From Last Time...

- Several important conceptual aspects of quantum mechanics
- Indistinguishability
  - particles are absolutely identical
  - Leads to Pauli exclusion principle (one Fermion / quantum state).
- Symmetry
  - Characterizes the wavefunctions
  - Leads to different energy levels.
The two-atom molecule

- Talked last time about a molecule formed by two atoms (one electron).
- Electron could be either on the left atom or on the right atom.
- Should be no preference of electron location.
- Wavefunction is an equal superposition of electron on left atom and electron on right atom.
Symmetry of the wavefunction

Two-atom molecule

Compare particle in a box

\[ \lambda = 2L \]
One half-wavelength

\[ p = \frac{h}{\lambda} = \frac{h}{2L} \]

\[ \lambda = L \]
Two half-wavelengths

\[ p = \frac{h}{\lambda} = \frac{h}{L} \]
Energy levels

Wavefunction  Charge density  Energy level

\[ \Psi_1 \quad \Psi_A = \Psi_1 - \Psi_2 \quad \Psi_2 \]

\[ \Psi_1 \quad \Psi_S = \Psi_1 + \Psi_2 \quad \Psi_2 \]

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Energy differences

- Symmetric state is the ‘ground state’.
- Antisymmetric state is the excited state.
- Actual energy difference determined by details
Other systems too!

- Ground state
- First excited state

Connection between symmetry and energy is very general.
A three-atom molecule

Wavefunctions

Energy levels
A six-atom molecule

Wavefunctions

Energy levels
Energy levels in a solid

- Solids consist of \( \sim 10^{24} \) atoms
- Energy levels spaced *extremely* close together

3-atom molecule  6-atom molecule  \( 10^{24} \)-atom ‘molecule’
Crystal structures

- So far have pretended that solids are a string of atoms.
- Clearly they have a three-dimensional structure.
- Immense variety of ways to pack atoms into three-dimensional regular structures.
- These are different crystal structures.
Examples of crystal structures

- Table salt (NaCl = Sodium Chloride)
- Very common “cubic” structure.
- Na and Cl atoms alternate in a regular pattern
- Similar to one-dimensional structure.
Another variant

- Body-centered cubic structure. (CsCl)
Even more complicated: The diamond structure

- Diamond is carbon atoms arranged in the ‘diamond structure’.
- Other crystal structures of same carbon atoms appears as graphite (in your pencil).
- Many semiconductors have the crystallize in the diamond structure.
Electron bands

- Many atoms in a solid give many different quantum states.
- Spaced so closely together they are considered a ‘band’ of available energies.
- Different bands correspond top different atomic orbitals on the atom
- E.g. a 1s band, a 2s band, etc.
- Energies depend on details (e.g. separation)
Band ‘gaps’ in a solid

- This example is for silicon, an important ‘semiconducting’ material

\[ E \]

\[ R_C \approx 0.15 \text{ nm} \]

\[ R_{Ge} \approx R_{Si} \approx 0.24 \text{ nm} \]
Electrical properties

- Metals, insulators and semiconductors are usually differentiated by their ability to carry electrical current.
- Copper is an example of a good metal.
- Diamond is an example of a good insulator.
- Silicon is an example of a semiconductor.
Two configurations of a metal

- Partially full band

- Overlapping bands
Insulators

- All bands either full or empty.
- No response to applied electrical voltage.
- Insulators carry no current.
Semiconductors

- Semiconductors are insulators with a small bands gap.
- In pure form, they behave as insulators at room temperature.
Why semiconductors?

- Semiconductors become useful when they are doped.
- Different atom is substituted for Si.
- Possibilities: one extra electron, one fewer electron.
**n-type semiconductor**

- Atom with extra electron added.
- Behaves like a metal, with electrons as carriers.
**p-type semiconductor**

- Atom with one fewer electron is substituted
- Behaves like a metal, but with an apparently *positively*-charged object that carries the current
Semiconductor devices

- Semiconductor devices often made by combining $n$-type and $p$-type semiconductors into diodes, transistors, LEDs, laser diodes

![Diagram of a simple transistor](image)

**A simple transistor**
Integrated circuits

• Your computer processor contains *millions* of transistors
• Fabricated in thin film form.
• Patterned with characteristic dimensions on the order of 100 nm!