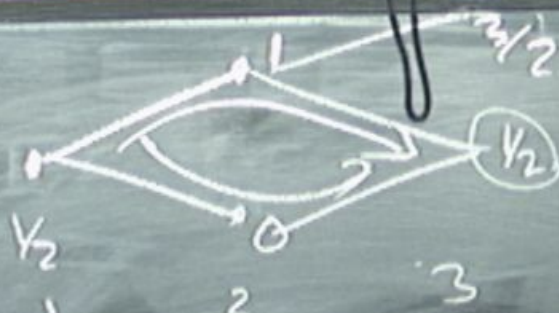
10 MHz

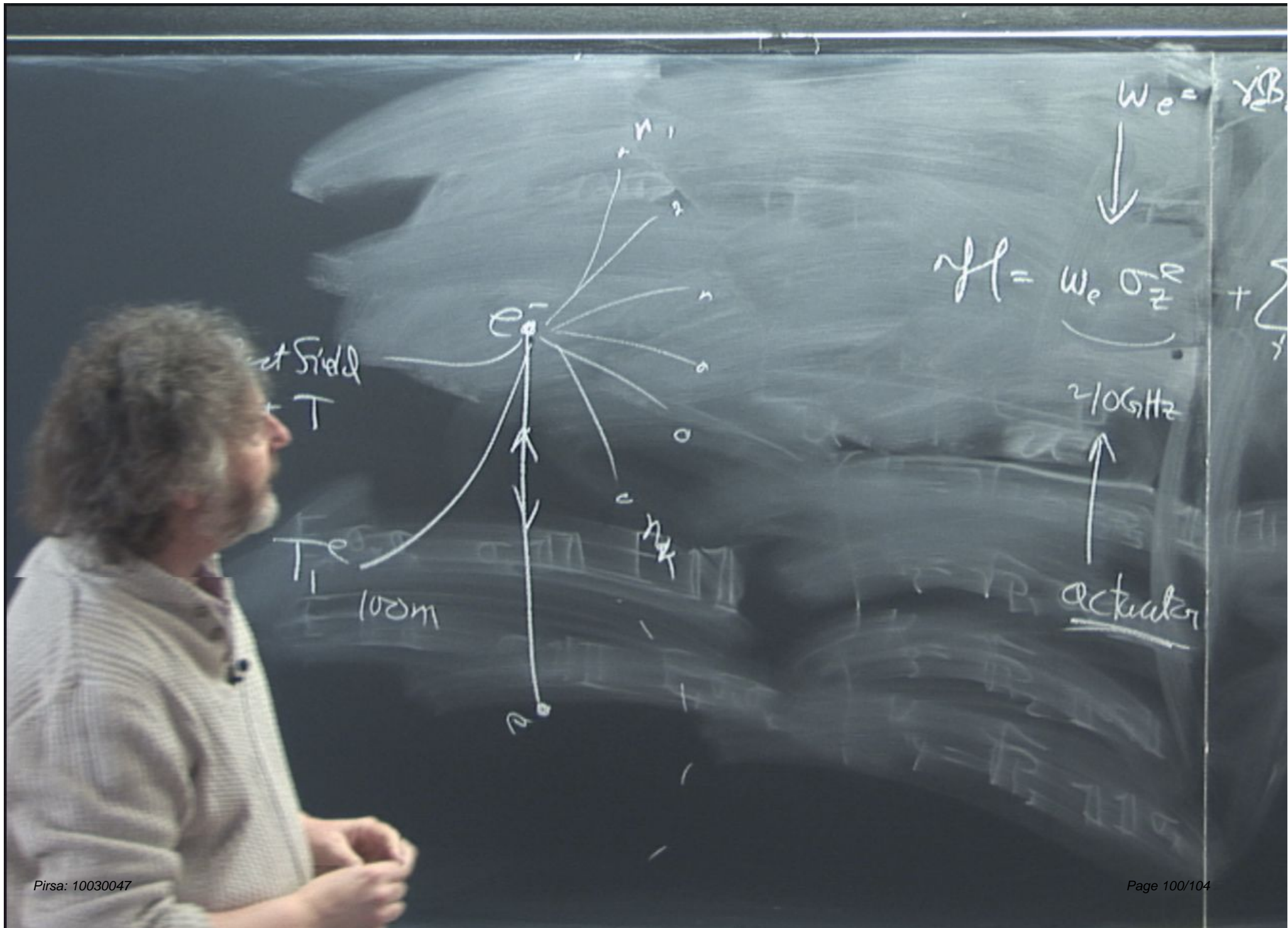
30 MHz

10



↑





$$W_e = \gamma B$$



$$H = W_e \sigma_z^R$$

210 GHz



actuator

at field

T

100m

modest field
modest T

T_e
100

e^-

n_1
 n_2

$$\mathcal{H} = W_e^1 \sigma_z^a + W_e^2 \sigma_z^{e_i} + \dots$$

$E \sigma^e$

210 GHz

actuator

$W_e = \gamma B$
↓

mod
mo



$$\mathcal{H} = W_e^1 \sigma_z^a + W_e^2 \sigma_z^{Ri} + \dots$$

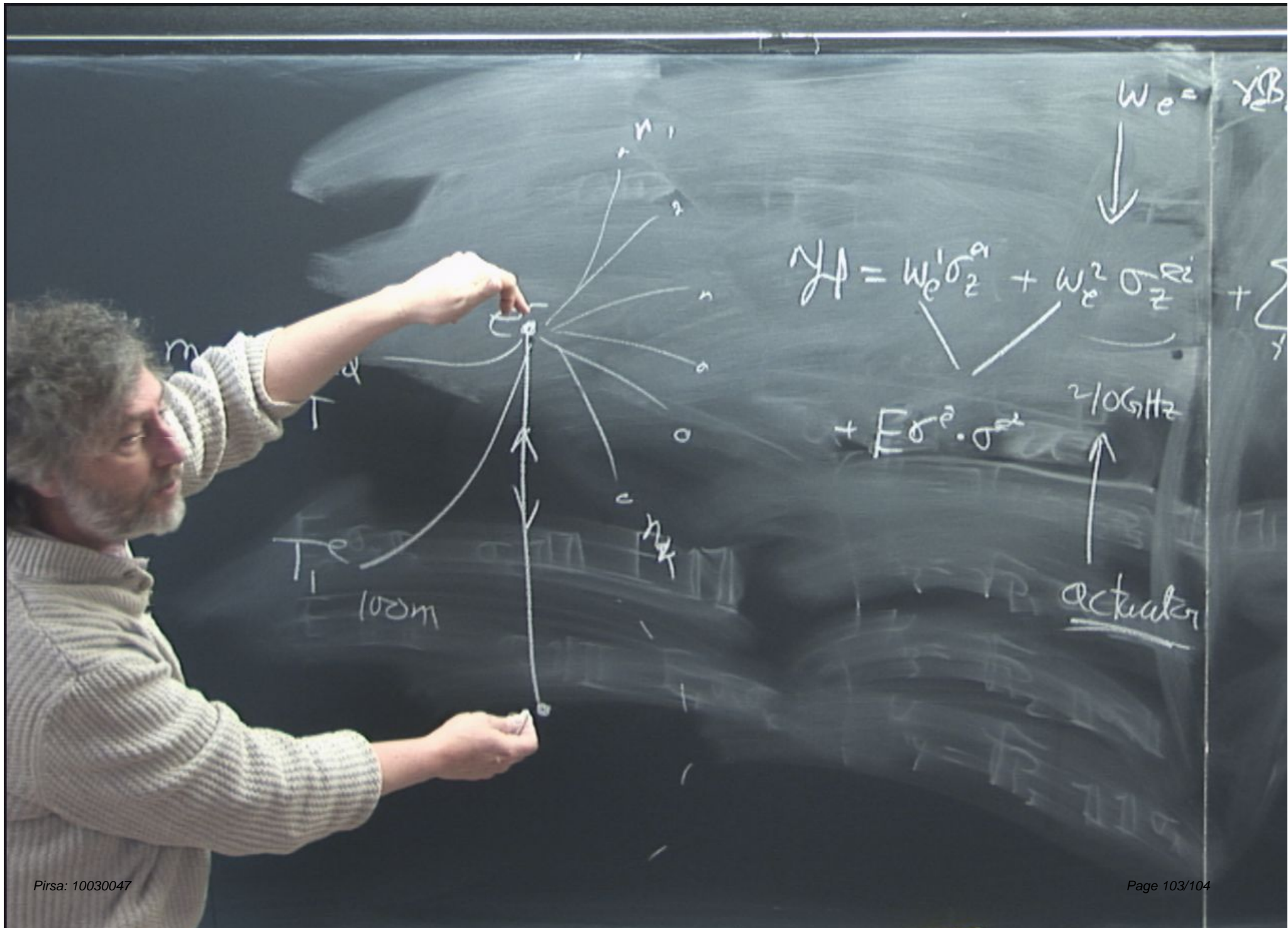
$$+ E \sigma^a \cdot \sigma^b$$

210 GHz

actuator

$$W_e = \gamma \beta$$





$$w_e = \gamma \beta$$



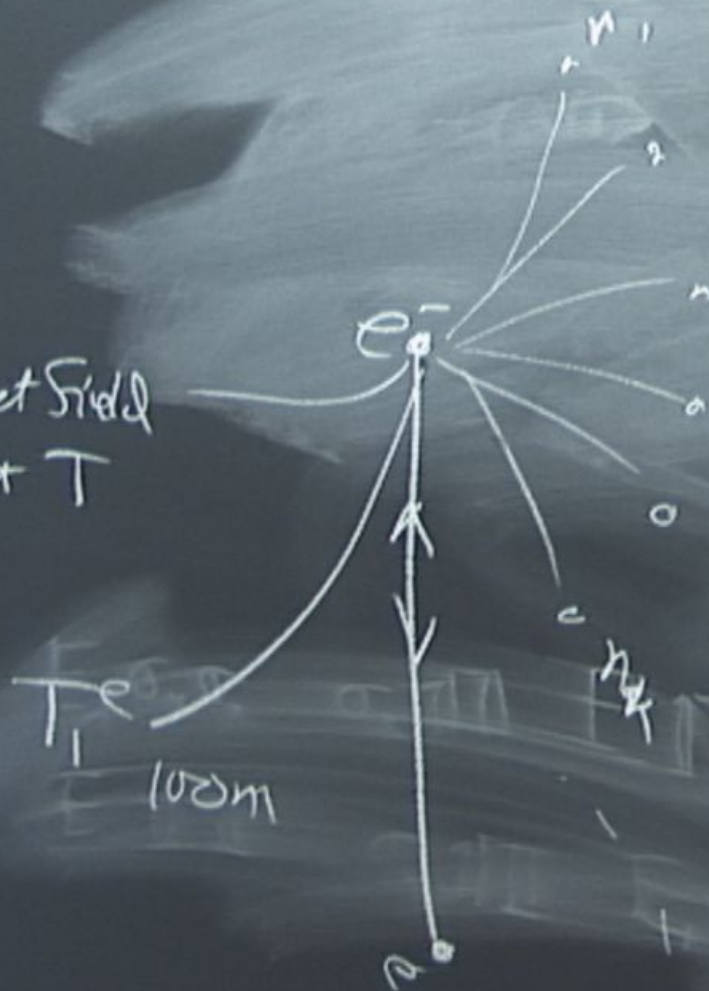
$$\mathcal{H} = w_e^1 \sigma_z^a + w_e^2 \sigma_z^{Ri} + \dots$$

$$+ F\sigma^2 \cdot \sigma^2$$

2106Hz

actuator

modest field
modest T



$$\mathcal{H} = w_e^1 \sigma_z^a + w_e^2 \sigma_z^{ri} + \dots$$

$$+ E \sigma^2 \cdot \sigma^2 \quad 2106 \text{ Hz}$$

actuator

$$w_e = \gamma \beta$$

