Intro. to Electro-physics

Introduction

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Syllabus (1/2)

Lecture: Introduction to Electro-physics (430.435)

* *Prerequisite*: Semiconductor devices (430.312), Quantum mechanics (430.326), Electromagnetics (430.203A)

Staff:

- ***Instructor:*** Jaesang Lee (*email: jsanlgee@snu.ac.kr*)
- ***TAs:*** Heechan Lim (*email:* degris@snu.ac.kr), Hyeong-oh Park (*email: power7610306@snu.ac.kr*)

Textbook: S. H. Simon, "The Oxford Solid State Basics", Oxford University Press, 2019 (Reprint)

+ Ashcroft & Mermin, "Solid State Physics", Cengage

+ C. Kittel, "Introduction to Solid State Physics", 8E, Wiley

Homework:

- Total **6 sets**
- A problem set (HW) will be assigned approximately ***every two weeks***.
- Submission due date: ***a week after the assignment***
  - Scan and upload it on eTL until 11:59 PM
- There will be a penalty for late submission!

Grading Policy:

Attendance (10 %)

Homework (42 %)

Midterm (24 %): "Presentation on achievements by Nobel laureates/key contributors in solid-state physics"

Final (24 %): "Presentation on free topics related solid-state physics"

Syllabus (2/2)

Class schedule

1. Intro to Electro-physics (w1)

2. The study of metals

- The classical theory (Drude model) (w2)
- The quantum theory (Sommerfeld model) (w3~4)

3. Chemical bonding [w5]

- Ionic / covalent / van der Waals / Metallic / Hydrogen bonding

4. Crystal vibrations [w6~7]

- Monatomic / diatomic chain

[Midterm: “Presentation on achievements by Nobel laureates/key contributors in solid-state physics”]

6. Crystal structure [w9]

7. Reciprocal lattice and X-ray diffraction (XRD) [w10]

8. Electrons in periodic potential [w11]

9. Insulator, Semiconductor and metal [w12]

10. Semiconductor Physics and devices [w13]

11. Magnetic properties of solids [w14]

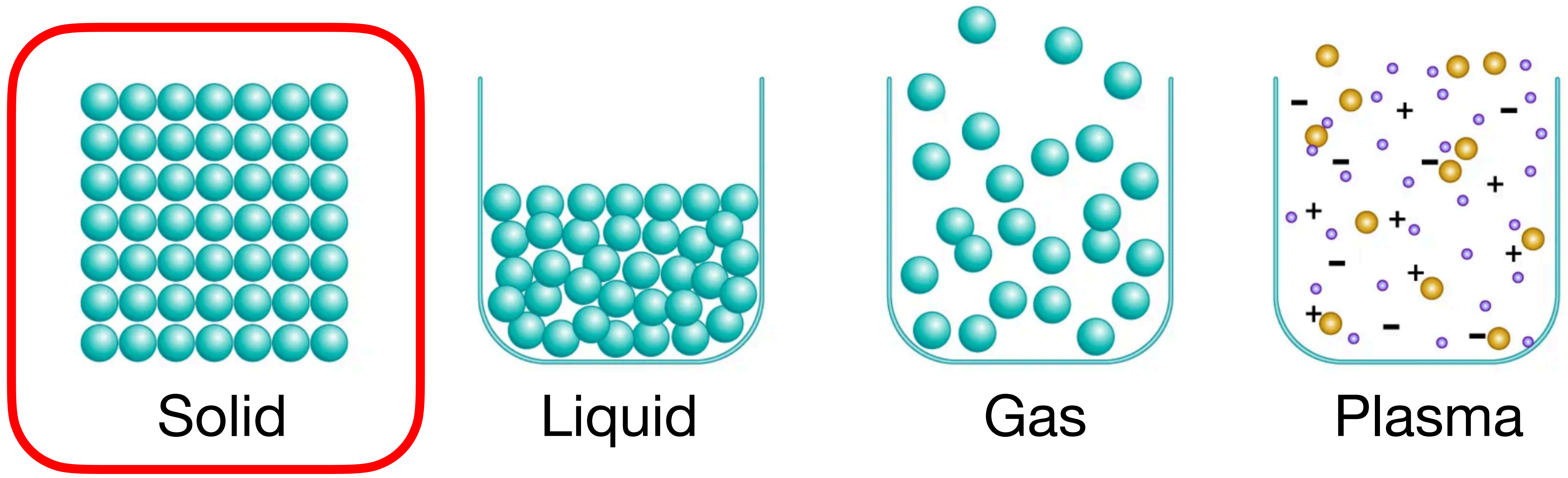
[Final: “Presentation on free topics related solid-state physics”]

Course definition

- What is electro-physics?
  - The study of physics of electrical phenomena observed in practically useful materials
  - Useful materials studied in ECE
    : Semiconductors, metals, insulators, magnets, superconductors, ⋯

- Electro-physics ~ **Solid-state physics!**

- What is solid-state physics?
  - The study of matter in its solid state
  - The largest sub-field of “Condensed-matter physics”



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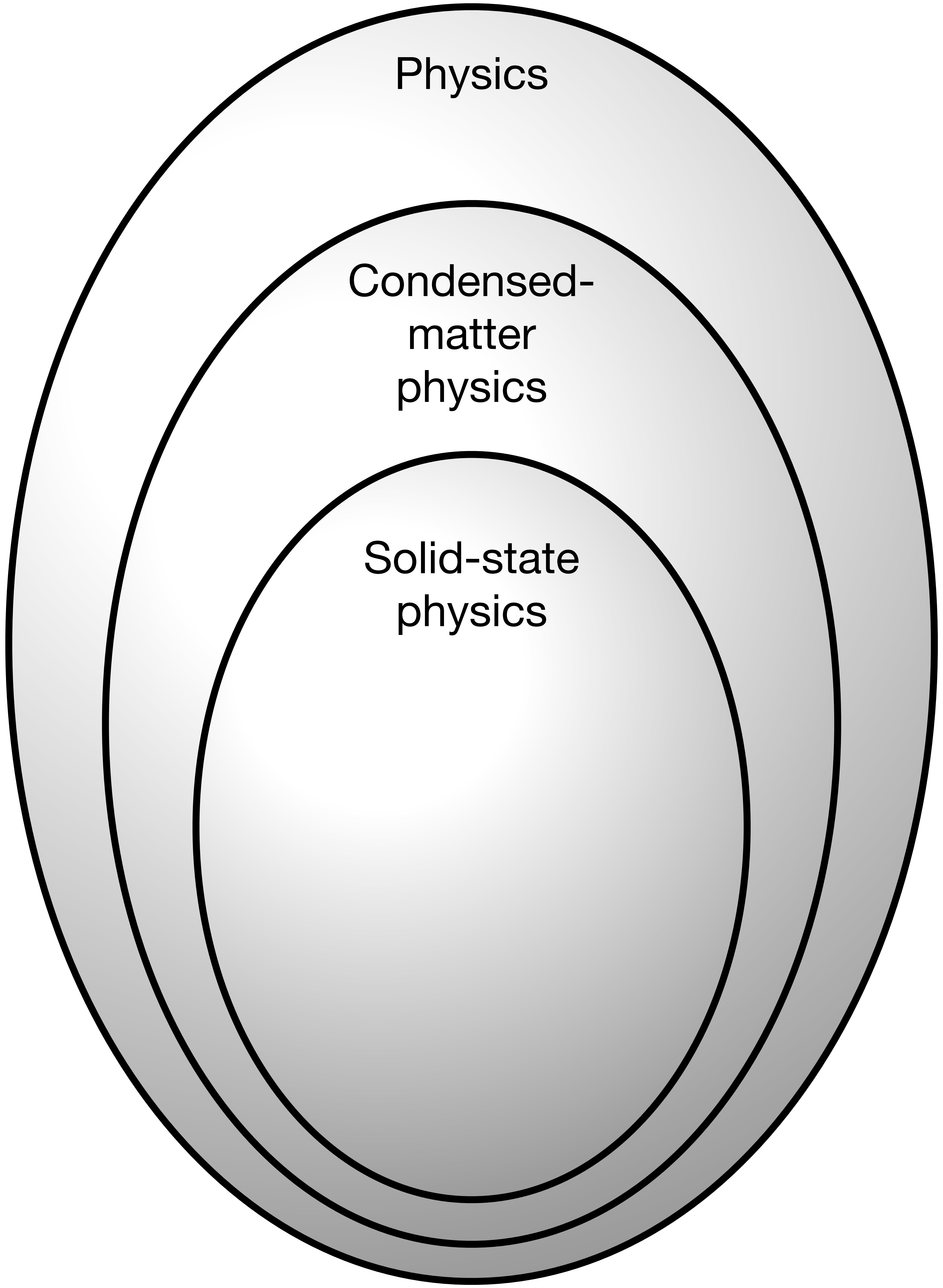
Condensed-matter, solid-state physics?



- Condensed-matter physics
  - The largest sub-field of physics (>60%)
  - The study that deals with macro- and microscopic physical properties of matter in condensed phase
  - Condensed phase
    - The number of constituents in a system is extremely large
    - Interactions among them are very strong
    - Solids and liquids
- **Solid-state physics**
  - **The most successful and technologically useful sub-field of condensed matter physics!**

CMP at SNU Physics

- Faculty members in SNU physics
  - # of professors studying condensed matter phys.:

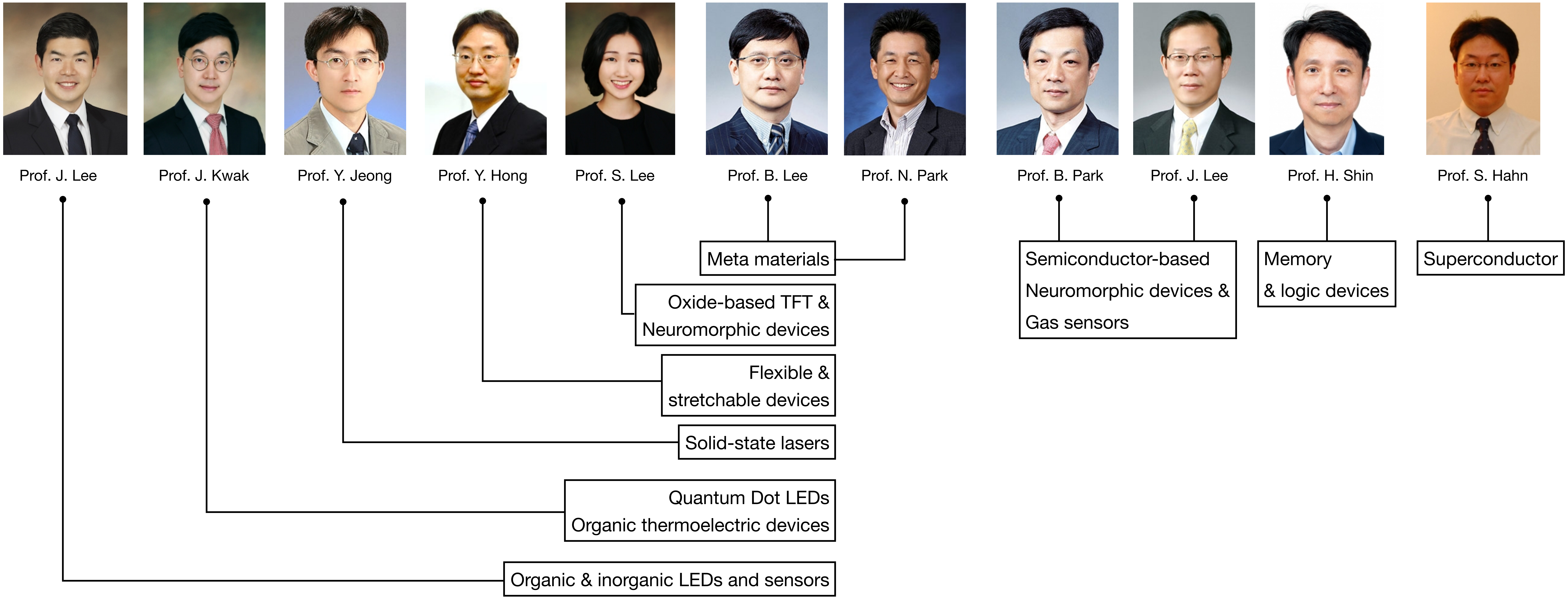
    $24/38 \simeq 63\,\%$!

  - Research topics

    New materials, emerging phenomena, correlation and topological effects, compound semiconductors, high-T superconductors, surfaces, interfaces, synthetic metals, transition and rare-earth oxides, quantum dots & wells, magnetism, spintronics and low-T properties ⋯

Solid-state devices at SNU ECE

- ECE faculty members working on solid-state devices & applications

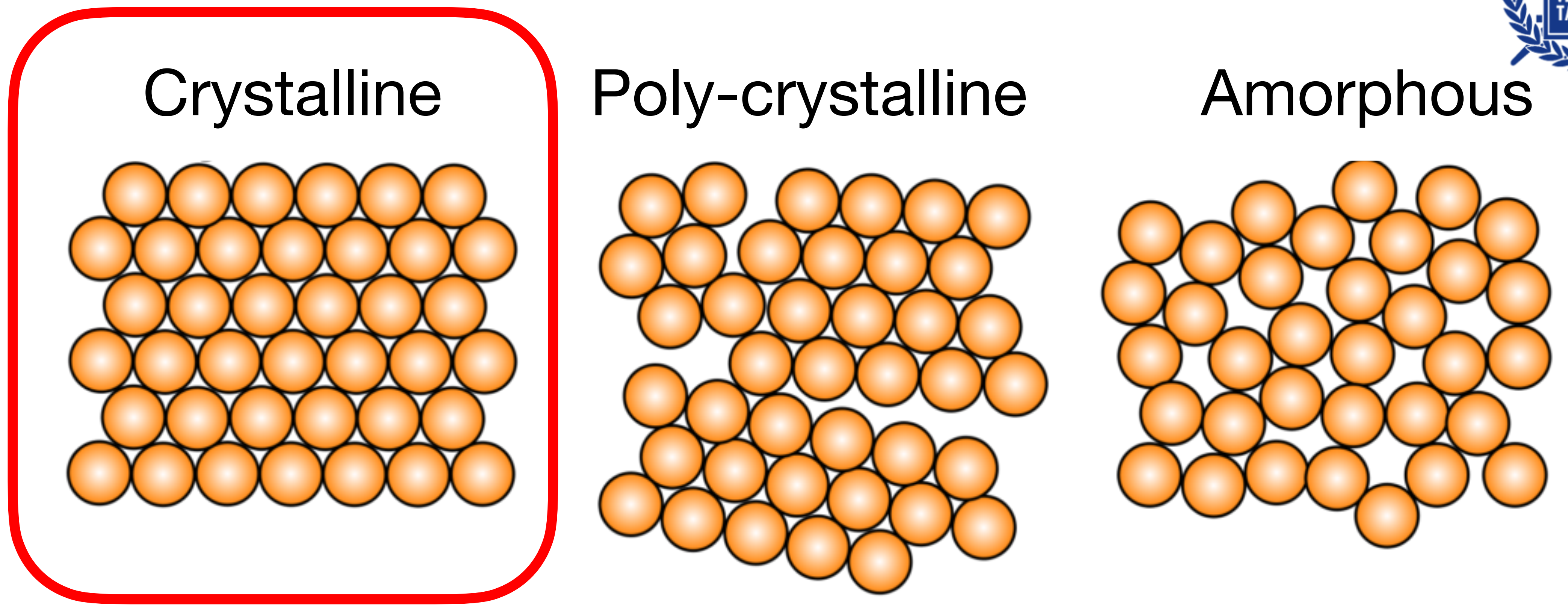


- What we do: based on understanding of electrical, optical, chemical properties of solid-state matters, we make technologically useful devices and applications!

what is solid-state physics? (1/2)

- Solid-state physics: the study of rigid matters (i.e., solids)
  - It studies how the macroscopic properties of solids result from their atomic-scale properties
  - Macroscopic properties: electrical, mechanical, thermal, optical, magnetic, ⋯
  - Solid: "densely-packed" atoms that strongly interact altogether
  - Atomic-scale properties
    - Types of atoms that comprise a solid
    - Interaction forces (i.e., how they are bound to form a solid)
    - Arrangement pattern for the atoms (crystalline vs. amorphous)
    - etc.

what is solid-state physics? (2/2)



- Major focus: crystalline solids
  - Determining characteristics – the periodicity of the comprising atoms
  - Easy to mathematically model their macroscopic properties
  - Knowledge derived from the crystalline solids “loosely” applicable to amorphous solids (But, not always!)
- Interacting force between atoms

  (how the atoms are held together to form solids)
  - Ionic bond (NaCl, LiF, ···)
  - Covalent bond (C, Si, GaAs, ···)
  - Metallic bond
  - van der Waals bond (molecular solids)

<Topic 1> Classical theory for metals

Paul K. L. Drude
(Germany)
1863-1906

- Major interest of early solid-state physicists:

  Explaining electrical & heat conduction of a metal

- Earliest model by **Paul Drude in 1900**

  - Application of a kinetic theory of gases to electrons (→ "electron gas")
    - No electron-electron interaction ("Independent electron approx.")
    - No electron-ion interaction ("Free-electron approx.")
    - Electrons collide elastically with immobile ions and get scattered
    - Electrons follow Maxwell-Boltzmann distribution
  - (Roughly) explains electrical (σ) and thermal (κ) conductivities, Hall effects
  - Fails to explain electronic heat capacity*

    (* The amount of heat to be supplied to a matter to produce a unit change in its temperature [J/K])

<Topic 2> Semi-classical theory for metals

- Improved model by **Arnold Sommerfeld**
  - Drude model + a bit of quantum mechanics
    - Free-electron approximation (same)
    - Immobile positive ions act as scattering centers (same)
    - A gas of non-interacting electrons follows **Fermi-Dirac distribution**, **NOT** Maxwell-Boltzmann distribution (∵Electrons = Fermions that obey the Pauli Exclusion principle!)
  - Able to explain the electronic heat capacity
  - Fails to explain the existence of insulators and semiconductors

Arnold J. W. Sommerfeld
(Germany)
1868-1951

Wolfgang E. Pauli
(Switzerland)
1900-1958

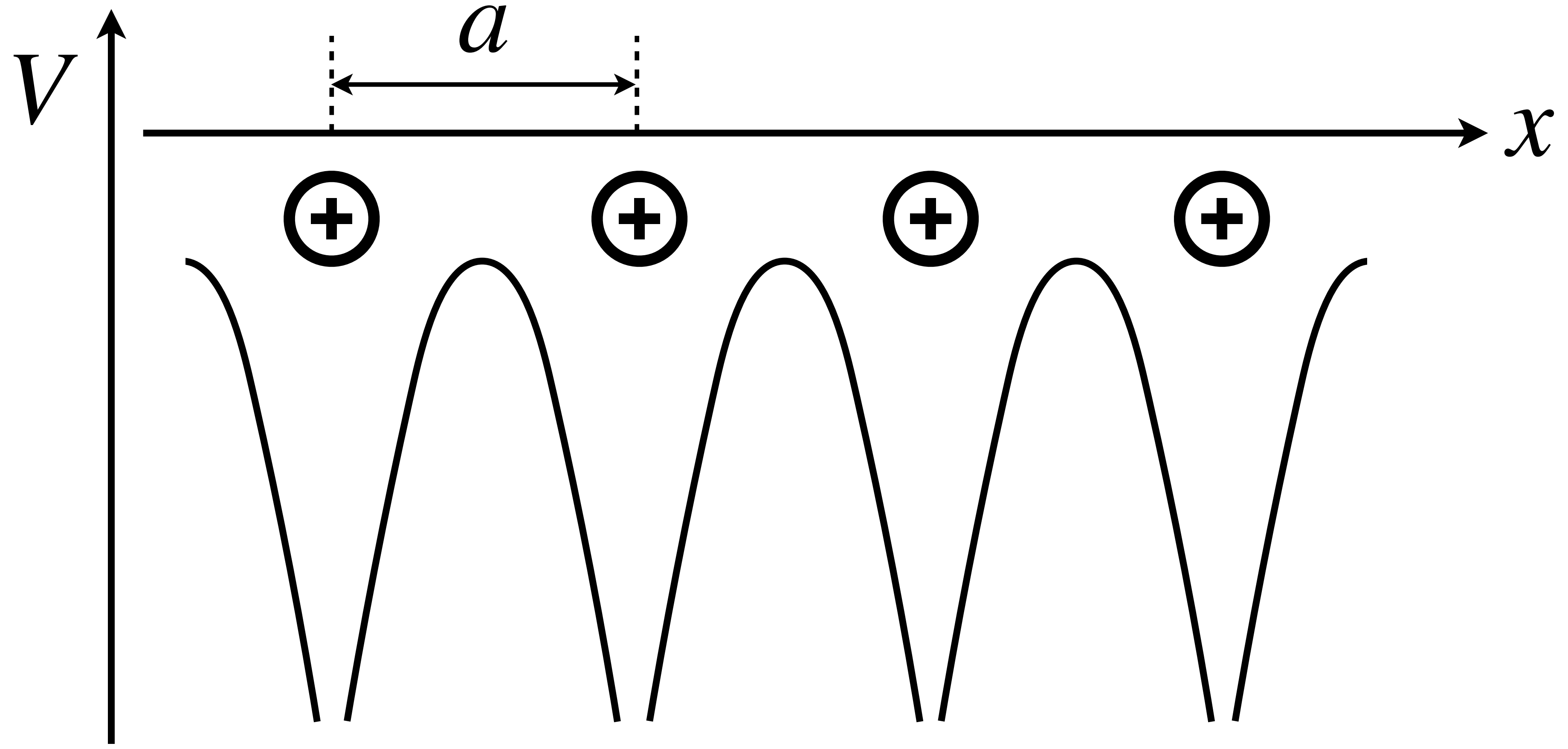
<Topic 3> Quantum theory for solids (1/2)

Erwin Schrödinger
(Austria)
1887-1961

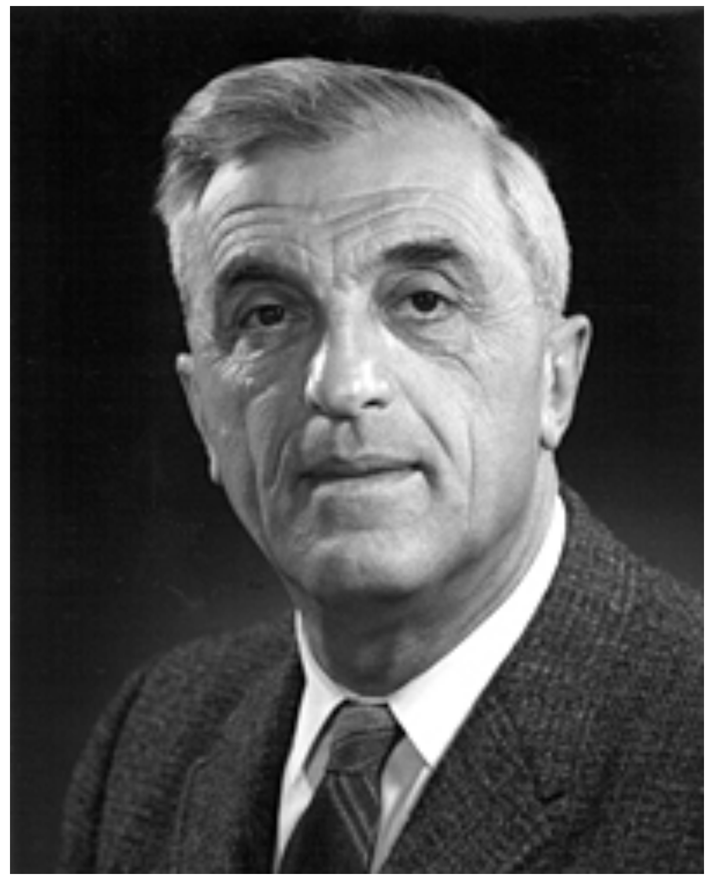
- **"Nearly" free electron model**
  - In a crystalline solid, electrons move almost freely but subject to a weak, periodic potential due to the periodically arranged ions
  - Quantum mechanics plays a role!
    - Schrödinger's equation for the periodic potential:

$$-\frac{\hbar^2}{2m}\frac{d^2\psi(x)}{dx}+V(x)\psi(x)=E\psi(x), \text{ where } V(x+na)=V(x)$$

    - Solution $\psi(x)$: "Bloch's state"

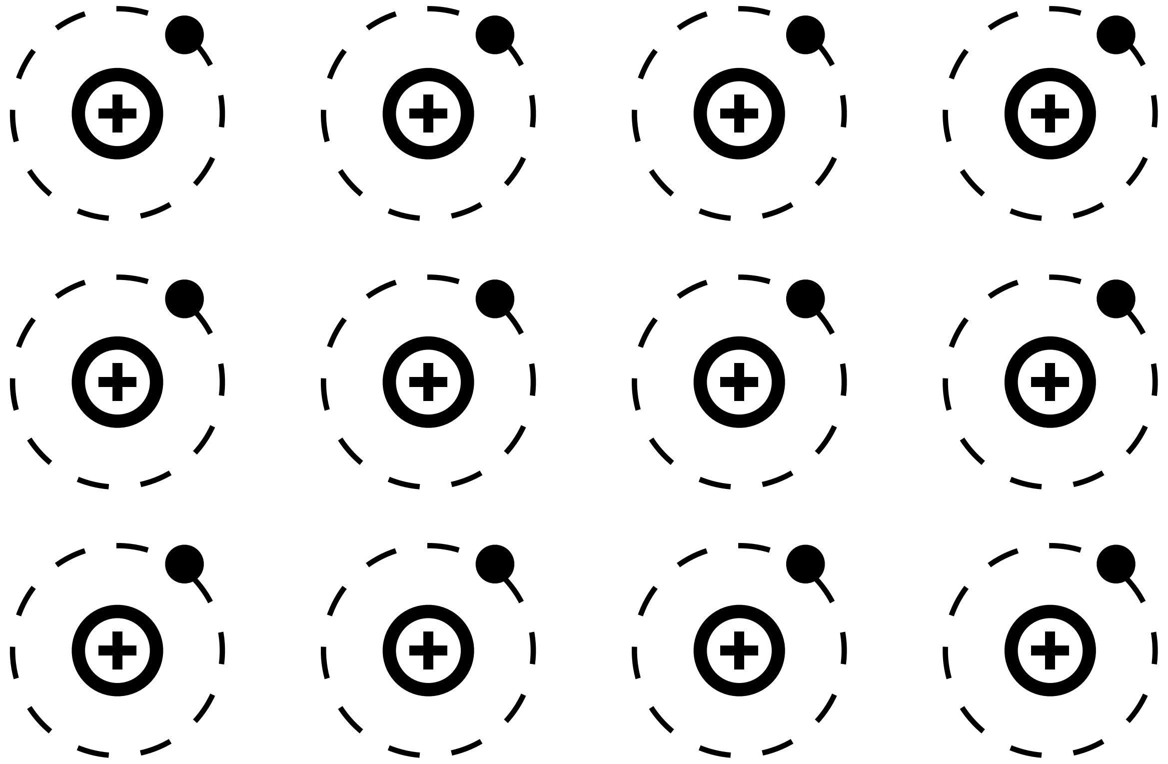


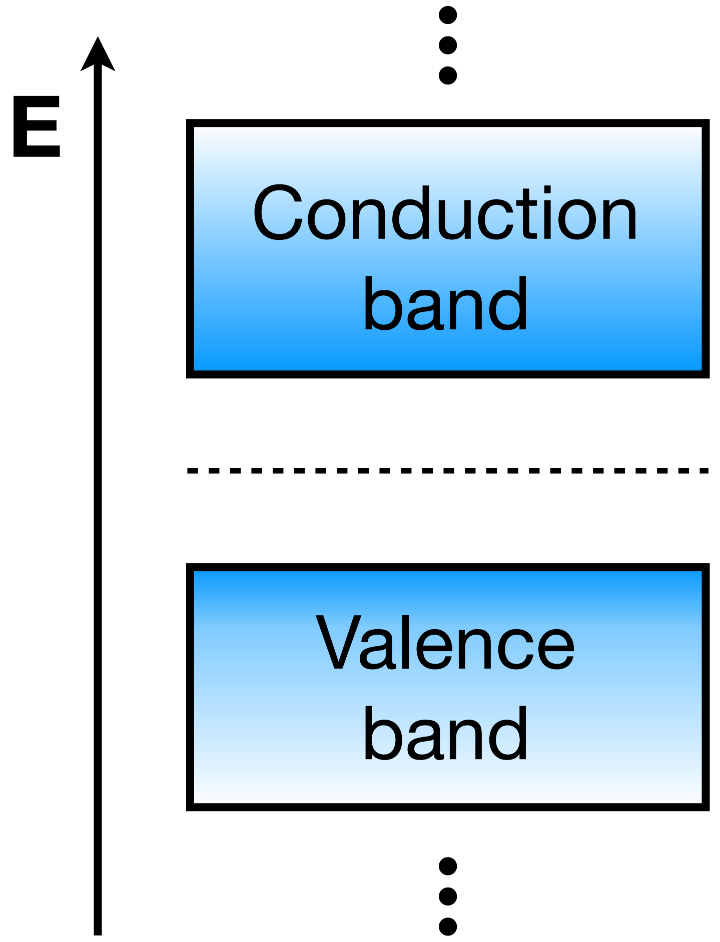
<Topic 3> Quantum theory for solids (2/2)



Felix Bloch
(Switzerland)
1905-1983

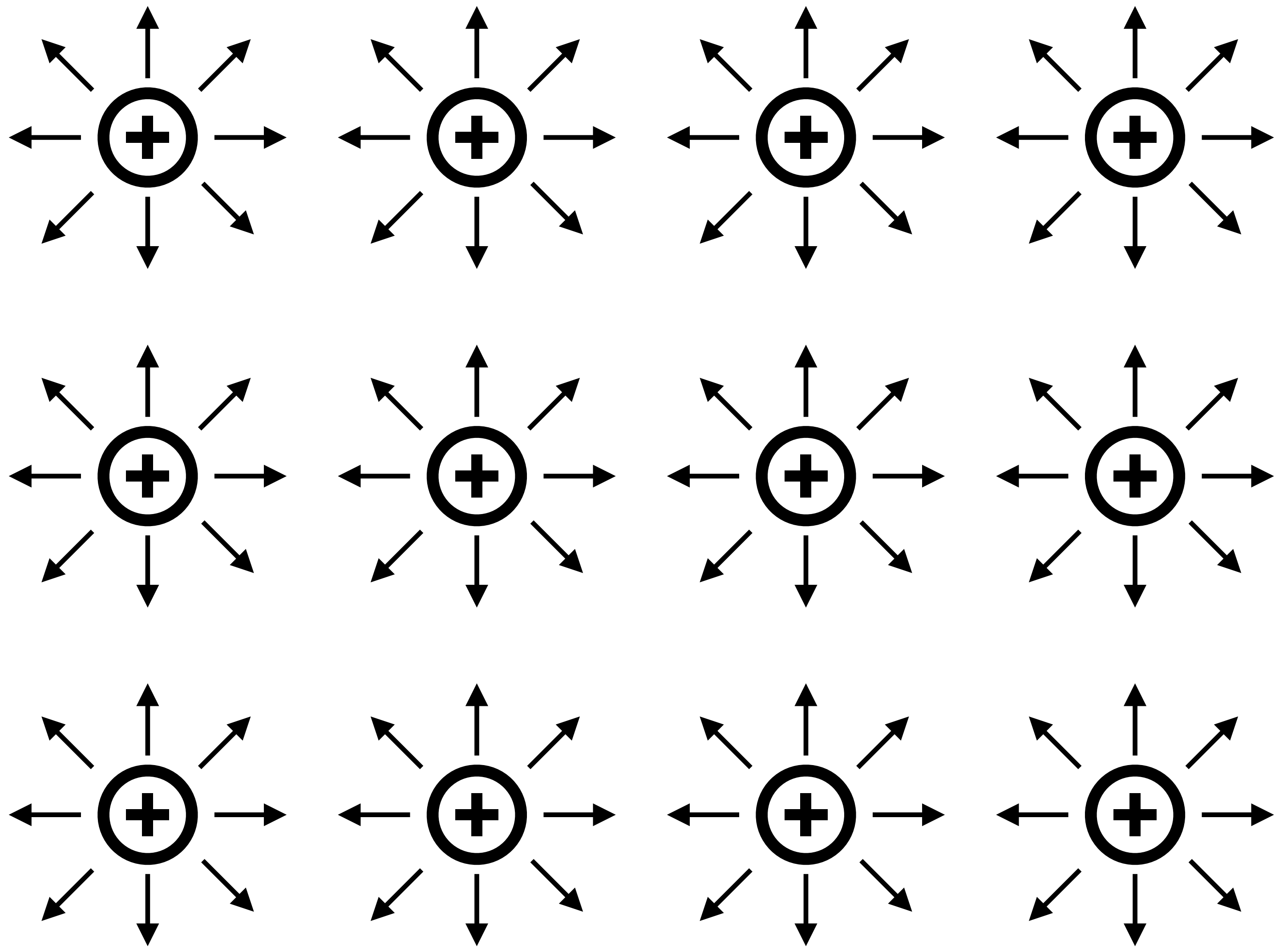
- **Bloch's state**
  - Electrons are largely delocalized across the crystalline solid
  - Electrons occupy the closely-spaced electronic states ("Energy band")





- **Band theory**
  - Enables to distinguish conductors, insulators and semiconductors
  - Forms a foundation of the understanding of solid-state devices (transistors, solar cells, LEDs, lasers, and etc)!

<Topic 4> Crystal vibrations in solids

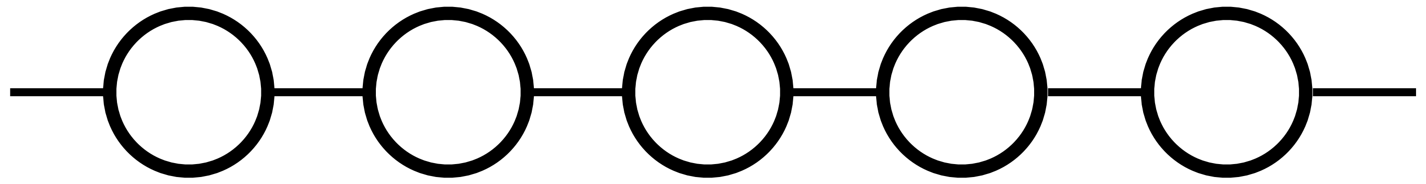
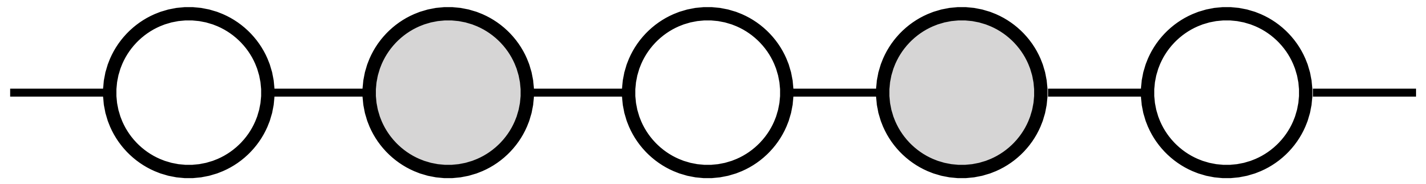


- A collective vibration of "periodically arranged" atoms
  - The vibration at a given frequency (ω) is quantized:

$$E_n = \hbar\omega\left(n + \frac{1}{2}\right), \quad (n = 0, 1, 2, \cdots)$$

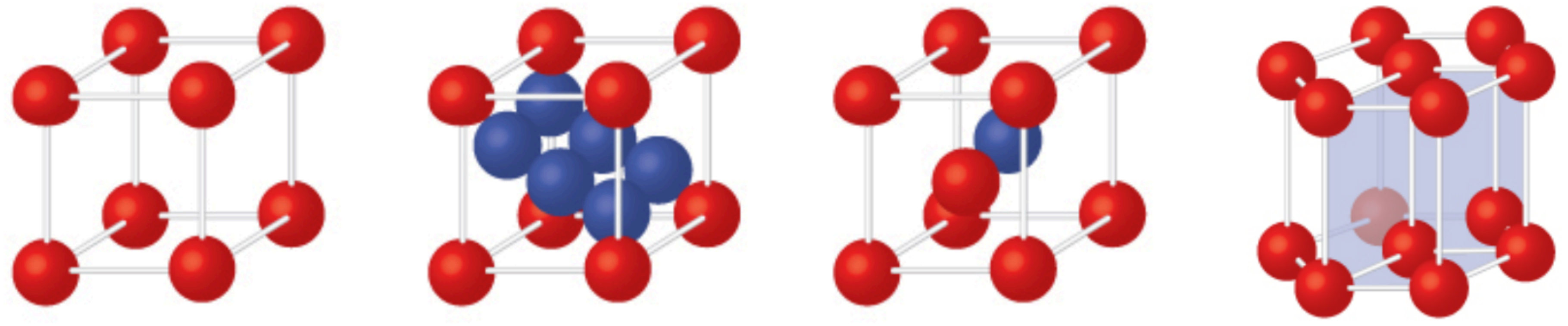
  - A discrete quantum of crystal vibration: **"phonon"**

c.f.) A discrete quantum of electromagnetic vibration: "photon"

- Phonon affects the electrical, thermal conductivities and many other properties!
- What we will study: A simple 1D model
  - Monatomic chain 
  - Diatomic chain 

<Topic 5> Crystal structure

- Important terminology in crystals
  - Lattice: A periodic arrangement of points in space
  - Basis: A component that fills the lattice
    (e.g. atom, ion, molecule, ⋯)

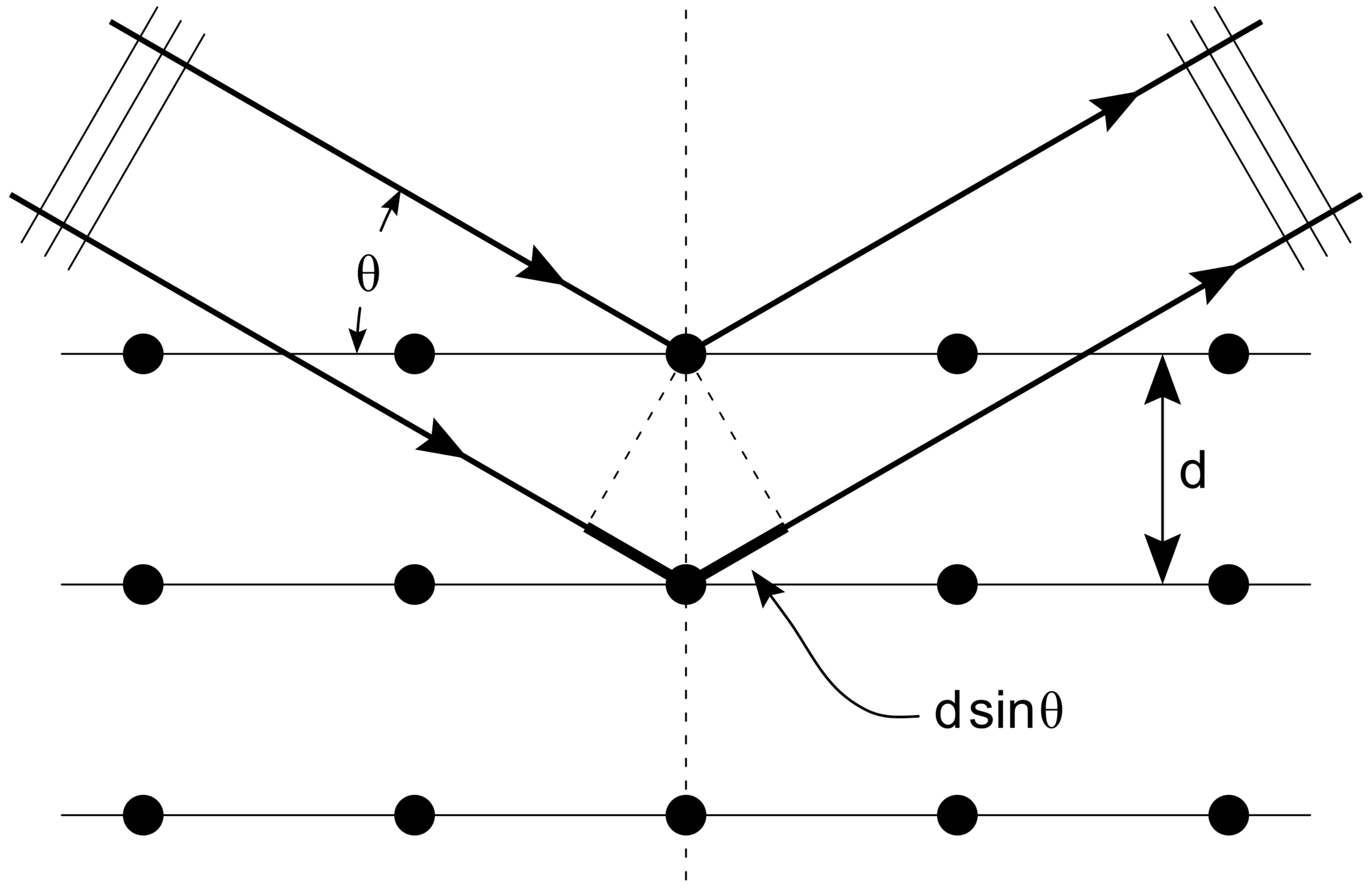


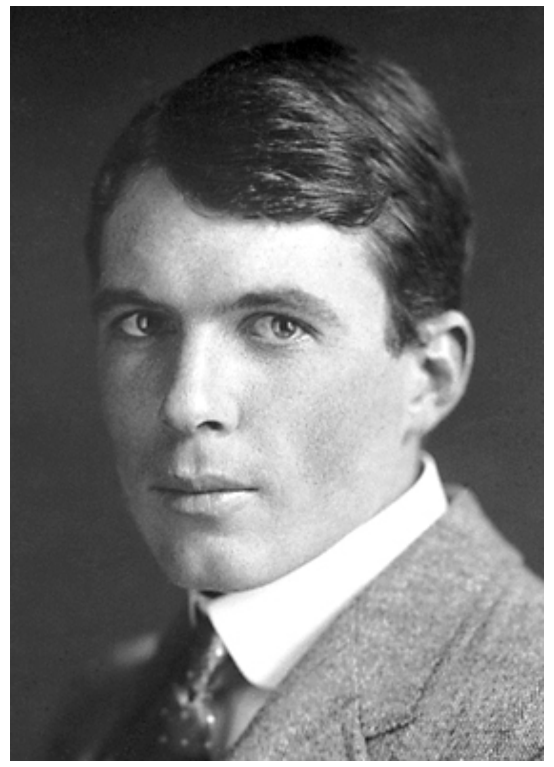
Simple cubic Face-centered Body-centered Hexagonal

14 Different lattice structures

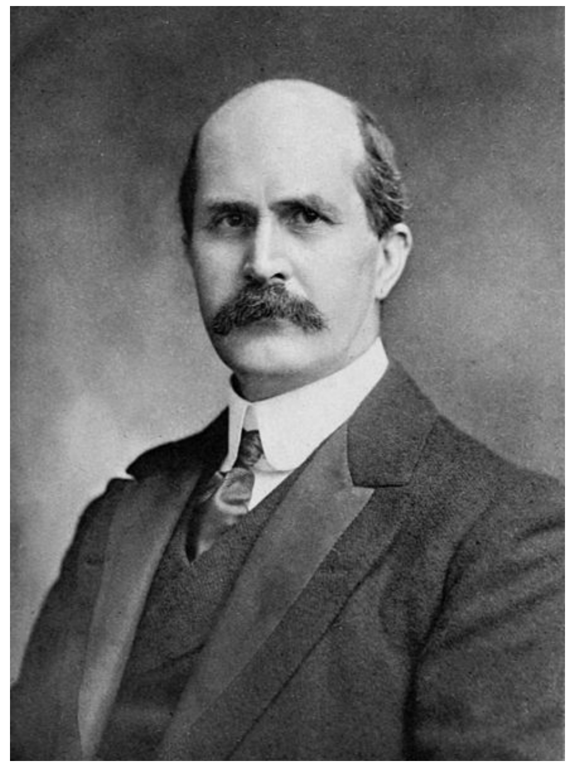
(Not all shown here; opentextbc.ca)

- A method of identifying the crystal structure : X-Ray Diffraction (XRD)
- Bragg's law : $n\lambda = 2d\sin\theta$, where $n = 1, 2, 3, \cdots$





Lawrence Bragg
(Australia)
1890-1915
Son



William Bragg
(United Kingdom)
1862-1942
Father

...and further topics

- **<Topic 6> Chemical bonding**

- **<Topic 7> Basics of semiconductor physics and devices**

- **<Topic 8> Magnetic properties of solids**

- **< Topic 9> Superconductor and its applications (if time allows…)**