東京大学
THE UNIVERSITY OF TOKYO

04/11/2010
Global Focus on Knowledge

The World of Diverse Matter
— The Distant Journey from Space to Earth

The Diversity of Materials Borne from the Collective Actions of Atoms, Electrons, and Molecules

5th Lecture

Modern Hi-Tech Society and Materials Science
From Atoms to Solids

Yasuhiro Iye
The Institute for Solid State Physics,
The University of Tokyo

Lost in Hi-Tech Society

- People living today daily benefit from the advanced science and technology.
- Nevertheless, those hi-tech apparatus are becoming more and more like black-boxes. I fear that despite (or, because of?) the development of science and technology the science literacy of general public and youngster is deteriorating.
- Many people tend to view the science and technology as “somebody else’s business”.
- There are so many important issues on which people have to make decisions on the basis of good understanding of science and technology. Without scientific knowledge, people have no other choice than to blindly follow what media will tell them, or to rely on uneducated gut feeling.

The Utility of Learning Physics

- The utility of learning science for those who are not science-major is that it helps to develop "common sense". Armed with such common sense, one can immediately discern such questionable paranormal phenomena that contradicts the basic principles of physics, such as the low of energy conservation, the law of increasing entropy, and the principle of causality. Namely, one is able to exercise "sound skepticism".

- By contrast, what is the best part of being a practicing physicist? I think the best of physicist's joy is to encounter a novel phenomenon that overturn the pre-existing "common sense".

Lecture Plan

Lectures 1-4: Sachio Komamiya and Yasushi Suto Elementary Particle Physics and Space

"From Micro Particles to Macro Space"

Lectures 5-7: Yasuhiro Iye and Norimichi Kojima Condensed Matter Science

"The Diversity of Matter Born from the Actions of Atoms, Electrons, and Molecules"

My lecture

Lecture 5: Modern Hi-Tech Society and Materials Science
From Atoms to Solids

Lecture 6: Quantum World
Nanoscience, Superconductivity, Superfluidity

Lectures 8-10: Yuichi Sugiyama Pharmaceutical sciences

"The Search for and Creation of Matter with Desirable Properties — Discoveries from the Field of Pharmaceutical Science"

Lectures 11-12:Toshihiko Koseki and Akira Toriumi Materials Engineering

"Changing Matter — From Matter to Material"

Lectures 13: Hiroshi Komiyama Environmental and System Engineering

"An Everlasting Future for Our Small Earth"

Today's Talk

Modern Hi-Tech Society and Materials Science

The Tale of Big and Small
Modern Hi-Tech Society and Materials Science
Some Fundamental Concepts in Physics
What is Condensed Matter Physics all about?

From Atoms to Solids

Quantum Mechanics and Atomic Structure
From Atoms to Solids

Textbook

(a bit of advertisement)

50th Anniversary of The Institute for Solid-State Physics Memorial Edition

"Materials Science in the 21st Century"

The Institute for Solid-State Physics

The Institute for Solid-State Physics at Kashiwa Campus

Baifukan Publishing (￥2000 + Tax)

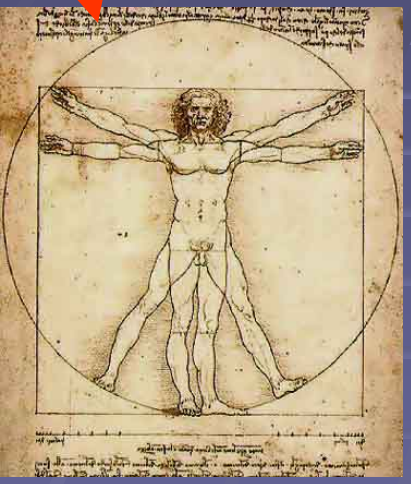
The Tales of Big and Small

The Tale of Big: Traveling Up the Scale

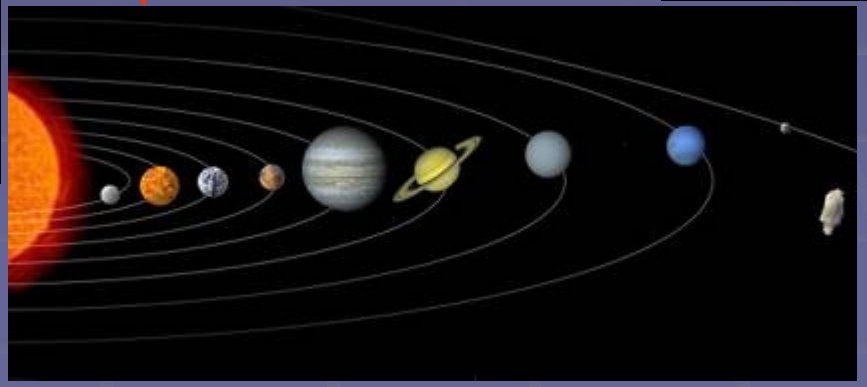
the size of the universe

1 m 10^3 m 10^6 m 10^{12}m 10^{18}m 10^{24}m

1km 1000km 1 Astronomical Unit 1 Light Year 2.3 million Light Years 13.7 billion Light Years



12800km



The Tale of Small: Traveling Down the Scale

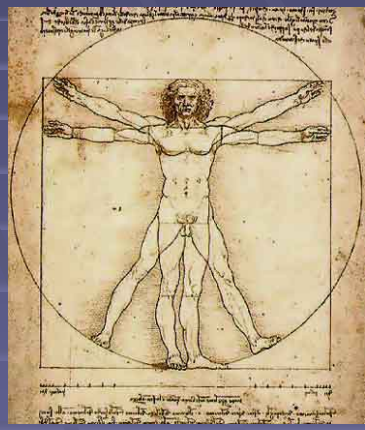
10^{-12} m | 10^{-9} m | 10^{-6} m | 10^{-3} m | 1 m

1 pm — Picometer

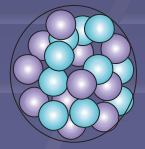
1 nm — Nanometer

1 μm — Micrometer (Micron)

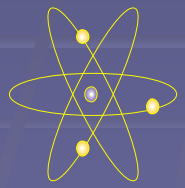
1 mm — Millimeter



Size of a nucleus



Size of an Atom



Virus

Visible Light Wavelength

Bacteria

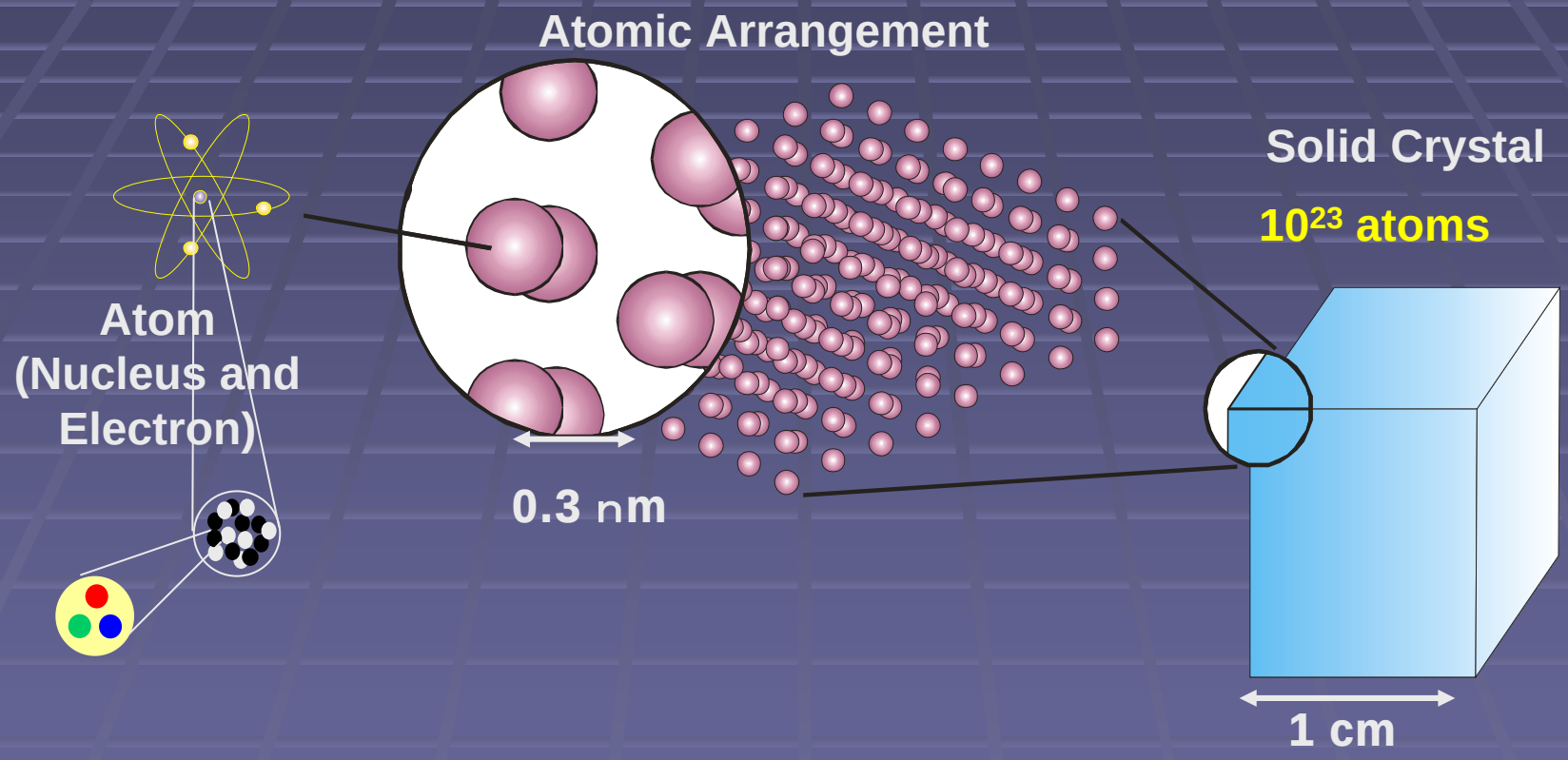
10^{-35}m Planck Scale

10^{-32}m Grand Unification

10^{-21}m

10^{-18}m Electroweak Unification

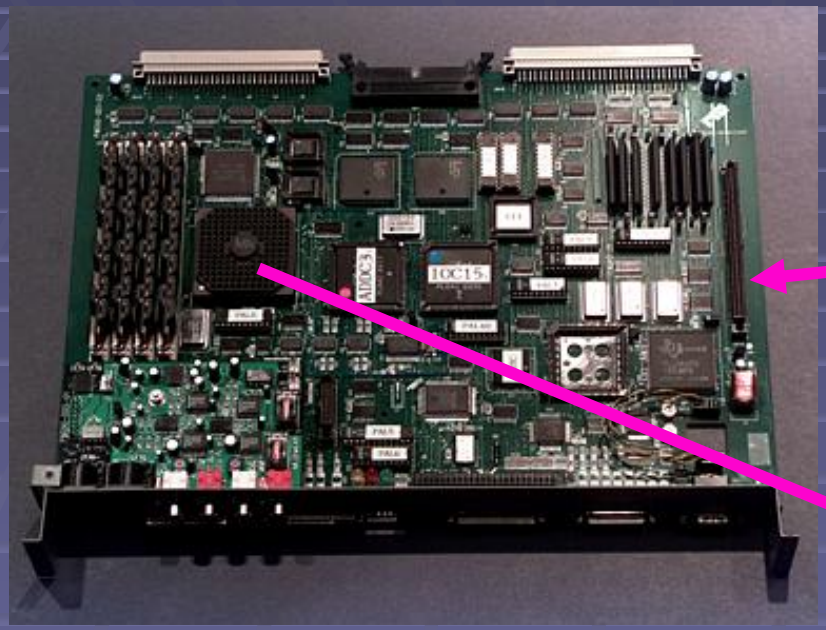
The Hierarchical Structure of the Material World

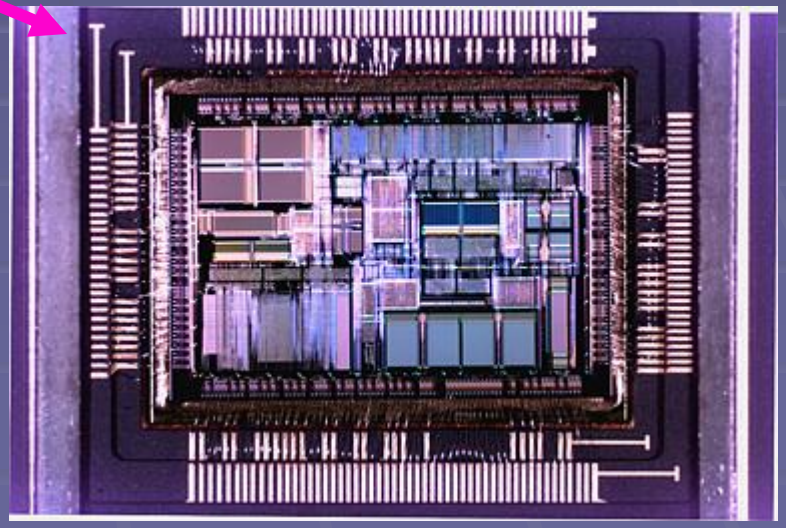


Modern Hi-Tech Society and Physics

Computers

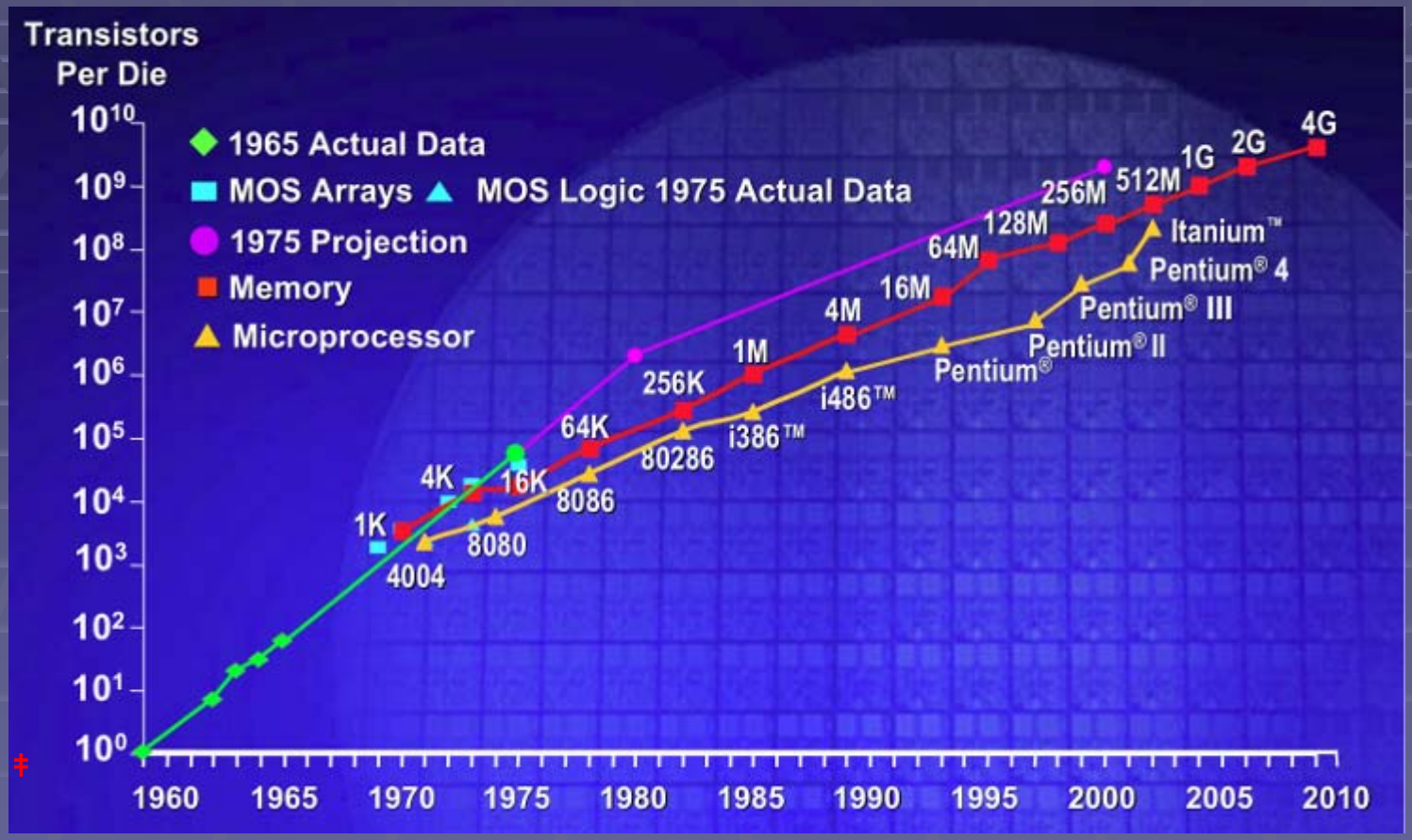
Personal Computer





The device operation is based on the theory of electrons' behavior in semiconductors as elucidated by condensed matter physics based on quantum mechanics

Moore's Law



The degree of integration of LSI (Large Scale Integrated Circuit), in other words, the number of transistors that can packed into a unit area doubles roughly every one-and-a-half years.

⇒ further details in Toriumi-Sensei's lecture

Memory Devices

Magnetic Hard Disk

CD-ROM/DVD

Semiconductor Memory Devices

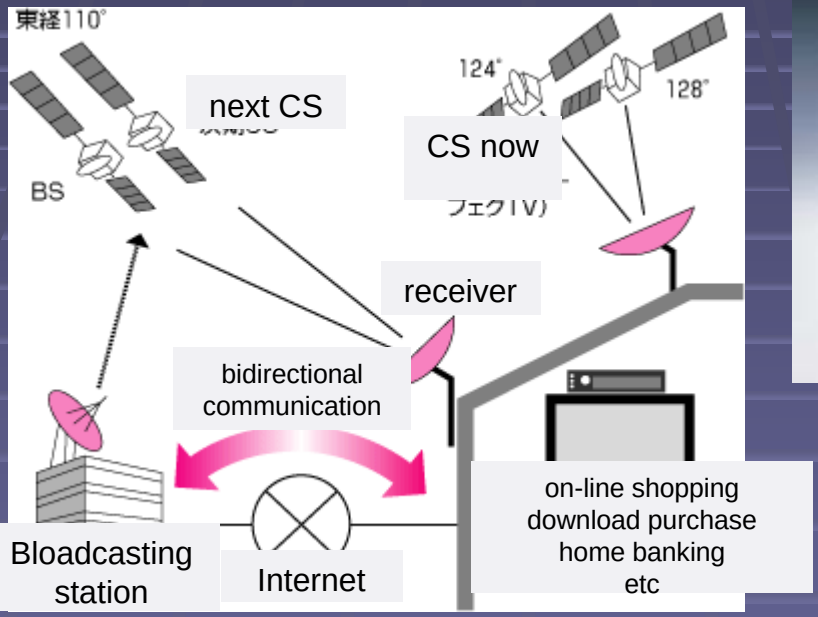
- Flash Memory
- Ferroelectric Memory

Digital information stored as local magnetization of a ferromagnetic material.

Digital information recorded as undulation pattern on a plastic disk written and read with a laser beam.

Radio (High-Frequency) and Optical Communications

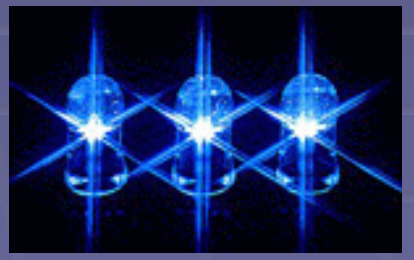
Mobile Phone



Satellite Communications
Satellite Broadcasting

Optical Fiber

High Electron Mobility Transistor (HEMT)



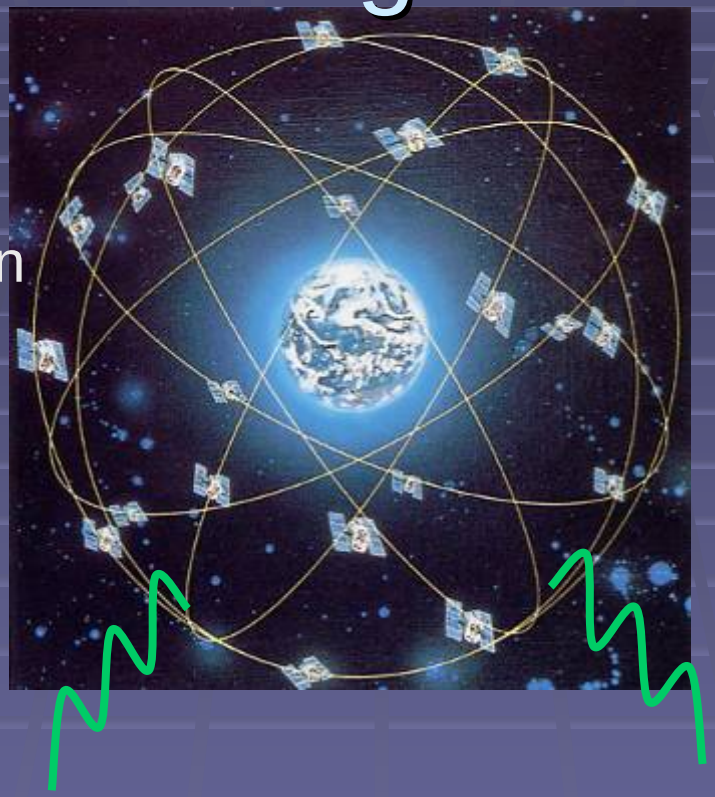
Light Emitting Diode (LED)
Semiconductor Laser

GPS (Global Positioning System) Navigation

24 satellites are stationed in orbit.

Position determination by “triangulation”

Accuracy in timing is essential. Satellites have an atomic clock on board

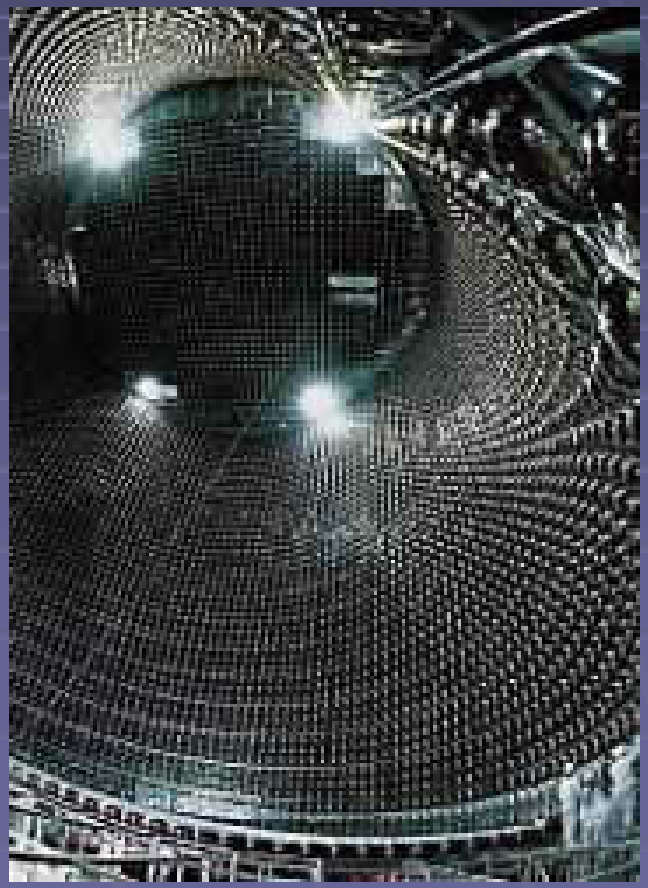


For **GPS** to function, proper corrections based on special and general theories of relativity are necessary.

At the Research Forefront of Astrophysics and Elementary Particle Physics

Subaru Telescope
CCD camera

Super-Kamiokande
photomultipliers



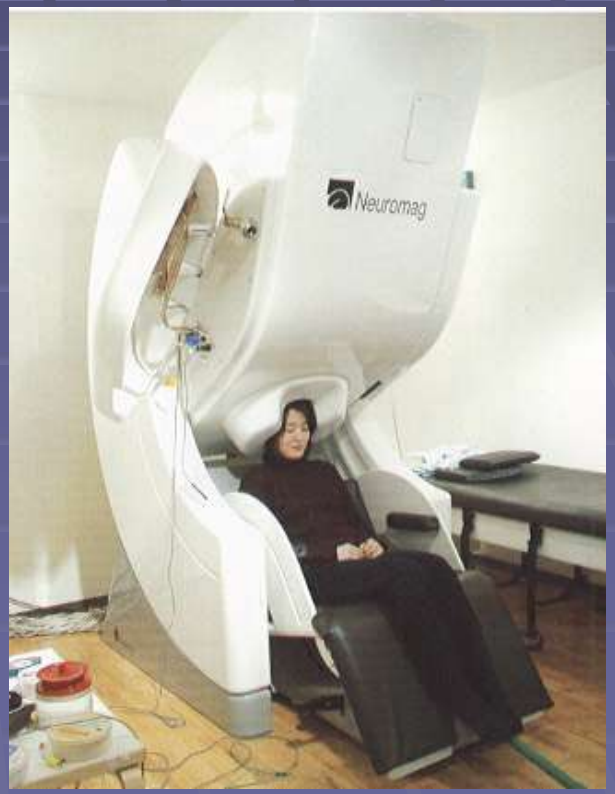
For Medical Diagnostics

Magnetic Resonance Imaging (MRI)

‡ KasugaHuang
http://ja.wikipedia.org/wiki/ファイル:Modern_3T_MRI.JPG

Magnetoencephalograph (MEG)

Detection of weak magnetic signals by using a Superconducting Quantum Interference Device (SQUID)



‡

Also in many Daily Scenes

- Liquid Crystal (TV Display)
- High-Strength Fiber (Tennis Racquet)
- Polymer Gel (Disposable Diaper)
- Shape-Memory Alloy
- Fuel Cell
- Photocatalyst
- Solar Power
- ……

Some Basic Concepts in Physics

Causality

- No result precedes its cause.

  The effect (physical consequence) of an event does not retroact on the past.

  ⇒ Time machines are impossible.

  cf. “Delayed choice experiment” for the measurement problem in quantum mechanics

- Effect cannot propagate faster than the speed of light.

  No causal relationship between two space-time that cannot be connected by the speed of light.

Symmetry and Conservation Law

"Where there is a symmetry, there is a conservation law"

Noether's theorem

- The homogeneity of space (the same physical law holds everywhere in the universe)

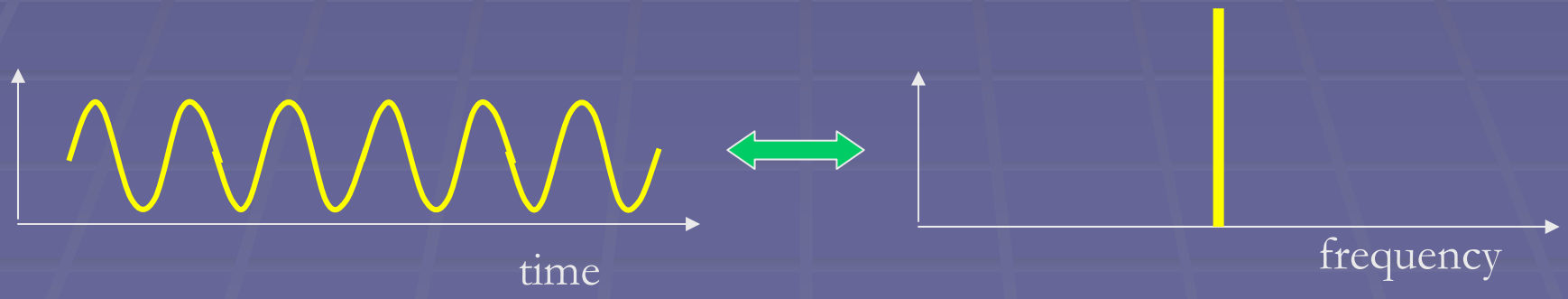
  ⇒ the law of momentum conservation

- The isotropy of space (every spatial direction is equivalent)

  ⇒ the law of angular momentum conservation

- The uniformity of time (the same physical law always holds)

  ⇒ the law of energy conservation



The Laws of Thermodynamics

- The first law: Energy conservation
  ⇒ There are no perpetual motion machines of the first kind.
  There is no free lunch.
  You cannot win.

An engine that produces more energy than the input

An engine that converts thermal energy into work with efficiency 100%

- The second law: Entropy always increases
  ⇒ There no perpetual motion machines of the second kind
  Left alone, things tend to get messy.
  You cannot break even.

Entropy S : the degree of disorder of the system

The number of microscopic states

$$S = k_B \log \Omega$$

Boltzmann constant

- The third law: The absolute zero of temperature is unreachable

Equilibrium/ Non-equilibrium

Physical system, when left alone, tend to relax toward equilibrium (a state with minimum free energy)

Free energy

This is nothing to do with the occult concept of “energy with no cost or effort”.

$$F = U - TS$$

energy

temperature

entropy

At absolute zero temperature (T=0), the minimum energy state is realized (ground state).
As the temperature is raised, the entropy term gain importance.

If the state with the smallest free energy changes

⇒ Phase transition

Linear / Nonlinear

- Linear equation: an equation that is first order with respect to variables
- Many physical phenomena are described with linear differential equations
  - Newton equation (classical mechanics), Maxwell equation (electrodynamics), Schroedinger equation (quantum mechanics)
  - Examples of nonlinear equation: Lorentz equation (chaotic dynamics), Navier-Stokes equation (fluid mechanics)

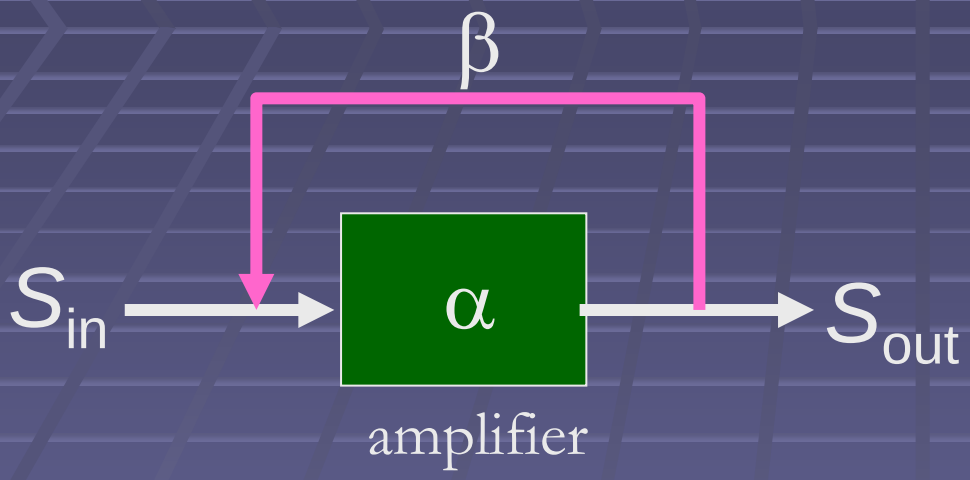
- For a linear equation, the superposition principle holds:

  If X and Y are solutions, then the sum $X+Y$ is also a solution

- Nonlinear equations are far more difficult to solve than linear equations

Feedback

Feeding some part of the output into input



$$S_{out} = \alpha S_{in}$$

$$S_{out} = \alpha\,(S_{in} + \beta S_{out})$$

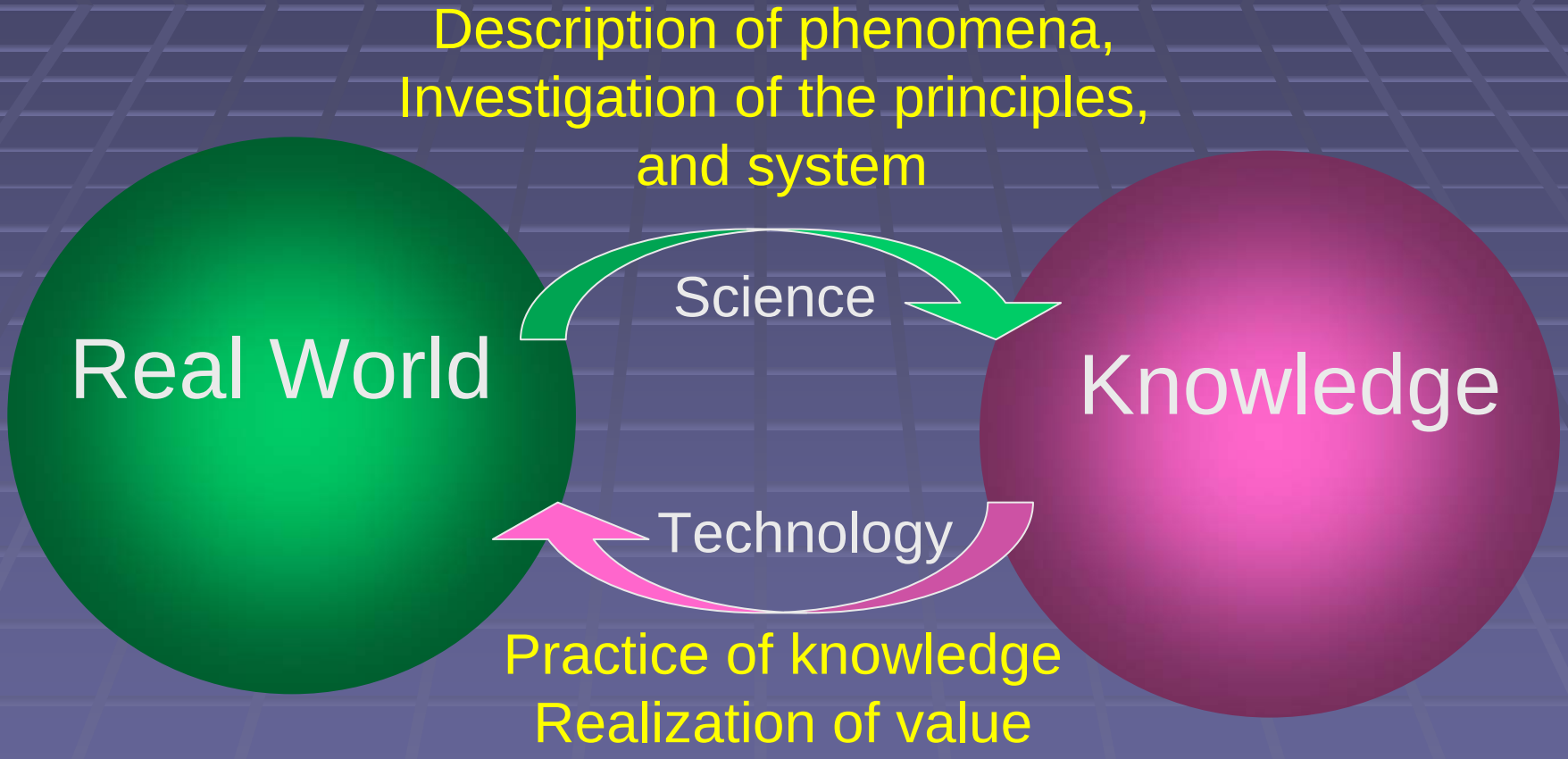
$$S_{out} = \frac{\alpha}{(1 - \alpha\beta)}\, S_{in}$$

⇒ If β is negative (negative feedback) $S_{out} = \frac{\alpha}{(1 + \alpha|\beta|)} S_{in} \sim \frac{1}{|\beta|} S_{in}$ stability

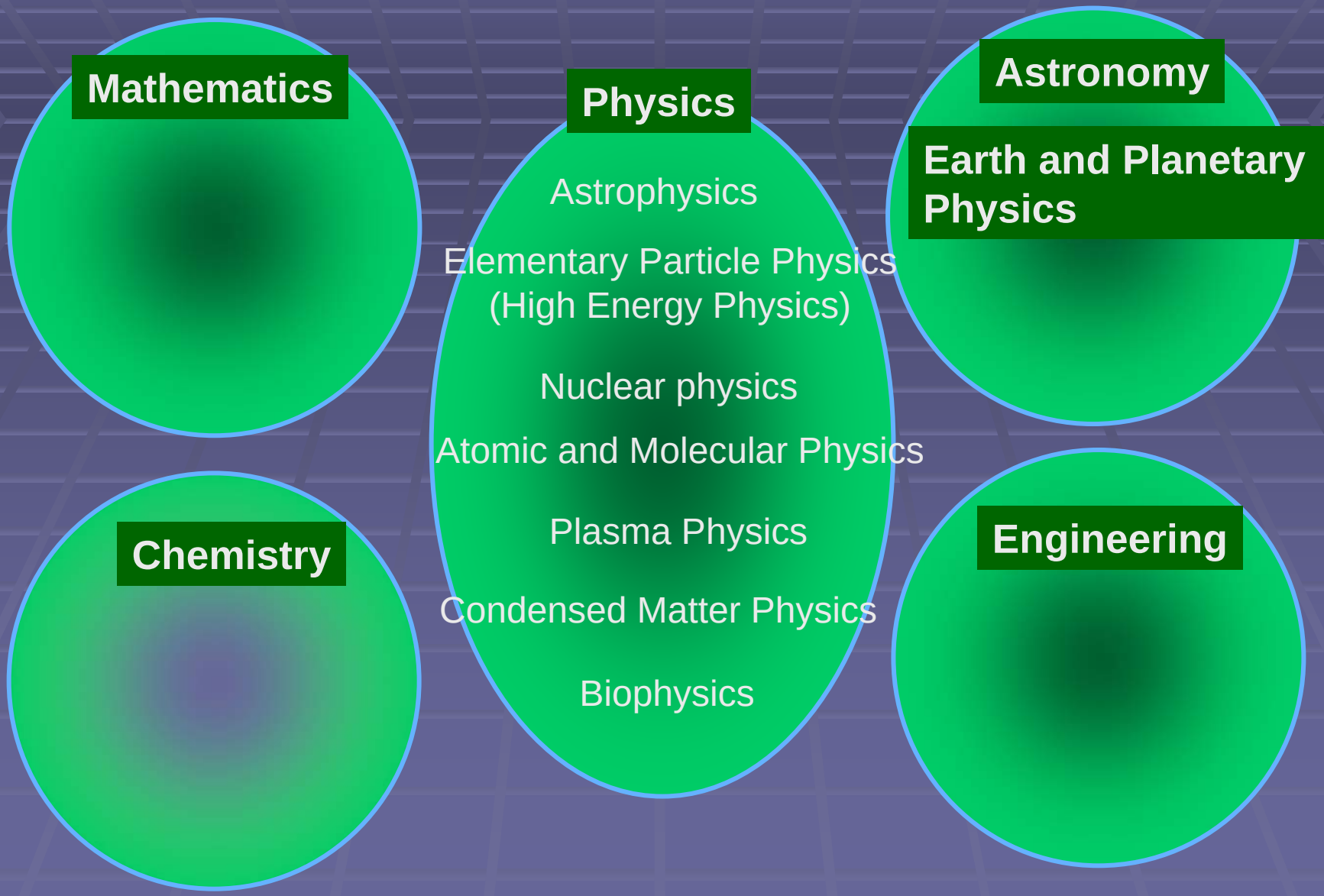
⇒ If β is positive (positive feedback) $S_{out} = \frac{\alpha}{(1 - \alpha\beta)}\, S_{in}$ $\alpha\beta = 1$

What is Condensed Matter Physics all about?

Science and Technology



Mathematical and Physical Sciences



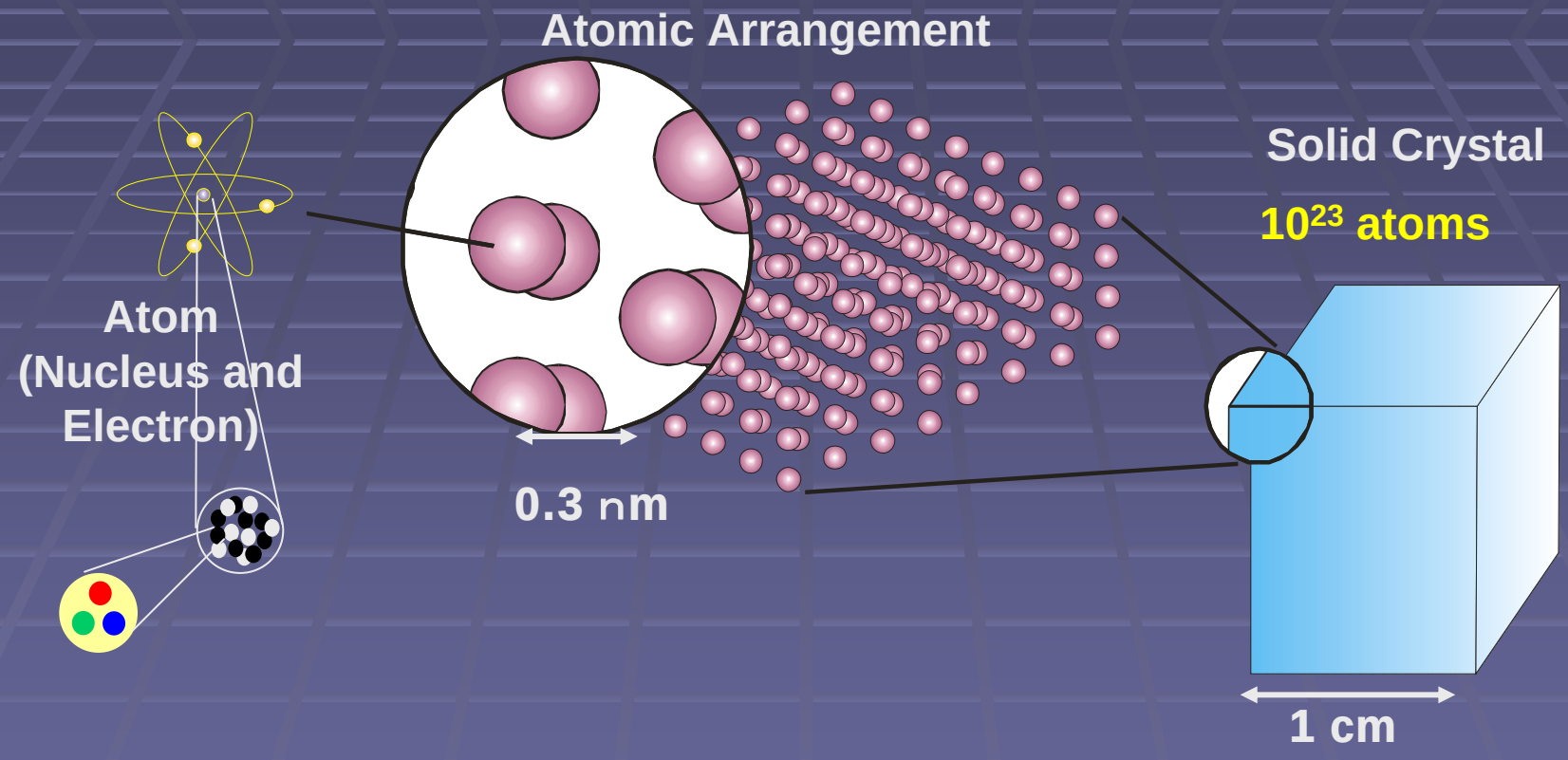
Physics Mindset

- Physics mindset (pursuit of truth) – seeking after logical and fundamental understanding of the natural world

  Unraveling the logical structure of nature

- Fundamental Questions of Elementary Particle Physics and Astrophysics
  - What are the basic building blocks of nature?
  - How did the universe begin? How will it end?
- Solid-State Physics (Condensed-Matter Physics)
  - To unravel the properties exhibited by diverse materials.
  - Diversity and complexity are the essential ingredients.
  - Nevertheless it is not “stamp-collection”. Systematic understandings and governing principles are sought in the diversity of materials and their properties.

The Hierarchical Structure of the Material World



Microscopic Scale ⟷ Macroscopic Scale

Physical World-View

Reductionism

Understanding the behavior of a system by reducing it to the laws of a more basic system.

e.g. What are the ultimate building blocks and forces?

=> Elementary particle physics

However even if we have found the ultimate building blocks and forces, we are still far from understanding everything, because each level of nature has its own laws of physics.

Emergent Properties

Systems of mutually interacting entities quite often exhibit novel and complex behavior that cannot be simply inferred from the properties of the individual entities.

Behavior of many body system => Phase transition

eg superconductivity, biological phenomena

”More is different.” (P.W.Anderson)

Workings of Condensed Matter Physics

- Efforts towards elucidation of various properties exhibited by diverse of materials on the basis of the fundamental principles of physics
  - Diversity does not mean “stamp-collection”. Universality and systematics are sought after.
- Characteristics of condensed matter physics
  - One can conduct controlled experiments.（as opposed to astrophysics, geophysics）
  - Small science（as opposed to Big Science）
  - Seamlessly connected to chemistry and applied physics. (and eventually to life sciences as well?)
- What does it mean that something is understood?
  - Comparison of theory and experiment: the cycle of modeling and experimental verification
  - The advent of computational physics

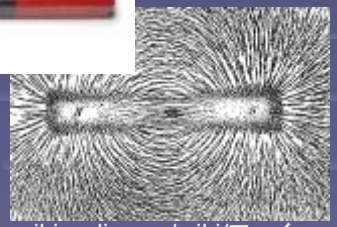
Diversity of Materials and Variety of Their Properties

- Why is diamond so hard?
- Why is ruby red?
- Why can iron become magnet?
- Why does copper conducts well?
- How does superconductivity occur?
- Optical fiber
- Liquid crystal
- ・・・・・・・・

http://commons.wikimedia.org/wiki/File:CZ_brilliant.jpg

http://ja.wikipedia.org/wiki/ファイル:Cut_Ruby.jpg

http://ja.wikipedia.org/wiki/ファイル:Bar_magnet.jpg

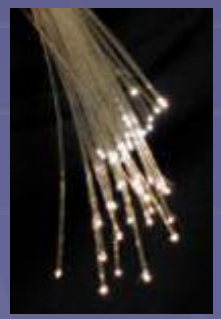


http://ja.wikipedia.org/wiki/ファイル:Magnet0873.png

http://ja.wikipedia.org/wiki/ファイル:Rg213_1.jpg

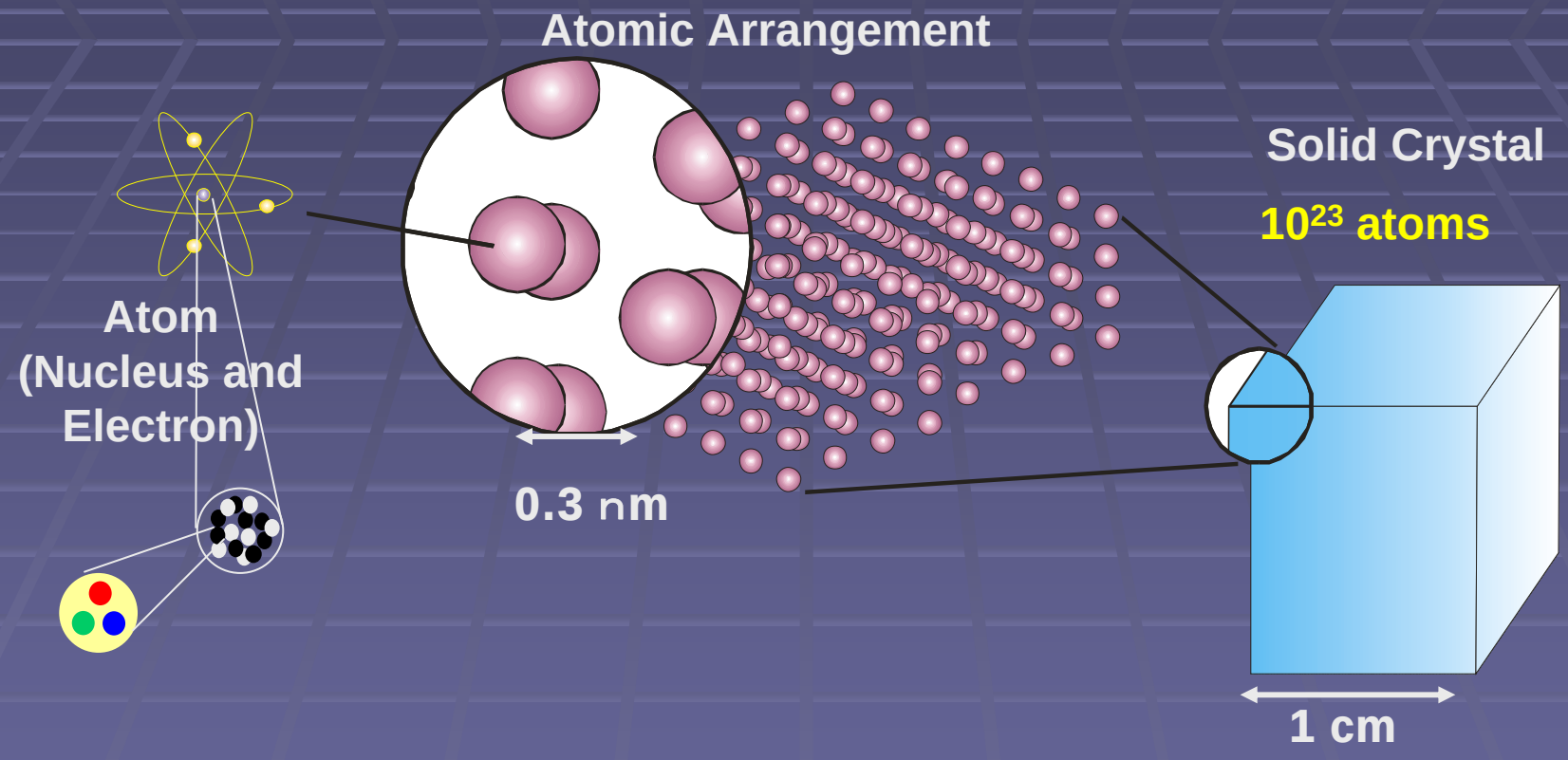
http://ja.wikipedia.org/wiki/ファイル:Shilirren_texture.jpg

http://ja.wikipedia.org/wiki/ファイル:Meissner_effect_p1390048.jpg



http://ja.wikipedia.org/wiki/ファイル:Fibreoptic.jpg

The Hierarchical Structure of the Material World



Microscopic Scale ⟷ Macroscopic Scale

Large Energy Scale ⟷ Small Energy Scale

Energy Scale

The Unit of Energy : Joule

$$\mathrm{J} = \mathrm{kg\,m^2/s^2}$$

Mass x Length^2/Time^2

Kinetic Energy

$$\frac{1}{2}mv^2$$

electron volt (eV)

The energy gained by an electron when it accelerates through an electrostatic potential of one volt

$$e = 1.6\times10^{-19}\,\mathrm{C}$$

$$1\,\mathrm{eV} = 1.6\times10^{-19}\,\mathrm{J}$$

Planck Constant

$$h = 6.62\times10^{-34}\,\mathrm{J\cdot s}$$

$$= 4.13\times10^{-15}\,\mathrm{eV\cdot s}$$

$$\hbar = \frac{h}{2\pi}$$

The Actors in Solid State Physics

Actors ("elementary" particles) in solid state physics

Electron

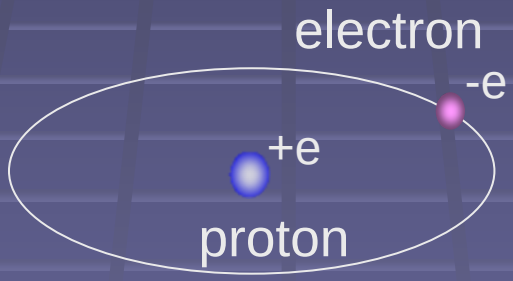
Nucleus (Proton + Neutron)

$$e = 1.60 \times 10^{-19}\ \mathrm{C}$$

$$m_e = 0.91 \times 10^{-30}\ \mathrm{kg}$$

$$m_p \approx m_n \approx 1840\, m_e$$

hydrogen atom



The interaction between the "elementary" particles: electromagnetic interaction

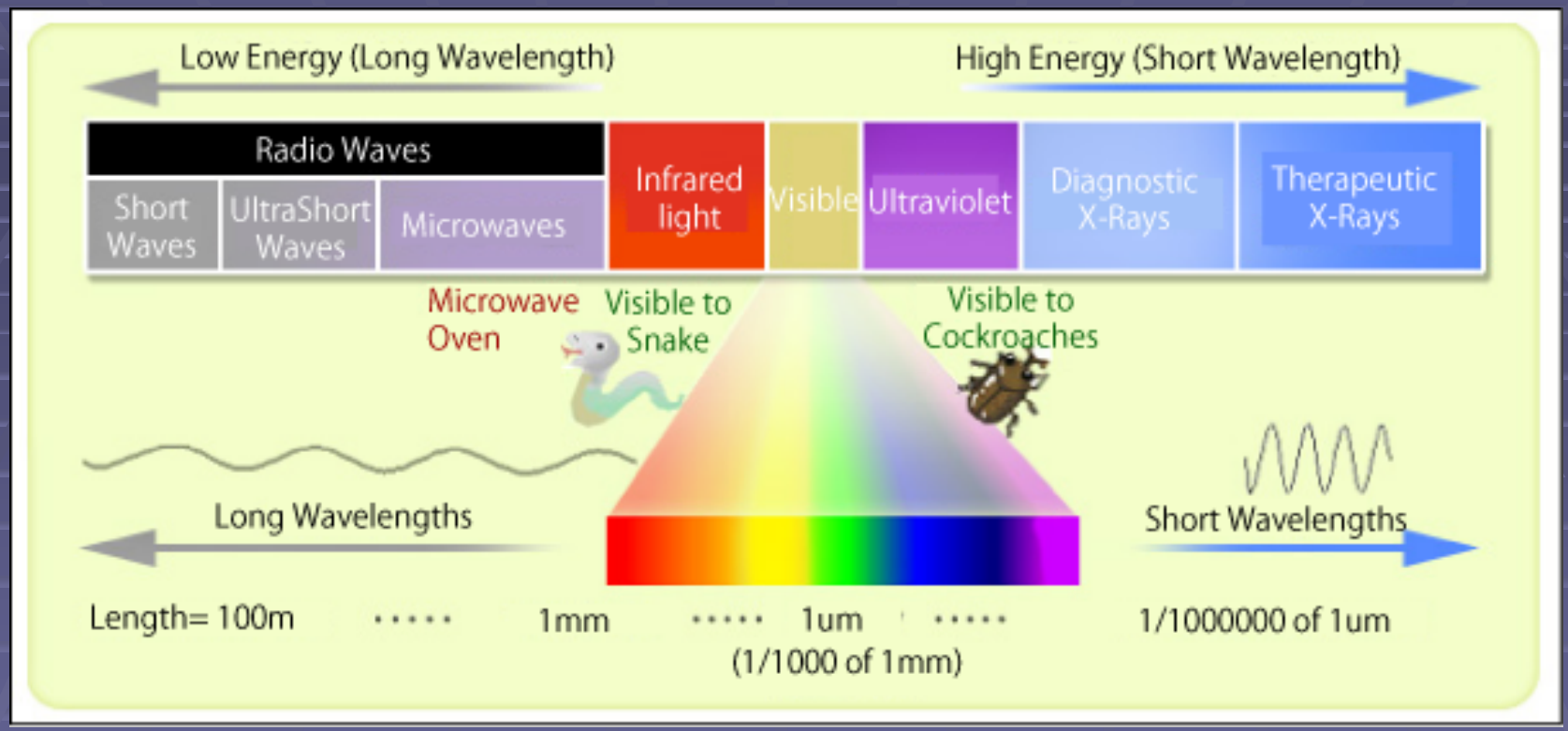
$h\nu$

Light (Electromagnetic Waves)

$$h = 6.62 \times 10^{-34}\ \mathrm{J \cdot s}$$

Photon

Light (Electromagnetic Waves)



From the Radiation Effects Research Foundation
http://www.rerf.or.jp/general/whatis/index.html 2009/3

Wavelength, frequency and wave number of light with energy 1eV are

$$h\nu = 1\,\mathrm{eV} \quad \leftrightarrow \quad \nu = 2.42\times10^{14}\ \mathrm{Hz}$$

$$\leftrightarrow \quad \frac{\nu}{c} = 8070\ \mathrm{cm}^{-1} \quad \leftrightarrow \quad \lambda = 1240\,\mathrm{nm}$$

quantum of light : photon

Objects of Condensed Matter Physics Research

Crystals (single crystal, polycrystal)
Disordered crystals (impurities, defects)
Amorphous, Glass, Quasicrystals
Liquids, Quantum fluids
Fine particles, Clusters
Surface, Interface
Artificial Crystals (Superlattices), Nanostructures
Soft matter (Polymers, Liquid crystals, Gels)
Cold Atoms (Bose condensate)

Material Properties

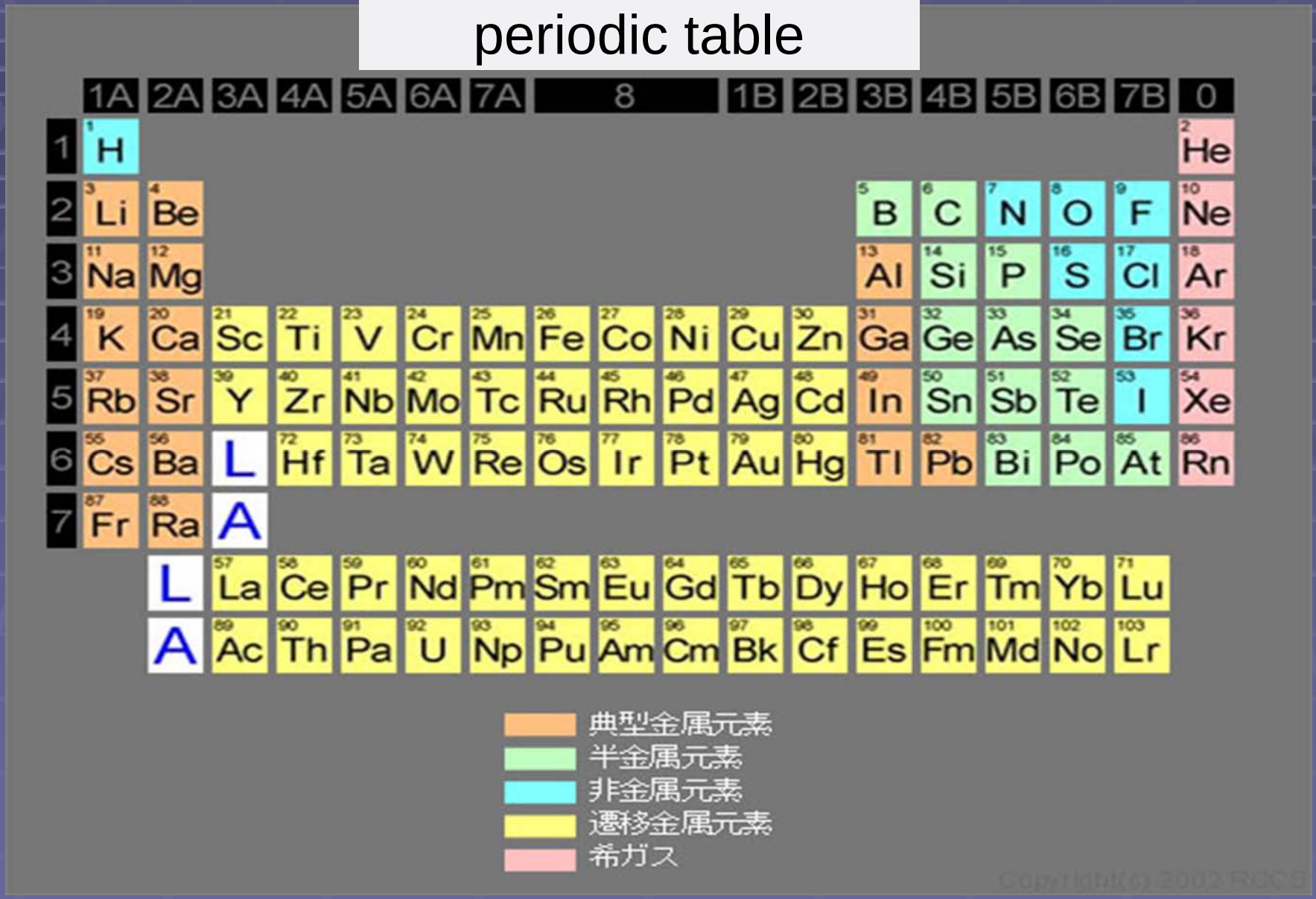
- Electrical Properties
  - Electrical Conduction (metal, insulator, semiconductor)
  - Ferroelectricity
  - Superconductivity
- Magnetic Properties
  - Ferromagnetism （Why is iron magnetic? ）
- Optical Properties
  - Color of jewels, Metallic luster ,
  - Light emission (LED, semiconductor laser)

Matter and the Physical Environment

- Physical properties: response to an external perturbation
- The same material can exhibit different properties depending on the physical environment
  - Temperature
  - Pressure, stress
  - Electric field
  - Magnetic field
  - Interaction with light (electromagnetic wave)
  - Sample size

The Structure of Atoms

The Periodic Table of Elements



Where Did Chemical Elements Come From?

⇒Suto Sensei's lecture

1. At the time of Big Bang, lighter atomic nuclei such as hydrogen, helium, are produced

2. Stars are formed due to gravitation, then in the course of nuclear reaction in stars heavier atomic nuclei (up to iron) are formed. then they were scattered by supernova explosion.

Stars are pressure cookers of elements.

∗ We are all made of "star-dusts".

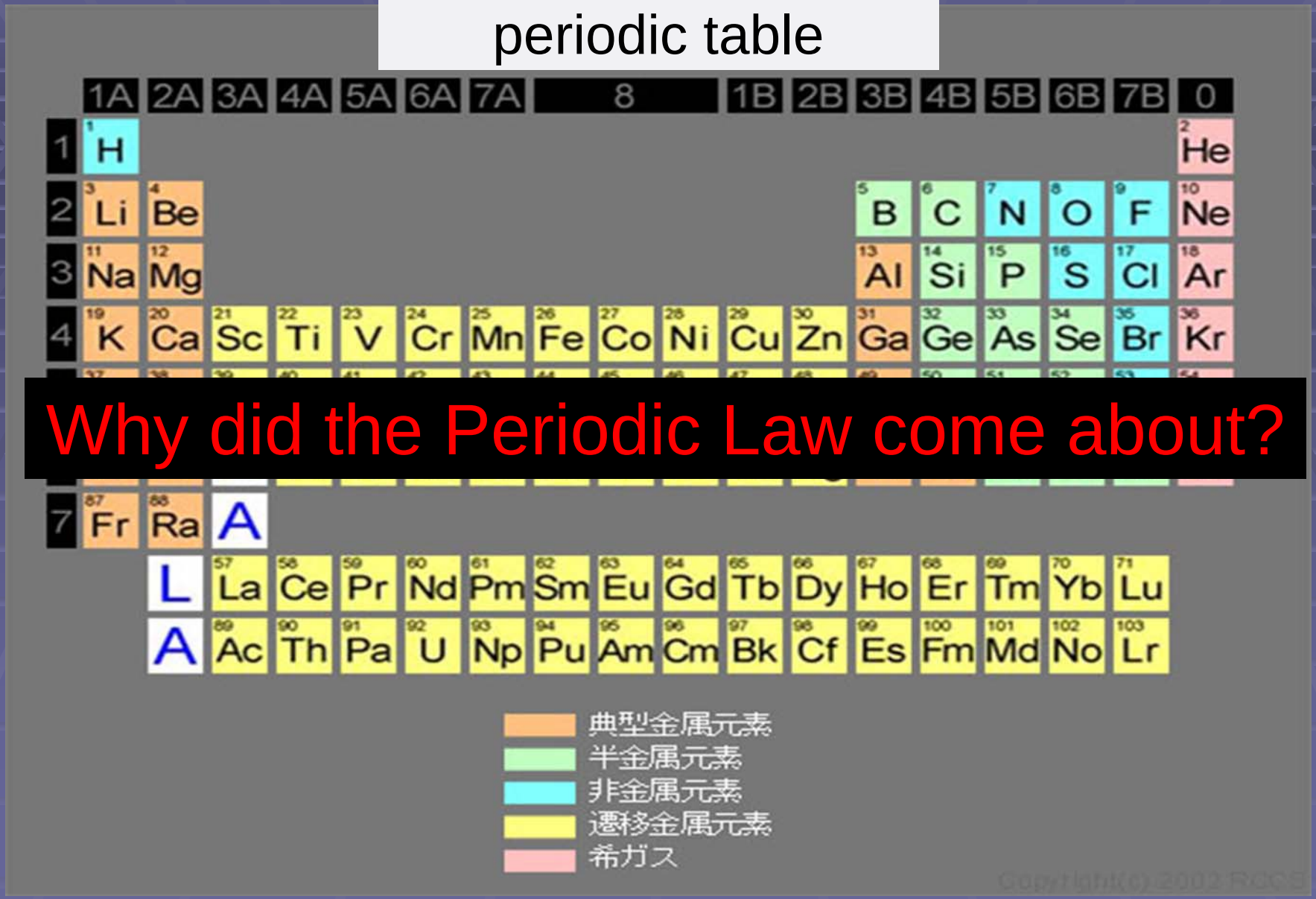
The Periodic Table of Elements in Chinese

周期	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
族	I A																	0
1	1 H 氫	II A											III A	IV A	V A	VI A	VII A	2 He 氦
2	3 Li 鋰	4 Be 鈹											5 B 硼	6 C 碳	7 N 氮	8 O 氧	9 F 氟	10 Ne 氖
3	11 Na 鈉	12 Mg 鎂	III B	IV B	V B	VI B	VII B		VIII		I B	II B	13 Al 鋁	14 Si 硅	15 P 磷	16 S 硫	17 Cl 氯	18 Ar 氬
4	19 K 鉀	20 Ca 鈣	21 Sc 鈧	22 Ti 鈦	23 V 釩	24 Cr 鉻	25 Mn 錳	26 Fe 鐵	27 Co 鈷	28 Ni 鎳	29 Cu 銅	30 Zn 鋅	31 Ga 鎵	32 Ge 鍺	33 As 砷	34 Se 硒	35 Br 溴	36 Kr 氪
5	37 Rb 銣	38 Sr 鍶	39 Y 釔	40 Zr 鋯	41 Nb 鈮	42 Mo 鉬	43 Tc 鎝	44 Ru 釕	45 Rh 銠	46 Pd 鈀	47 Ag 銀	48 Cd 鎘	49 In 銦	50 Sn 錫	51 Sb 銻	52 Te 碲	53 I 碘	54 Xe 氙
6	55 Cs 銫	56 Ba 鋇	57- 71 鑭系	72 Hf 鉿	73 Ta 鉭	74 W 鎢	75 Re 錸	76 Os 鋨	77 Ir 銥	78 Pt 鉑	79 Au 金	80 Hg 汞	81 Tl 鉈	82 Pb 鉛	83 Bi 鉍	84 Po 釙	85 At 砹	86 Rn 氡
7	87 Fr 鍅	88 Ra 鐳	89- 103 錒系	104 Rf 鑪	105 Db 𨧀	106 Sg 𨭎	107 Bh 𨨏	108 Hs 𨭆	109 Mt 䥑	110 Ds 鐽	111 Rg 錀	112 Uub	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo
		鑭系元素	57 La 鑭*	58 Ce 鈰	59 Pr 鐠	60 Nd 釹	61 Pm 鉕	62 Sm 釤	63 Eu 銪	64 Gd 釓	65 Tb 鋱	66 Dy 鏑	67 Ho 鈥	68 Er 鉺	69 Tm 銩	70 Yb 鐿	71 Lu 鎦	
		錒系元素	89 Ac 錒**	90 Th 釷	91 Pa 鏷	92 U 鈾	93 Np 錼	94 Pu 鈽	95 Am 鋂	96 Cm 鋦	97 Bk 鉳	98 Cf 鉲	99 Es 鑀	100 Fm 鐨	101 Md 鍆	102 No 鍩	103 Lr 鐒	

鹼金屬	鹼土金屬	鑭系元素	錒系元素	過渡金屬
主族金屬	類金屬	非金屬	鹵素	惰性氣體

The Periodic Table of Elements

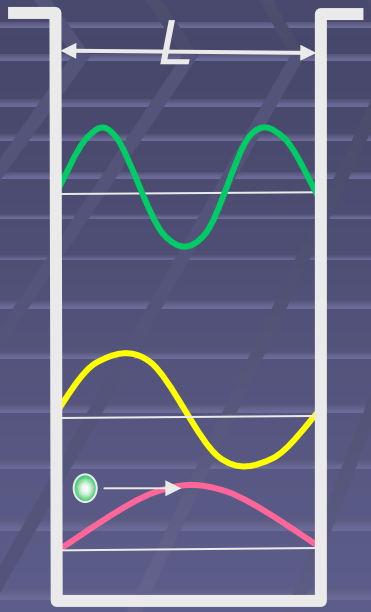
periodic table



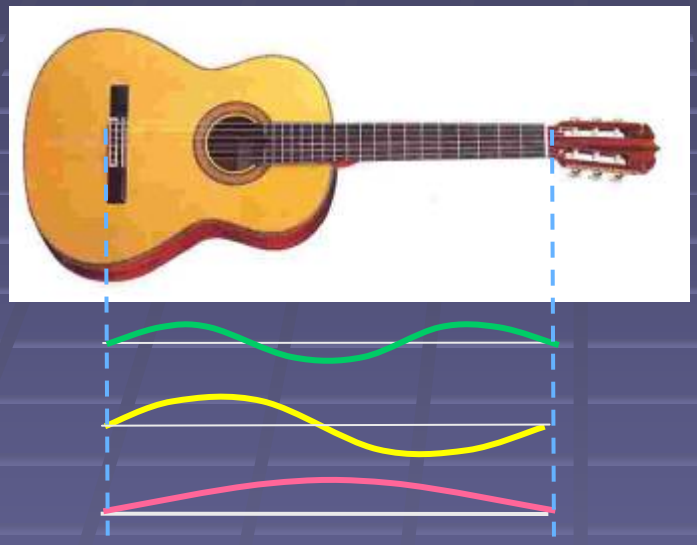
Why did the Periodic Law come about?

The Quantization of Energy

According to quantum mechanics, an electron behaves both particle-like and wave-like.

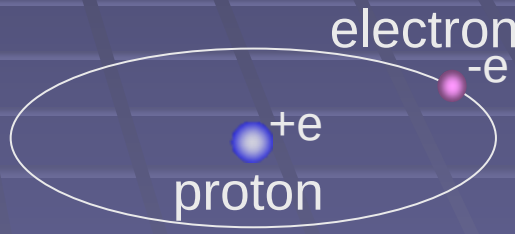


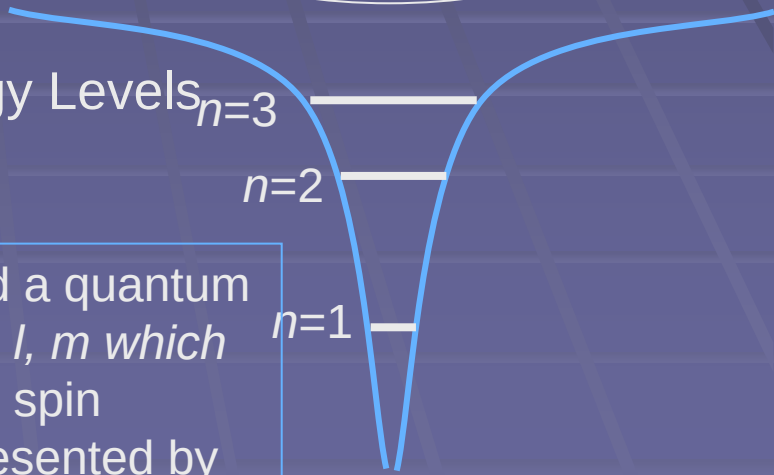
Electron in a box



Standing Wave ⇒ Discrete Energy Levels
（electrons' room）

The Hydrogen Atom：
an electron orbiting around an atomic nucleus (a proton)



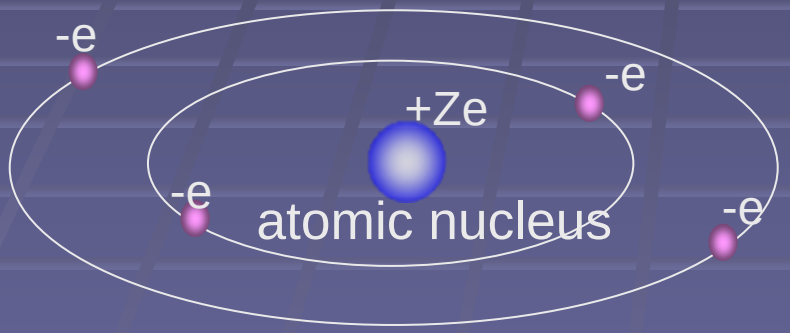


The index n, which represents energy level is called a quantum number. There are other kinds of quantum number *l, m which are concerned with* rotation, and σ concerned with spin (rotation).⇒ The energy level of an electron is represented by (n, l, m, σ).

Electron Energy Levels of Atom

Multi-electron atom consists of a nucleus with charge +Ze at the center and Z electrons orbiting around it.

Each energy level can accommodate two electrons with different spin orientations



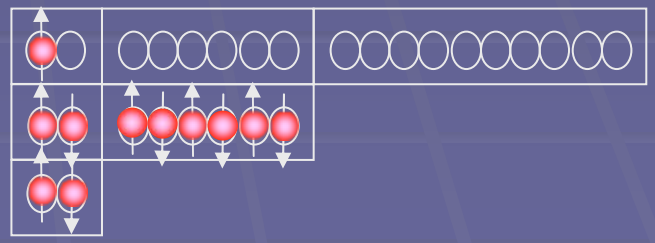
Hotel "ATOM"

1st floor	1 room
2nd floor	1+3 rooms
3rd floor	1+3+5 rooms
.....	

(Each room can accomodate two guests)

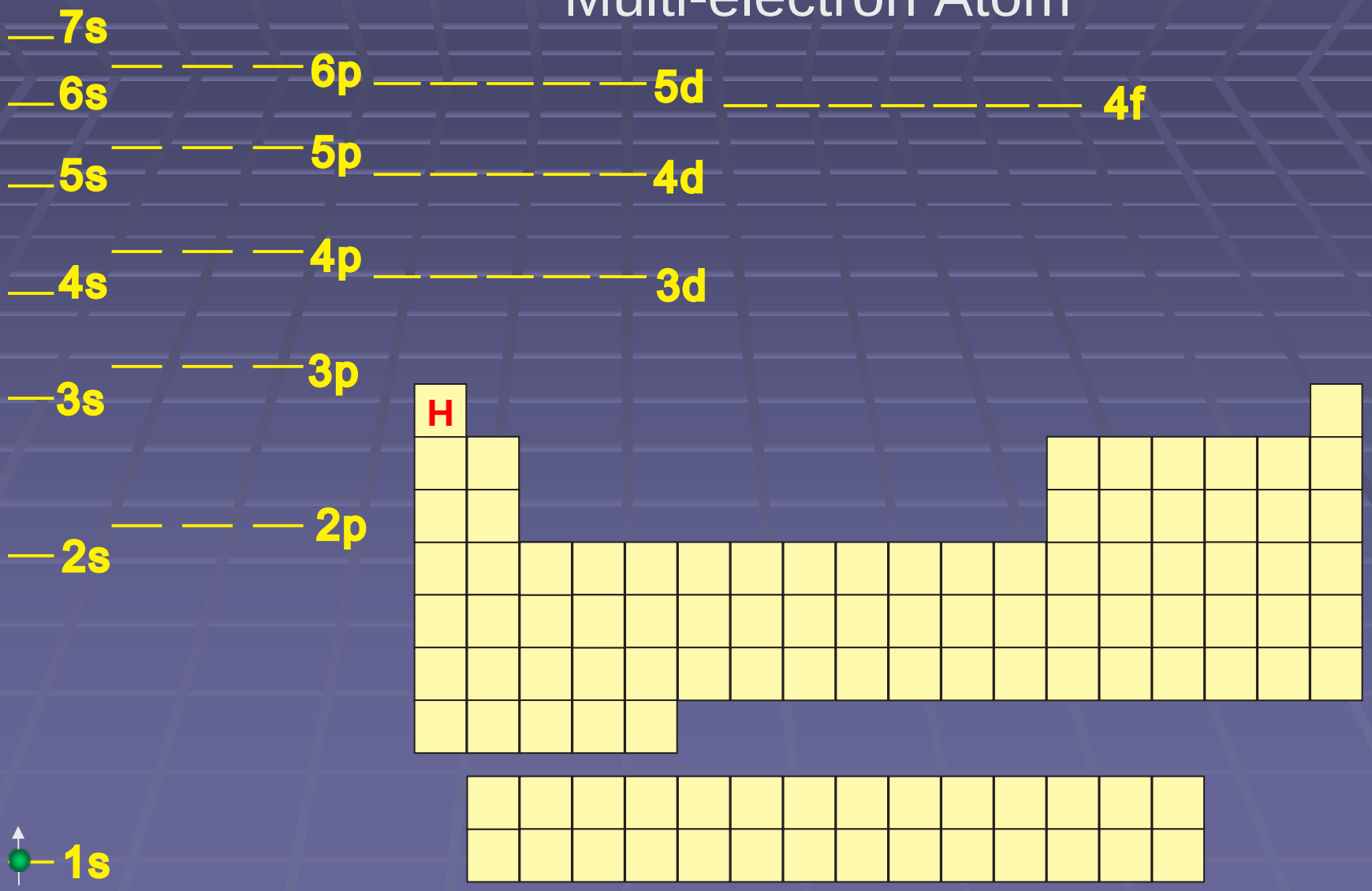
Na: Z=11

$$\text{Na}: (1s)^2(2s)^2(2p)^6(3s)^1$$



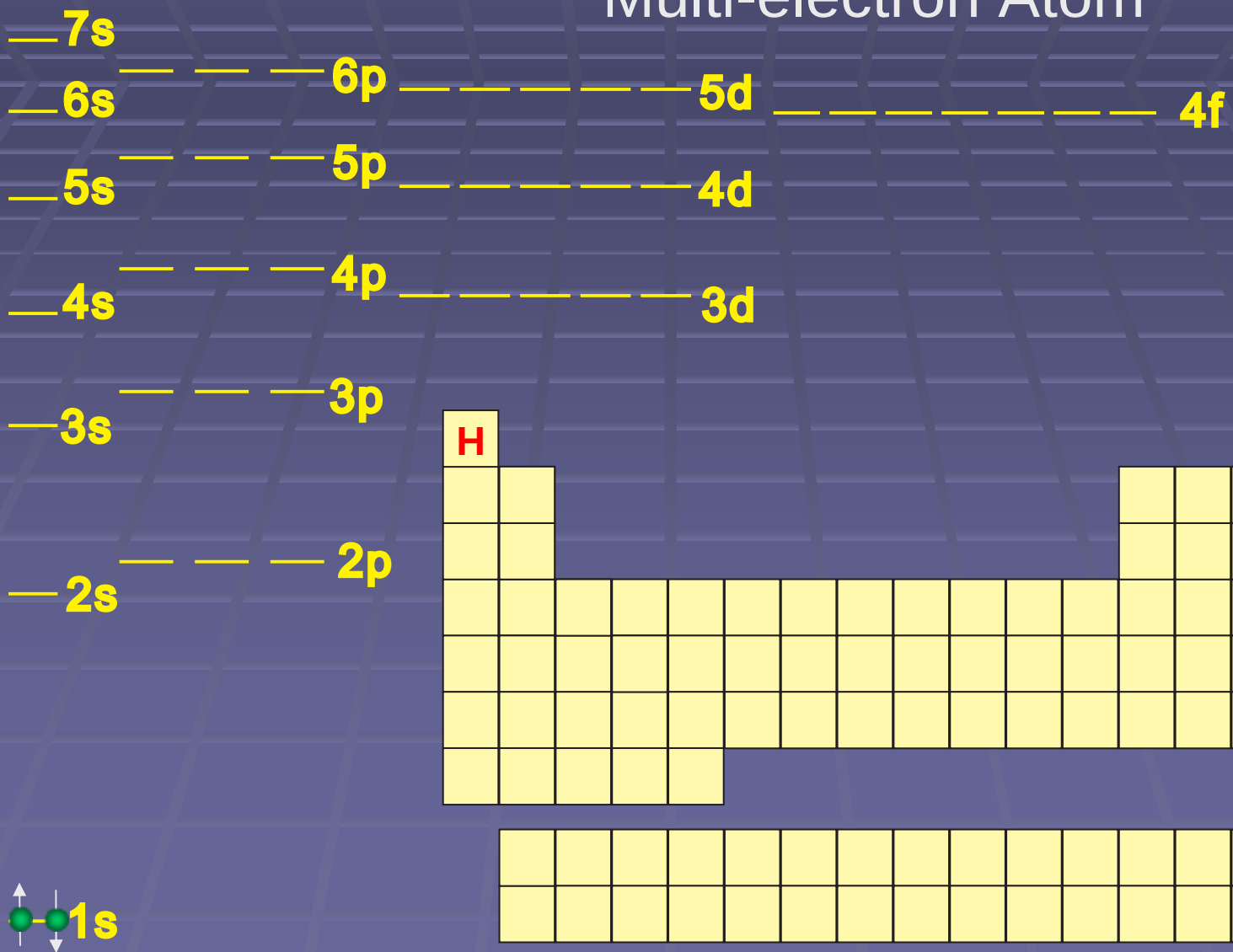
Filling the States with Electrons

Multi-electron Atom



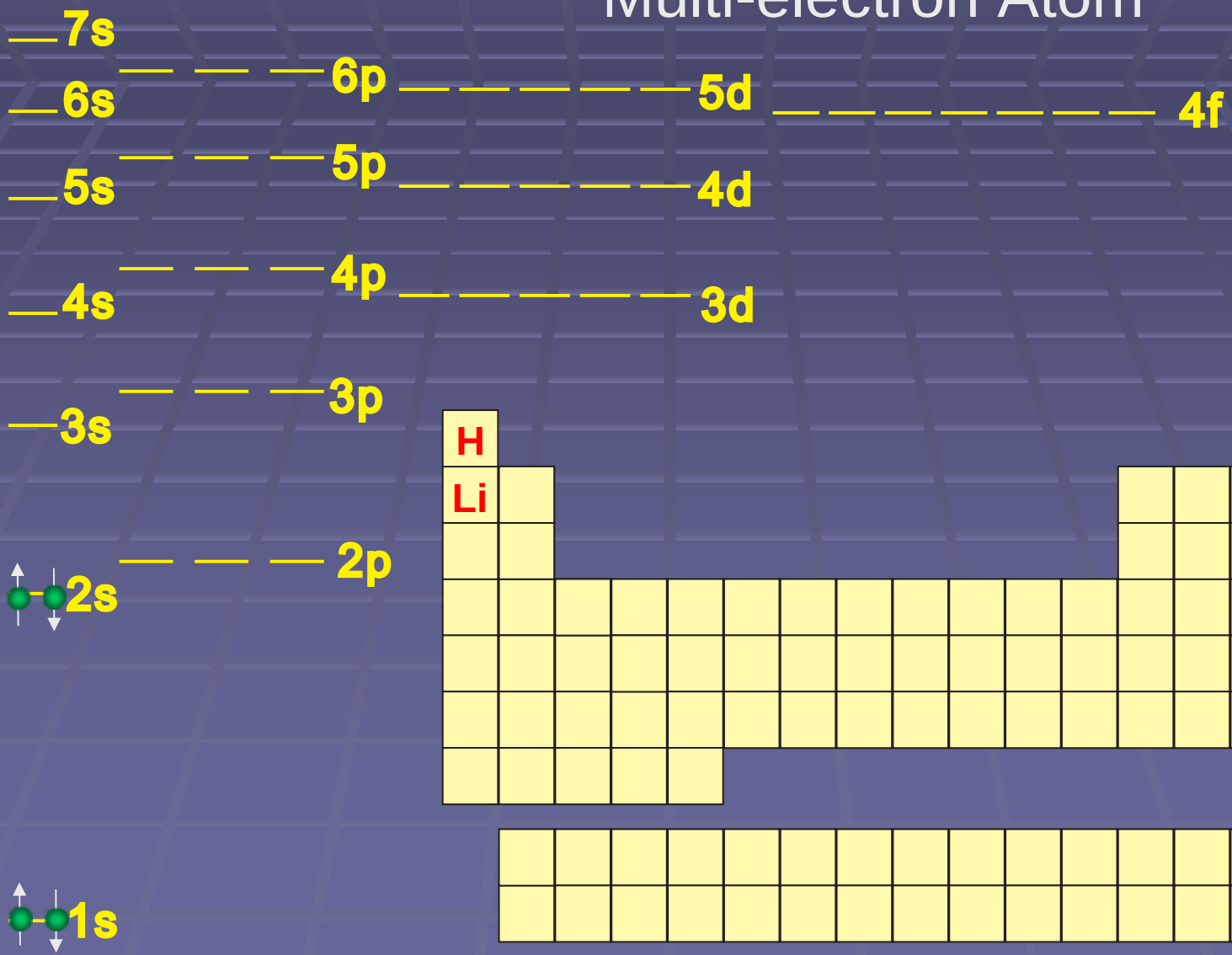
Filling the States with Electrons

Multi-electron Atom



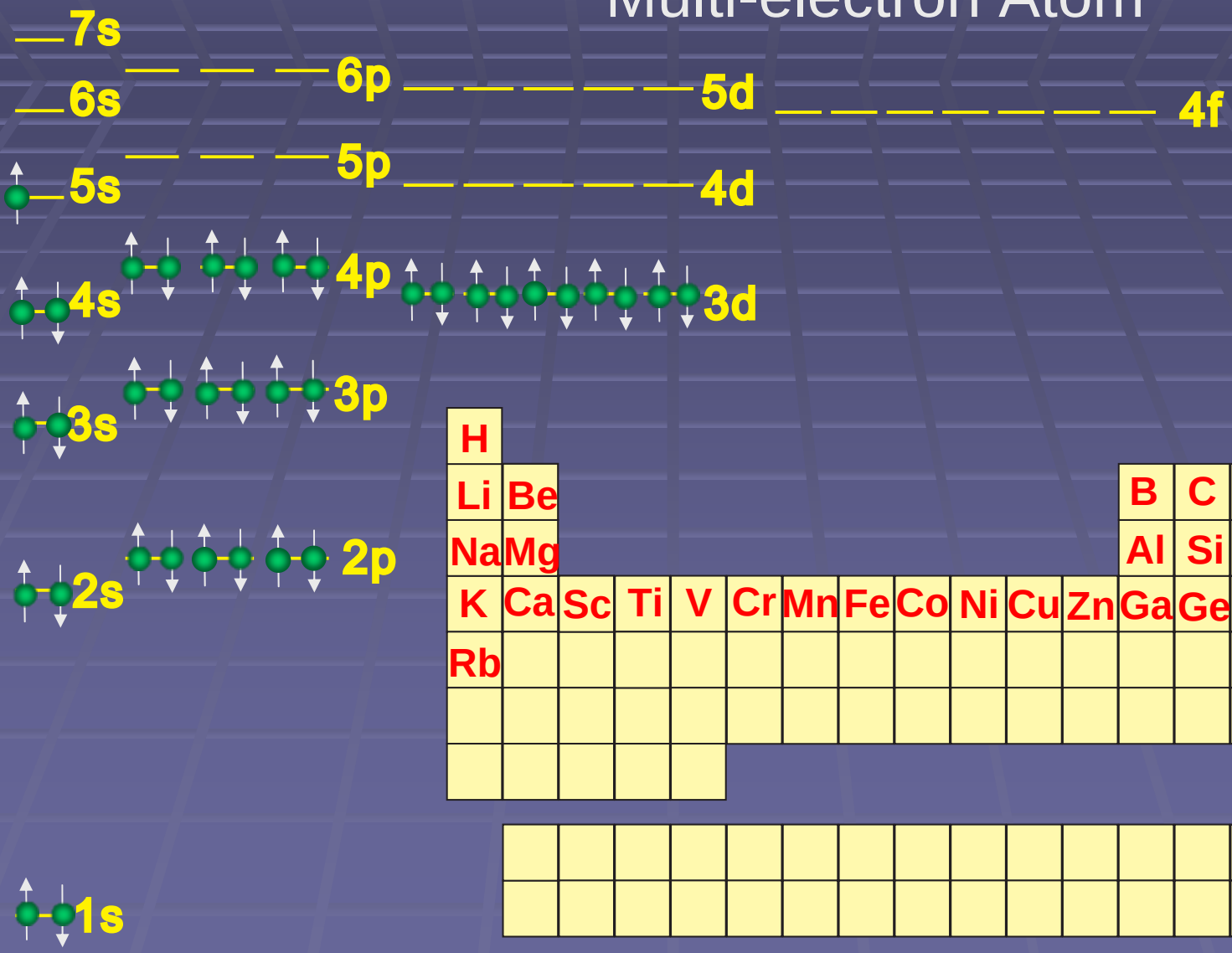
Filling the States with Electrons

Multi-electron Atom



Filling the States with Electrons

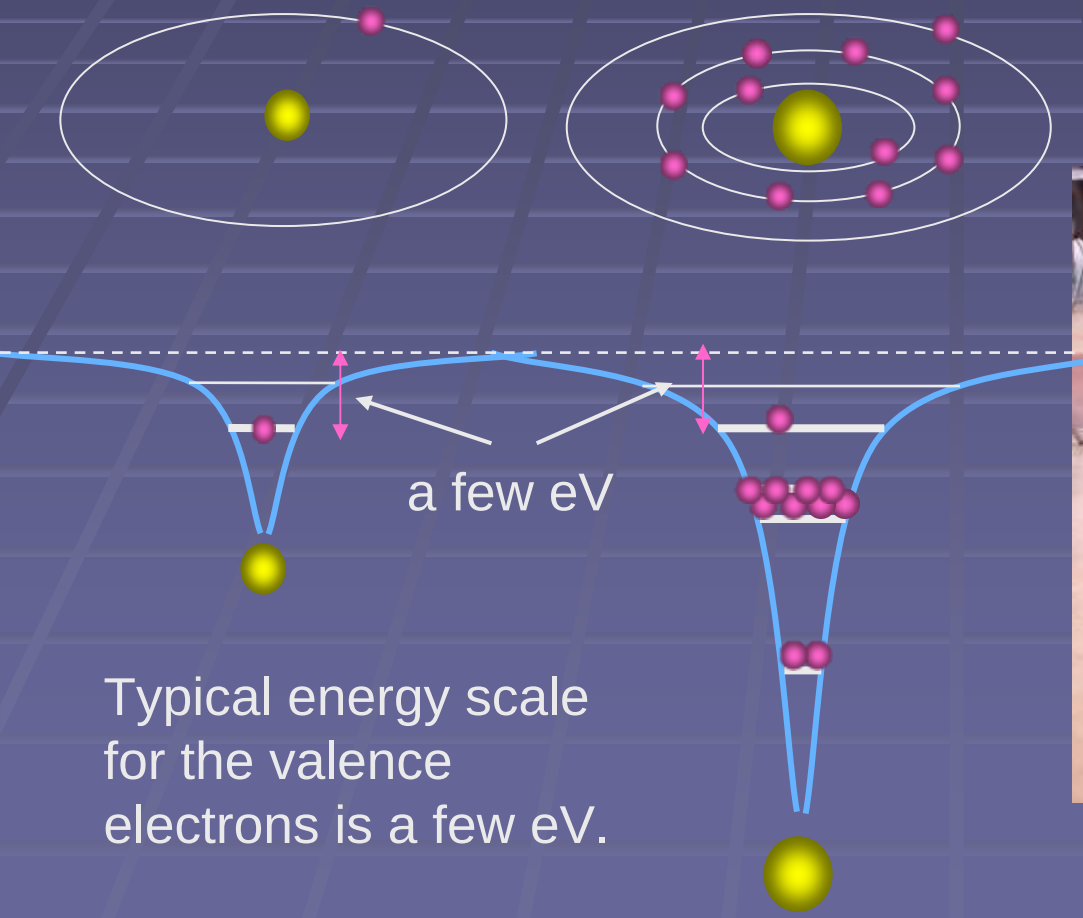
Multi-electron Atom



H																He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb																	

Valence Electrons

- The outermost electrons (valence electrons) determine the chemical properties of the atom



Typical energy scale for the valence electrons is a few eV.

The top-most tray always stays at the same position.

The Periodic Table of Elements

Those electrons that governs the chemical properties of an atom are those in the outer-most shell (which can be easily separated from the atom) => Valence Electrons

The atoms with similar electron configuration of the outer-most shell exhibit similar chemical properties => Periodic Law

It is more important to understand why the periodic law holds, than to blindly memorize the periodic table. However, it is certainly useful to memorize the periodic table.
If you try to memorize the periodic table, you should do so but along the column rather than along the row. (The reason should be clear for you by now.)

The Electronic Energy Level of Atoms

While the larger the Z of the atom, the stronger the Coulomb attraction of the nucleus, the number of electrons that screen the force also increase. As a result, the energy level of the electrons in the outer-most shell always stays on the order of a few eV.

The relevant energy scale of solid state physics is on the order eV to meV

Temperature T ⇔ Thermal Energy $k_B T$

Boltzmann Constant $k_B = 1.38 \times 10^{-23}\ \mathrm{J/K}$

Room Temperature $T = 300\ \mathrm{K} \quad \leftrightarrow \quad k_B T = 25\ \mathrm{meV}$

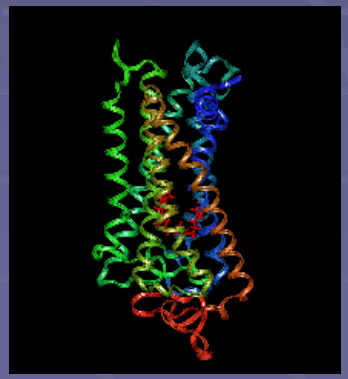
The energy scale for chemistry (and biology) is on this order of magnitude.

Familiar Examples

A battery is 1.5V
Electromotive force based on the exchange of electrons

Laser Pointer
Red light ~1.5eV, Green light ~2.5eV

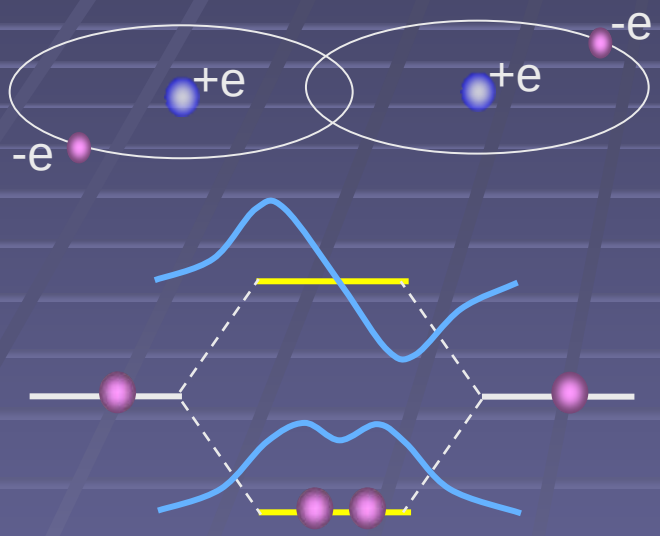
Why is visible light in the order of ~ eV to begin with?
Rhodopsin : the light-receiving protein of the retina is in keeping with the energy range of visible light



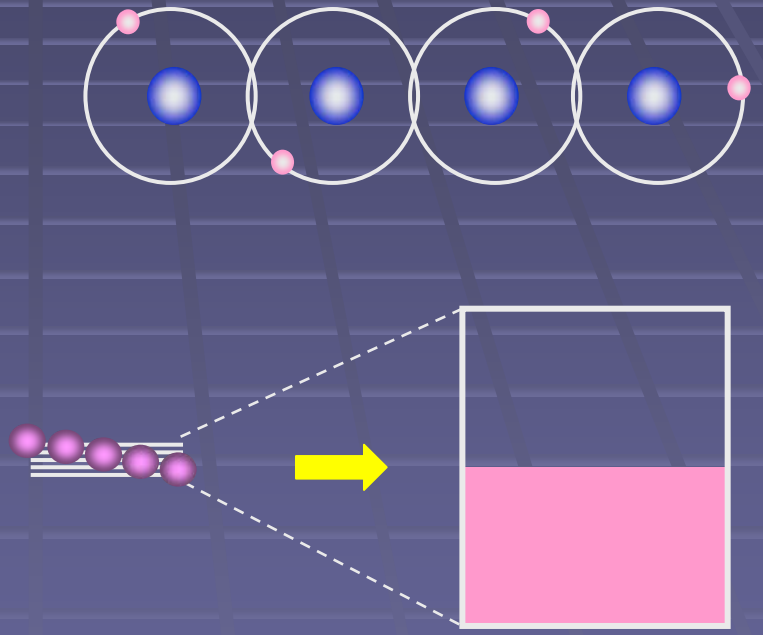
From Atoms to Solids

Putting Atoms Together

Hydrogen molecule :H_2

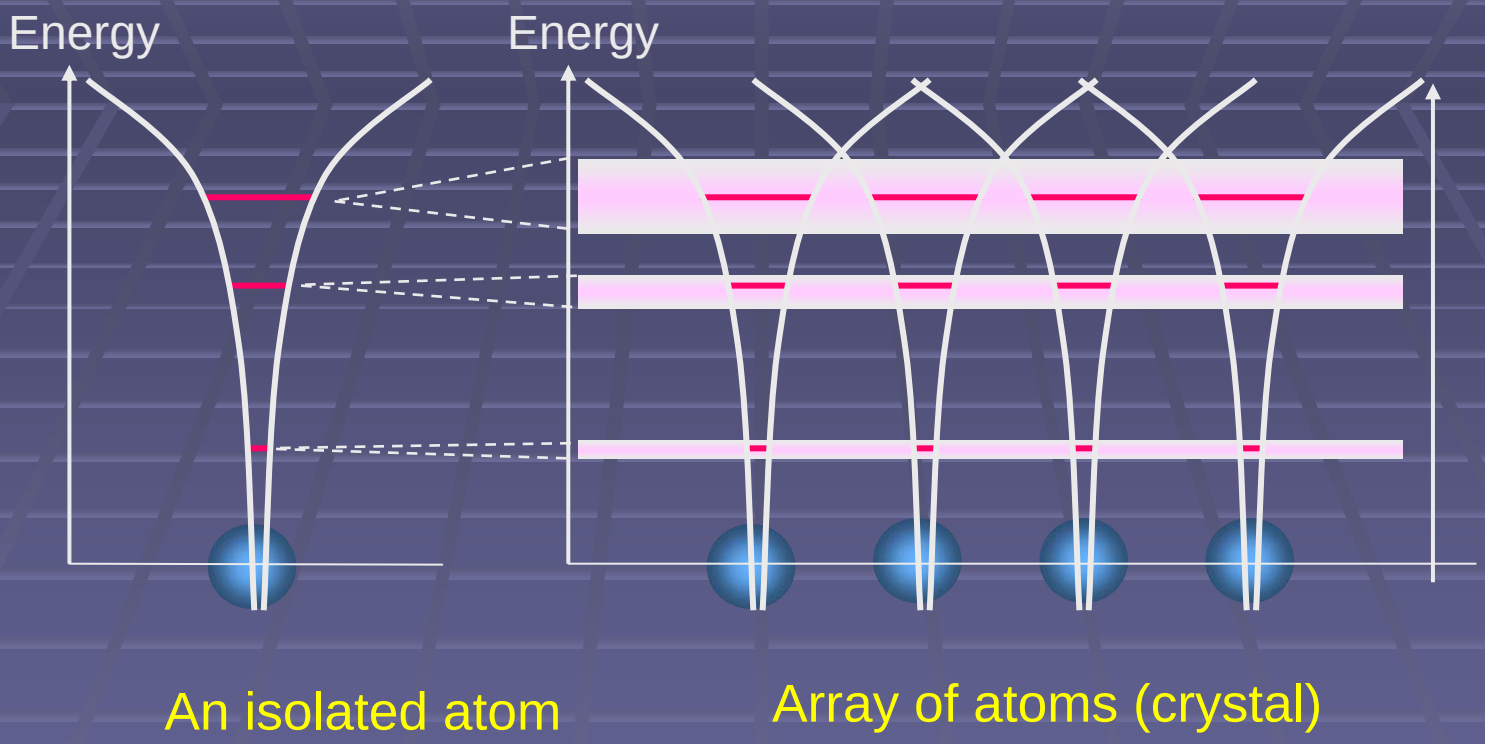


One-dimensional array of hydrogen atoms (hypothetical)



The transfer of electrons depends on the overlap of electron clouds of adjacent atoms.
With sufficient overlap, electrons can migrate over the entire crystal structure.

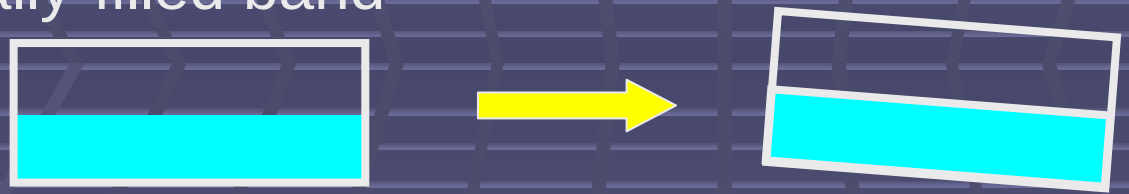
Formation of Energy Band by Electron Transfer



Due to the transfer of electrons between adjacent atoms, each of the discrete electronic levels is broadened and forms an energy band.

Metals and Insulators

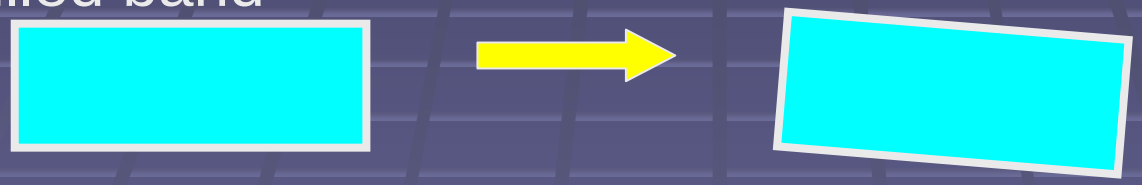
Partially-filled band



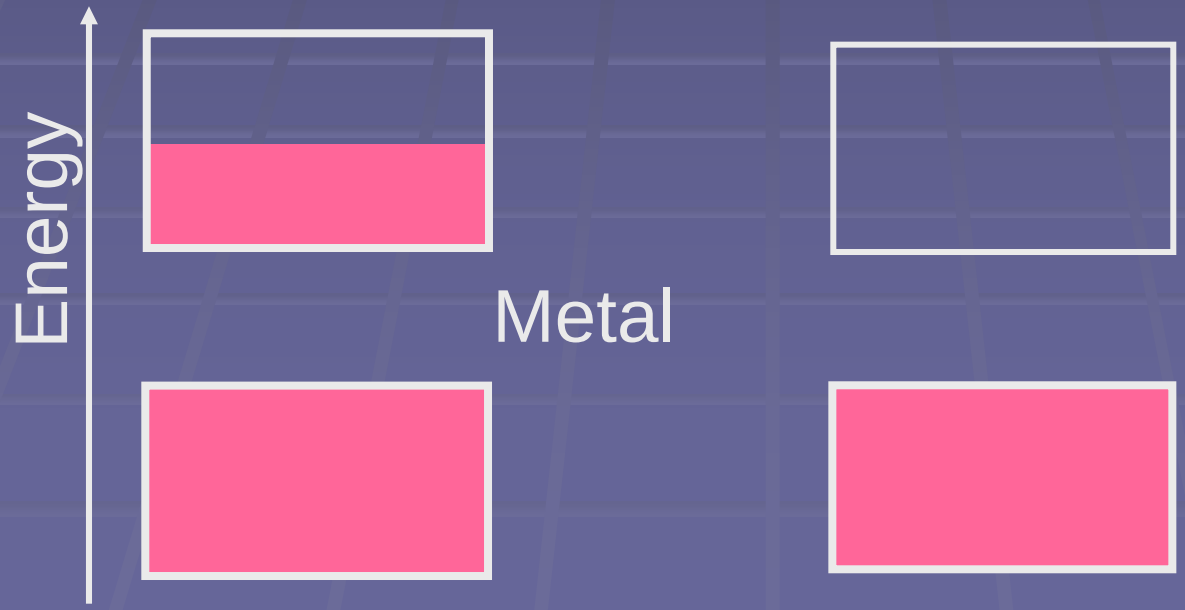
Electrical current does flow

upon applying an electrical field

Filled band



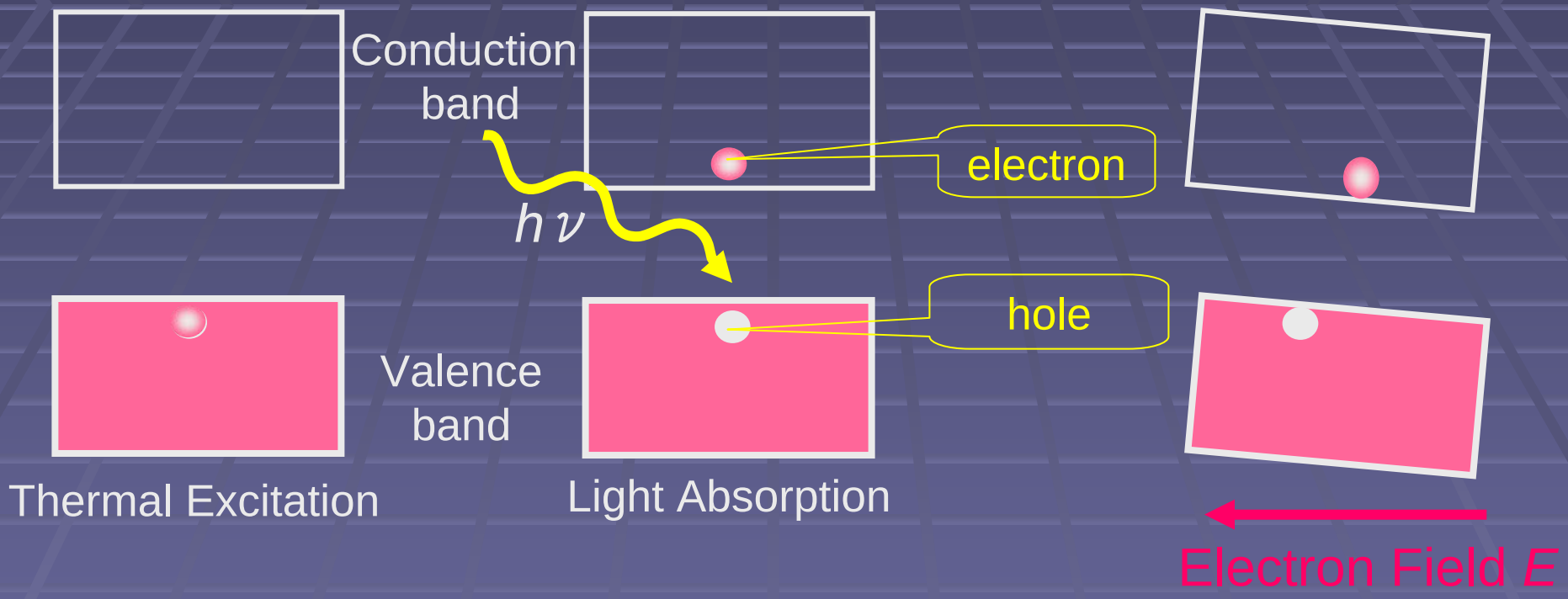
Electrical current does not flow



Metal

Insulator (band Insulator)

Electrons and Holes in Semiconductors



In semiconductors, low density carriers (electrons in the conduction band and holes in the valence band) are created by thermal excitation or photo-absorption and they conduct electricity.

Summary

- Modern hi-tech society and materials science
- The tales of big and small
- What is condensed matter physics all about?
- Some basic concepts in physics
- Hierarchy in materials world
- The structure of atoms
  - Periodic table
- From atoms to solids
  - Electronic bands
  - Metal, insulator, and semiconductor