

Title: Explorations in Condensed Matter - Lecture 2

Date: Mar 15, 2011 10:15 AM

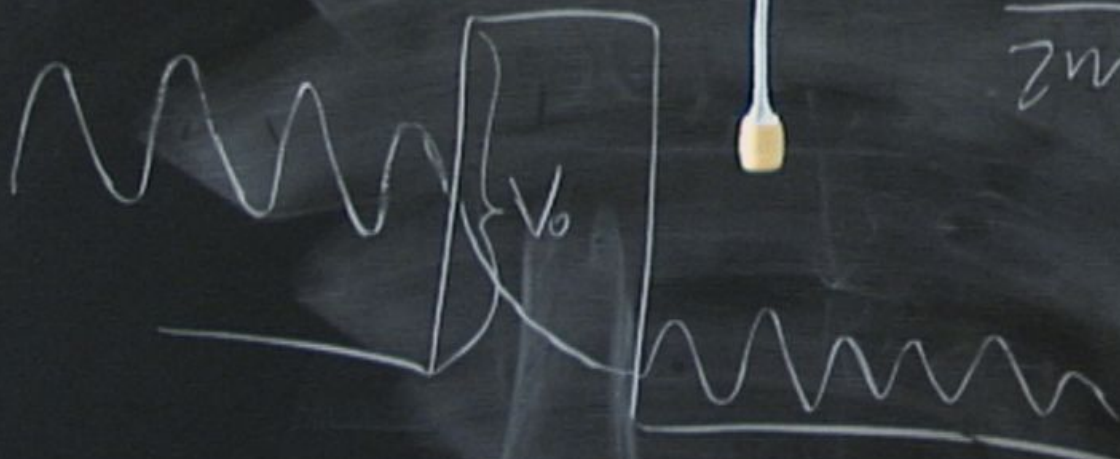
URL: <http://pirsa.org/11030031>

Abstract:

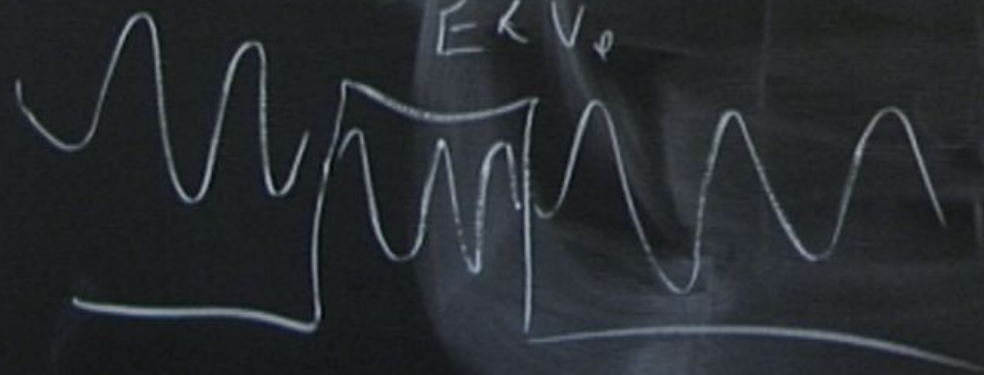


$$V_0 > E$$

$$\frac{p^2}{2m}$$

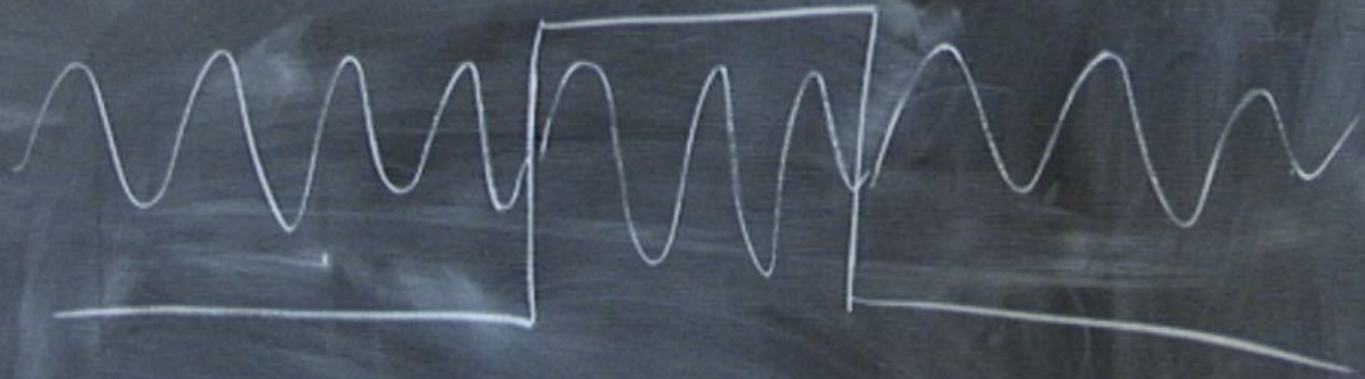


$$E < V_0$$



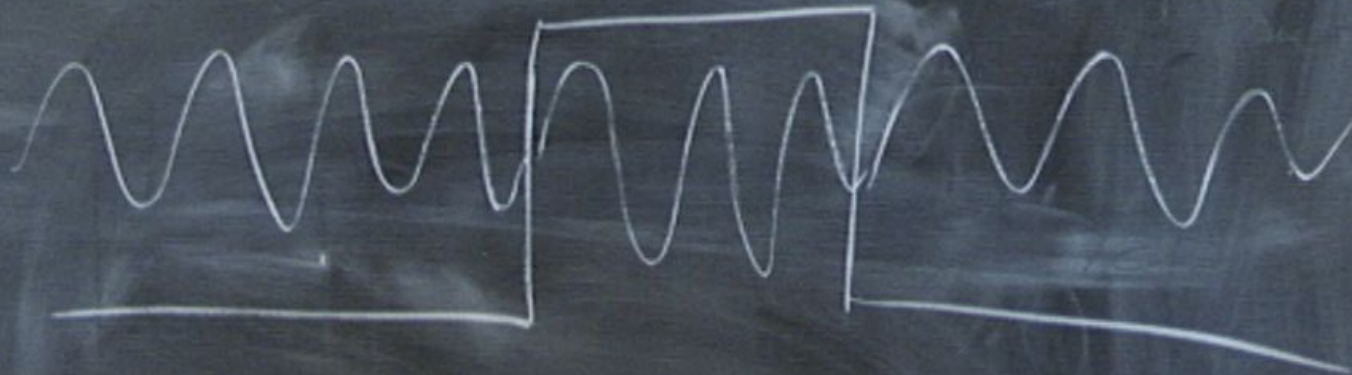
Dirac

$$V_0 > E$$



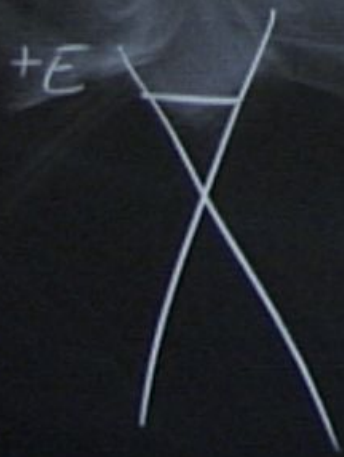
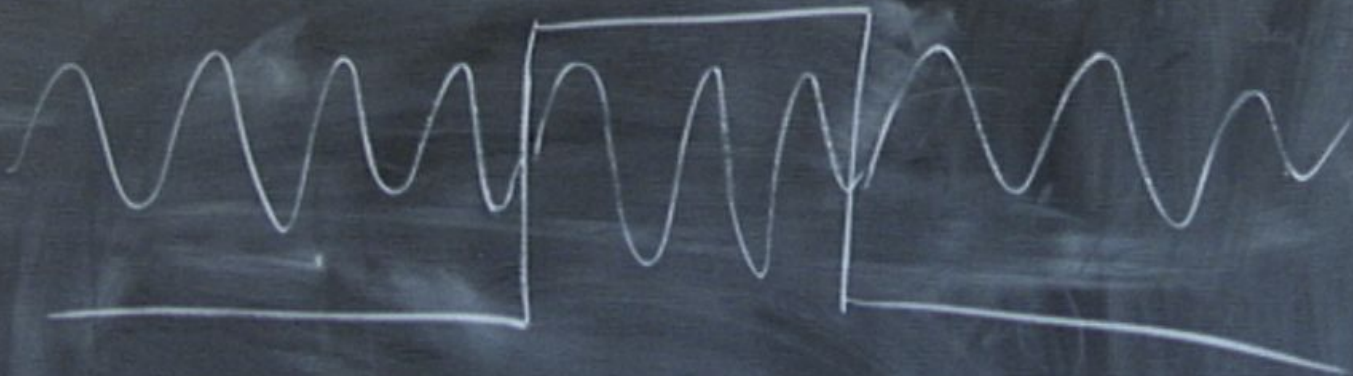
Dirac

$$V_0 > E$$



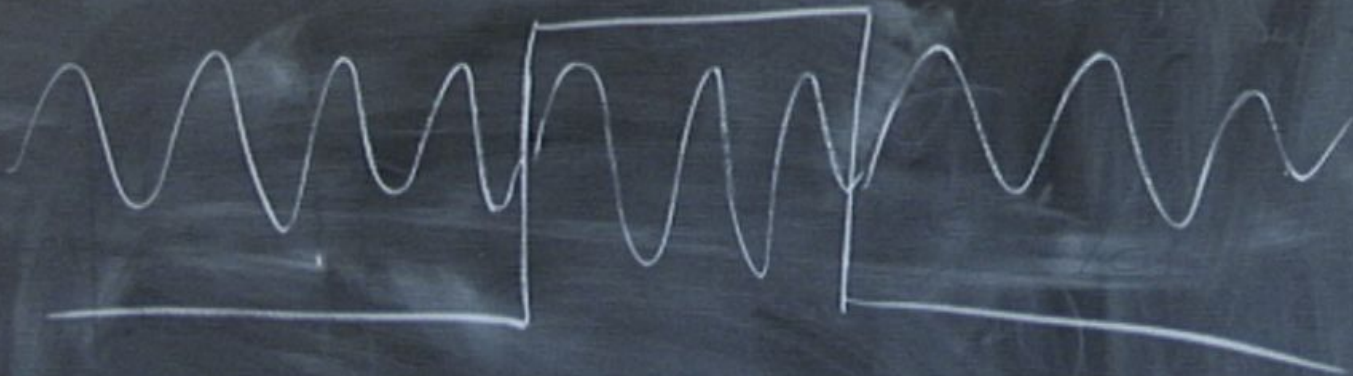
Dirac

$$V_0 > E$$



Dirac

$$N_0 > E$$



+E



$$\begin{pmatrix} k_x + ik_y \\ k_x - ik_y \end{pmatrix} \xrightarrow{\text{real}} \begin{pmatrix} 0 & -ih\alpha_x + \alpha_y \\ -ih\alpha_x - \alpha_y & 0 \end{pmatrix}$$

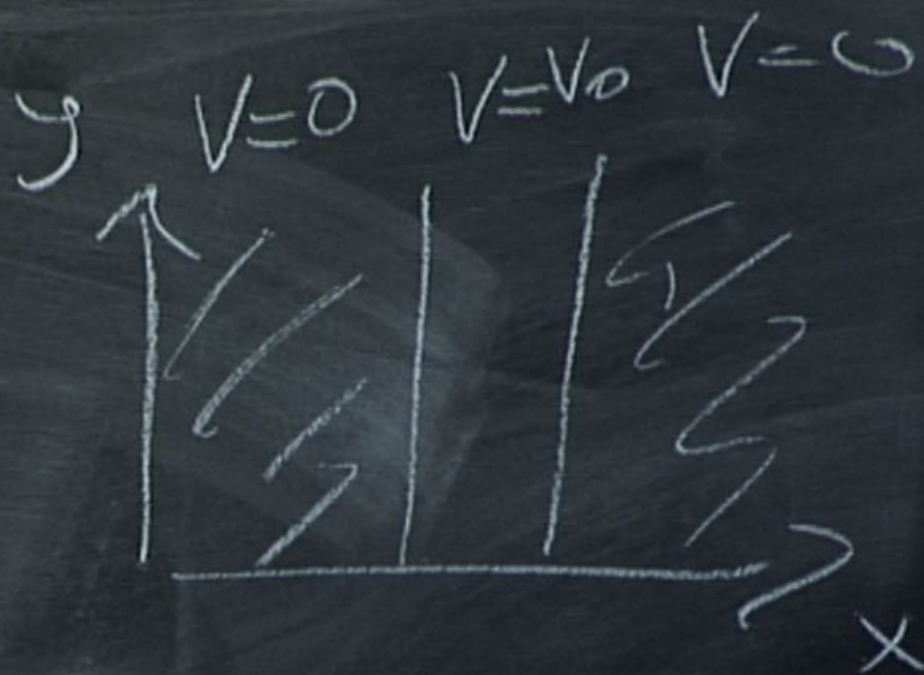
$$\begin{pmatrix} k_x + ik_y \\ k_x - ik_y \end{pmatrix} \xrightarrow{\text{real}} \begin{pmatrix} 0 & -i\hbar\alpha_x + \hbar\alpha_y \\ -i\hbar\alpha_x + \hbar\alpha_y & 0 \end{pmatrix}$$

$$\Psi_{(\pm E)} = \begin{pmatrix} + \\ - \end{pmatrix} e^{i\varphi_k} e^{ik_x x + ik_y y}$$

$$\begin{pmatrix} k_x + ik_y \\ k_x - ik_y \end{pmatrix} \xrightarrow{\text{real}} \begin{pmatrix} 0 & -i\hbar a_x + \hbar a_y \\ -i\hbar a_x + \hbar a_y & 0 \end{pmatrix}$$

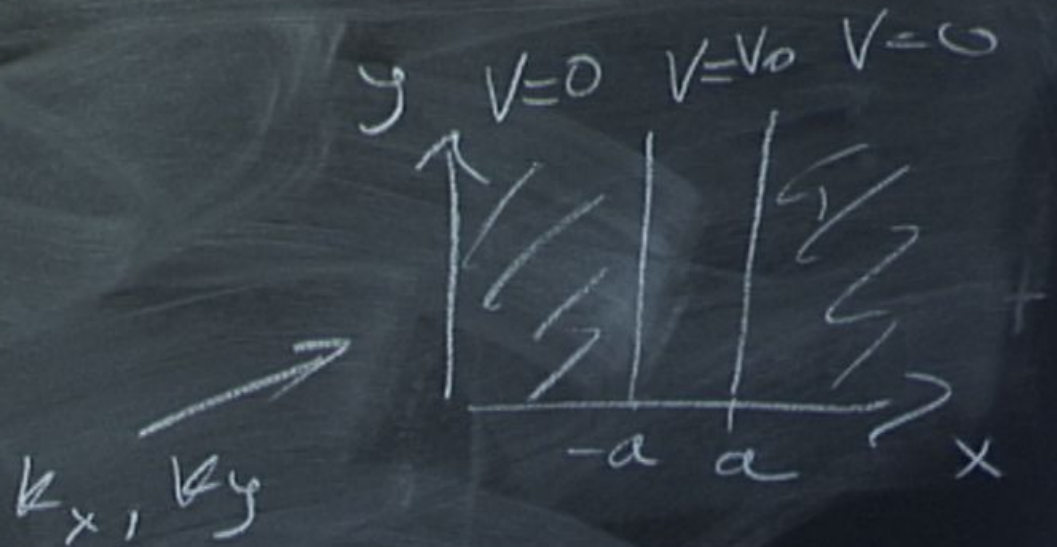
$$\Psi_{(\pm E)} = \begin{pmatrix} \pm e^{i\varphi_k} \\ \pm e^{-i\varphi_k} \end{pmatrix} e^{ik_x x + ik_y y}$$

$$\varphi_k = \text{Arg}(k)$$





$$E = \sqrt{k_x^2 + k_y^2}$$
$$= |k|$$



$$E = \sqrt{k_x^2 + k_y^2}$$

$$= |k|$$

$a_x + i a_y$
0

$$I) x < -a$$
$$e^{ikx + iky} \left(e^{i\varphi(k_x, k_y)} \right)$$

$$2y) \quad \text{I) } x < -a$$

$$e^{ik_x x + ik_y y} \left(\begin{array}{l} 1 \\ e^{i\varphi(k_x, k_y)} \end{array} \right) + r e^{ik_y y - ik_x x} \left(\begin{array}{l} 1 \\ e^{i\varphi(-k_x, k_y)} \end{array} \right)$$

$$\text{III) } x > a$$

$$t e^{ik_x x + ik_y y}$$

$$2y) \quad \text{I) } x < -a$$

$$e^{i k_x x + i k_y y} \begin{pmatrix} 1 \\ e^{i \varphi(k_x, k_y)} \end{pmatrix} + r e^{i k_y y - i k_x x} \begin{pmatrix} 1 \\ e^{i \varphi(-k_x, k_y)} \end{pmatrix}$$

$$\text{III) } x > a$$

$$t e^{i k_x x + i k_y y} \begin{pmatrix} 1 \\ e^{i \varphi(k_x, k_y)} \end{pmatrix}$$

$$2y) \text{ I) } x < -a$$

$$e^{i\kappa x + i\kappa y} \begin{pmatrix} 1 \\ e^{i\varphi(\kappa_x, \kappa_y)} \end{pmatrix} + r e^{i\kappa_y y - i\kappa_x x} \begin{pmatrix} 1 \\ e^{i\varphi(-\kappa_x, \kappa_y)} \end{pmatrix}$$

$$\text{II) } x > a$$

$$t e^{i\kappa x + i\kappa y} \begin{pmatrix} 1 \\ e^{i\varphi(\kappa_x, \kappa_y)} \end{pmatrix}$$

$$\text{III) } -a < x < a$$

$$I) e^{ik_x x + ik_y y} \left(e^{i\varphi(k_x, k_y)} \right) + r e^{i\varphi(-k_x, k_y)}$$

III) $x > a$

$$t e^{ik_x x + ik_y y} \left(e^{i\varphi(k_x, k_y)} \right)$$

III) $-a < x < a$

$$\alpha e^{iq_x x + ik_y y} \left(e^{i\varphi(q_x, k_y)} \right) +$$

$$\sqrt{k_x^2 + k_y^2} = E - V_0$$

$$I) \quad x < -a$$

$$e^{ik_x x + ik_y y} \begin{pmatrix} 1 \\ e^{i\varphi(k_x, k_y)} \end{pmatrix} + r e^{ik_y y - ik_x x} \begin{pmatrix} 1 \\ e^{i\varphi(-k_x, k_y)} \end{pmatrix}$$

$$II) \quad x > a$$

$$t e^{ik_x x + ik_y y} \begin{pmatrix} 1 \\ e^{i\varphi(k_x, k_y)} \end{pmatrix}$$

$$III) \quad -a < x < a$$

$$\alpha e^{iq_x x + ik_y y} \begin{pmatrix} 1 \\ e^{i\varphi(q_x, k_y)} \end{pmatrix} + \beta e^{-iq_x x + ik_y y} \begin{pmatrix} 1 \\ e^{i\varphi(-q_x, k_y)} \end{pmatrix}$$

$$\sqrt{k_x^2 + k_y^2} = E - V_0$$



$$E = \sqrt{k_x^2 + k_y^2}$$

$$= |k|$$



Katsnelson et al.

$$\begin{pmatrix} k_x + ik_y \\ k_x - ik_y \end{pmatrix} \xrightarrow{\text{real}} \begin{pmatrix} 0 & -i\hbar\alpha_x + \hbar\alpha_y \\ -i\hbar\alpha_x + \hbar\alpha_y & 0 \end{pmatrix}$$

$$\Psi_{(\pm E)} = \begin{pmatrix} \pm e^{i\varphi_k} \\ \pm e^{-i\varphi_k} \end{pmatrix} e^{i k_x x + i k_y y}$$

$$\varphi_k = \text{Arg}(k)$$

1. $k_y = 0$

2. $E - V_0 < 0$

I) $x < -a$
 $e^{i k_x x + i k_y y}$

III) $x > a$
 $t e^{i k_x x + i k_y y}$

III) $-a < x < a$

$\alpha e^{i k_x x + i k_y y}$

Katsnelson et al.

$$\begin{pmatrix} k_x + ik_y \\ k_x - ik_y \end{pmatrix} \xrightarrow{\text{real}} \begin{pmatrix} 0 & -i\hbar\alpha_x + \hbar\alpha_y \\ -i\hbar\alpha_x + \hbar\alpha_y & 0 \end{pmatrix} \quad \text{I)}$$

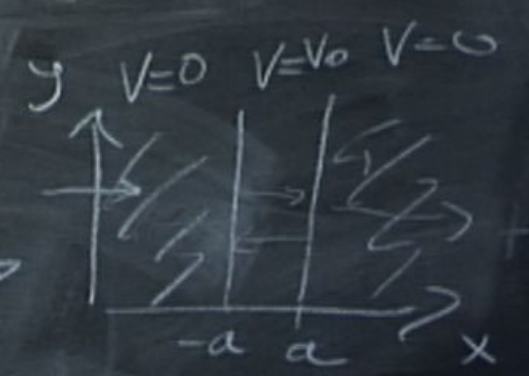
1. $k_y = 0$

2. $E - V_0 < 0$

$$\begin{aligned} \varphi(k_x, 0) &\rightarrow \varphi(-k_x, 0) \\ &= -\varphi(k_x, 0) + \pi \end{aligned} \quad \text{III}$$

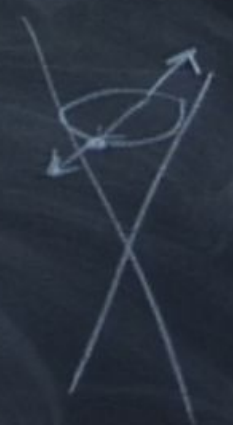


$$e^{iky} \begin{pmatrix} 1 \\ e^{i\varphi(k_x, k_y)} \end{pmatrix} + r e^{ik_y y - ik_x X} \begin{pmatrix} 1 \\ e^{i\varphi(-k_x, k_y)} \\ (-1) \end{pmatrix}$$



$$E = \sqrt{k_x^2 + k_y^2} = |k|$$

$$e^{ik_x x + ik_y y} \begin{pmatrix} 1 \\ e^{i\varphi(k_x, k_y)} \end{pmatrix}$$



$-a < x < a$

$$e^{iq_x X + ik_y y} \begin{pmatrix} 1 \\ e^{i\varphi(q_x, k_y)} \end{pmatrix} + \beta e^{-iq_x X + ik_y y} \begin{pmatrix} 1 \\ e^{i\varphi(-q_x, k_y)} \\ +1 \end{pmatrix}$$

Katsnelson et al.

$$-a) \begin{pmatrix} 1 \\ 1 \end{pmatrix} e^{-ika} + \begin{pmatrix} 1 \\ -1 \end{pmatrix} e^{ika}$$

$$= t e^{-ika} \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

$$a) t e^{ika} = \alpha e^{iga} \begin{pmatrix} 1 \\ -1 \end{pmatrix} + \beta e^{-iga} \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

$$I) x < -a$$
$$e^{ikx + i\epsilon t}$$

$$III) x > a$$

$$t e^{ikx}$$

$$III) -a < x$$

$$\alpha e^{igx}$$

$$\sqrt{v_x^2 + k_y^2} = F - v$$

katsne

$$\begin{aligned} -a) & \left(\begin{array}{c} 1 \\ 1 \end{array} \right) e^{-ika} + \left(\begin{array}{c} 1 \\ -1 \end{array} \right) e^{ika} \\ & = t e^{-ika} \left(\begin{array}{c} 1 \\ 1 \end{array} \right) \end{aligned}$$

$$\begin{aligned} a) \quad t e^{ika} &= \alpha e^{iza} \left(\begin{array}{c} 1 \\ -1 \end{array} \right) \\ &+ \beta e^{-iza} \left(\begin{array}{c} 1 \\ 1 \end{array} \right) \end{aligned}$$

$$\begin{aligned} T &= |t|^2 = 1 \\ R &= 0 \end{aligned}$$

↳ atsne

$$-a) \left(\begin{array}{c} 1 \\ 1 \end{array} \right) e^{-ika} + \left(\begin{array}{c} 1 \\ -1 \end{array} \right) e^{ika}$$

=

$$\alpha e^{iga} \left(\begin{array}{c} 1 \\ -1 \end{array} \right)$$

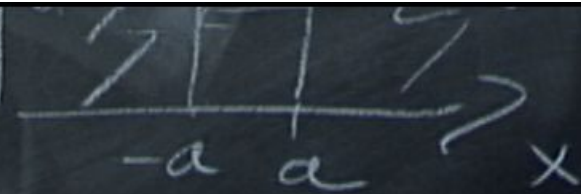
$$+ \beta e^{-iga} \left(\begin{array}{c} 1 \\ 1 \end{array} \right)$$

$$T = |t|^2 = 1$$

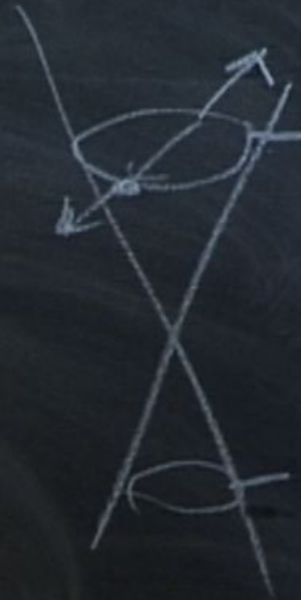
$$|r|^2 = 0$$

(0, -1)

k_x, k_y



$$E = \sqrt{k_x^2 + k_y^2}$$
$$= |k|$$



$$e^{ik_x x + ik_y y} \begin{pmatrix} 1 \\ e^{i\varphi(-g_x, k_y)} \\ +1 \end{pmatrix}$$

Katsnelson et al.

$$-a) \begin{pmatrix} 1 \\ 1 \end{pmatrix} e^{-ika} + \begin{pmatrix} 1 \\ -1 \end{pmatrix} e^{ika}$$


=

$$\alpha e^{iga} \begin{pmatrix} 1 \\ -1 \end{pmatrix}$$

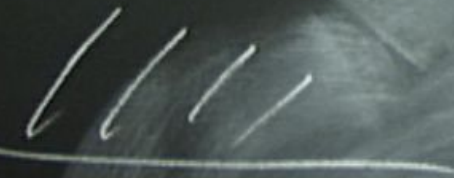
$$+ \beta e^{iga} \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

$$T = |t|^2 = 1$$
$$|r|^2 = 0$$

8-0



A hand-drawn diagram of a brain, likely a lateral view, with a line pointing to a specific area on the left side. The drawing is done in white on a dark background. The line starts at the handwritten text '8-0' and points to a region on the lateral surface of the brain, possibly the parietal lobe. There are several other lines drawn on the brain's surface, possibly representing sulci or gyri.

$y=0$ 

$y \rightarrow \infty$

$y=0$

$$e^{ik_y} \Rightarrow z^x$$

$$|\psi| \neq \infty \quad r \rightarrow \infty$$

$$|z^x| = 1$$

$$|z| = 1$$

$$e^{-\alpha y}, e^{\alpha y}$$

$$H = \sum_{\langle ij \rangle} \psi_i^+ \begin{pmatrix} t_{ij} & \\ & t_{ij}^* \end{pmatrix} \psi_j$$

$$| = |$$

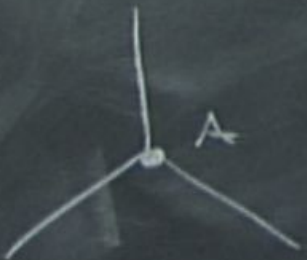
$$| = |$$

$$e^{xy}, e^{xy}$$

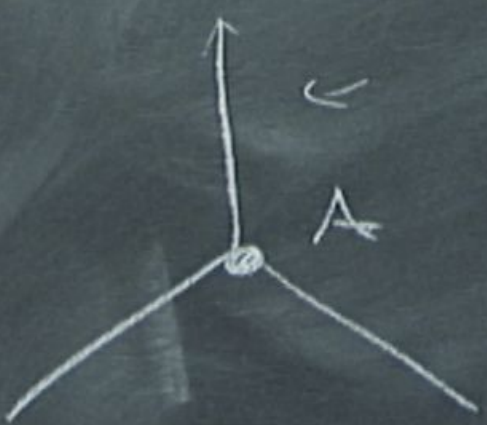
$$H = \sum_{i=0}^{N-1} \psi_i^\dagger \begin{pmatrix} \epsilon_{\sigma_i}^* & t_{\sigma_i} \end{pmatrix} \psi_{i+\sigma}$$

$e^{\alpha y}$

$$H = \sum_{i, \sigma} \psi_i^\dagger \left(t_{i, i+\sigma}^* \right) \psi_{i+\sigma} = \sum_{\substack{k_x, i_y \\ \sigma}} \psi_{k_x, i_y} \left(t_{k_x, i_y}(\vec{\sigma}) \right) \psi_{k_x, i_y}^*$$



$$H = \sum_{i, \vec{\sigma}} \psi_i^+ \left(t_{i, \vec{\sigma}}^* \right) \psi_{i+\vec{\sigma}} = \langle \dots \rangle$$



$$\sum_{\vec{\sigma}_y} t_{k, \vec{\sigma}_y} = R^+$$

$$\Psi_{i+\vec{\delta}} = \sum_{k_x, i_y} \Psi_{k_x, i_y} \left(t_k(\vec{\delta}) \right) \Psi_{k_x, i_y + \delta_y}$$

↕

x

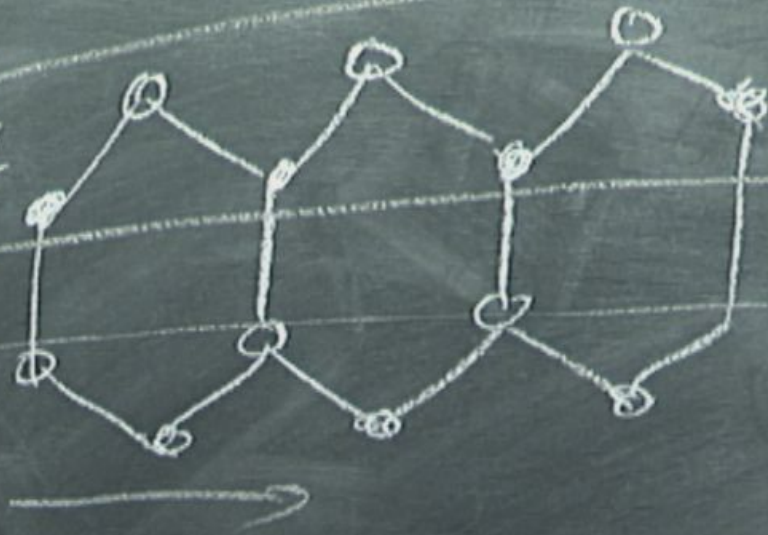
R^+

$$y \rightarrow \infty$$

$$y = 0$$

$$y = 1$$

$$y = 2$$



$$|\psi| \neq \infty$$
$$r \rightarrow \infty$$

$$|z^x| = 1$$

$$|z| = 1$$

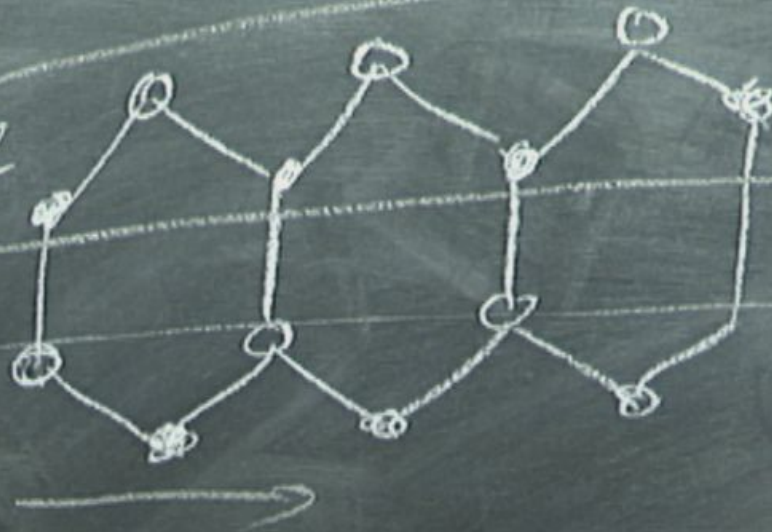
$$\rho^{-x,y}$$

$$y \rightarrow \infty$$

$$y = 0$$

$$y = 1$$

$$y = 2$$

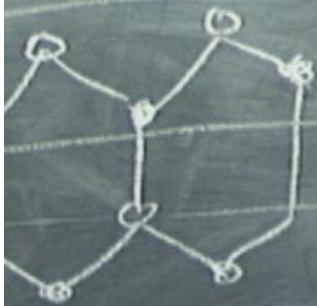


$$|\psi| \neq \infty$$
$$r \rightarrow \infty$$

$$|z^*| = 1$$

$$|z| = 1$$

$$\rho^{-x,y}$$

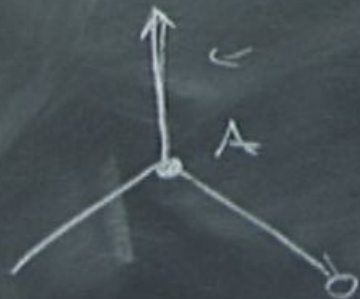


$$H = \sum_{i, \vec{\sigma}} \Psi_i^\dagger \begin{pmatrix} t_{\vec{\sigma}}^* & t_{\vec{\sigma}} \end{pmatrix} \Psi_{i+\vec{\sigma}} = \sum_{\vec{k}, i, \vec{\sigma}} \Psi_{\vec{k}, i, \vec{\sigma}}$$

$$|z^*| = 1$$

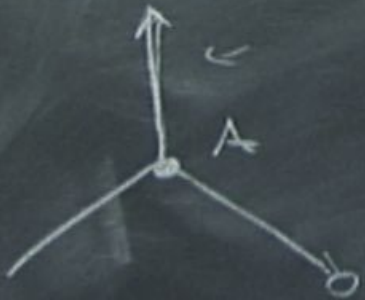
$$|z| = 1$$

$$e^{-i\alpha y}, e^{i\alpha y}$$



$$\sum_{\vec{\sigma}_y} t_{\vec{k}, \vec{\sigma}_y} = R^+ + e^{i\frac{k_y a}{2}}$$

$$H = \sum_{\vec{i}, \vec{\sigma}} \Psi_i^\dagger (t_{\vec{\sigma}}^* t_{\vec{\sigma}}) \Psi_{i+\vec{\sigma}} = \sum_{\vec{\sigma}} \Psi_{k_x, i_y} (t_{k_x}(\vec{\sigma}))$$



$$\sum_{\vec{\sigma}_y} t_{k_x, \vec{\sigma}_y} = R^+ + e^{i \frac{k_y a}{2}} + e^{-i \frac{k_y a}{2}}$$

$$= R^+ + 2 \cos\left(\frac{k_y a}{2}\right)$$

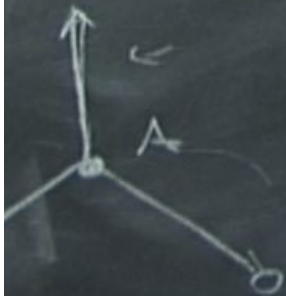
$$H = \sum_{i, \vec{\delta}_i} \Psi_i^+ (t_{\vec{\delta}_i}^*) \Psi_{i+\vec{\delta}_i} = \sum_{k_x, i_y} \Psi_{k_x, i_y} (t_{k_x(\vec{\delta}_y)}) \Psi_{k_x, i_y}$$

$$\Psi(x, y) = \frac{1}{\sqrt{N}} \sum_k e^{i k_x x} \Psi(y)$$

$$R^+ \Psi(y) = \Psi(y+1)$$

$$\sum_{\vec{\delta}_y} t_{k, \vec{\delta}_y} = R^+ + e^{i \frac{k_y a}{2}} + e^{-i \frac{k_y a}{2}}$$

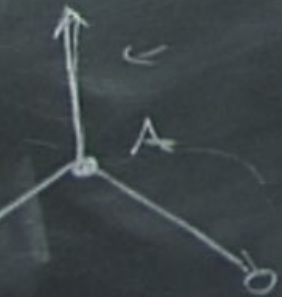
$$= R^+ + 2 \cos\left(\frac{k_y a}{2}\right)$$



$$H = \sum_{i, \vec{\delta}_i} \Psi_i^+ (t \vec{\delta}_i) \Psi_{i+\vec{\delta}_i} = \sum_{k_x, i_y} \Psi_{k_x, i_y} (t_k(\vec{\delta}_i)) \Psi_{k_x, i_y}$$

$$\Psi(x, y) = \frac{1}{\sqrt{K}} \sum_k e^{i k_x x} \psi(y)$$

$$R^+ \psi(y) = \psi(y+1)$$



$$\sum_{\vec{\delta}_y} t_{k, \vec{\delta}_y} = R^+ + e^{i \frac{k_y a}{2}} + e^{-i \frac{k_y a}{2}}$$

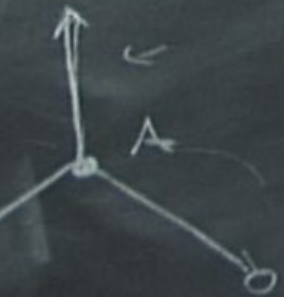
$$= R^+ + 2 \cos\left(\frac{k_y a}{2}\right)$$

$$H_k = \Psi_k^+ \begin{pmatrix} R^+ + 2 \cos \frac{k_y a}{2} \\ R \end{pmatrix}$$

$$H = \sum_{i, \vec{\delta}_i} \Psi_i^+ \left(t_{\vec{\delta}_i}^* \right) \Psi_{i+\vec{\delta}_i} = \sum_{k_x, i_y} \Psi_{k_x, i_y} \left(* t_{k_x, \vec{\delta}_y} \right) \Psi_{k_x, i_y}$$

$$\Psi(x, y) = \frac{1}{\sqrt{N}} \sum_k e^{i k \cdot x} \Psi(y)$$

$$R^+ \Psi(y) = \Psi(y+1)$$



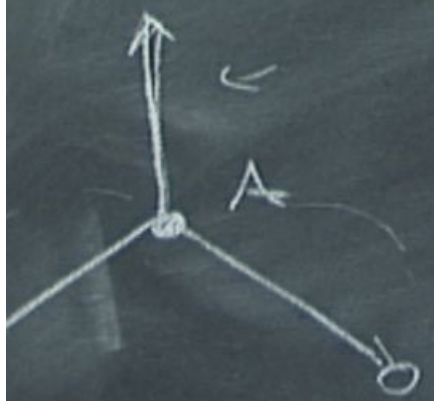
$$\sum_{\vec{\delta}_y} t_{k, \vec{\delta}_y} = R^+ + e^{i \frac{k_y a}{2}} + e^{-i \frac{k_y a}{2}}$$

$$= R^+ + 2 \cos\left(\frac{k_y a}{2}\right)$$

$$H_k = \Psi_k^+ \begin{pmatrix} 0 & R^+ + 2 \cos \frac{k_y a}{2} \\ R + 2 \cos \frac{k_y a}{2} & 0 \end{pmatrix} \Psi_k$$

$$H = \sum_{\vec{k}, \vec{\sigma}} \Psi_{\vec{k}} \left(e^{i\vec{k} \cdot \vec{\sigma}} \right) \quad | \quad \vec{k}_x, i y$$

$$\Psi(x, y) = \sum_{\vec{k}} e^{i\vec{k} \cdot \vec{\sigma}} \Psi(\vec{y})$$



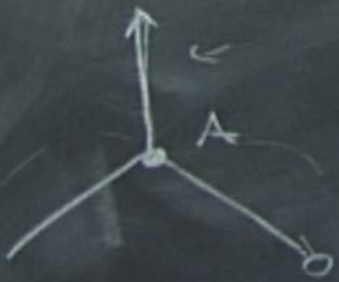
$$\sum_{\vec{\sigma}} t_{\vec{k}, \vec{\sigma}} = R^+ + e^{i \frac{k_x a}{2}} + e^{-i \frac{k_x a}{2}}$$

$$= R^+ + 2 \cos\left(\frac{k_x a}{2}\right)$$

$$H_{\vec{k}} = \Psi_{\vec{k}}^+ \begin{pmatrix} 0 & R^+ + 2 \cos \frac{k_x a}{2} \\ R + 2 \cos \frac{k_x a}{2} & 0 \end{pmatrix} \Psi_{\vec{k}}$$

$$H = \sum_{i, \vec{\sigma}_i} \Psi_i^+ (t_{\vec{\sigma}_i}^*) \Psi_{i+\vec{\sigma}} = \sum_{k_x, i_y} \Psi_{k_x, i_y} (t_{k(\vec{\sigma}_y)}) \Psi_{k_x, i_y}$$

$$\Psi(x, y) = \frac{1}{\sqrt{a}} \sum_k e^{ik \cdot x} \Psi(y) \quad R^+ \Psi(y) = \Psi(y+1)$$



$$\sum_{\vec{\sigma}_y} t_{k, \vec{\sigma}_y} = R^+ + e^{i \frac{k_y a}{2}} + e^{-i \frac{k_y a}{2}}$$

$$= R^+ + 2 \cos\left(\frac{k_y a}{2}\right)$$

$$H_k = \Psi_k^+ \begin{pmatrix} 0 & R^+ + 2 \cos \frac{k_y a}{2} \\ R^+ + 2 \cos \frac{k_y a}{2} & 0 \end{pmatrix} \Psi_k \quad \bar{E} = 0$$

$y \rightarrow \infty$

$y=0$

$y=2$

$y=1$



$$\begin{pmatrix} & A \\ A^\dagger & \end{pmatrix} \begin{pmatrix} 0 \\ \varphi_- \end{pmatrix} = 0$$

$$A\varphi_- = 0$$

$$\begin{pmatrix} & A \\ A^\dagger & \end{pmatrix} \begin{pmatrix} \varphi_+ \\ 0 \end{pmatrix} = 0$$

$$A\varphi_+ = 0$$

$y \rightarrow \infty$

$y=0$

$y=2$

$y=1$



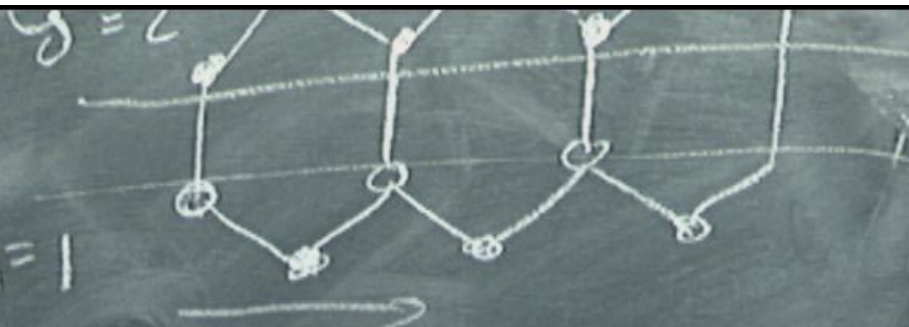
$$\begin{pmatrix} & A \\ A^\dagger & \end{pmatrix} \begin{pmatrix} 0 \\ \varphi \end{pmatrix} = 0$$

$$A\varphi = 0$$

$$\psi_k = \begin{pmatrix} 0 \\ \varphi_k(y) \end{pmatrix} = \begin{pmatrix} 0 \\ z^k \end{pmatrix}$$

$$y=0$$

$$y=1$$



$$\begin{pmatrix} A & \\ & A^+ \end{pmatrix} \begin{pmatrix} 0 \\ \varphi \end{pmatrix} = 0$$

$$\boxed{A\varphi = 0}$$

$$\begin{pmatrix} 0 \\ \dots \\ \kappa(y) \end{pmatrix} = \begin{pmatrix} 0 \\ \dots \\ z^h \end{pmatrix}$$

$$\begin{pmatrix} R^+ + 2\cos\frac{kx}{2} \\ Z + 2\cos\frac{kx}{2} \end{pmatrix} z^h = 0$$



$$= 0$$

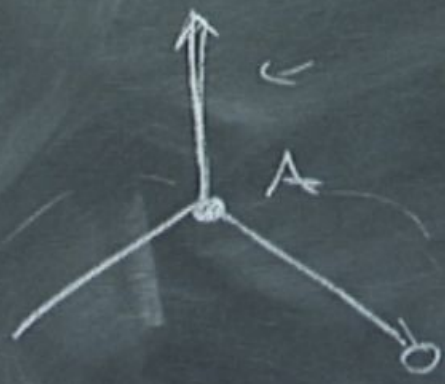
$$A\psi = 0$$

$$\begin{pmatrix} 0 \\ \vdots \\ z^n \end{pmatrix}$$

$$\begin{pmatrix} R^+ + 2\cos\frac{k_x}{2} \\ \vdots \\ z^n \end{pmatrix}$$

$$\begin{pmatrix} z + 2\cos\frac{k_x}{2} \\ \vdots \\ z^n \end{pmatrix} = 0$$

$$H = \sum_i \psi_i^\dagger (t \delta_{ij} + \dots)$$



$$\psi(x, y)$$

$$\sum_{\vec{s}_y} t_{\vec{k}, \vec{s}_y} = F$$

$$H_{\vec{k}} = \psi_{\vec{k}}^\dagger \begin{pmatrix} 0 & R^+ + 2\cos\frac{k_x}{2} \\ R^+ + 2\cos\frac{k_x}{2} & z - 2\cos\frac{k_x}{2} \end{pmatrix} \psi_{\vec{k}}$$

$$y=0$$

$$y=1$$



$$\begin{pmatrix} & A \\ A^+ & \end{pmatrix} \begin{pmatrix} 0 \\ \varphi \end{pmatrix} = 0$$

$$\boxed{A\varphi = 0}$$

$$\psi_k = \begin{pmatrix} 0 \\ \varphi_k(y) \end{pmatrix} = \begin{pmatrix} 0 \\ z^k \end{pmatrix}$$

$$|z| = 1$$

$$|z| < 1$$

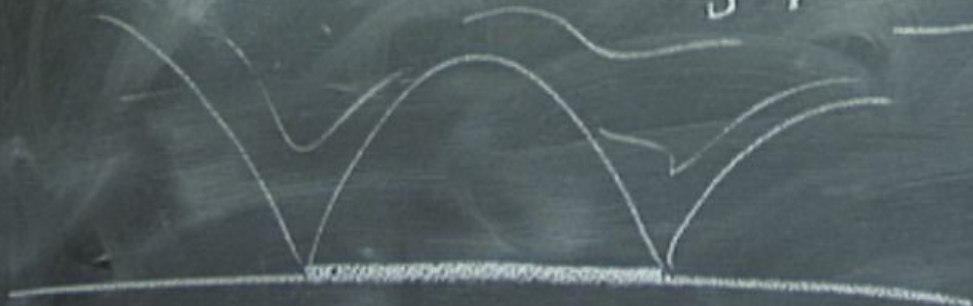
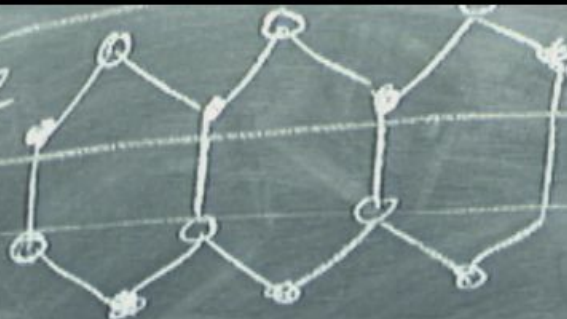
$$\begin{pmatrix} R^+ + 2\cos\frac{kx}{2} \\ Z + 2\cos\frac{kx}{2} \end{pmatrix}$$

$y=0$

$y=0$

$y=2$

$y=1$



k

k'

$$A^+ \varphi_+ = 0$$

$$|z| = 1$$
$$|z| < 1$$

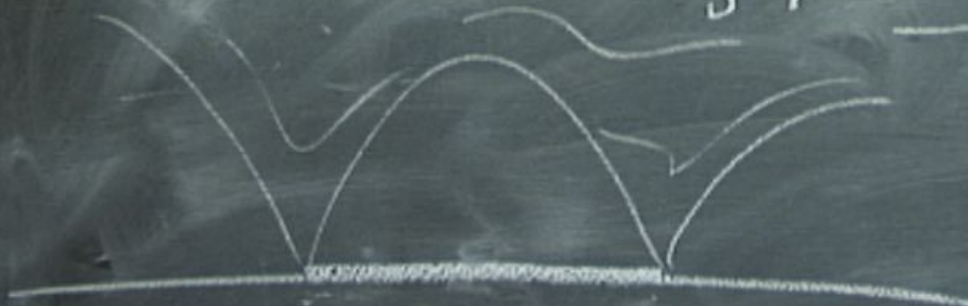
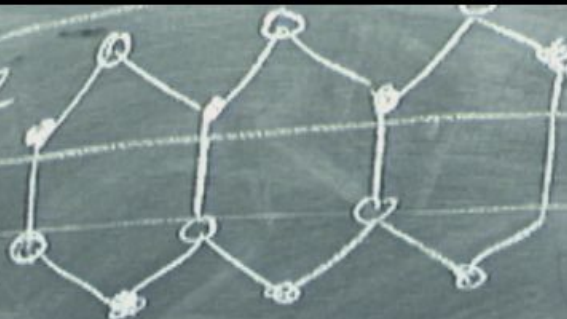
$$\begin{pmatrix} R^+ + 2 \cos \frac{k_x}{2} \\ Z + 2 \cos \frac{k_x}{2} \end{pmatrix}$$



$y=0$

$y=2$

$y=1$



k

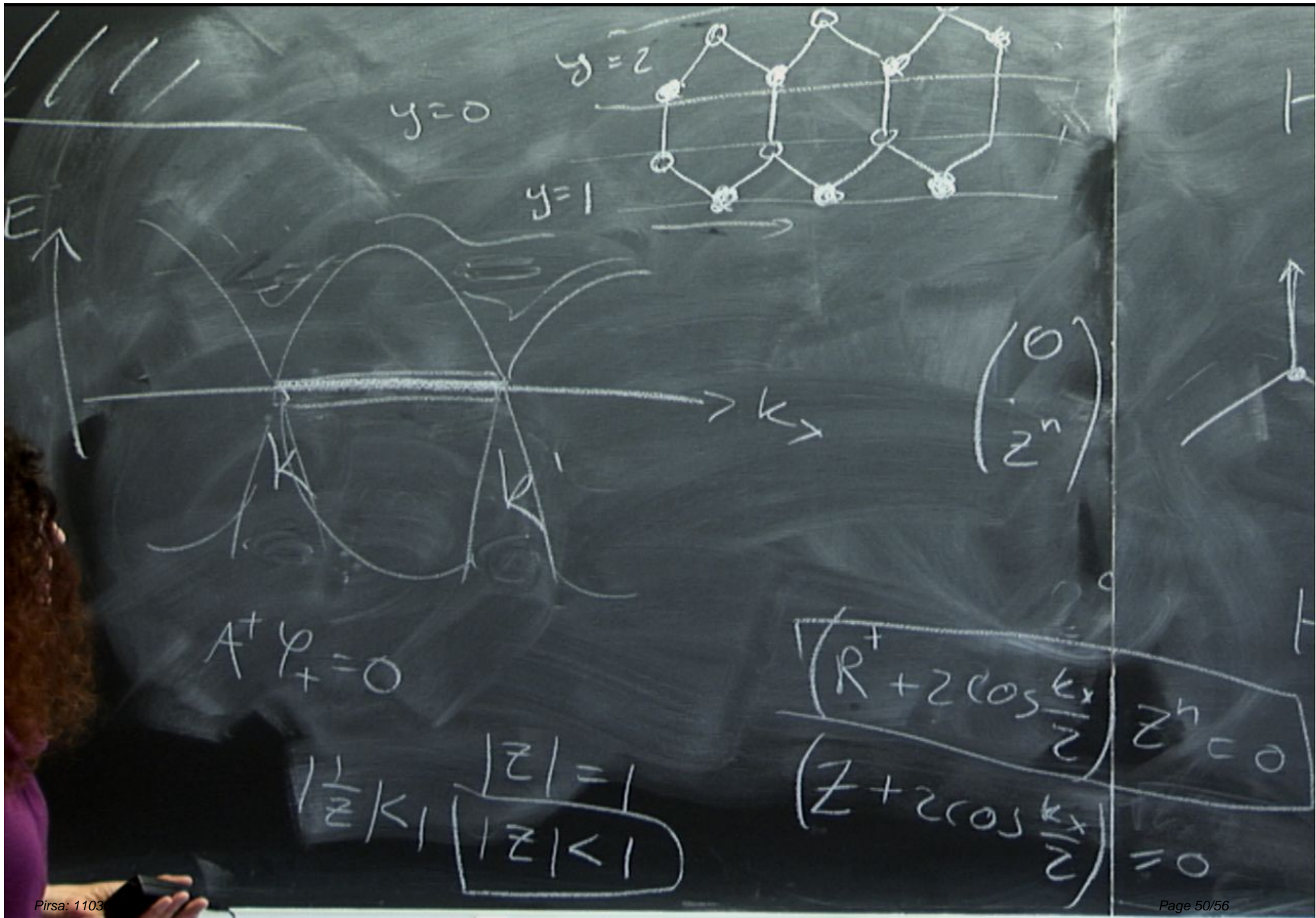
k'

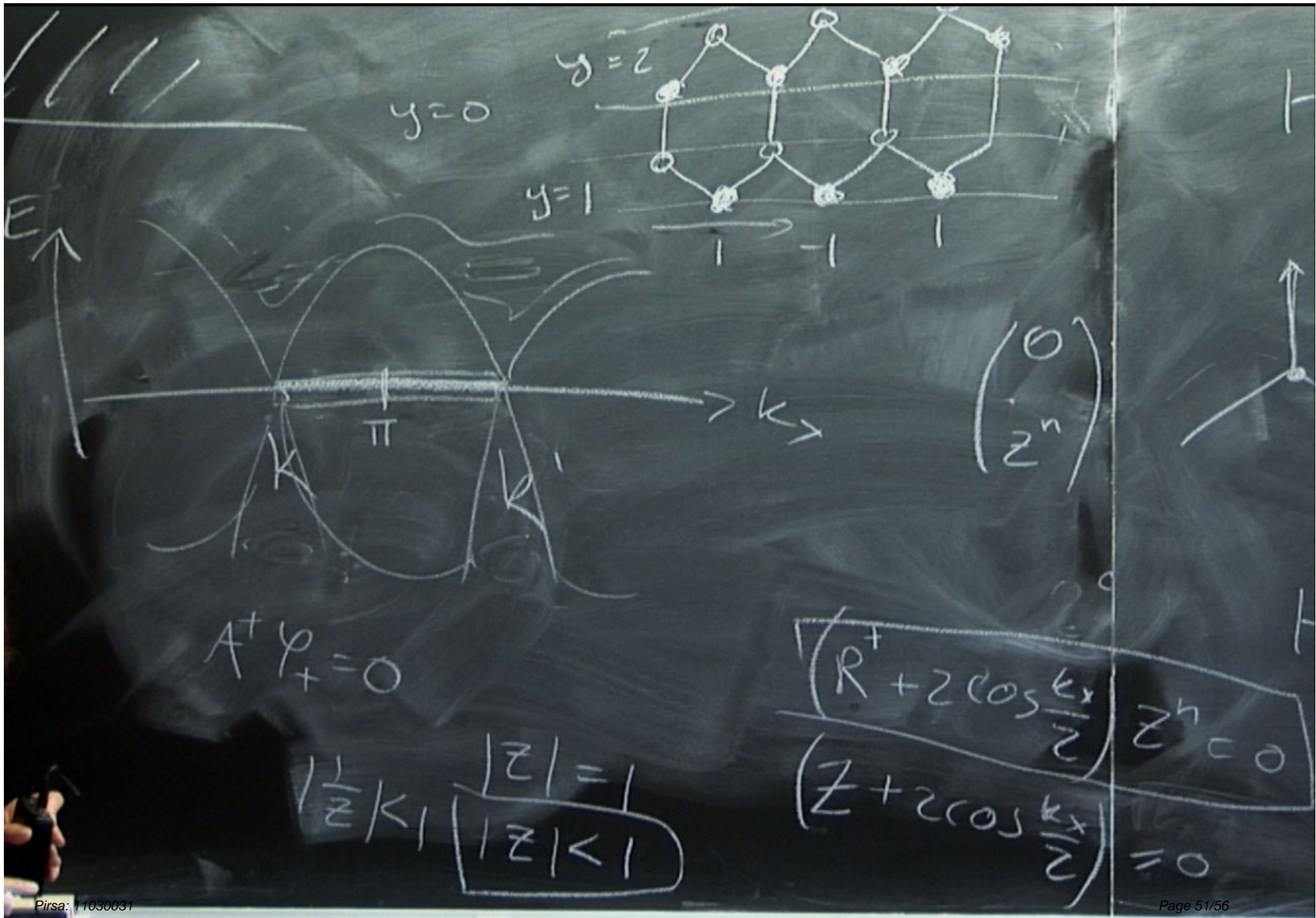
$$A^+ \varphi_+ = 0$$

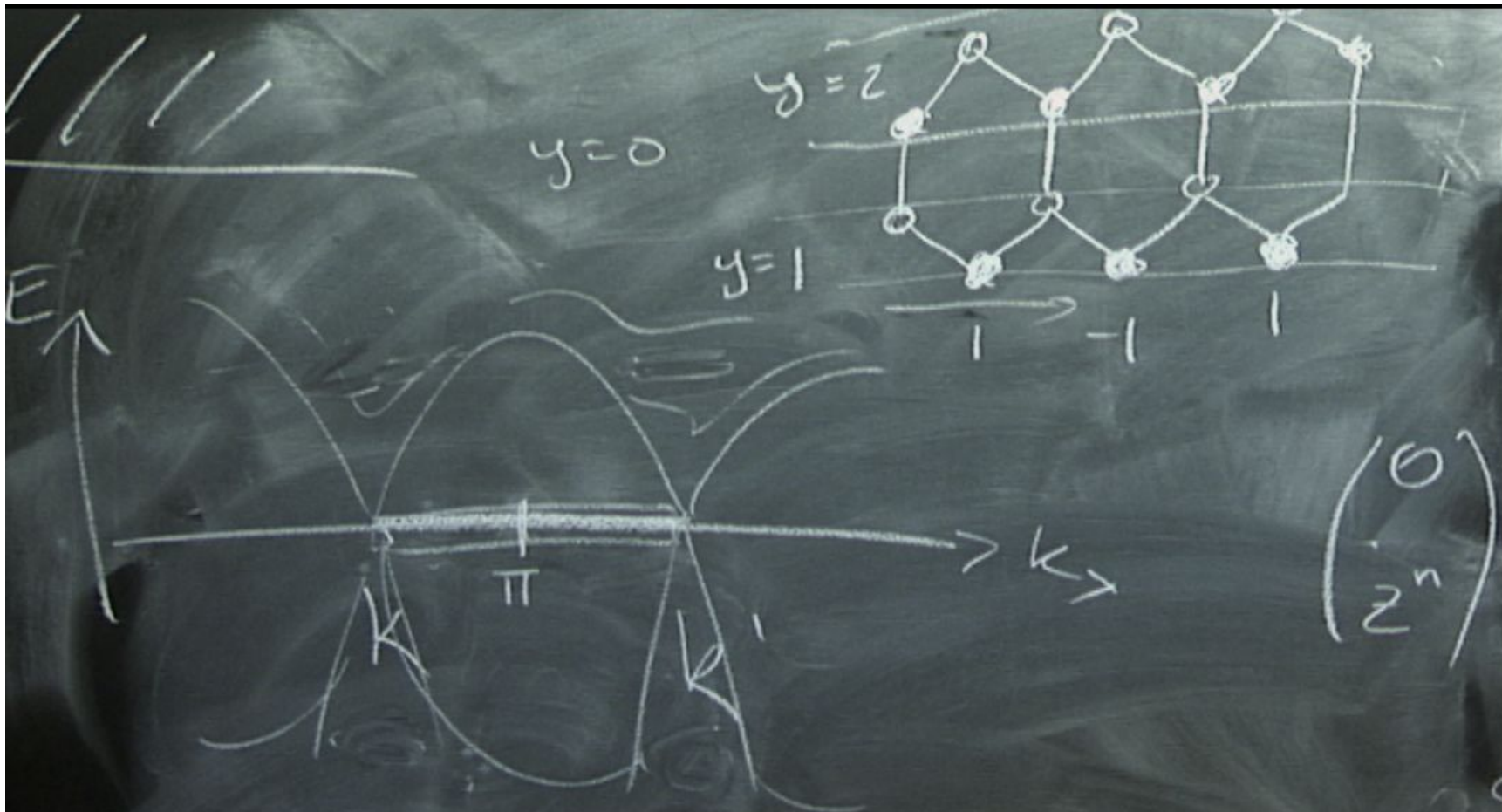
$$\frac{1}{z} |k| \quad |z| = 1$$

$$|z| > 1 \quad |z| < 1$$

$$\begin{pmatrix} R^+ + 2 \cos \frac{k_x}{2} \\ Z + 2 \cos \frac{k_x}{2} \end{pmatrix}$$







$$\begin{pmatrix} 0 \\ \vdots \\ z^n \end{pmatrix}$$

$$A^+ \psi_+ = 0$$

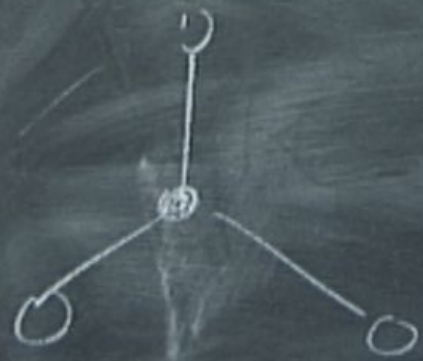
$$\frac{1}{z} < 1, \quad |z| = 1, \quad |z| < 1$$



$$H = \sum_{i, \sigma} \psi_i^\dagger (t \delta_{i, \sigma}^* + \dots) \psi_{i+\sigma}$$

$$t \sum_i c_i^\dagger c_j \approx 0$$

$$\begin{pmatrix} 0 \\ \vdots \\ \psi_i \end{pmatrix}$$



$$t_{\vec{\sigma}} \Psi_{i+\vec{\sigma}} = \sum_{\vec{k}_x, i_y} \Psi_{\vec{k}_x, i_y} \left(t_{\vec{k}}(\delta_j) \right) \Psi_{\vec{k}_x, i_y, i_y + \delta_j}$$

$$j = 0 \quad \begin{pmatrix} 0 & 2 \cos \frac{k_x}{2} + R^+ \\ 2 \cos \frac{k_x}{2} + R^- & 0 \end{pmatrix} \begin{pmatrix} 0 \\ \varphi \end{pmatrix}$$

$$\vec{E} = 0$$

$$t = \sum_{i, \vec{\delta}} \Psi_i^+ (t \vec{\delta}) \Psi_{i+\vec{\delta}} = \sum_{\substack{k_x, i_y \\ \vec{r}}} \Psi_{k_x, i_y} (t \vec{\delta}) \Psi_{k_x, i_y}^*$$

$$t \sum_i c_i^+ c_j = 0 \quad \begin{pmatrix} 0 & 2 \cos \frac{k_x}{2} + R^+ \\ 2 \cos \frac{k_x}{2} + R^- & 0 \end{pmatrix} \begin{pmatrix} 0 \\ \varphi \end{pmatrix}$$

$$\Psi^+ H \Psi$$

$$\hat{\Psi} = \begin{pmatrix} c \\ d \end{pmatrix}$$

$$E = 0$$

$$t = \sum_{i, \vec{\delta}} \Psi_i^+ (t \vec{\delta}) \Psi_{i+\vec{\delta}} = \sum_{\substack{k_x, i_y \\ \Rightarrow}} \Psi_{k_x, i_y} (t \vec{\delta}) \Psi_{k_x, i_y}^*$$

$$t \sum_i c_i^+ c_j = 0 \quad \begin{pmatrix} 0 & 2 \cos \frac{k_x}{2} + R^+ \\ 2 \cos \frac{k_x}{2} + R & 0 \end{pmatrix} \begin{pmatrix} 0 \\ \Psi \end{pmatrix}$$

$$\Psi^+ H \Psi = H \chi = 0$$

$$\hat{\Psi} = \begin{pmatrix} c \\ d \end{pmatrix}$$

$$E = 0$$