

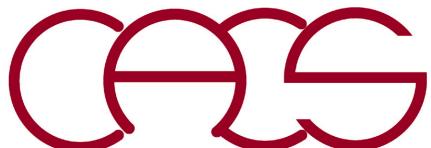
Tight-Binding Model of Electronic Structures

Aiichiro Nakano

*Collaboratory for Advanced Computing & Simulations
Department of Computer Science
Department of Physics & Astronomy
Department of Chemical Engineering & Materials Science
Department of Biological Sciences
University of Southern California*

Email: anakano@usc.edu

Goals: Quantum eigenvalue problem
Vectors (projection &
addition theorem)

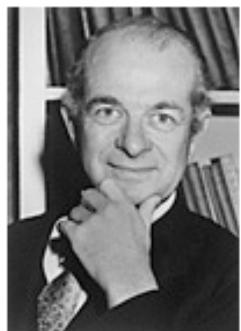


Electronic Structures



The Nobel Prize in Chemistry 1954

"for his research into the nature of the chemical bond and its application to the elucidation of the structure of complex substances"



Linus Carl Pauling

- Atomic wave functions
- Bonds
- Bands
- Reaction
- ...



The Nobel Prize in Chemistry 1981

"for their theories, developed independently, concerning the course of chemical reactions"



Kenichi Fukui



Roald Hoffmann



The Nobel Prize in Chemistry 1966

"for his fundamental work concerning chemical bonds and the electronic structure of molecules by the molecular orbital method"

PHYSICAL REVIEW

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Robert S. Mulliken

Inhomogeneous Electron Gas*

P. HOHENBERG†

École Normale Supérieure, Paris, France

AND

W. KOHN‡

École Normale Supérieure, Paris, France and Faculté des Sciences, Orsay, France

and

University of California at San Diego, La Jolla, California

(Received 18 June 1964)

This paper deals with the ground state of an interacting electron gas in an external potential $v(r)$. It is proved that there exists a universal functional of the density, $F[n(r)]$, independent of $v(r)$, such that the expression $E = \int v(r)n(r)dx + F[n(r)]$ has as its minimum value the correct ground-state energy associated with $v(r)$. The functional $F[n(r)]$ is then discussed for two situations: (1) $n(r) = n_0 + \bar{n}(r)$, $\bar{n}/n_0 < 1$, and (2) $n(r) = \varphi(r/r_0)$ with φ arbitrary and $r_0 \rightarrow \infty$. In both cases F can be expressed entirely in terms of the correlation energy and linear and higher order electronic polarizabilities of a uniform electron gas. This approach also sheds some light on generalized Thomas-Fermi methods and their limitations. Some new extensions of these methods are presented.



Walter Kohn



The Nobel Prize in Chemistry 1998

"for his development of the density-functional theory"



John A. Pople

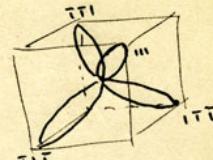
"for his development of computational methods in quantum chemistry"

Pauling's Note (1930)

Calculations such as these are simplified by the fact that for a complete orthogonal transformation the sum of the squares of the coefficients for a given initial eigen ψ is unity. ③

Four equivalent bonds from p^3 .

$$\begin{aligned}\psi_{111} &= \frac{1}{2}(x + y + z) & \text{Max. value.} \\ \psi_{11\bar{1}} &= \frac{1}{2}(x + y - z) \\ \psi_{1\bar{1}1} &= \frac{1}{2}(x - y + z) \\ \psi_{\bar{1}\bar{1}\bar{1}} &= \frac{1}{2}(x - y - z)\end{aligned}$$



We can point one ψ along the x axis, say.

$$\begin{aligned}\psi_1 &= \frac{1}{2}x + \frac{\sqrt{3}}{2}z \\ \psi_2 &= \frac{1}{2}x - \frac{1}{2}\sqrt{3}z + \frac{\sqrt{2}}{2}y \\ \psi_3 &= \frac{1}{2}x - \frac{1}{2}\sqrt{3}z - \frac{1}{2}y + \frac{1}{2}z \\ \psi_4 &= \frac{1}{2}x - \frac{1}{2}\sqrt{3}z - \frac{1}{2}y - \frac{1}{2}z\end{aligned}$$

The coeff. of z is $\frac{1}{2}$ to make the ψ 's equivalent.
Then the coeffs. of z are fixed for norm. with ψ_1 .

tetrahedral angles. But if R_s stretches out farther than R_p (which it actually does for same $Z_{eff.}$), then things are different.
Let us assume $\text{Max } r_s = \text{Max } r_p = 1$. Then

$$\frac{d}{da}(a + \sqrt{1-a^2}) = 0, a = \frac{1}{\sqrt{2}}. \text{ Maximum possible} = \sqrt{2} = 1.414$$

Two bonds, Max value

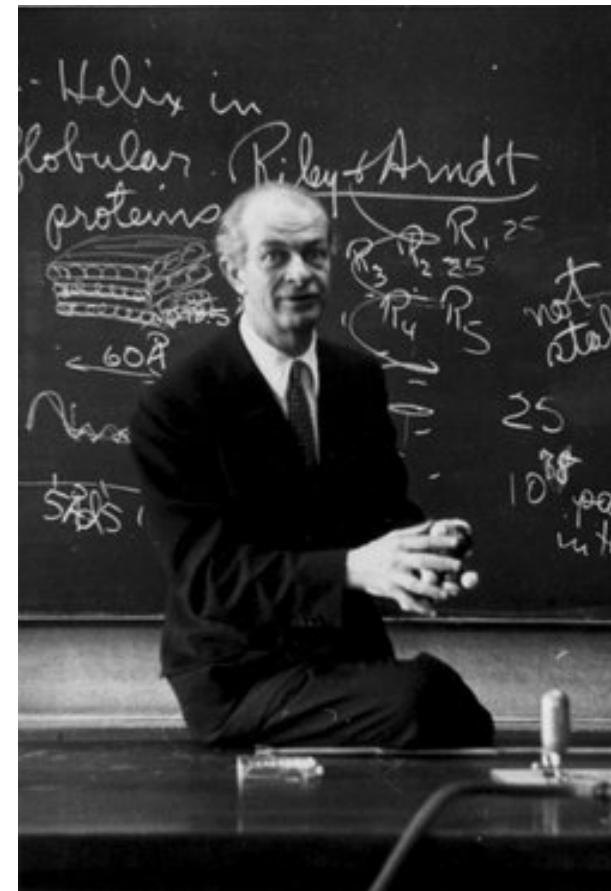
$$\begin{aligned}\sigma_+ &= 1.414 \\ \sigma_- &= 1.414\end{aligned}$$

Three equal bonds: 1.392

Four equal bonds: 1.366

It may be significant that we get 4 tetrahedrally-directed bonds, each with the maximum possible strength (assuming $R_s = R_p$). This means that if R_s happens to equal R_p , two bonds or three bonds will be strongest where at

In this case two strong bonds will be oppositely directed (linear molecule), three will lie in a plane, four towards tetrahedron corners.



Energy Eigenstates

- Time-independent Schrödinger equation

$$\begin{array}{ccc} \text{Hamiltonian} & \longrightarrow & \text{Eigenstate} \\ \text{operator} & & \\ & & \text{Eigenvalue} \end{array}$$

- Stationary state

$$i\hbar \frac{\partial}{\partial t} \psi(t) = H\psi(t)$$

$$\psi(t) = \exp(-i\epsilon_n t/\hbar)\psi_n$$

- Hamiltonian operator

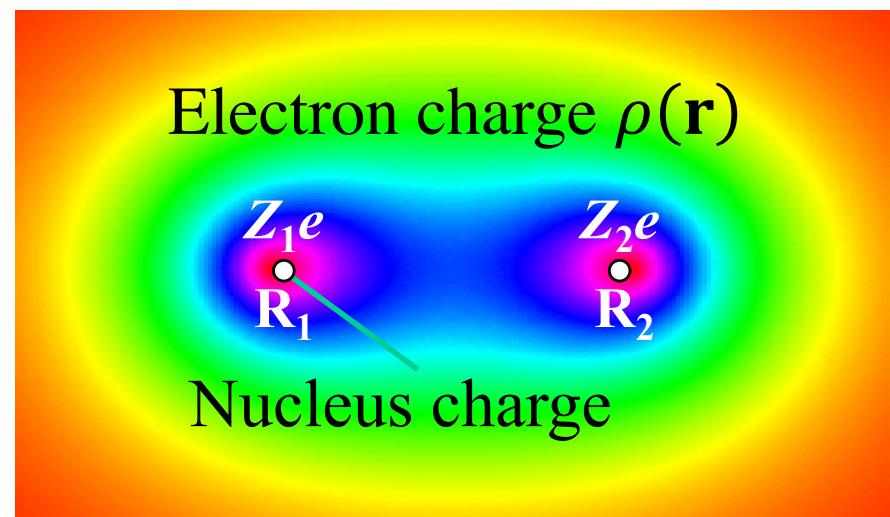
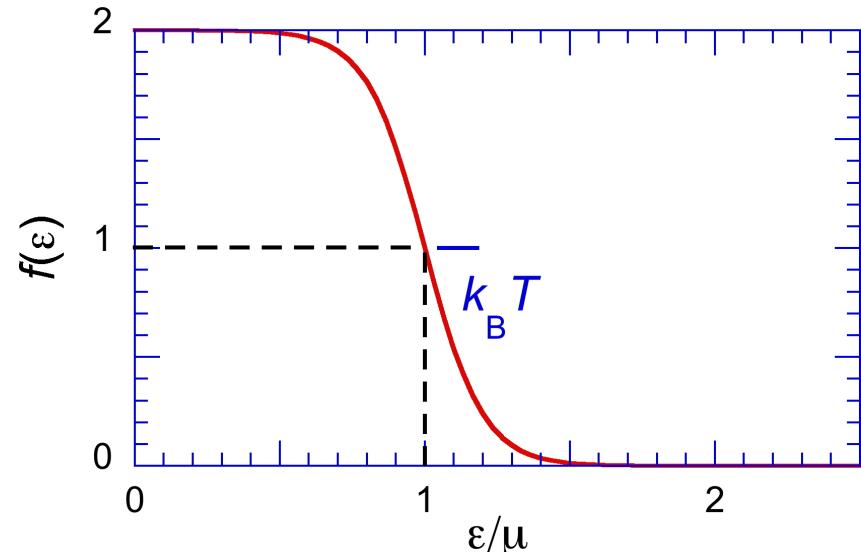
$$H = -\frac{\hbar^2}{2m} \frac{\partial^2}{\partial \mathbf{r}_i^2} + v(\mathbf{r})$$

- Density functional theory

$$v(\mathbf{r}) = - \sum_I \frac{Z_I e^2}{|\mathbf{r} - \mathbf{R}_I|} + \int d\mathbf{r}' \frac{e^2 \rho(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|} + v_{xc}(\mathbf{r})$$

$$\rho(\mathbf{r}) = \sum_n \frac{2}{\exp\left(\frac{\epsilon_n - \mu}{k_B T}\right) + 1} |\psi_n(\mathbf{r})|^2$$

exchange-correlation potential



See CSC1699: Extreme-scale Quantum Simulations
<http://cacs.usc.edu/education/cs699.html>

Density Functional Theory

- P. Hohenberg & W. Kohn, “Inhomogeneous electron gas,”

Phys. Rev. **136**, B864 ('64)

The electronic ground state is a functional of the electron density $\rho(\mathbf{r})$

- W. Kohn & L. Sham, “Self-consistent equations including exchange & correlation effects,” *Phys. Rev.* **140**, A1133 ('65)

Derived a formally exact self-consistent single-electron equations for many-electron systems (*cf.* the previous page)



Background: Atomic Orbitals

$$\begin{cases} n = 1, 2, \dots \\ l \in [0, n-1] \\ m \in [-l, l] \end{cases} \quad \psi_{nlm}(r, \theta, \phi) = R_{nl}(r)Y_{lm}(\theta, \phi)$$

Radial function Spherical harmonics

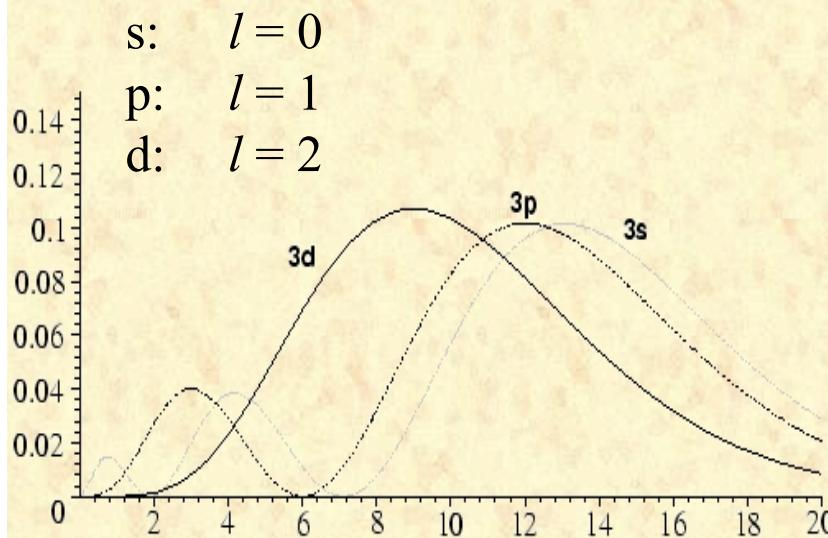
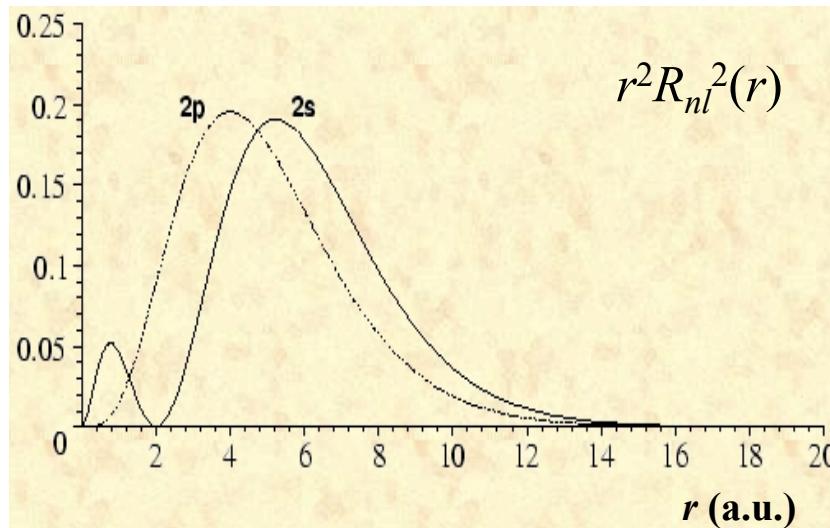
| | |
|----|---------|
| s: | $l = 0$ |
| p: | $l = 1$ |
| d: | $l = 2$ |

- Hydrogen eigenstates ($\rho = v_{xc} = 0$)

| n | ℓ | m | R_{nl} | $Y_{\ell m}$ |
|----|--------|---------|--|---|
| 1s | 1 | 0 | $2 \left(\frac{1}{a_0} \right)^{3/2} e^{-r/a_0}$ | $\frac{1}{2\sqrt{\pi}}$ |
| | | | | |
| 2s | 2 | 0 | $\left(\frac{1}{2a_0} \right)^{3/2} \left(2 - \frac{r}{a_0} \right) e^{-r/2a_0}$ | $\frac{1}{2\sqrt{\pi}}$ |
| | | | | |
| 2p | 2 | 1 | $\left(\frac{1}{2a_0} \right)^{3/2} \frac{1}{\sqrt{3}} \frac{r}{a_0} e^{-r/2a_0}$ | $\frac{1}{2} \sqrt{\frac{3}{\pi}} \cos \theta$ |
| | | | | |
| : | 2 | ± 1 | $\left(\frac{1}{2a_0} \right)^{3/2} \frac{1}{\sqrt{3}} \frac{r}{a_0} e^{-r/2a_0}$ | $\pm \frac{1}{2} \sqrt{\frac{3}{2\pi}} \sin \theta e^{\pm i\phi}$ |
| | | | | |

Laguerre polynomial

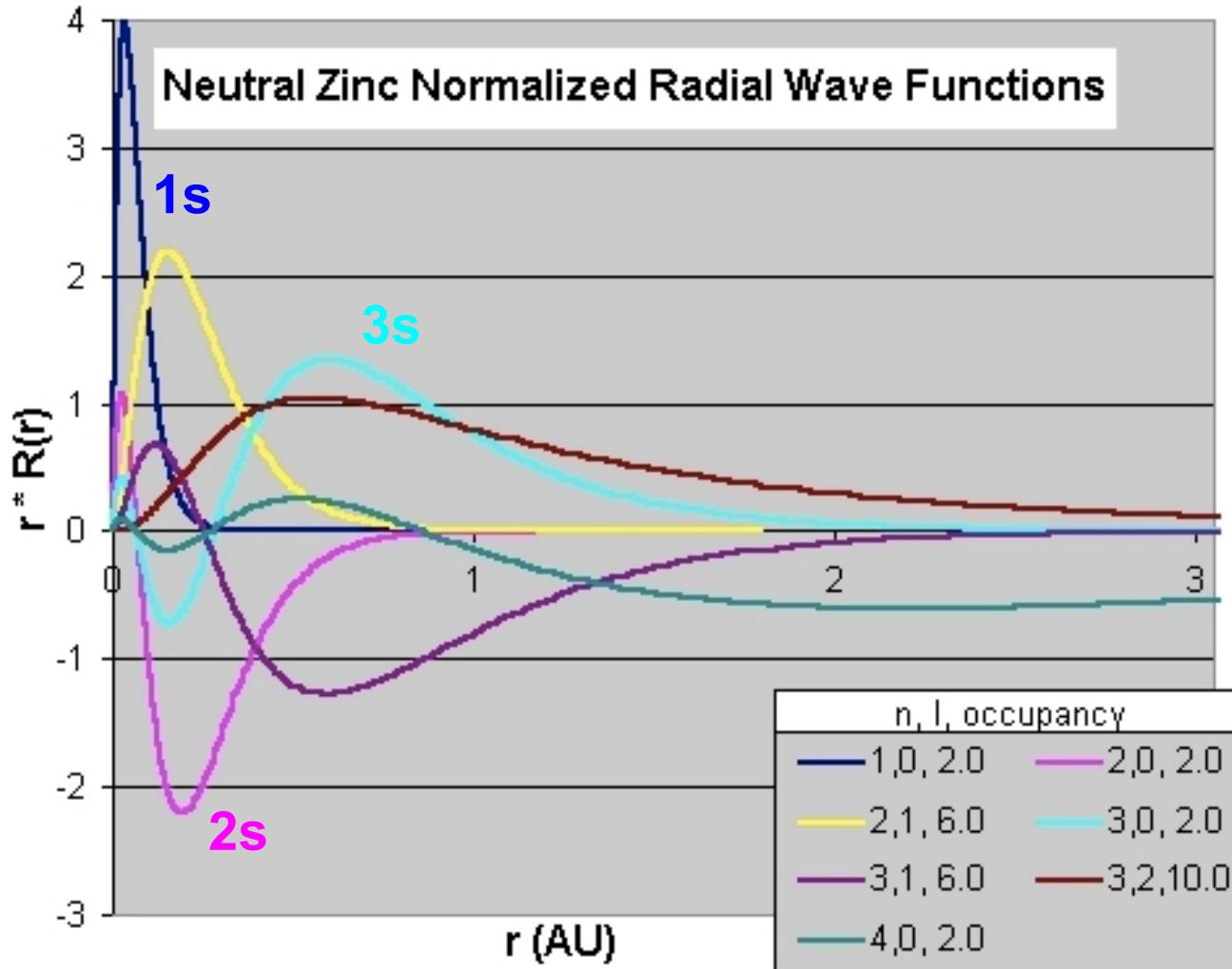
Hydrogen Eigenstates



Outer shells (*i.e.*, larger n) spread outward

Herman-Skillman Solutions for Atoms

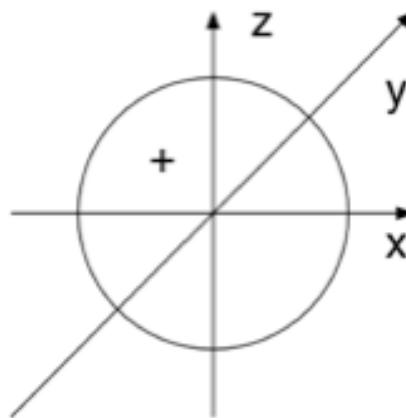
- Hartree approximation ($v_{xc} = 0$) for many-electron interaction



Outer shells (*i.e.*, larger n) still spread outward

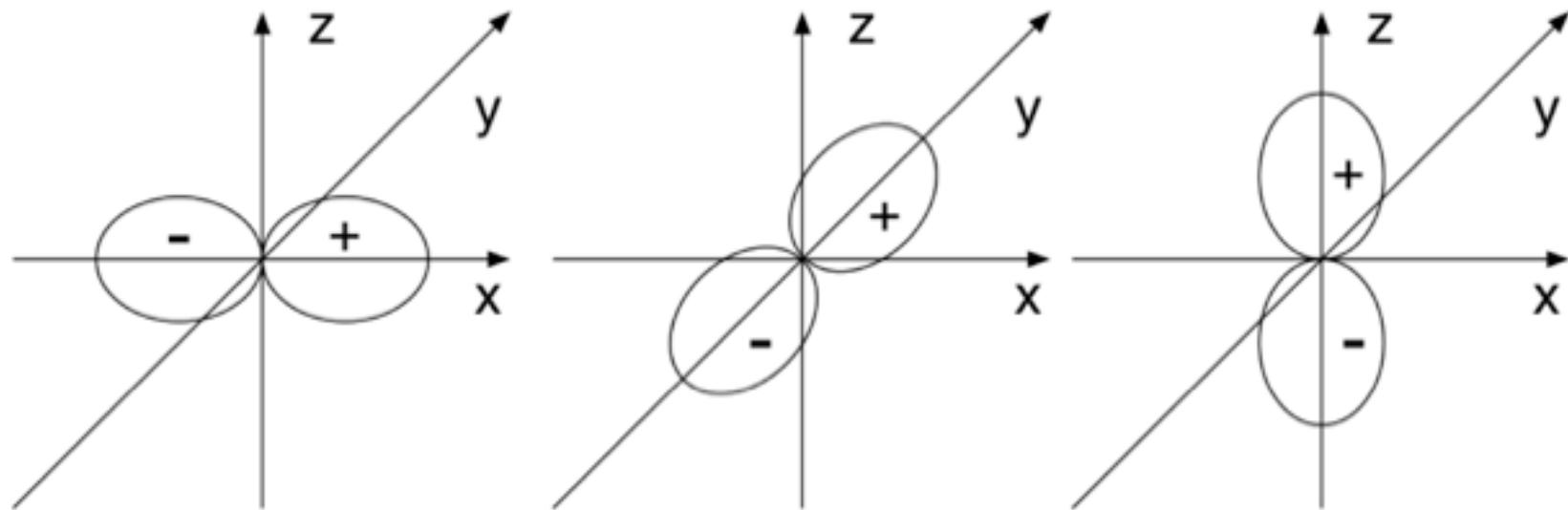
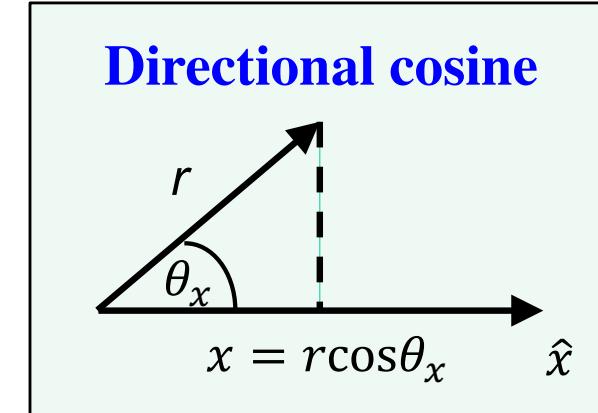
Atomic Orbitals

- s orbital ($l = 0$)



- p orbital ($l = 1$): Cartesian representation

$$\psi_{n1m}(r, \theta, \phi) \rightarrow \left(\frac{3}{4\pi}\right)^{1/2} R_{n1}(r) \begin{cases} x/r \\ y/r \\ z/r \end{cases} \quad r = \sqrt{x^2 + y^2 + z^2}$$



Tight-Binding Model

- **Linear combination of atomic orbitals (LCAO)**

$$\psi(\vec{r}) = \sum_{i=1}^N \sum_{\alpha \in \{s, p_x, p_y, p_z\}} c_{i\alpha} \psi_\alpha(\vec{r} - \vec{r}_i)$$

PHYSICAL REVIEW

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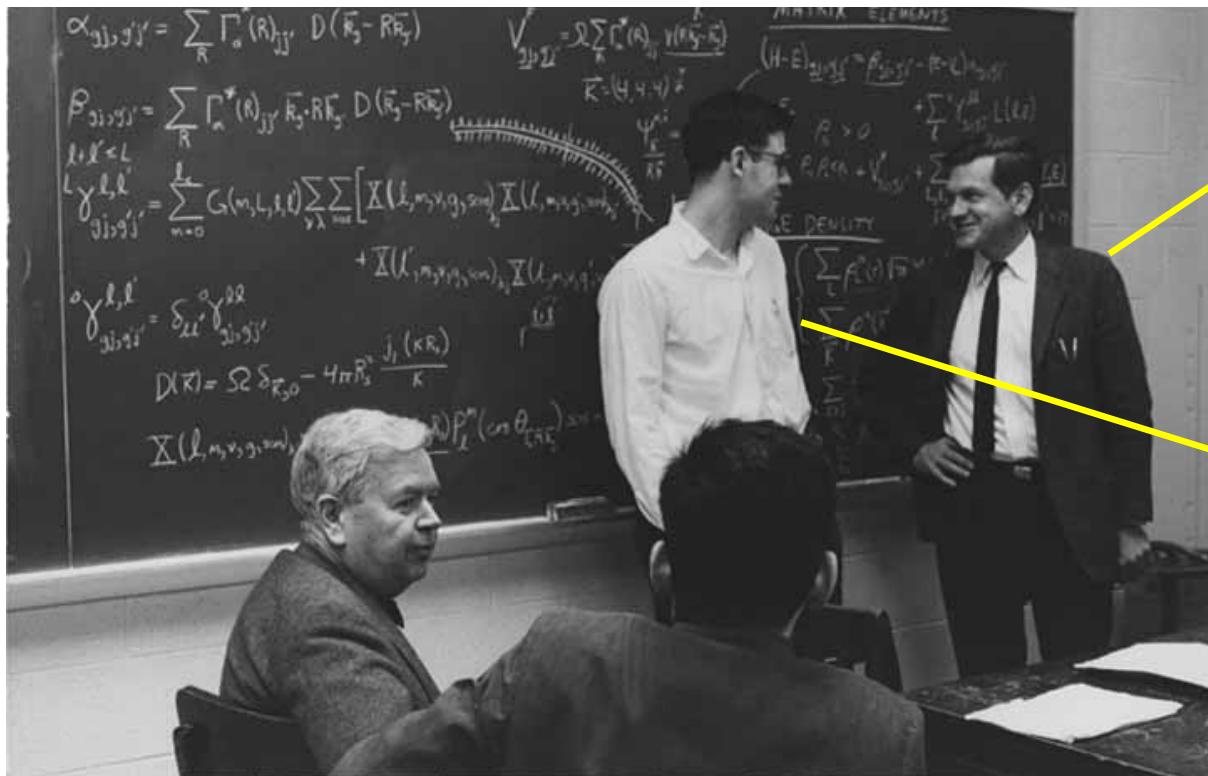
J U N E 15, 1954

Simplified LCAO Method for the Periodic Potential Problem*

J. C. SLATER AND G. F. KOSTER†

Massachusetts Institute of Technology, Cambridge, Massachusetts

(Received February 17, 1954)



John Slater

George Koster

Valence Electrons

- Example: Silicon— $1s^22s^22p^63s^23p^2$

WebElements™ periodic table

| Group | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | |
|--------------|----------|----------|----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|------------|------------|------------|------------|------------|------------|------------|
| Period | | | | | | | | | | | | | | | | | | | |
| 1 | 1 H | | | | | | | | | | | | | | | | | 2 He | |
| 2 | 3 Li | 4 Be | | | | | | | | | | | | | | | | | |
| 3 | 11 Na | 12 Mg | | | | | | | | | | | | | | | | | |
| 4 | 19 K | 20 Ca | 21 Sc | 22 Ti | 23 V | 24 Cr | 25 Mn | 26 Fe | 27 Co | 28 Ni | 29 Cu | 30 Zn | 31 Ga | 32 Ge | 33 As | 34 Se | 35 Br | 36 Kr | |
| 5 | 37 Rb | 38 Sr | 39 Y | 40 Zr | 41 Nb | 42 Mo | 43 Tc | 44 Ru | 45 Rh | 46 Pd | 47 Ag | 48 Cd | 49 In | 50 Sn | 51 Sb | 52 Te | 53 I | 54 Xe | |
| 6 | 55 Cs | 56 Ba | * | 71 Lu | 72 Hf | 73 Ta | 74 W | 75 Re | 76 Os | 77 Ir | 78 Pt | 79 Au | 80 Hg | 81 Tl | 82 Pb | 83 Bi | 84 Po | 85 At | 86 Rn |
| 7 | 87 Fr | 88 Ra | ** | 103 Lr | 104 Rf | 105 Db | 106 Sg | 107 Bh | 108 Hs | 109 Mt | 110 Ds | 111 Rg | 112 Uub | 113 Uut | 114 Uuq | 115 Uup | 116 Uuh | 117 Uus | 118 Uuo |
| *Lanthanoids | | * | 57 La | 58 Ce | 59 Pr | 60 Nd | 61 Pm | 62 Sm | 63 Eu | 64 Gd | 65 Tb | 66 Dy | 67 Ho | 68 Er | 69 Tm | 70 Yb | | | |
| **Actinoids | | ** | 89 Ac | 90 Th | 91 Pa | 92 U | 93 Np | 94 Pu | 95 Am | 96 Cm | 97 Bk | 98 Cf | 99 Es | 100 Fm | 101 Md | 102 No | | | |

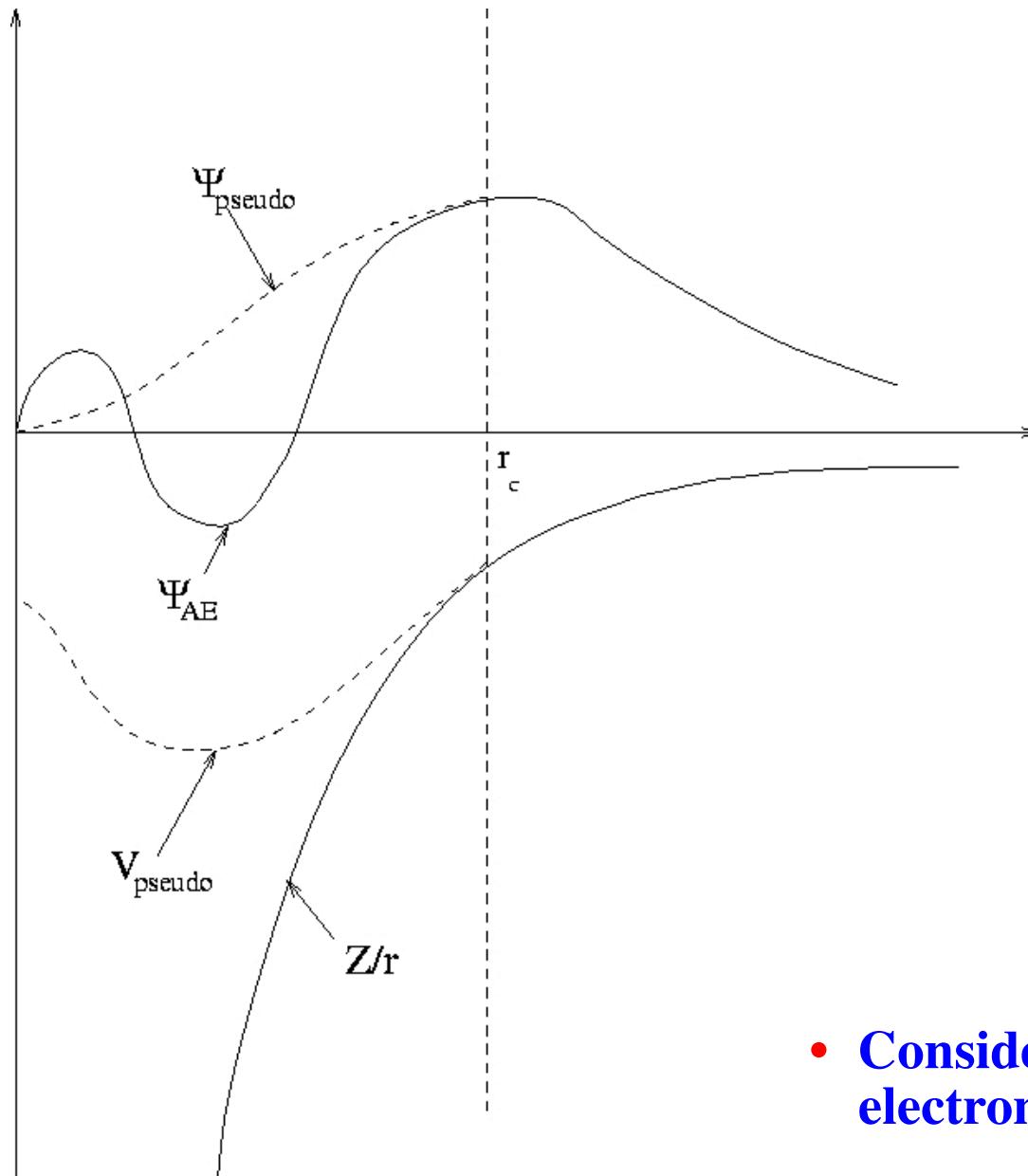
Electronic Configuration

The following represents the electronic configuration and its associated term symbol for the **ground state neutral gaseous atom**. The configuration associated with silicon in its compounds is not necessarily the same.

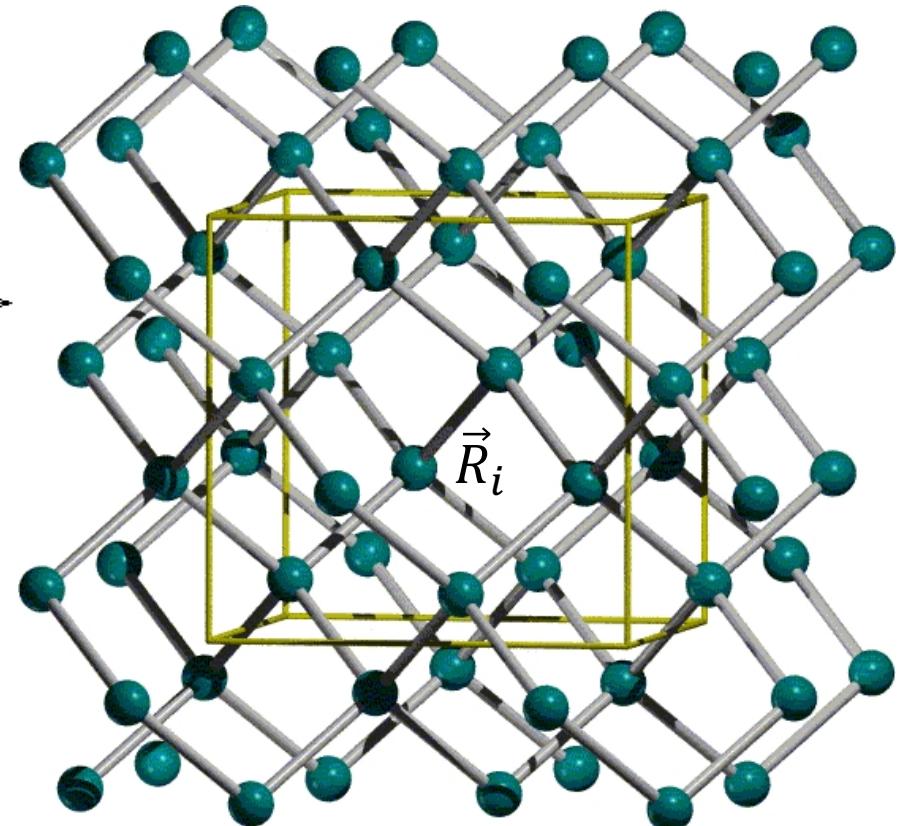
- Ground state electron configuration: [Ne]. $3s^2.3p^2$
- Shell structure: 2.8.4

Pseudopotential

- Silicon— $1s^2 2s^2 2p^6 3s^2 3p^2$



$$\psi(\vec{r}) = \sum_{i=1}^N \sum_{\alpha \in \{s, p_x, p_y, p_z\}} c_{i\alpha} \psi_{\alpha}(\vec{r} - \vec{R}_i)$$

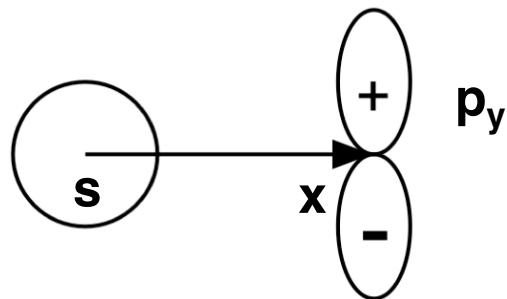


- Consider only (chemically active) valence electrons

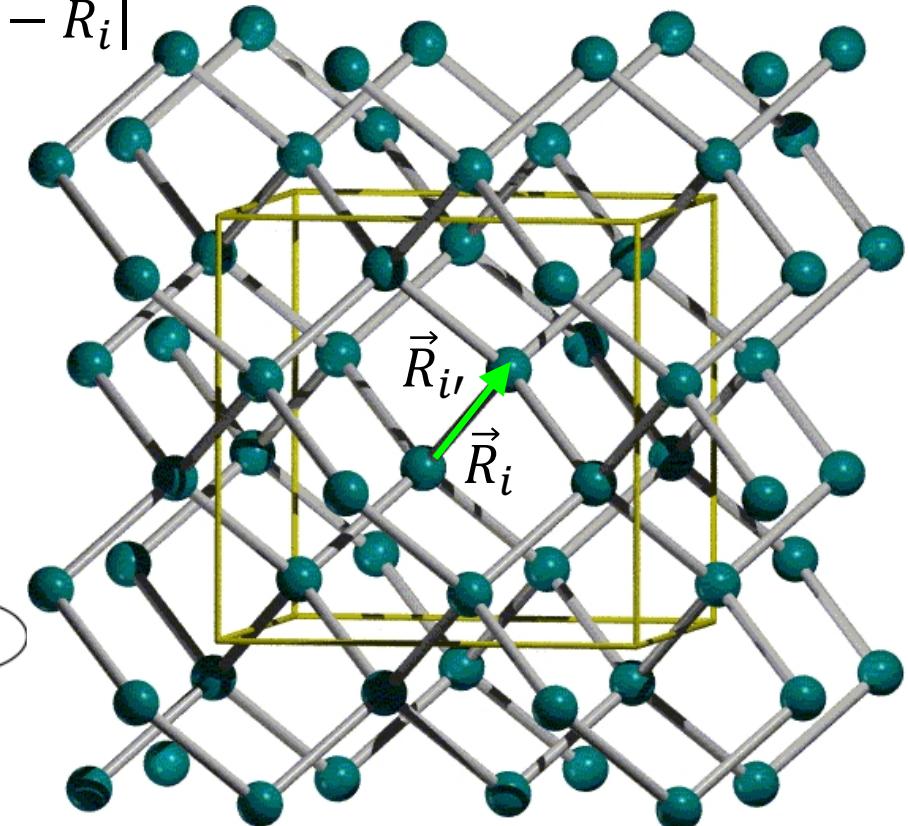
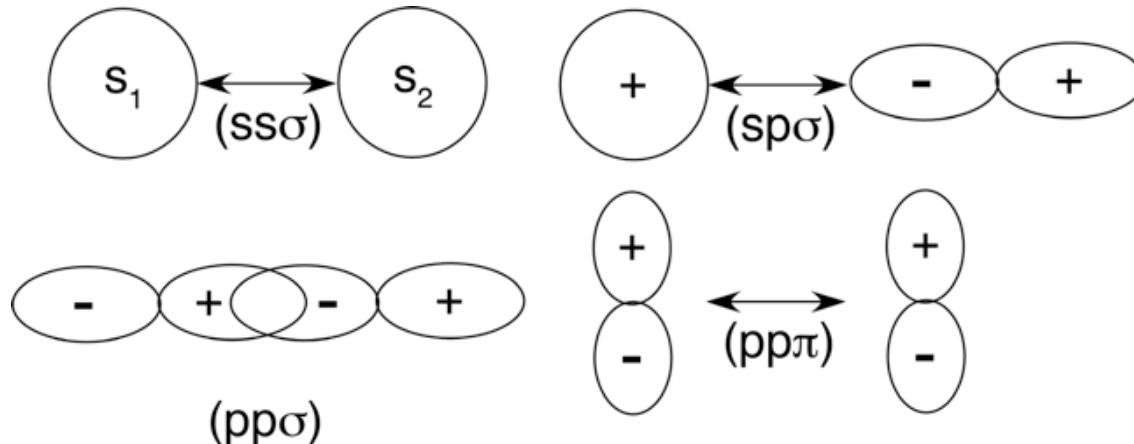
Hamiltonian Matrix Elements

$$H_{i'\alpha',i\alpha} = \int d\vec{r} \psi_{\alpha'}^*(\vec{r} - \vec{R}_{i'}) \left(-\frac{\nabla^2}{2} + v(\vec{r}) \right) \psi_\alpha(\vec{r} - \vec{R}_i)$$

- Exponential decay $\sim \exp(-R_{ii'}/a)$ $R_{ii'} = |\vec{R}_{i'} - \vec{R}_i|$
- Many elements are 0 by symmetry



- Nonvanishing matrix elements



Overlap Integrals

TABLE I. Energy integrals for crystal in terms of two-center integrals.

| | |
|-----------|----------------------------------|
| $E_{s,s}$ | $(ss\sigma)$ |
| $E_{s,z}$ | $l(sp\sigma)$ |
| $E_{z,z}$ | $l^2(pp\sigma) + (1-l^2)(pp\pi)$ |
| $E_{x,y}$ | $lm(pp\sigma) - lm(pp\pi)$ |
| $E_{x,z}$ | $ln(pp\sigma) - ln(pp\pi)$ |

J. C. Slater & G. F. Koster, *Phys. Rev.* **94**, 1498 ('54)

Parameterization:

- L. Goodwin, A. J. Skinner, & D. G. Pettifor, *Europhys. Lett.* **9**, 701 ('89)
- I. Kwon *et al.*, *Phys. Rev. B* **49**, 7242 ('94)

Eigenvalue Problem

$$H|\psi\rangle = \varepsilon|\psi\rangle \quad |\psi\rangle = \sum_{i=1}^N \sum_{\alpha \in \{s, p_x, p_y, p_z\}} c_{i\alpha} |i\alpha\rangle$$
$$\sum_{i\alpha} c_{i\alpha} \langle i'\alpha' | H | i\alpha \rangle = \varepsilon \sum_{i\alpha} c_{i\alpha} \langle i'\alpha' | i\alpha \rangle$$
$$\langle i'\alpha' | i\alpha \rangle = \delta_{ii'} \delta_{\alpha\alpha'}$$
$$\sum_{i\alpha} H_{i'\alpha', i\alpha} c_{i\alpha} = \varepsilon c_{i'\alpha'}$$

$$H_{i'\alpha', i\alpha} = \langle i'\alpha' | H | i\alpha \rangle = \int d\vec{r} \psi_{\alpha'}^*(\vec{r} - \vec{R}_{i'}) \left(-\frac{\nabla^2}{2} + v(\vec{r}) \right) \psi_\alpha(\vec{r} - \vec{R}_i)$$

- **4N×4N matrix:**
 $\kappa = 4(i - 1) + \alpha$, where $i \in \{1, 2, \dots, N\}$ & $\alpha \in \{1 \leftrightarrow s, 2 \leftrightarrow p_x, 3 \leftrightarrow p_y, 4 \leftrightarrow p_z\}$

$$\sum_{\kappa} H_{\kappa', \kappa} c_{\kappa} = \varepsilon c_{\kappa'} \text{ or } \mathbf{C}^T \mathbf{H} \mathbf{C} = \mathbf{E}$$

Eigen Decomposition

- **4N-dim. vector:** $|\kappa\rangle = |4(i-1) + \alpha\rangle$ $i = 1, \dots, N$; $\alpha \in \{3s, 3p_x, 3p_y, 3p_z\}$

$$\langle \kappa' | \times \begin{matrix} H |\psi\rangle = \varepsilon |\psi\rangle \\ \langle \kappa' | H |\psi\rangle = \varepsilon \langle \kappa' | \psi\rangle \end{matrix}$$

- **Closure approximation (assume completeness, i.e., narrow the world)**

$$\sum |\kappa\rangle \langle \kappa| = 1 \Leftrightarrow |\psi\rangle = \sum |\kappa\rangle \langle \kappa| \psi\rangle$$

$$\therefore \sum_{\kappa} \underbrace{\langle \kappa' | H | \kappa \rangle}_{H_{\kappa' \kappa}} \underbrace{\langle \kappa | \psi_n \rangle}_{c_{\kappa}^{(n)} = C_{\kappa n}} = \varepsilon_n \underbrace{\langle \kappa' | \psi_n \rangle}_{C_{\kappa' n}} \quad (n = 1, \dots, 4N)$$

$$\sum_{\kappa} H_{\kappa' \kappa} C_{\kappa n} = C_{\kappa' n} \varepsilon_n = \sum_{n'} C_{\kappa' n'} \underbrace{\delta_{n' n} \varepsilon_n}_{E_{n' n}} = \sum_{n'} C_{\kappa' n'} E_{n' n}$$

- **Matrix eigenvalue problem:** $\mathbf{H}\mathbf{C} = \mathbf{CE}$

$$\mathbf{C} = [\mathbf{c}^{(1)} \dots \mathbf{c}^{(4N)}]$$

$$\mathbf{E} = \begin{bmatrix} \varepsilon_1 & & \\ & \ddots & \\ & & \varepsilon_{4N} \end{bmatrix}$$

- **Orthonormality:** $\delta_{nn'} = \sum_{\kappa=1}^{4N} c_{\kappa}^{(n)} c_{\kappa}^{(n')} = \sum_{\kappa=1}^{4N} C_{n\kappa}^T C_{\kappa n'} = (\mathbf{C}^T \mathbf{C})_{nn'}$, or $\mathbf{I} = \mathbf{C}^T \mathbf{C}$
- **Eigen decomposition:** $\mathbf{C}^T \mathbf{H} \mathbf{C} = \mathbf{E}$ ($\because \mathbf{C}^T \times \mathbf{H} \mathbf{C} = \mathbf{C}^T \times \mathbf{C} \mathbf{E} = \mathbf{E}$)

Silicon Tight-Binding Parameters

Inter-atom

$$h_\lambda(r) = \begin{cases} \langle s_1 | H | s_2 \rangle & \lambda = ss\sigma \\ \langle s_1 | H | p_{2d} \rangle & \lambda = sp\sigma \\ \langle p_{1d} | H | p_{2d} \rangle & \lambda = pp\sigma \\ \langle p_{1n} | H | p_{2n} \rangle & \lambda = pp\pi \end{cases} = h_\lambda(r_0) \left(\frac{r_0}{r}\right)^n \exp\left(n\left[-\left(\frac{r}{r_\lambda}\right)^{n_\lambda} + \left(\frac{r_0}{r_\lambda}\right)^{n_\lambda}\right]\right)$$

Intra-atom

$$\begin{cases} \langle s | H | s \rangle = E_s \\ \langle p_x | H | p_x \rangle = \langle p_y | H | p_y \rangle = \langle p_z | H | p_z \rangle = E_p \end{cases}$$

| r_0 (Å) | n | E_s (eV) | E_p (eV) |
|-----------|-----|------------|------------|
| 2.360352 | 2 | -5.25 | 1.20 |

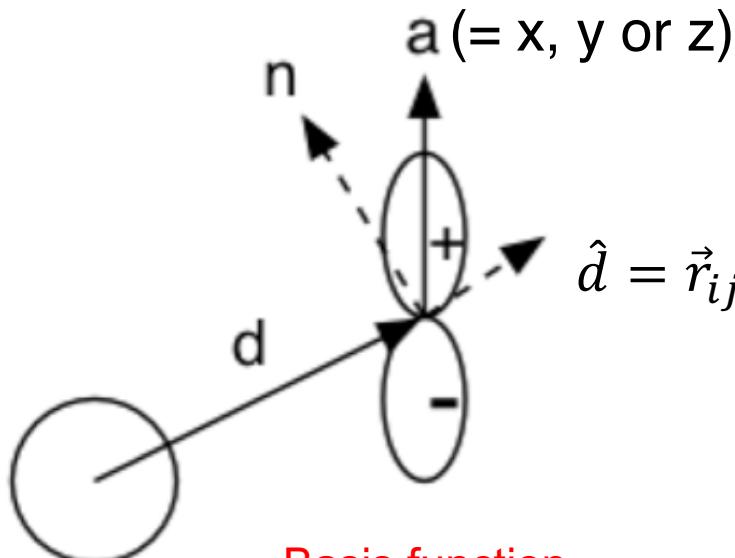
| λ | $ss\sigma$ | $sp\sigma$ | $pp\sigma$ | $pp\pi$ |
|-----------------------|------------|------------|------------|---------|
| $h_\lambda(r_0)$ (eV) | -2.038 | 1.745 | 2.75 | -1.075 |
| n_λ | 9.5 | 8.5 | 7.5 | 7.5 |
| r_λ (Å) | 3.4 | 3.55 | 3.7 | 3.7 |

- **Atomic unit:** length—Bohr radius, $a_B = 0.5291772083$ Å;
energy—Hartree energy, $E_H = 27.2113834$ eV

Projection of s-p Integrals

$$|p_\alpha\rangle = \hat{a} \bullet \hat{d}|p_d\rangle + \hat{a} \bullet \hat{n}|p_n\rangle \quad (\hat{a} = \hat{x}, \hat{y}, \hat{z}; \hat{a} \bullet \hat{a} = 1)$$

$\because |p_\alpha\rangle = \cos(\chi - \theta) = \cos\chi\cos\theta + \sin\chi\sin\theta = \cos\theta|p_d\rangle + \sin\theta|p_n\rangle$ **addition theorem**
 $= \hat{a} \bullet \hat{d}|p_d\rangle + \cos(\pi/2 - \theta)|p_n\rangle = \hat{a} \bullet \hat{d}|p_d\rangle + \hat{a} \bullet \hat{n}|p_n\rangle$

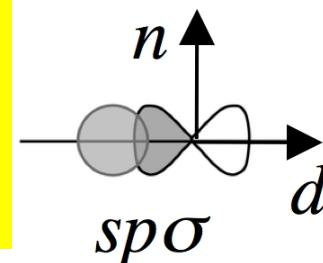
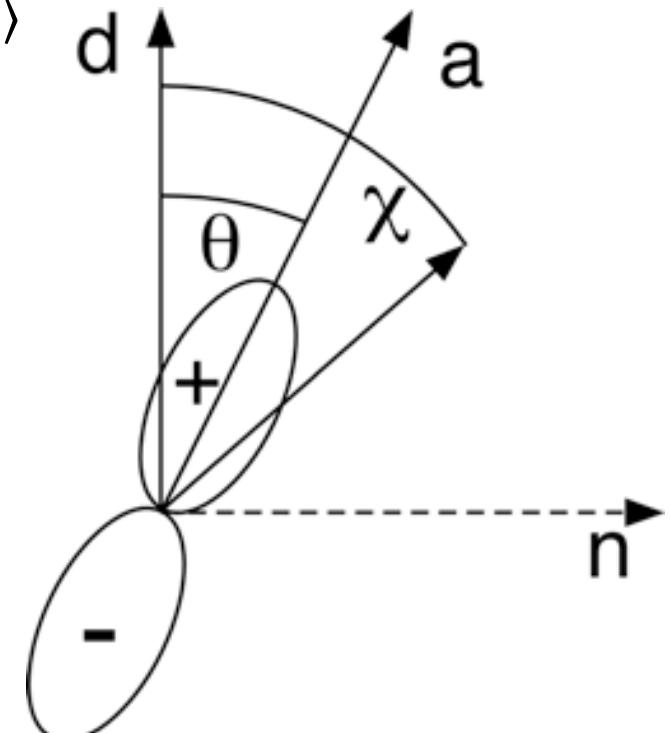


$$\begin{aligned}\vec{r}_{ij} &= \vec{r}_i - \vec{r}_j \\ r &= |\vec{r}_{ij}| \\ \hat{d} &= \vec{r}_{ij}/r = \left(\frac{d_x}{\hat{x} \bullet \hat{d}}, \frac{d_y}{\hat{y} \bullet \hat{d}}, \frac{d_z}{\hat{z} \bullet \hat{d}} \right)\end{aligned}$$

Hamilton matrix element

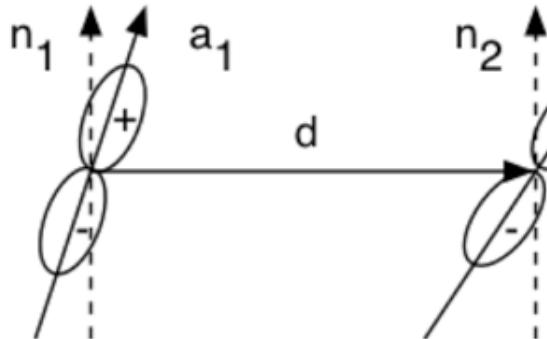
$$\langle s | H | p_a \rangle = \langle s | H (\hat{a} \bullet \hat{d} | p_d \rangle + \hat{a} \bullet \hat{n} | p_n \rangle) = (\hat{a} \bullet \hat{d}) h_{sp\sigma}$$

$$\begin{pmatrix} \langle s_1 | H | p_{2x} \rangle \\ \langle s_1 | H | p_{2y} \rangle \\ \langle s_1 | H | p_{2z} \rangle \end{pmatrix} = - \begin{pmatrix} \langle p_{1x} | H | s_2 \rangle \\ \langle p_{1y} | H | s_2 \rangle \\ \langle p_{1z} | H | s_2 \rangle \end{pmatrix} = \begin{pmatrix} d_x h_{sp\sigma}(r) \\ d_y h_{sp\sigma}(r) \\ d_z h_{sp\sigma}(r) \end{pmatrix}$$

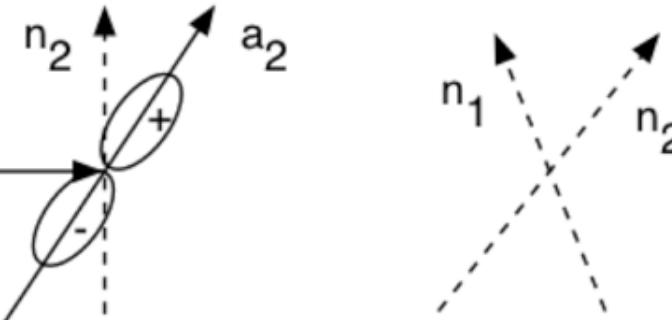


Projection of p-p Integrals

$$|p_1\rangle = \hat{a}_1 \cdot \hat{d} |p_{d1}\rangle + \hat{a}_1 \cdot \hat{n}_1 |p_{n1}\rangle \quad |p_2\rangle = \hat{a}_2 \cdot \hat{d} |p_{d2}\rangle + \hat{a}_2 \cdot \hat{n}_2 |p_{n2}\rangle$$



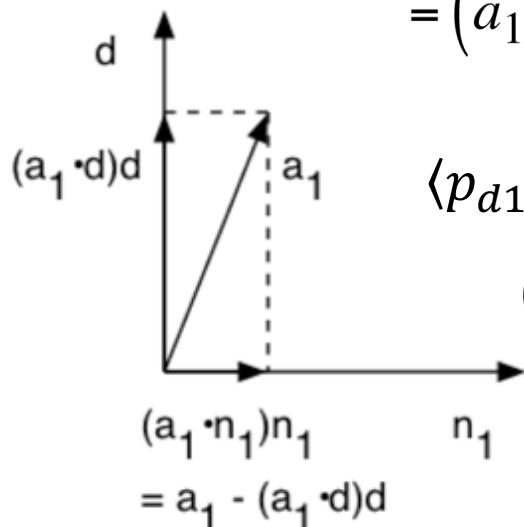
Side view of vector d



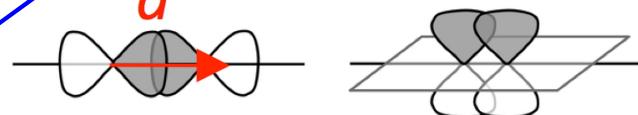
View from vector d direction

$$\langle p_1 | H | p_2 \rangle = (\hat{a}_1 \cdot \hat{d} \langle p_{d1} | + \hat{a}_1 \cdot \hat{n}_1 \langle p_{n1} |) H (\hat{a}_2 \cdot \hat{d} | p_{d2} \rangle + \hat{a}_2 \cdot \hat{n}_2 | p_{n2} \rangle)$$

$$= (\hat{a}_1 \cdot \hat{d}) (\hat{a}_2 \cdot \hat{d}) \langle p_{d1} | H | p_{d2} \rangle + (\hat{a}_1 \cdot \hat{n}_1 \langle p_{n1} |) H (\hat{a}_2 \cdot \hat{n}_2 | p_{n2} \rangle)$$



$$\langle p_{d1} | H | p_{d2} \rangle = h_{pp\sigma}(r)$$

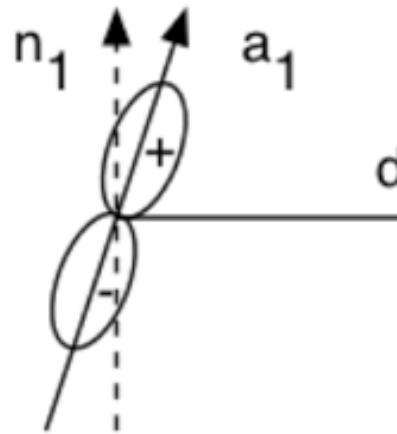


$$\begin{aligned} (\hat{a}_1 \cdot \hat{n}_1 \langle p_{n1} |) H (\hat{a}_2 \cdot \hat{n}_2 | p_{n2} \rangle) &= (\hat{a}_1 \cdot \hat{n}_1) (\hat{a}_2 \cdot \hat{n}_2) \langle p_{n1} | H | p_{n2} \rangle \\ &= (\hat{a}_1 \cdot \hat{n}_1) (\hat{a}_2 \cdot \hat{n}_2) (\hat{n}_1 \cdot \hat{n}_2) h_{pp\pi}(r) \\ &= ((\hat{a}_1 \cdot \hat{n}_1) \hat{n}_1) \cdot ((\hat{a}_2 \cdot \hat{n}_2) \hat{n}_2) h_{pp\pi}(r) \\ &= (\hat{a}_1 - (\hat{a}_1 \cdot \hat{d}) \hat{d}) \cdot (\hat{a}_2 - (\hat{a}_2 \cdot \hat{d}) \hat{d}) h_{pp\pi}(r) \end{aligned}$$

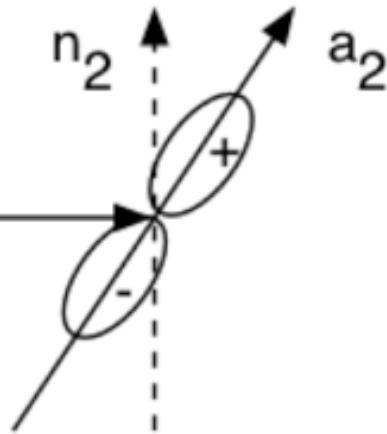
$$(\hat{a}_1 \cdot \hat{n}_1) \hat{n}_1 = \hat{a}_1 - (\hat{a}_1 \cdot \hat{d}) \hat{d} \quad \text{::: 2D completeness: } 1 = |d\rangle\langle d| + |n\rangle\langle n|$$

Projection of p-p Integrals

$$\langle p_1 | H | p_2 \rangle = (\hat{a}_1 \bullet \hat{d}) \bullet (\hat{a}_2 \bullet \hat{d}) h_{pp\sigma}(r) + (\hat{a}_1 - (\hat{a}_1 \bullet \hat{d})\hat{d}) \bullet (\hat{a}_2 - (\hat{a}_2 \bullet \hat{d})\hat{d}) h_{pp\pi}(r)$$



Side view of vector d

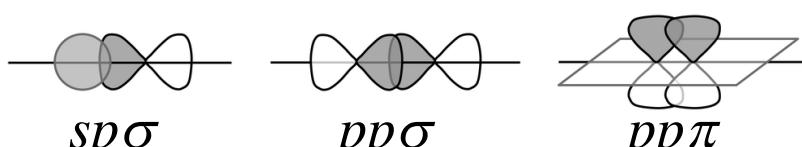


View from vector d direction

$$\begin{pmatrix} \langle p_{1x} | H | p_{2x} \rangle & \langle p_{1x} | H | p_{2y} \rangle & \langle p_{1x} | H | p_{2z} \rangle \\ \langle p_{1y} | H | p_{2x} \rangle & \langle p_{1y} | H | p_{2y} \rangle & \langle p_{1y} | H | p_{2z} \rangle \\ \langle p_{1z} | H | p_{2x} \rangle & \langle p_{1z} | H | p_{2y} \rangle & \langle p_{1z} | H | p_{2z} \rangle \end{pmatrix} \begin{pmatrix} \hat{x} \bullet \hat{d}, \hat{y} \bullet \hat{d}, \hat{z} \bullet \hat{d} \\ = (d_x, d_y, d_z) \end{pmatrix}$$

$$= \begin{pmatrix} d_x^2 h_{pp\sigma} + (1 - d_x^2) h_{pp\pi} & d_x d_y (h_{pp\sigma} - h_{pp\pi}) & d_x d_z (h_{pp\sigma} - h_{pp\pi}) \\ d_y d_x (h_{pp\sigma} - h_{pp\pi}) & d_y^2 h_{pp\sigma} + (1 - d_y^2) h_{pp\pi} & d_y d_z (h_{pp\sigma} - h_{pp\pi}) \\ d_z d_x (h_{pp\sigma} - h_{pp\pi}) & d_z d_y (h_{pp\sigma} - h_{pp\pi}) & d_z^2 h_{pp\sigma} + (1 - d_z^2) h_{pp\pi} \end{pmatrix}$$

TB Hamiltonian Matrix

$$H = \begin{pmatrix} & & j & & \\ & & \vdots & & \\ s_i s_j & s_i p_{jx} & s_i p_{jy} & s_i p_{jz} & \\ i \dots & p_{ix} s_j & p_{ix} p_{jx} & p_{ix} p_{jy} & p_{ix} p_{jz} \dots \\ p_{iy} s_j & p_{iy} p_{jx} & p_{iy} p_{jy} & p_{iy} p_{jz} & \\ p_{iz} s_j & p_{iz} p_{jx} & p_{iz} p_{jy} & p_{iz} p_{jz} & \\ & \vdots & & & \\ & & \text{ss}\sigma & & \end{pmatrix} \xrightarrow{i=j} \begin{pmatrix} E_s & 0 & 0 & 0 \\ 0 & E_p & 0 & 0 \\ 0 & 0 & E_p & 0 \\ 0 & 0 & 0 & E_p \end{pmatrix}$$


$\vec{r}_{ij} = \vec{r}_i - \vec{r}_j$

$r = |\vec{r}_{ij}|$

$\hat{d} = \vec{r}_{ij}/r = (d_x, d_y, d_z)$

$i \neq j$

$H_{i'\alpha',i\alpha} = \langle i'\alpha' | H | i\alpha \rangle$

$= \int d\vec{r} \psi_{\alpha'}^*(\vec{r} - \vec{R}_{i'}) \left(-\frac{\nabla^2}{2} + v(\vec{r}) \right) \psi_{\alpha}(\vec{r} - \vec{R}_i)$

Apply periodic boundary condition (pick the minimum image)

$$\begin{pmatrix} h_{ss\sigma} & d_x h_{sp\sigma} & d_y h_{sp\sigma} & d_z h_{sp\sigma} \\ -d_x h_{sp\sigma} & d_x^2 h_{pp\sigma} + (1 - d_x^2) h_{pp\pi} & d_x d_y (h_{pp\sigma} - h_{pp\pi}) & d_x d_z (h_{pp\sigma} - h_{pp\pi}) \\ -d_y h_{sp\sigma} & d_y d_x (h_{pp\sigma} - h_{pp\pi}) & d_y^2 h_{pp\sigma} + (1 - d_y^2) h_{pp\pi} & d_y d_z (h_{pp\sigma} - h_{pp\pi}) \\ -d_z h_{sp\sigma} & d_z d_x (h_{pp\sigma} - h_{pp\pi}) & d_z d_y (h_{pp\sigma} - h_{pp\pi}) & d_z^2 h_{pp\sigma} + (1 - d_z^2) h_{pp\pi} \end{pmatrix}$$

TB Matrix Elements

$$\begin{cases} \langle s | H | s \rangle = E_s \\ \langle p_x | H | p_x \rangle = \langle p_y | H | p_y \rangle = \langle p_z | H | p_z \rangle = E_p \end{cases}$$

| r_0 (Å) | n | E_s (eV) | E_p (eV) |
|-----------|-----|------------|------------|
| 2.360352 | 2 | -5.25 | 1.20 |

$$\begin{pmatrix} h_{ss\sigma} & d_x h_{sp\sigma} & d_y h_{sp\sigma} & d_z h_{sp\sigma} \\ -d_x h_{sp\sigma} & d_x^2 h_{pp\sigma} + (1 - d_x^2) h_{pp\pi} & d_x d_y (h_{pp\sigma} - h_{pp\pi}) & d_x d_z (h_{pp\sigma} - h_{pp\pi}) \\ -d_y h_{sp\sigma} & d_y d_x (h_{pp\sigma} - h_{pp\pi}) & d_y^2 h_{pp\sigma} + (1 - d_y^2) h_{pp\pi} & d_y d_z (h_{pp\sigma} - h_{pp\pi}) \\ -d_z h_{sp\sigma} & d_z d_x (h_{pp\sigma} - h_{pp\pi}) & d_z d_y (h_{pp\sigma} - h_{pp\pi}) & d_z^2 h_{pp\sigma} + (1 - d_z^2) h_{pp\pi} \end{pmatrix}$$

$$h_\lambda(r) = \begin{cases} \langle s_1 | H | s_2 \rangle & \lambda = ss\sigma \\ \langle s_1 | H | p_{2d} \rangle & \lambda = sp\sigma \\ \langle p_{1d} | H | p_{2d} \rangle & \lambda = pp\sigma \\ \langle p_{1n} | H | p_{2n} \rangle & \lambda = pp\pi \end{cases} = h_\lambda(r_0) \left(\frac{r_0}{r}\right)^n \exp\left(n \left[-\left(\frac{r}{r_\lambda}\right)^{n_\lambda} + \left(\frac{r_0}{r_\lambda}\right)^{n_\lambda}\right]\right)$$

| λ | ssσ | spσ | ppσ | ppπ |
|-----------------------|--------|-------|------|--------|
| $h_\lambda(r_0)$ (eV) | -2.038 | 1.745 | 2.75 | -1.075 |
| n_λ | 9.5 | 8.5 | 7.5 | 7.5 |
| r_λ (Å) | 3.4 | 3.55 | 3.7 | 3.7 |

Overlap Integrals

$$\begin{pmatrix} h_{ss\sigma} & d_x h_{sp\sigma} & d_y h_{sp\sigma} & d_z h_{sp\sigma} \\ -d_x h_{sp\sigma} & d_x^2 h_{pp\sigma} + (1 - d_x^2) h_{pp\pi} & d_x d_y (h_{pp\sigma} - h_{pp\pi}) & d_x d_z (h_{pp\sigma} - h_{pp\pi}) \\ -d_y h_{sp\sigma} & d_y d_x (h_{pp\sigma} - h_{pp\pi}) & d_y^2 h_{pp\sigma} + (1 - d_y^2) h_{pp\pi} & d_y d_z (h_{pp\sigma} - h_{pp\pi}) \\ -d_z h_{sp\sigma} & d_z d_x (h_{pp\sigma} - h_{pp\pi}) & d_z d_y (h_{pp\sigma} - h_{pp\pi}) & d_z^2 h_{pp\sigma} + (1 - d_z^2) h_{pp\pi} \end{pmatrix}$$

TABLE I. Energy integrals for crystal in terms of two-center integrals.

| | |
|-----------|------------------------------------|
| $E_{s,s}$ | $(ss\sigma)$ |
| $E_{s,z}$ | $l(sp\sigma)$ |
| $E_{z,z}$ | $l^2(pp\sigma) + (1 - l^2)(pp\pi)$ |
| $E_{x,y}$ | $lm(pp\sigma) - lm(pp\pi)$ |
| $E_{x,z}$ | $ln(pp\sigma) - ln(pp\pi)$ |

J. C. Slater & G. F. Koster, *Phys. Rev.* **94**, 1498 ('54)

Eigenvalue Problem

$$H|\psi\rangle = \varepsilon|\psi\rangle \quad |\psi\rangle = \sum_{i=1}^N \sum_{\alpha \in \{s, p_x, p_y, p_z\}} c_{i\alpha} |i\alpha\rangle$$
$$\sum_{i\alpha} c_{i\alpha} \langle i'\alpha' | H | i\alpha \rangle = \varepsilon \sum_{i\alpha} c_{i\alpha} \langle i'\alpha' | i\alpha \rangle$$
$$\langle i'\alpha' | i\alpha \rangle = \delta_{ii'} \delta_{\alpha\alpha'}$$
$$\sum_{i\alpha} H_{i'\alpha', i\alpha} c_{i\alpha} = \varepsilon c_{i'\alpha'}$$

$$H_{i'\alpha', i\alpha} = \langle i'\alpha' | H | i\alpha \rangle = \int d\vec{r} \psi_{\alpha'}^*(\vec{r} - \vec{R}_{i'}) \left(-\frac{\nabla^2}{2} + v(\vec{r}) \right) \psi_\alpha(\vec{r} - \vec{R}_i)$$

- **4N×4N matrix:**
 $\kappa = 4(i - 1) + \alpha$, where $i \in \{1, 2, \dots, N\}$ & $\alpha \in \{1 \leftrightarrow s, 2 \leftrightarrow p_x, 3 \leftrightarrow p_y, 4 \leftrightarrow p_z\}$

$$\sum_{\kappa} H_{\kappa', \kappa} c_{\kappa} = \varepsilon c_{\kappa'} \text{ or } \mathbf{C}^T \mathbf{H} \mathbf{C} = \mathbf{E}$$

Spectral
decomposition

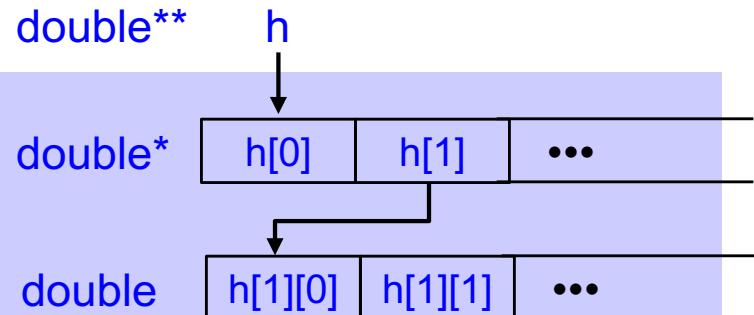
Numerical Recipes Routines

download eigen.c!

```
double **h; /* Hamiltonian matrix */
double *d; /* Eigenvalues */
double *e;
...
/* Allocate memory for matrices & vectors*/
n4 = 4*nAtom; // Hamiltonian matrix size with s-p basis
h = dmatrix(1,n4,1,n4); // Use h[1:n4][1:n4]
d = dvector(1,n4); // d[1:n4]
e = dvector(1,n4); // e[1:n4]

/* Set up the Hamiltonian matrix elements h here */

/* Diagonalize the Hamiltonian matrix */
tred2(h,n4,d,e);
tqli(d,e,n4,h); CTHC = E
```



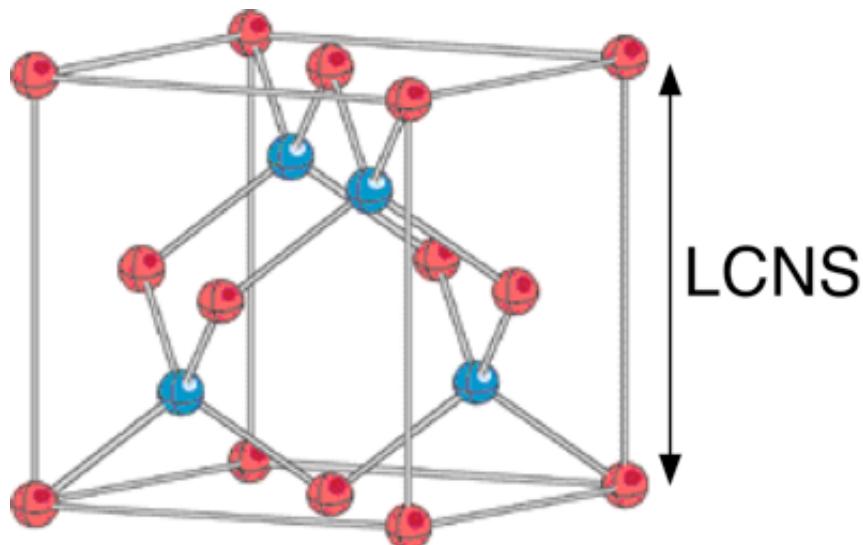
\mathbf{H} in $\xrightarrow{\text{tred2}}$ out $\mathbf{C}, \mathbf{d}, \mathbf{e}$ in $\xrightarrow{\text{tqli}}$ \mathbf{C}', \mathbf{d}' = eigenvectors, eigenvalues

$$\mathbf{C}^T \mathbf{H} \mathbf{C} = \begin{bmatrix} & & \\ & \text{e} & \\ & & \end{bmatrix} \mathbf{d}$$

$$\mathbf{C}'^T \mathbf{H} \mathbf{C}' = \begin{bmatrix} & & \\ & & \\ & & \end{bmatrix} \mathbf{d}'$$

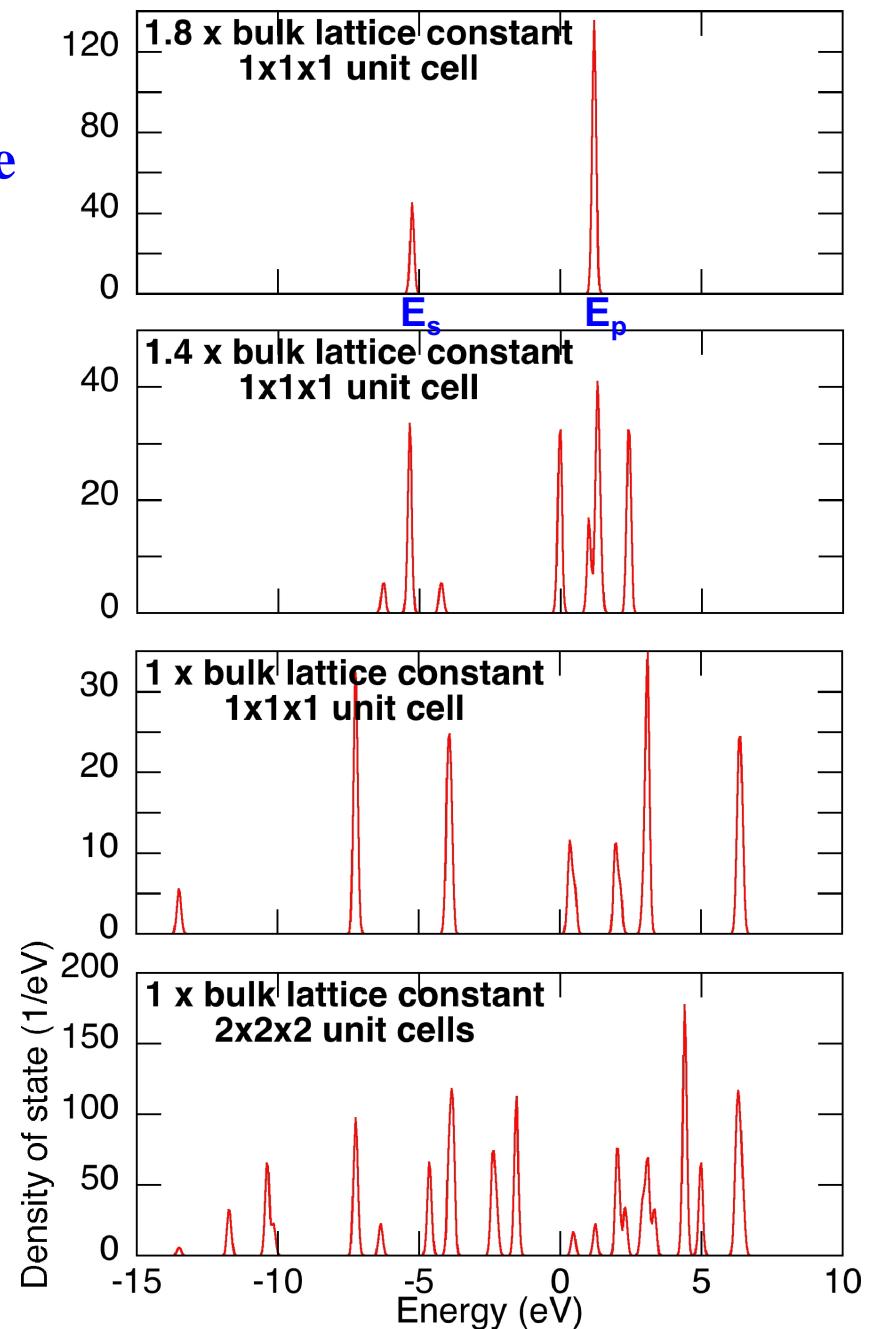
Example

- Si crystal: $1 \times 1 \times 1$ or $2 \times 2 \times 2$ cubic unit cells (8 atoms per unit cell), with lattice constant = 1.8, 1.4 & $1 \times$ bulk crystalline lattice constant (5.43 \AA or 10.2622 a.u.)

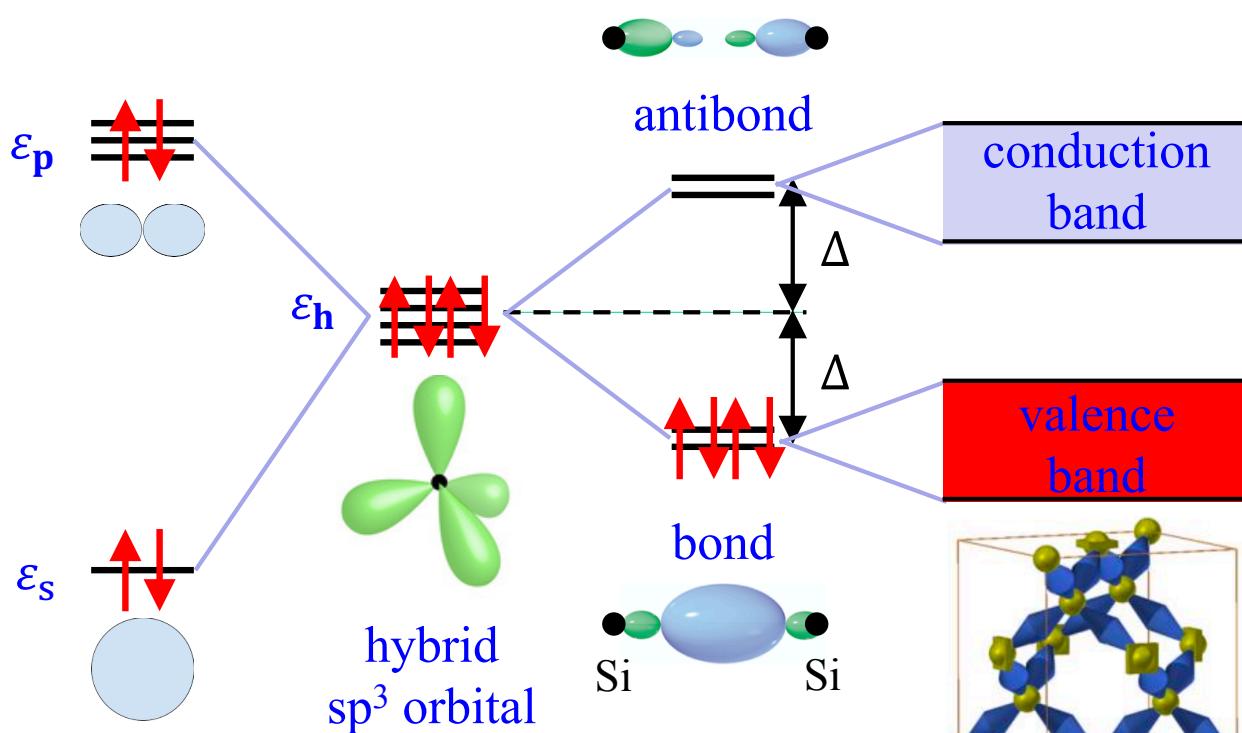


- Density of states: $\sigma = 0.1 \text{ eV}$

$$D(\varepsilon) = \sum_{n=1}^{n^4} \frac{1}{\sqrt{\pi}\sigma} \exp\left(-\frac{(\varepsilon - \varepsilon_n)^2}{\sigma^2}\right)$$



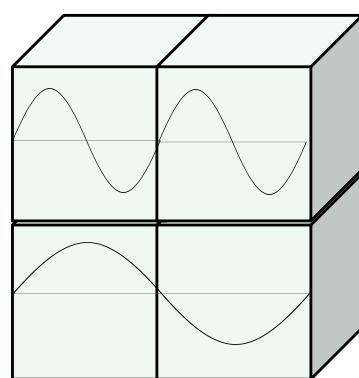
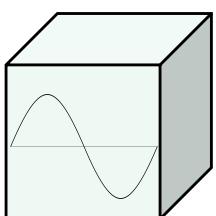
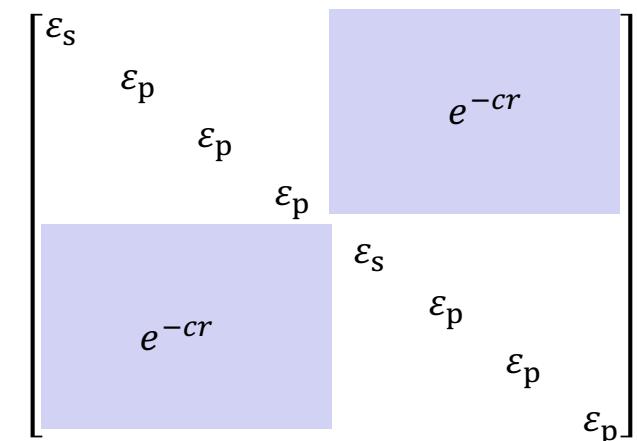
Energy Band in a Nutshell



$$H = \begin{bmatrix} \varepsilon_h & \Delta \\ \Delta & \varepsilon_h \end{bmatrix}$$

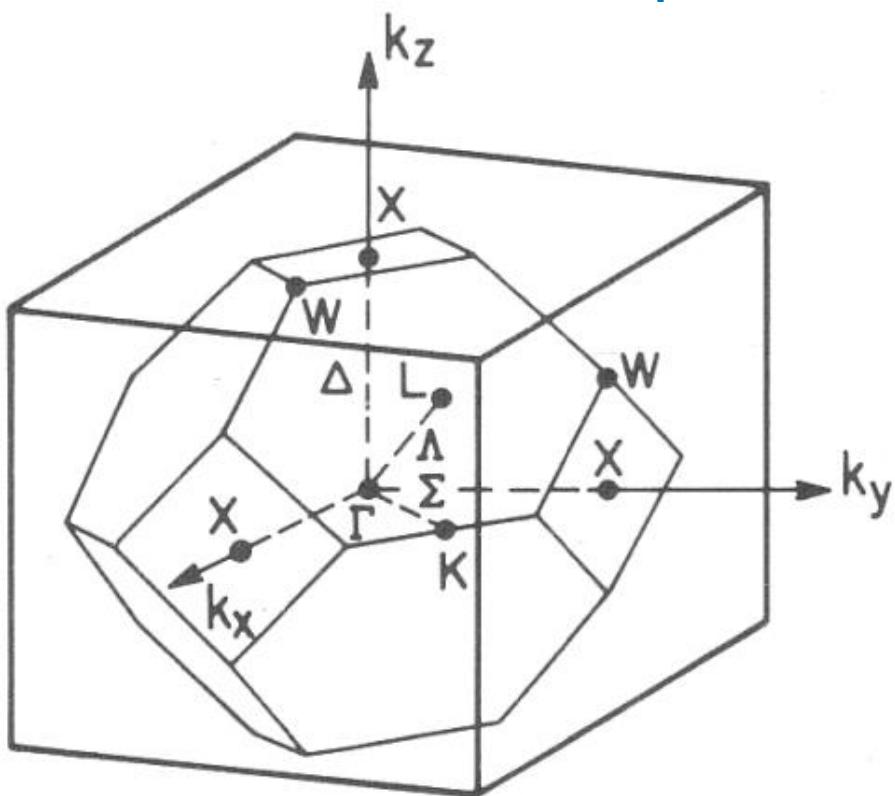
$$\begin{aligned} |H - \lambda I| &= \begin{vmatrix} \varepsilon_h - \lambda & \Delta \\ \Delta & \varepsilon_h - \lambda \end{vmatrix} \\ &= (\lambda - \varepsilon_h)^2 - \Delta^2 = 0 \end{aligned}$$

$$\therefore \lambda_{\pm} = \varepsilon_h \pm \Delta$$

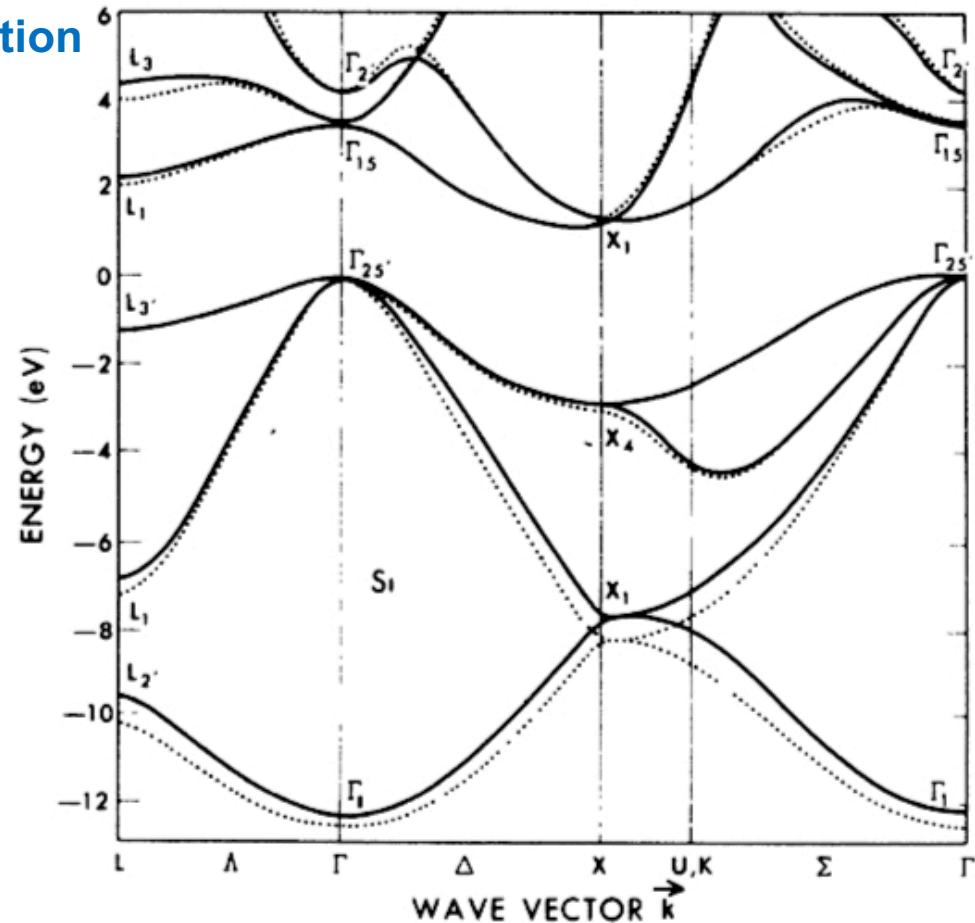


Band: Infinite Lattice

- **Bloch theorem:** $\psi_{n\mathbf{k}}(\mathbf{r}) = \exp(i\mathbf{k} \cdot \mathbf{r})u_{n,\mathbf{k}}(\mathbf{r})$

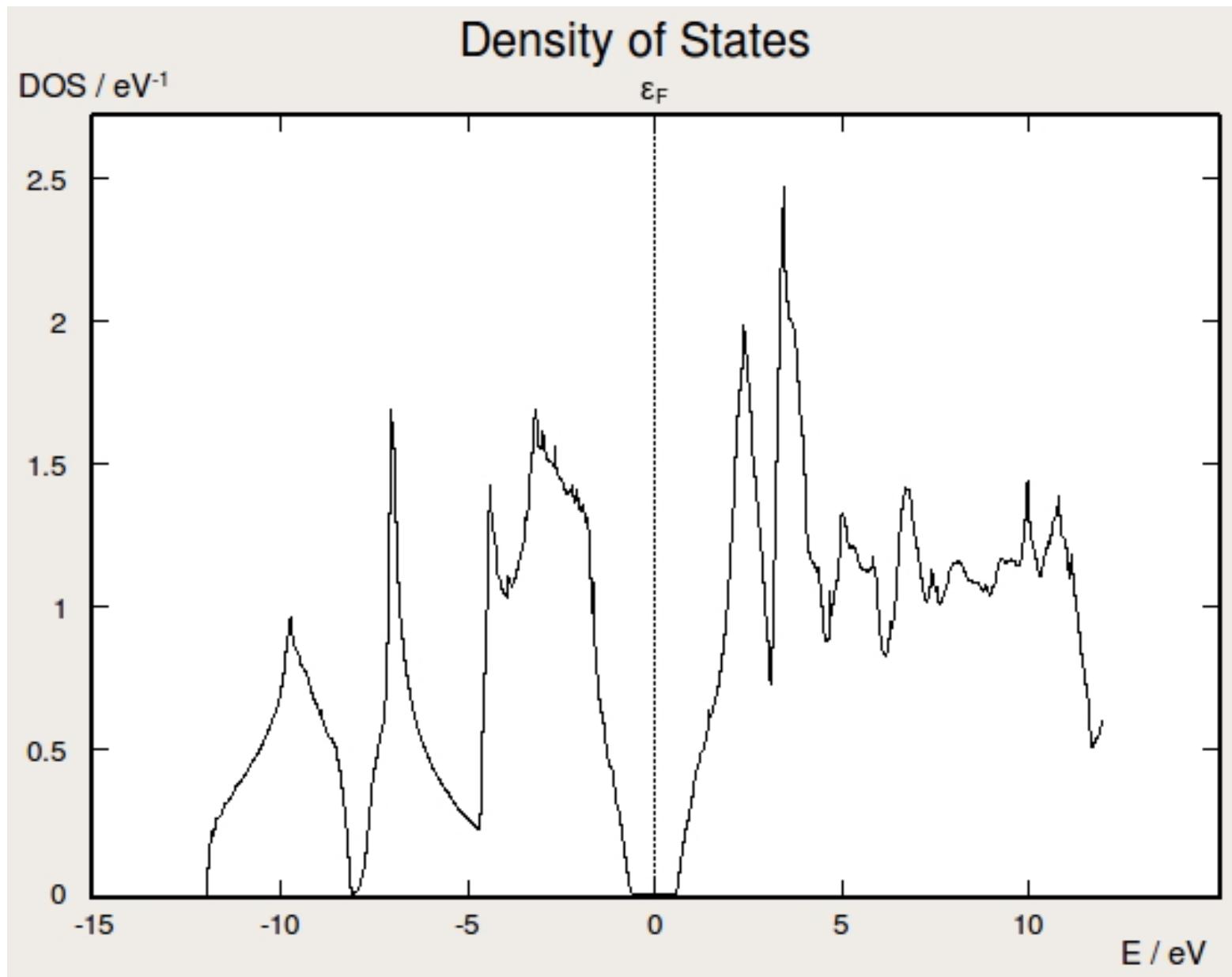


Brillouin zone of Si crystal



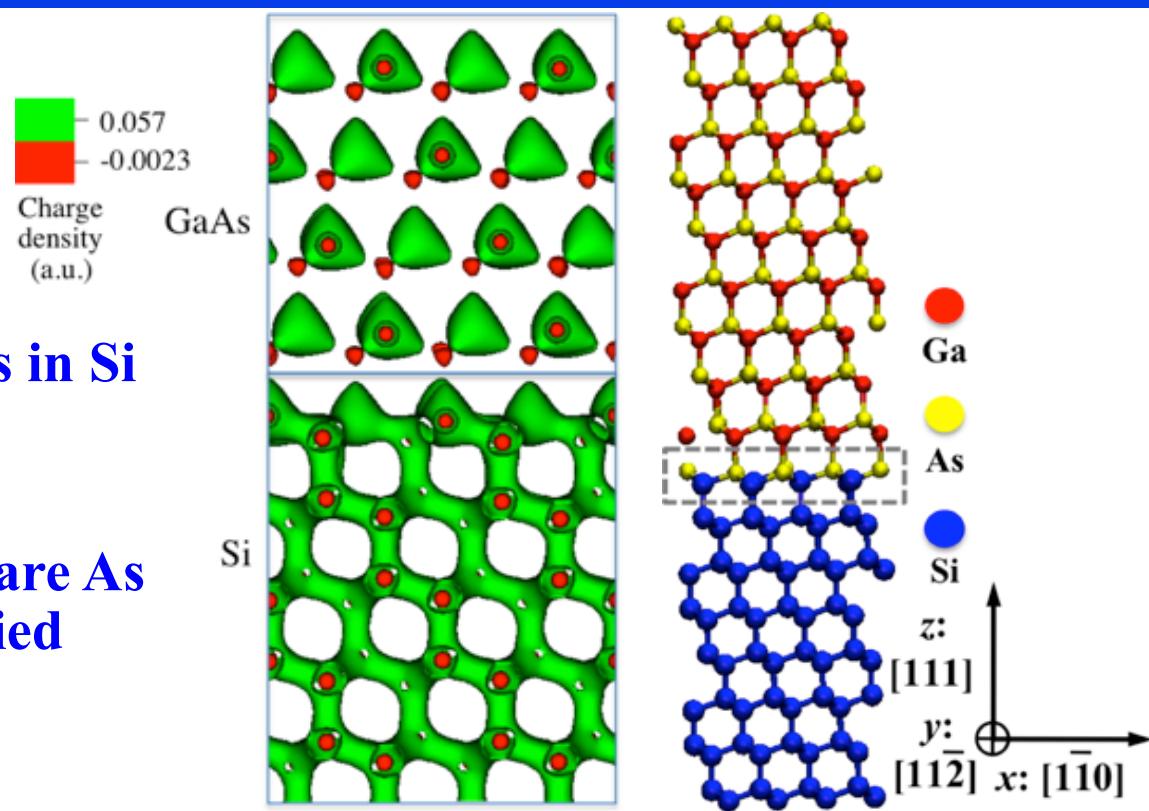
J. R. Chelikowsky & M. L. Cohen, *Phys. Rev. B* **10**, 5095 ('74)

Density of States: Silicon Crystal



Charge Density at GaAs/Si (111) Interface

- Highest occupied states in Si have the hybrid sp^3 character
- Occupied GaAs states are As p-like (lowest unoccupied states are s-like)

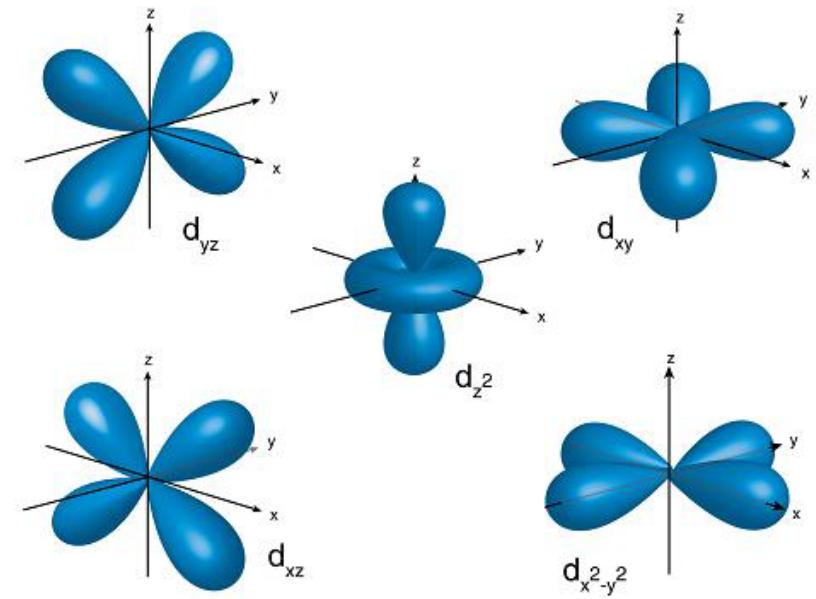
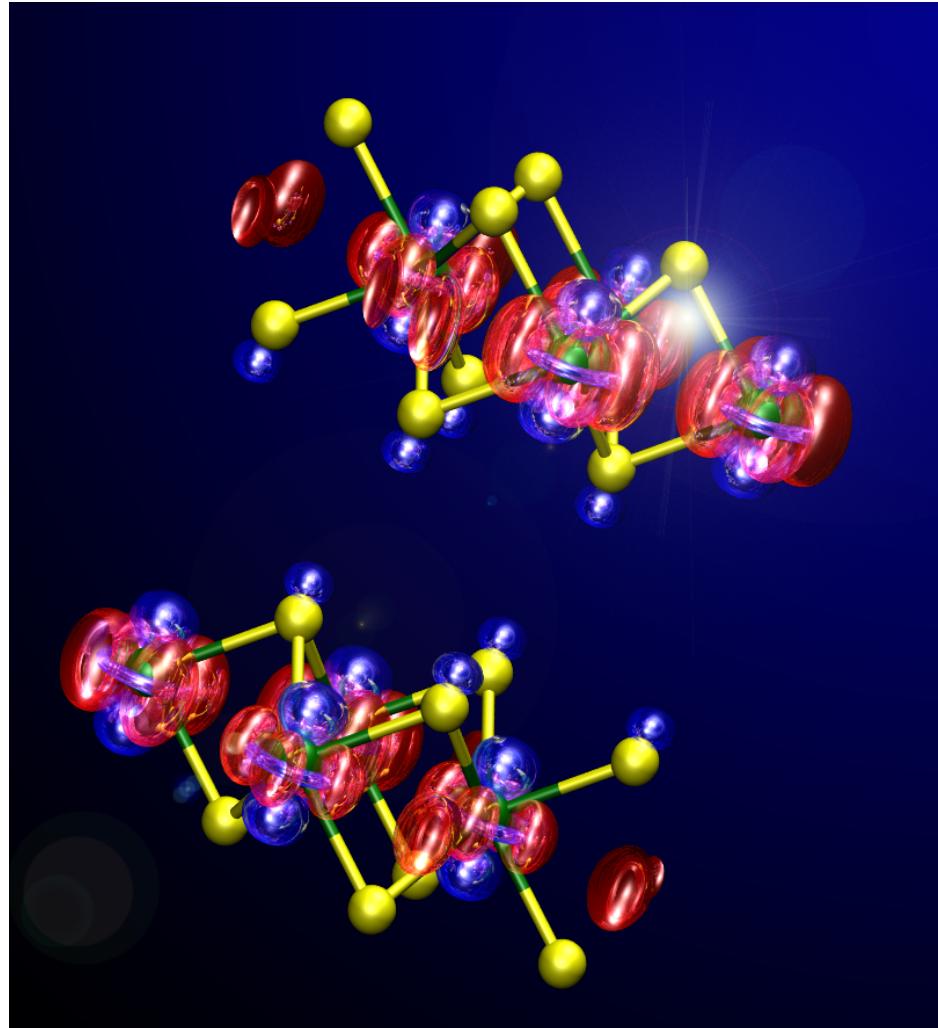


Projection of Kohn-Sham wave functions onto atomic orbitals

| | Band | Ga 4s | Ga 4p | Ga 4d | As 4s | As 4p | As 4d | Total |
|------------|------|---------------|--------|--------|---------------|---------------|--------|-------|
| Occupied | 1150 | 0.0000 | 0.1157 | 0.0708 | 0.0000 | 0.8033 | 0.0101 | 1 |
| | 1151 | 0.0000 | 0.1158 | 0.0709 | 0.0000 | 0.8033 | 0.0100 | 1 |
| | 1152 | 0.0000 | 0.1166 | 0.0713 | 0.0000 | 0.8017 | 0.0104 | 1 |
| Unoccupied | 1153 | 0.6763 | 0.0000 | 0.0000 | 0.3236 | 0.0001 | 0.0000 | 1 |

Wave Functions in MoSe₂ Bilayer

- Highest occupied states (blue) are d_{z^2} -like
- Lowest unoccupied states (red) are d_{xy} -like



Electron
Hole

M.-F. Lin *et al.*, *Nature Commun.* **8**, 1745 ('17); L. Bassman *et al.*, *Nano Lett.* **18**, 4653 ('18);
I. Tung *et al.*, *Nature Photon.* **13**, 425 ('19)