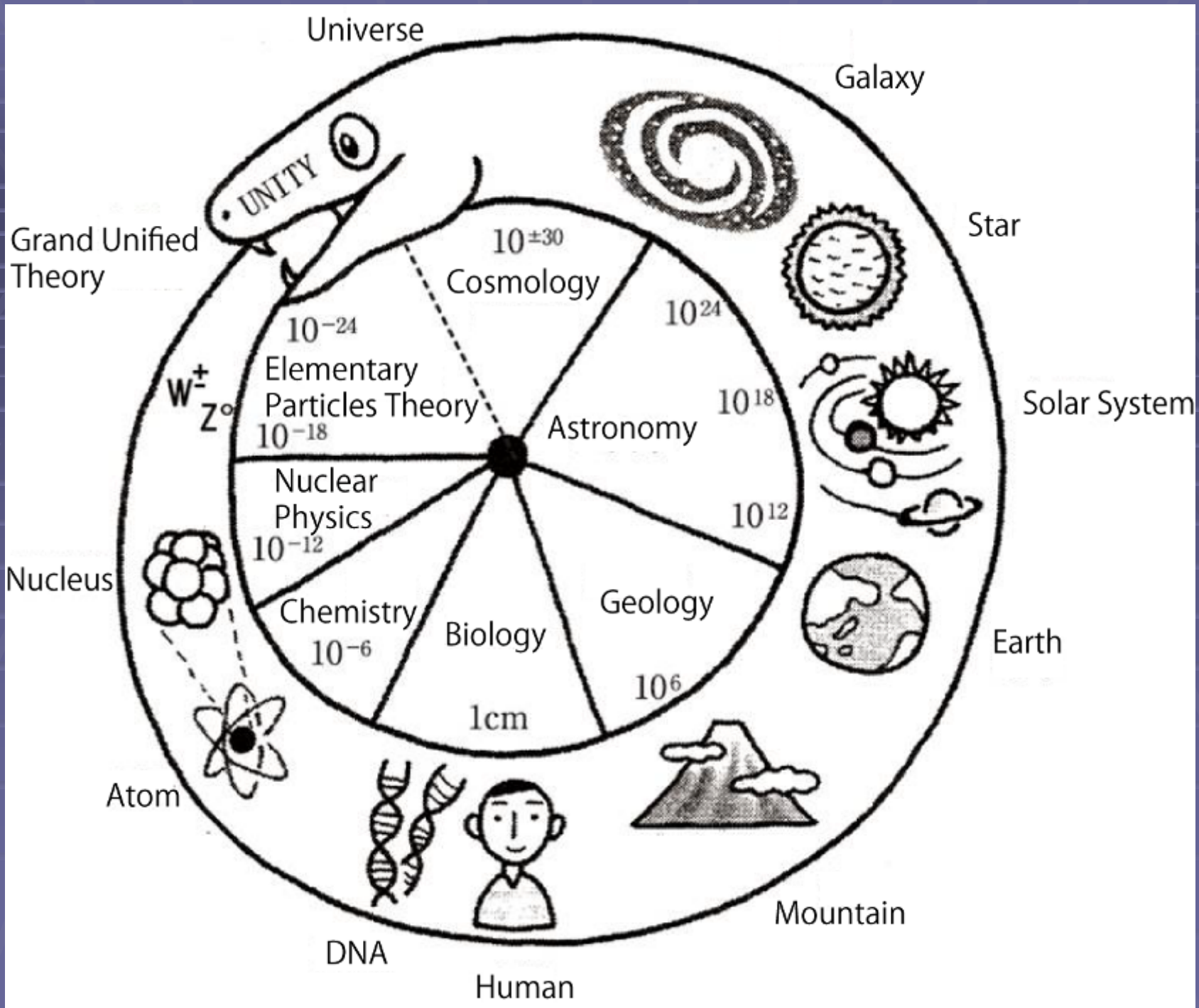

Universe
Galaxy
Star
Solar System
Earth
Mountain
Human
DNA
Atom
Nucleus
Grand Unified Theory
UNITY
$10^{\pm 30}$
Cosmology
10^{24}
10^{18}
Astronomy
10^{12}
Geology
10^{6}
1cm
Biology
Chemistry
10^{-6}
Nuclear Physics
10^{-12}
Elementary Particles Theory
10^{-18}
10^{-24}
$W^{\pm}$
Z^{0}

A Synopsis on Science
A Journey through 13.7 billion years of "Matter"
from The Big Bang to a Green Earth

Lectures 4～6
The Properties of Matter

Tokyo University Institute for Solid State Physics
Yasuhiro Iye

A Synopsis on Science
=> Towards a “Combination of The Arts and Sciences”

- (Fortunately or unfortunately) Those who have been accepted into Tokyo University, (whether they like it or not) are expected to be active participants at the center (although not limited to the center) of future society.
- Therefore, you are expected to acquire both specialized knowledge and a broad education.
- This erudition will also be a key to enriching your own lives.
- (A little voice says “What about myself?)
- ⇒ Being a teacher is an occupation where you make demands of students while remaining blind to your own shortcomings.

The Utility of Learning Physics

- The value in people learning physics, who are not majoring in physics, is that it "develops common sense". For example, common sense can skeptically discern talk of questionable paranormal phenomenon that contradicts the principles of physics. Principles such as the Law of Conservation of Energy, the Law of Increasing Entropy, and the Principle of Causality.
- On the other hand, to people who major in physics, one of the best things about physics is the "joy of defying common sense".
- In these lectures, I want to convey the fundamental way of thinking in Material Science and Solid-State Physics, as well as a few surprises!

Lecture Plan

Lectures 1-3: Yasushi Suto “A Physics View of The World”

Lectures 4-6: Yasuhiro Iye “The Properties of Matter”

Lecture 4: Modern Society and Material Science
What does the discipline of Solid-State Physics do?

Lecture 5: From an Atom to a Solid Object
Diverse Matter, Varied Physicality

Lecture 6: Manipulate an Atom, Manipulate a Quantum
High-Tech and Nano-Science

Lectures 7-9: Masakatsu Shibasaki “The Origins of Matter”

Lecture 10: Akira Fujishima “Special Lecture – Scientific Gifts From Heaven”

Lectures 11-13: Hiroshi Komiyama “The Utility of Matter”

Today's Talk

Modern Society and Material Science
What does the discipline of Solid-State Physics do?

- Scale
- Modern Society and Material Science
- Solid-State Physics within Physics
- Quantum Mechanics and Atomic Structure

Textbook

(a little advertisement)

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

"Solid-State Science in the 21st Century"

The Institute for Solid-State Physics Press

The Institute for Solid-State Physics at Kashiwa Campus

Baifukan Publishing (￥2000 + Tax)

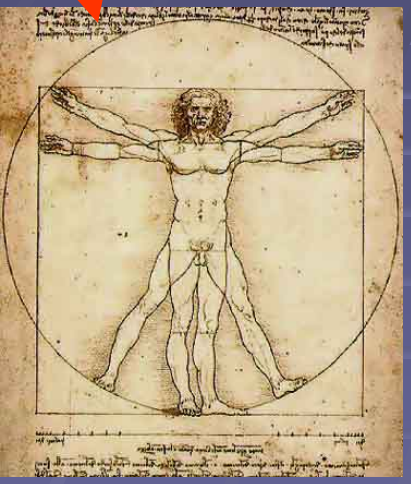
Scale

The Large Scale

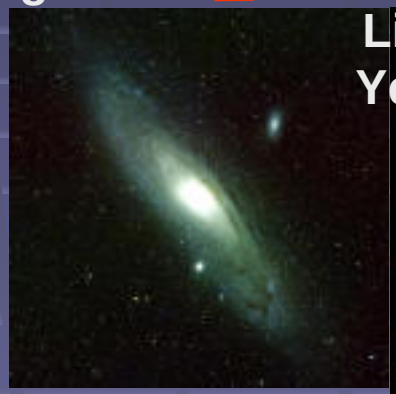
The Edge of the Universe

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

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



12800km



source : http://www.solarviews.com/eng/homepage.htm

The Small Scale

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

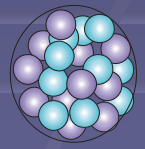
1 pm — Picometer

1 nm — Nanometer

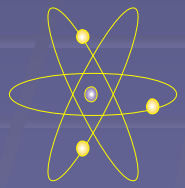
1 μm — Micrometer (Micron)

1 mm — Millimeter

Size of a nucleus



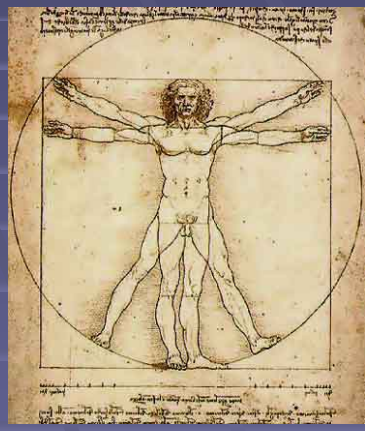
Size of an Atom



Virus

Visible Light Wavelength

Eye of a Needle, Hair



Bacteria

10^{-35}m
Plank Scale

10^{-32}m
Grand Unified Scale

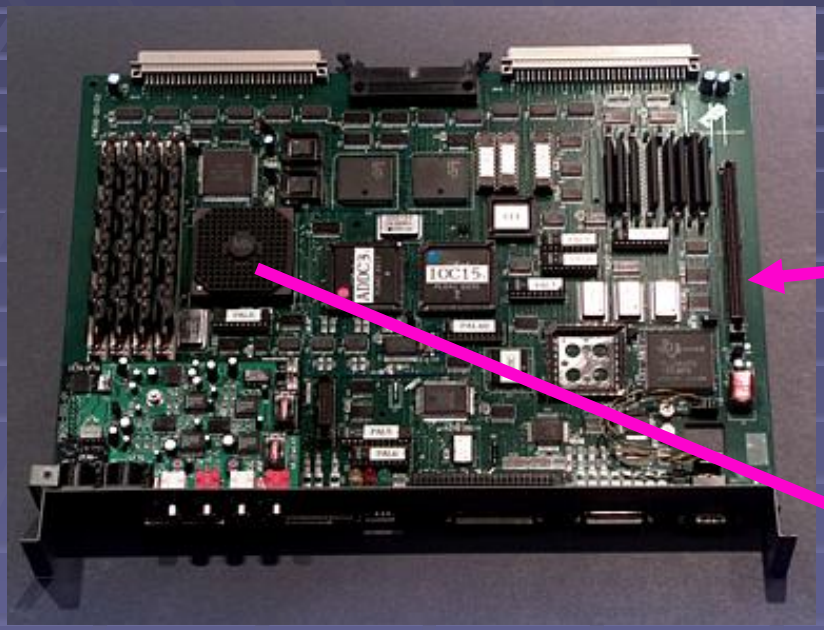
10^{-21}m

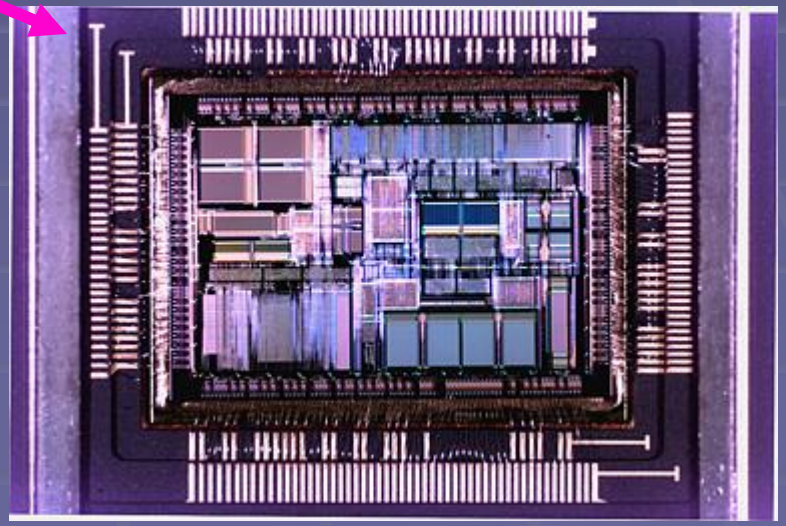
10^{-18}m
Electroweak Unified Scale

Modern Society and Physics

Computers

Personal Computer





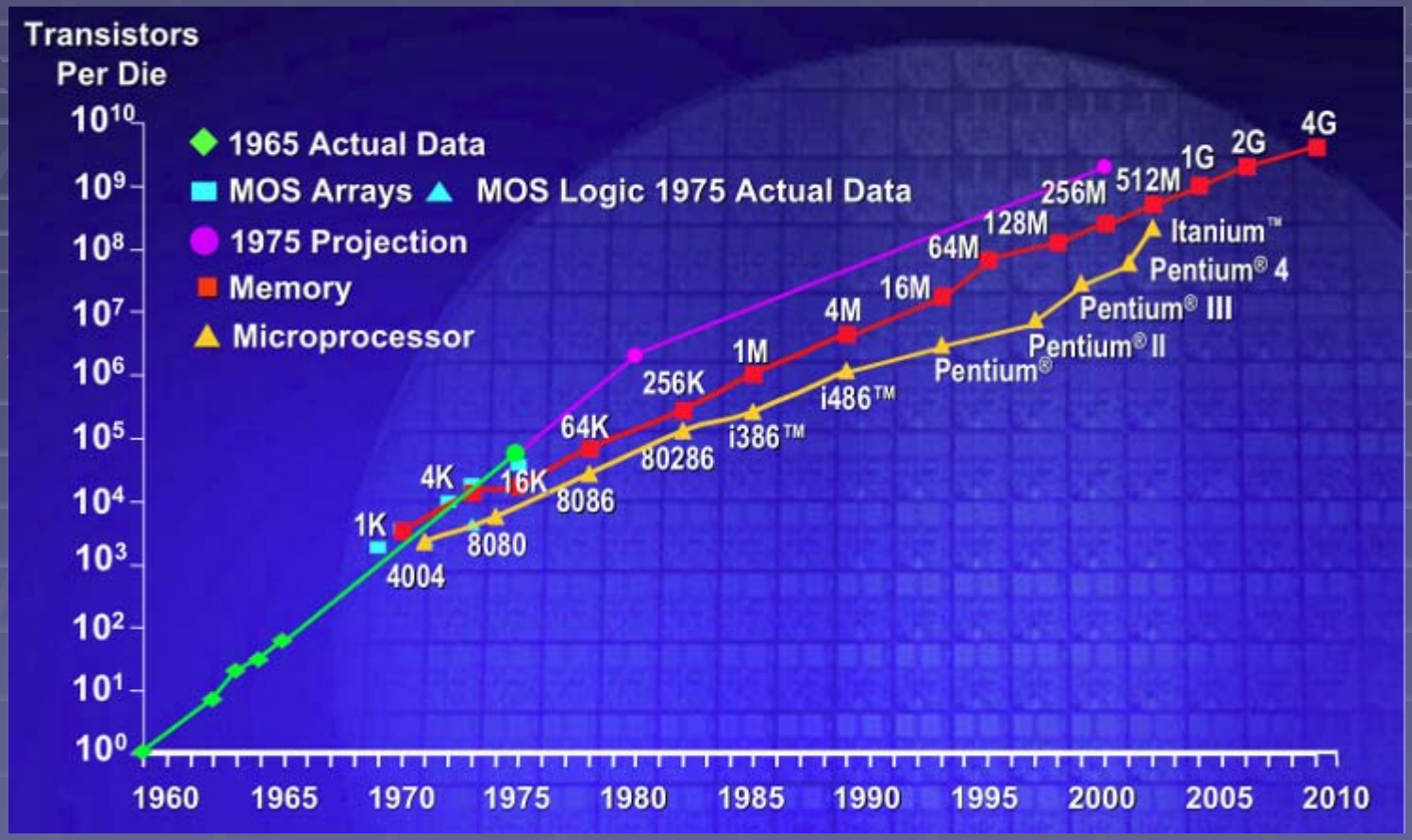
The behavior of electrons within superconductors

Solid-State

Physics based on Quantum Mechanics

Moore's Law

"Integrated Circuit Complexity"



Gordon E.Moore "NO EXPONENTIAL IS FOREVER…"

‡ Intel Copyright Permission Department

The degree of integration of LSI (Large Scale Integration), in other words, the number of transistors that can fit within a unit area will double approx. every one-and-a-half years.

Memory Devices

Magnetic Hard Disk

Digital information is recorded by magnetization of a magnetic substance

CD-ROM/DVD

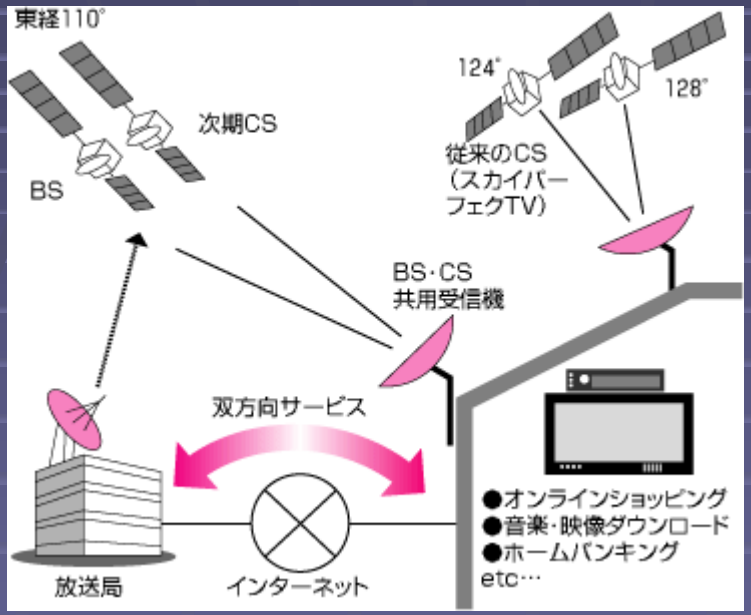
Discrepancies in reflection of a laser striking the uneven recording surface of a disk

Superconductor Memory

- Flash Memory
- Ferroelectric Memory

Radio (High-Frequency), Fiber-Optics

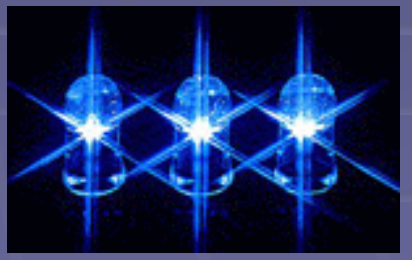
Mobile Phone



Satellite Communications
Satellite Broadcasting

Optic Fiber

High Electron Mobility Transistor (HEMT)



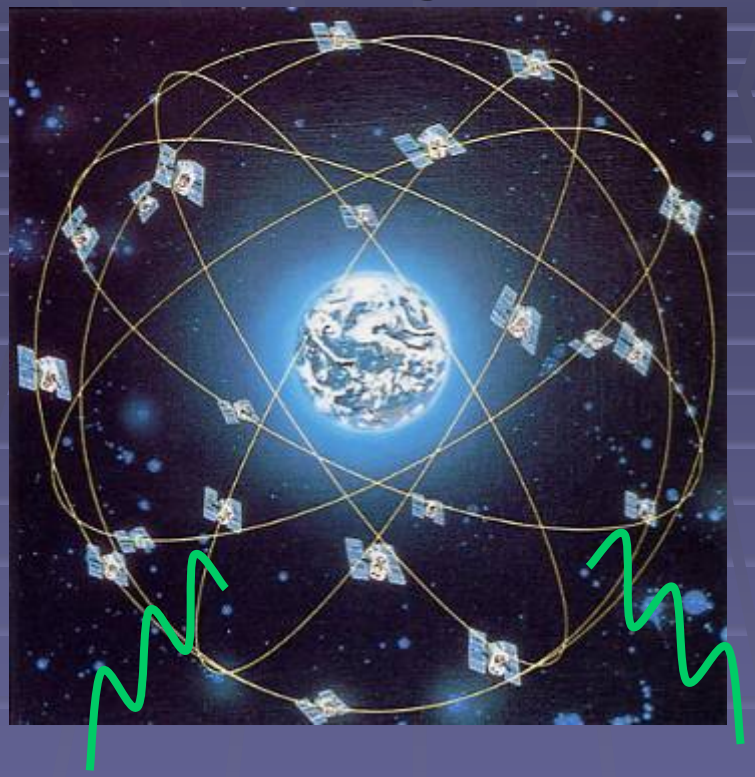
Light Emitting Diode(LED)
Semiconductor Laser

GPS (Global Positioning System) Navigation

24 satellites are stationed in orbit.

Plot positions by “Triangulation”

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

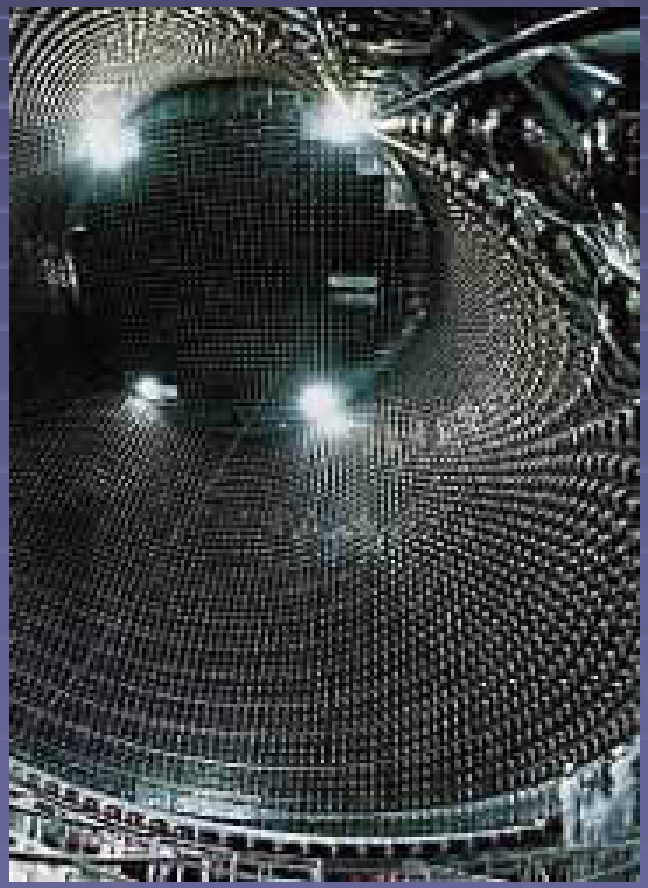


For **GPS** to function, a correction of Special Relativity and General Relativity is required.

Also in Elementary Particle Physics and Space Research

Subaru Telescope
CCD camera

Super-Kamiokande
Photomultiplier

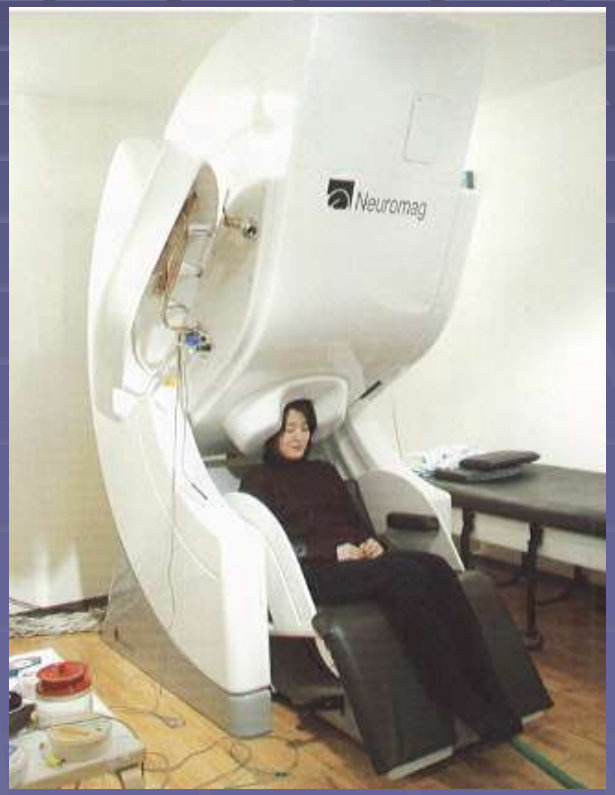


Also in State-of-the-art Medicine

Magnetic Resonance Imaging (MRI)

Magnetoencephalograph (MEG)

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



Also in Familiar Places

- Liquid Crystal (Display)
- High-Strength Fiber (Tennis Racquet)
- Polymer Gel (Disposable Diaper)
- Shape-Memory Alloy
- Fuel Cell
- Photocatalyst => Prof Fujishima's Lecture
- Solar Power => Prof Komiyama's Lecture
- ……

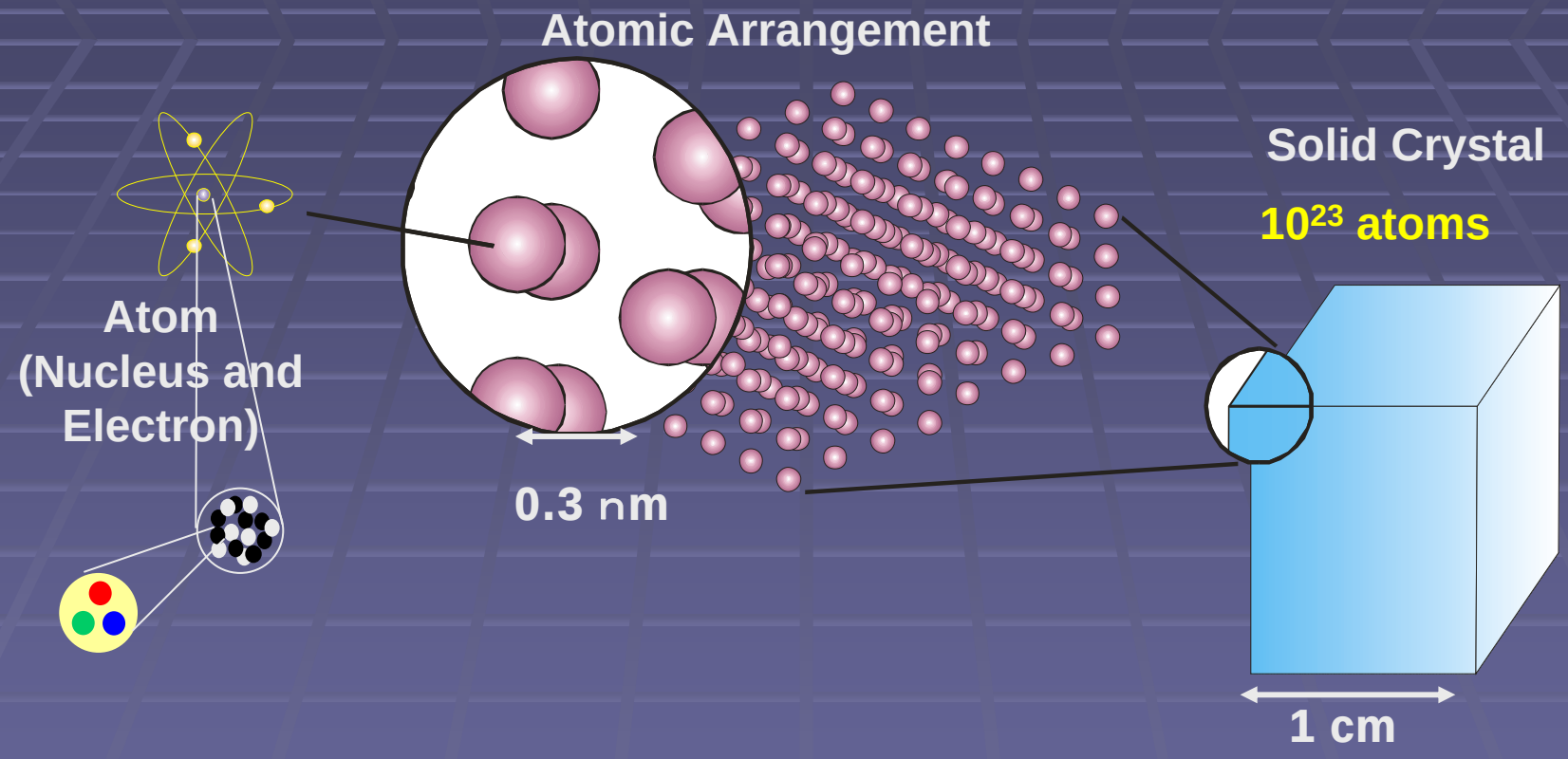
Solid-State Physics within Physics

A Physics Mind

- A Physics (Pursuit of Truth) Mind – The intention to pursue a logical understanding of the foundations of the universe
- Essential Questions of Elementary Particle Physics and Astrophysics
  - What are the fundamental elements of the universe?
  - How did the universe begin? How will it end?
- Solid-State Physics (Condensed-Matter Physics)

  To explain the properties displayed by various matter
  - Diversity and complexity is essential
  - But not by studying natural history, rather by seeking universality and unity

The hierarchial Structure of the Material World



Microscopic Scale ⟷ Macroscopic Scale

Large Energy Scale ⟷ Small Energy Scale

A Physics View of the World

Reductionism

You will understand the behavior of a certain level's system by reducing it to the laws of a more basic system. What are the ultimate building blocks and forces? => Particle Physics

But it certainly doesn't mean that if we understand the ultimate building blocks and forces we will understand everything

Each level of the natural world has its own laws of physics

Emergence

Groups of "units" interacting with each other reveal qualitative new behavior that can't be predicted from the properties of the "units"

Behavior of a Multi-Body System: Phase Transition

eg Super-conduction, Life Phenomena

More is different. (P.W.Anderson)

The Significance of Solid-State Physics

An intellectual appetite that wants to understand the property of matter based on the fundamental ideas of physics

⇒ Structure of a Matter-based Perspective

Understanding and using The Physical. Pioneering and mastering useful capabilities

⇒ Closely relating to engineering

Curiosity-Driven Research and
Mission-Oriented Research

But there are no boundaries between these, rather they coexist in a certain ratio within the consciousness of each individual researcher

The Significance of Solid-State Physics

"Playing catch" with the concepts of Solid-State Physics, Elementary Particle Physics/ Nuclear Physics, and Astrophysics

Phase Transition: Spontaneous Symmetry Breaking
Nambu-Goldstone Mode⇔ Higgs Mechanism

Asymptotic Freedom:
Quark Confinement ⇔ Kondo Effect

Topological Excitation, Quantum Phase

.....

The Work of Research into The Physical

- The work of understanding the diverse properties (The Physical) of a variety of Matter based on the fundamental ideas of physics
  - Even though varied it's not "Natural History". Pursuit of Universality and Unifying Principles
- Characteristics
  - Can conduct experiments（⇔ Astrophysics, Geophysics）
  - Small Science（⇔ Big Science）
  - Seamless connection of Chemistry and Applied Physics, and eventually the Life Sciences as well?
- Whether there is "Understanding" or not
  - Comparing theory with experimentation: the cycle of models and verification
  - The rise of computational physics

The Objects of Material Physics

Solid-State (Monocrystal, Polycrystal)
Disordered Crystals (Impurities, Deficiencies…)
Amorphous, Glass, Paracrystals
Fluids, Quantum Liquids
Microparticles, Cluster
Surface, Interface
Artificial Crystals (Super Lattice), Nanostructure
Soft Matter (Macromolecules, Liquid Crystals, Gels)
Atomic Gas Laser (Bose condensate)

Properties of Matter

- Structural Properties
  - Crystalline Structure (Solid, Liquid, Glass, ….)
  - Composition
- Mechanical Properties
  - Steel is hard, Gold is malleable
  - Glass is hard but brittle
  - Diamond is hard, Graphite is hard but easy to cleave (flaky)
- Thermal Properties
  - Copper conducts heat well, stainless steel poorly

Properties of Matter

- Electrical Properties
  - Conduction (Metal, Insulator, Semi-conductor)
  - Ferro electricity
  - Super-conduction
- Magnetic Properties
  - Ferro magnetism （Why is iron magnetic?）
- Optical Properties
  - Color of jewels, Metallic luster ,
  - Luminescence (Light-emitting diode, semiconductor laser)

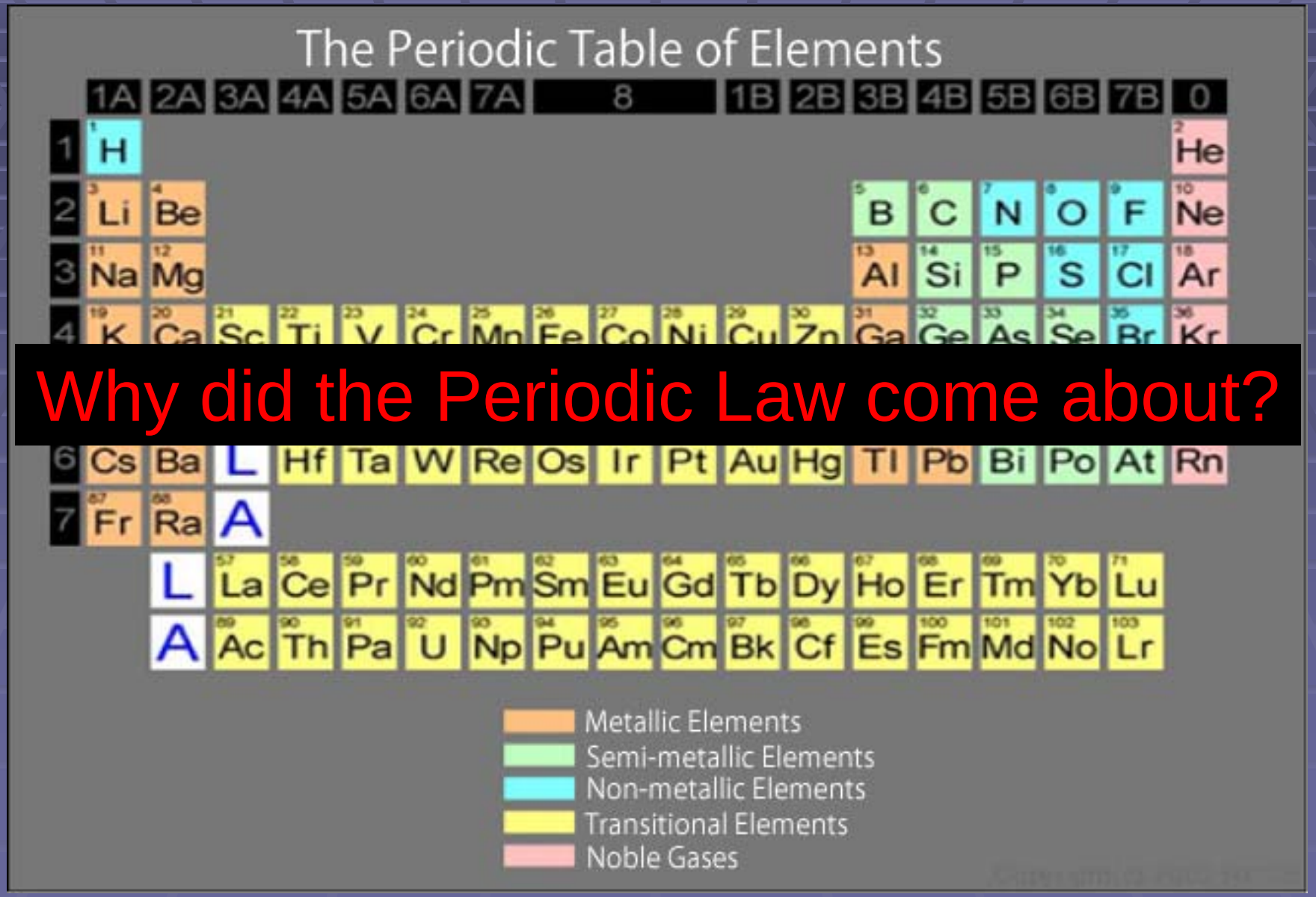
Matter and the Physical Environment

The Physical: Reaction to an outside stimulus
Behavior that changes according to the environment that the Matter is in

- Temperature
- Pressure, Stress
- Electrical field
- Magnetic field
- Interaction with Light (Electromagnetic waves)
- Sample size

Quantum Mechanics and the Structure of Atoms

The Periodic Table of Elements



The Players in Solid-State Physics

The Players（The “Basic” Particles）

Electron

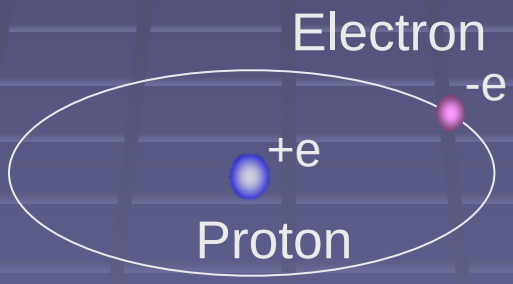
Nucleus (Proton + Neutron)

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

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

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

Hydrogen atom



The energy that’s at work between the “Basic” Particles: Electromagnetic Interaction

$h\nu$

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

Light (Electromagnetic Waves)　　Photon

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

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

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

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

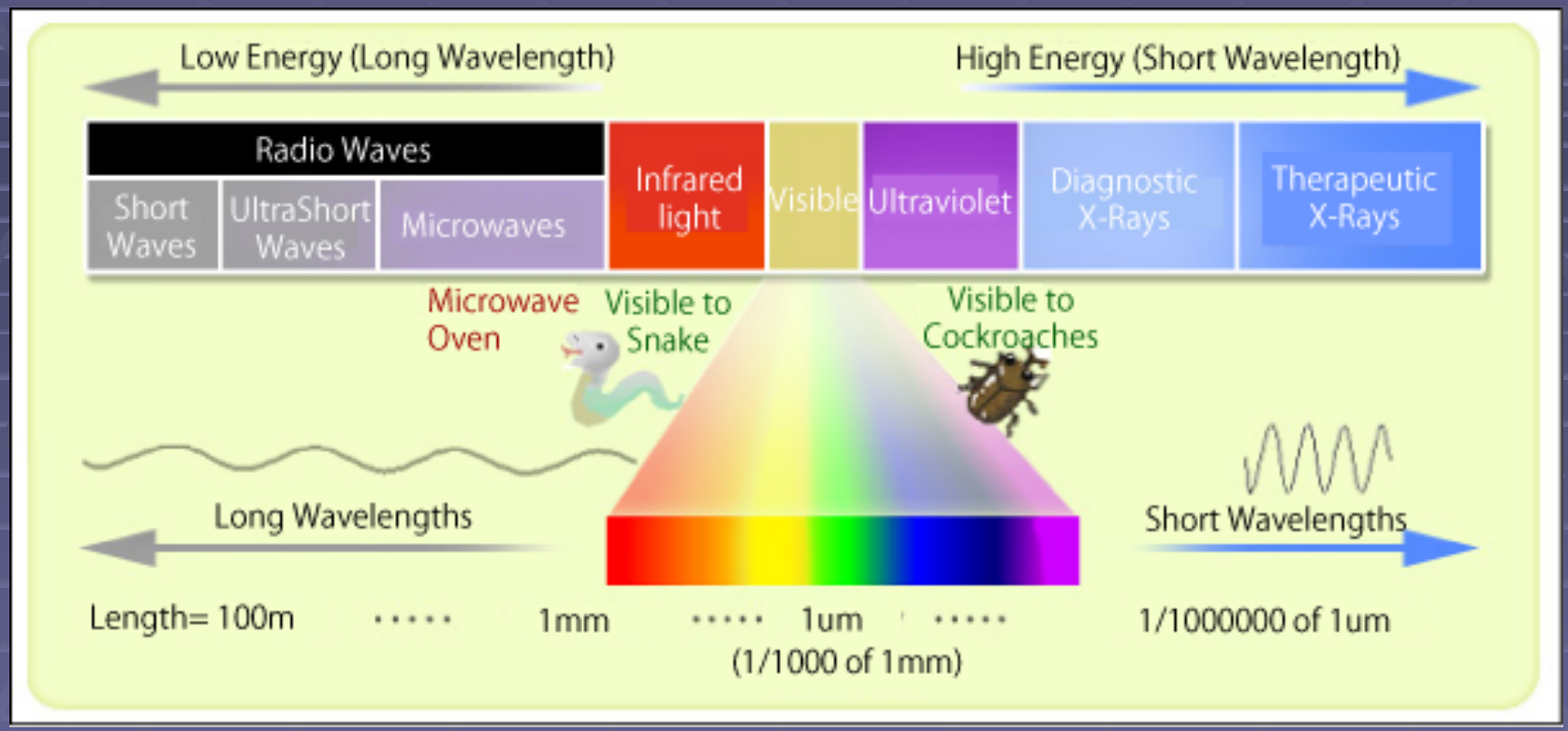
Planck's Constant

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

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

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

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 that has the Energy of 1eV

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

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

Quantum of Light : Photon

Quantum Mechanics

"Quantum Mechanical Particles such as Electrons etc are Particles and Waves"

de Broglie wavelength λ

Relationship between Wavelength, Wave number and Momentum

$$p = \hbar k = \hbar \frac{2\pi}{\lambda}$$

The Wave function $\psi(x, y, z)$ that represents this state follows the Schroedinger Equation

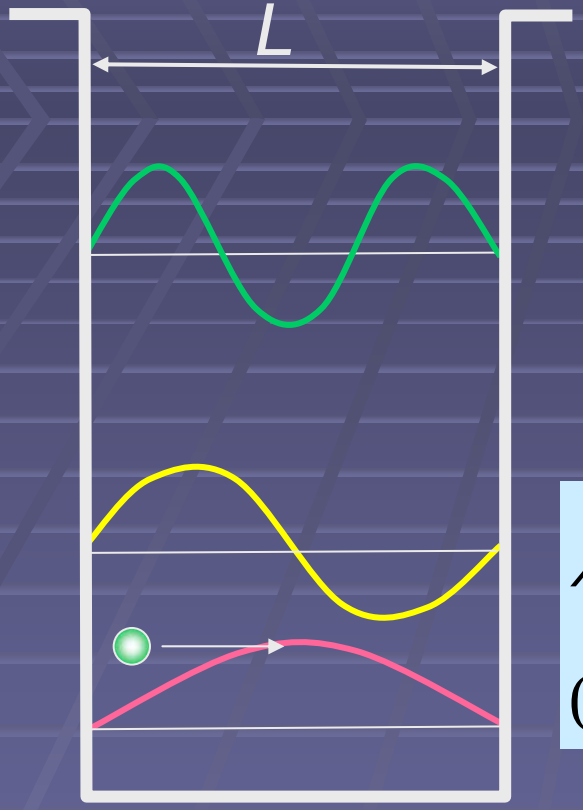
$$\left(-\frac{\hbar^2}{2m} \nabla^2 + V(r) \right) \psi(x, y, z) = E \psi(x, y, z)$$

$$\nabla^2 \equiv \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$$

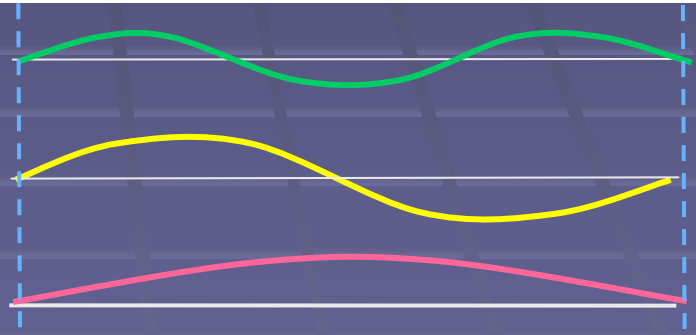
The Existing Probability of a Particle

$$\left| \psi(x, y, z) \right|^2$$

The Quantization of Energy



$$\lambda = \frac{2L}{n} \qquad (n = 1,2,3,\cdots)$$

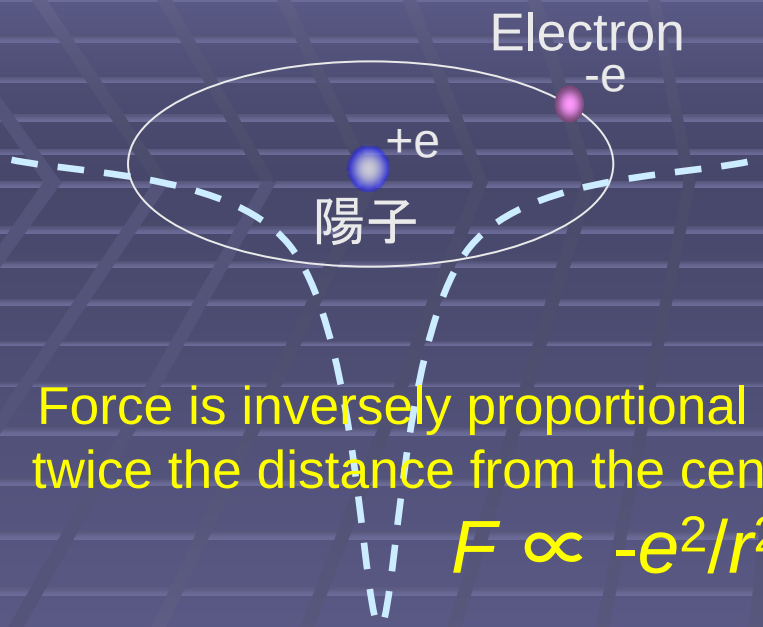


Electron inside a box

⇒ Standing Wave : Discrete Energy Level

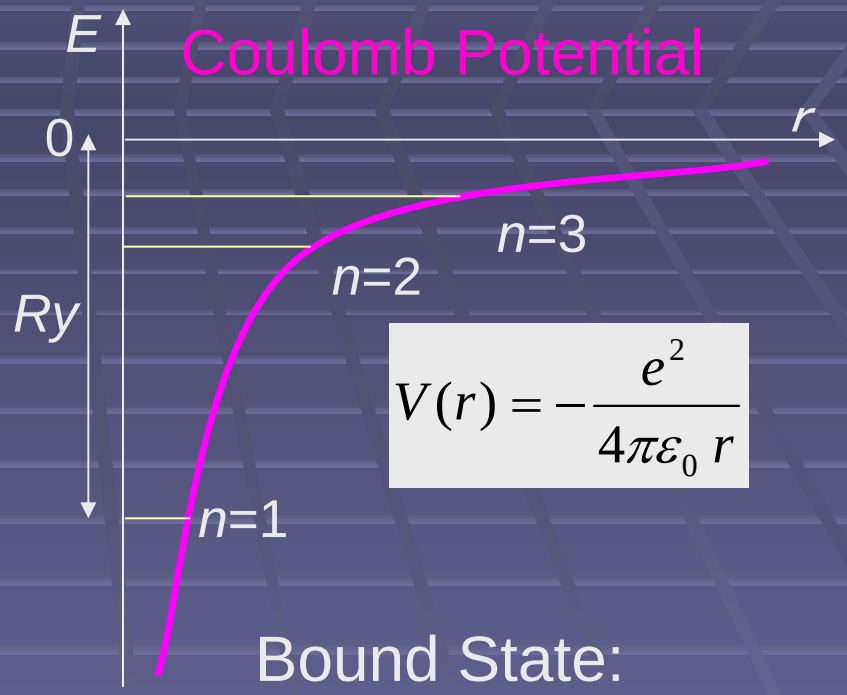
$$p = \hbar\frac{2\pi}{\lambda} = \hbar\frac{2\pi}{2L}n \quad \Rightarrow \quad E = \frac{p^2}{2m} = \frac{\hbar^2}{2m}\left(\frac{\pi}{L}n\right)^2 \qquad (n = 1,2,3,\cdots)$$

The Hydrogen Atom



Force is inversely proportional to twice the distance from the center

$F \propto -e^2/r^2$



$$V(r) = -\frac{e^2}{4\pi\varepsilon_0 r}$$

Bohr Radius

$$a_0 = \frac{4\pi\varepsilon_0\hbar^2}{me^2} = 0.053\text{nm}$$

Rydberg Constant

$$Ry = \left(\frac{1}{4\pi\varepsilon_0}\right)^2 \frac{me^4}{2\hbar^2} = 13.6\,\text{eV}$$

Bound State:
Discrete Energy Level

$$E_n = -\frac{1}{n^2} Ry$$

$$\langle r \rangle_n = n^2 a_0$$

Energy Levels of the Hydrogen Atom

Direction of the Radius (distance form the center) Vector
⇒ Discrete Energy Level
Circular motion around the center
⇒ Quantization of Angular Momentum

Angular Momentum Quantum Number

$$l = 0, 1, 2, \cdots$$
$$m = -l, \cdots, l-1, l \quad (2l+1)$$

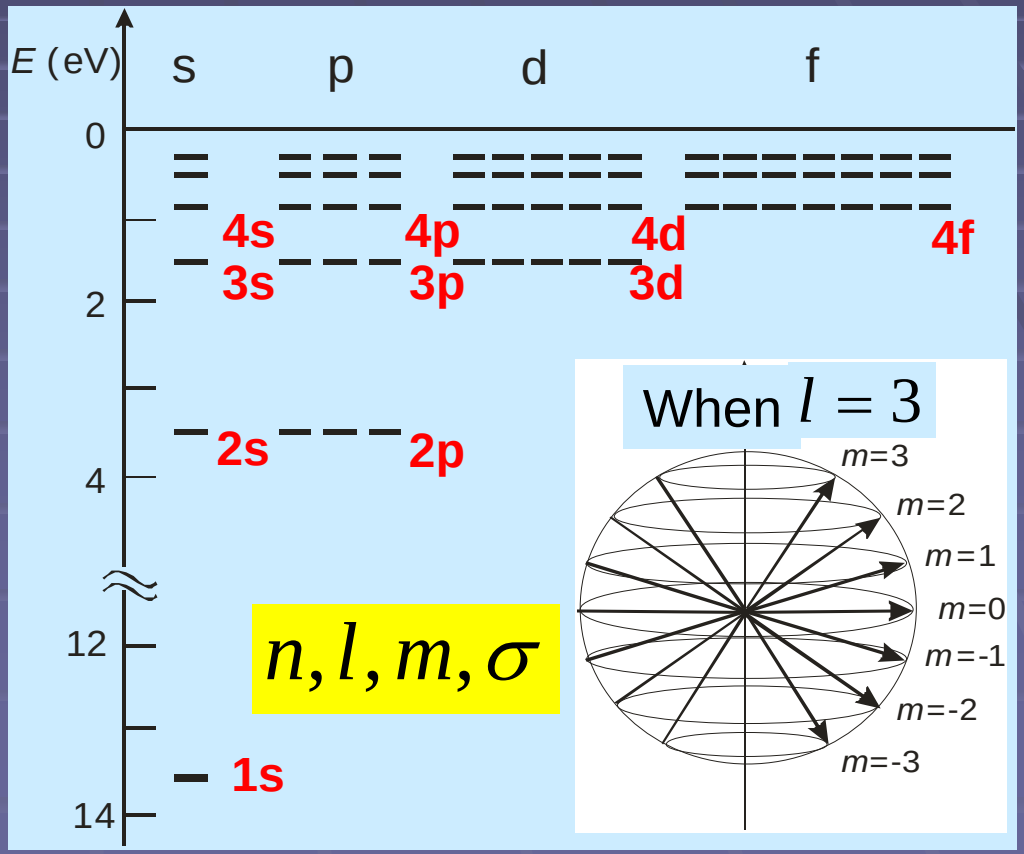
First Quantum Number

$$n = l, l+1, \cdots$$

The Degree of Freedom of Spin possessed by an Electron (but only upwards or downwards)

Spin Quantum Number

$$\sigma = \pm 1$$

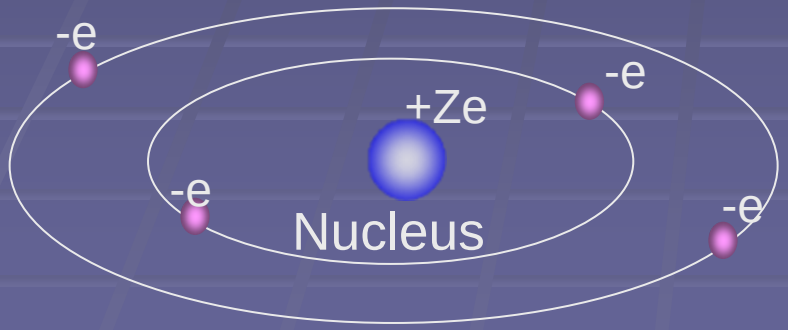


Electron Energy Levels of the Atom

Multi-electron atom:

Nucleus with a charge of +Ze and Z-number of Electrons

Electrons are Fermi Particles =>
Energy Levels denoted by（n, l, m, σ）are restricted to one electron each.

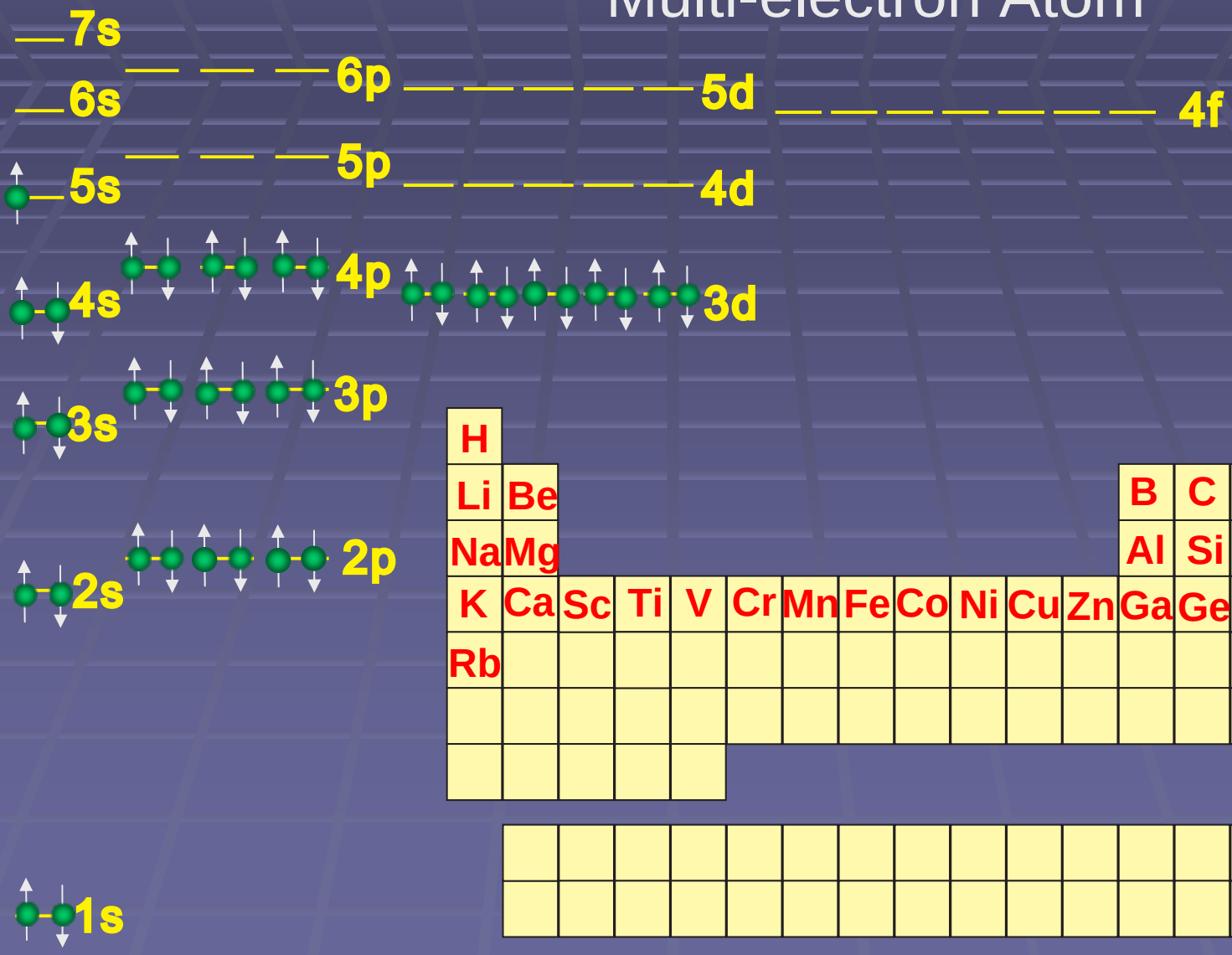


Na： Z=11

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

The Filling of Electron Energy Levels

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																	

Electron Energy Levels of Atoms

Electrons are Fermi Particles => Energy Levels denoted by (n, l, m, σ) are restricted to one electron each.

Shell Structure denoted by n values

$n=1$	2×1	$= 2$
$n=2$	$2 \times (1+3)$	$= 8$
$n=3$	$2 \times (1+3+5)$	$=18$

When 1 shell is filled with the appropriate number of electrons 2, 10, 18, 36 … it is energetically stable

Noble (Inert) Gas Atoms：
He, Ne, Ar, Kr, Xe

The Periodic Law

What's important to Matter is the electrons in the outer-most shell (easily separated from the atom) => Valence Electron

The electron configuration of the outer-most shell shows that similar atoms show similar chemical properties => Periodic Law

Rather than remembering the Periodic Table, it's more important to understand why the Periodic Law holds tru (Of course, it's better to remember but…)

If you're going to remember the Periodic Table, don't learn it by rote, rather learn it by row

The Electrical Energy Level of Atoms

While the larger the Z of the atom, the stronger the Coulomb attraction of the nucleus, the number of electrons also increase, so there's a degree of balancing out and eventually the energy level of the electrons in the outer-most shell become a number of degrees of eV.

The energy scale of Solid-State Physics is a number of eV to meV

Temperature T ⇔ Thermal Energy $k_B T$

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

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

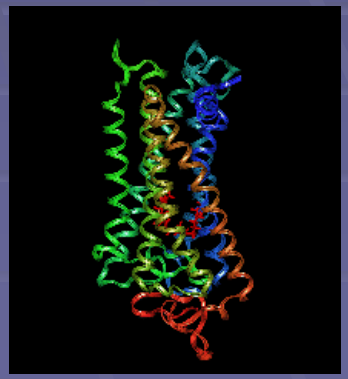
The energy scale of chemistry and living things is around this

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



Today's Summary

- Scale
  - Atoms (Micro) and Matter (Macro)
- Modern Civilization and Physics
- Solid-State Physics within Physics
  - Seeking Universality and Unity within Variety
- Hierarchy of the Natural World
  - Emergence and Phase Transition
- Quantum Mechanics and Atomic Structure
  - The reason the Periodic Law holds true

    ⇔ The structure of atoms
  - The energy scale of Solid-State Physics (as well as Chemistry and Biology) is ~eV