나노 기술의 이해
(Understanding Nanotechnology)

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Lecture 5.
Nano Physics

Lecture Review

Lecture 1 — **History of Nanotechnology**
- Definition of Nano Size
- Feynman's Lecture

Lecture 2 — **Introduction to Nanotechnology**
- Definition of Nanotechnology
- Briefing about the Advancement of Nanotech.

Lecture 3 — **Scanning Probe Microscope**
- STM
- AFM

Lecture 4 — **Fundamental Problems in Nanotechnology**
- Biological & Environmental Problems
- Uncertainty of Nano-scale phenomenon

Nano Physics

Scale Law

Quantum Size Effect (양자 효과)

Schrödinger Wave Equation (슈뢰딩거의 파동 방정식)

Tunnel Effect (터널 효과)

Single Electron Effect (단전자 현상)

Nano Physics – Scale Law

Water Strider | **Steel-needle Floating** | **Capillary Action**

?

Nano Physics – Scale Law

(I) Surface ~ (length)^2
or $S \sim L^2$

(II) Volume ~ (length)^3
or $V \sim L^3$

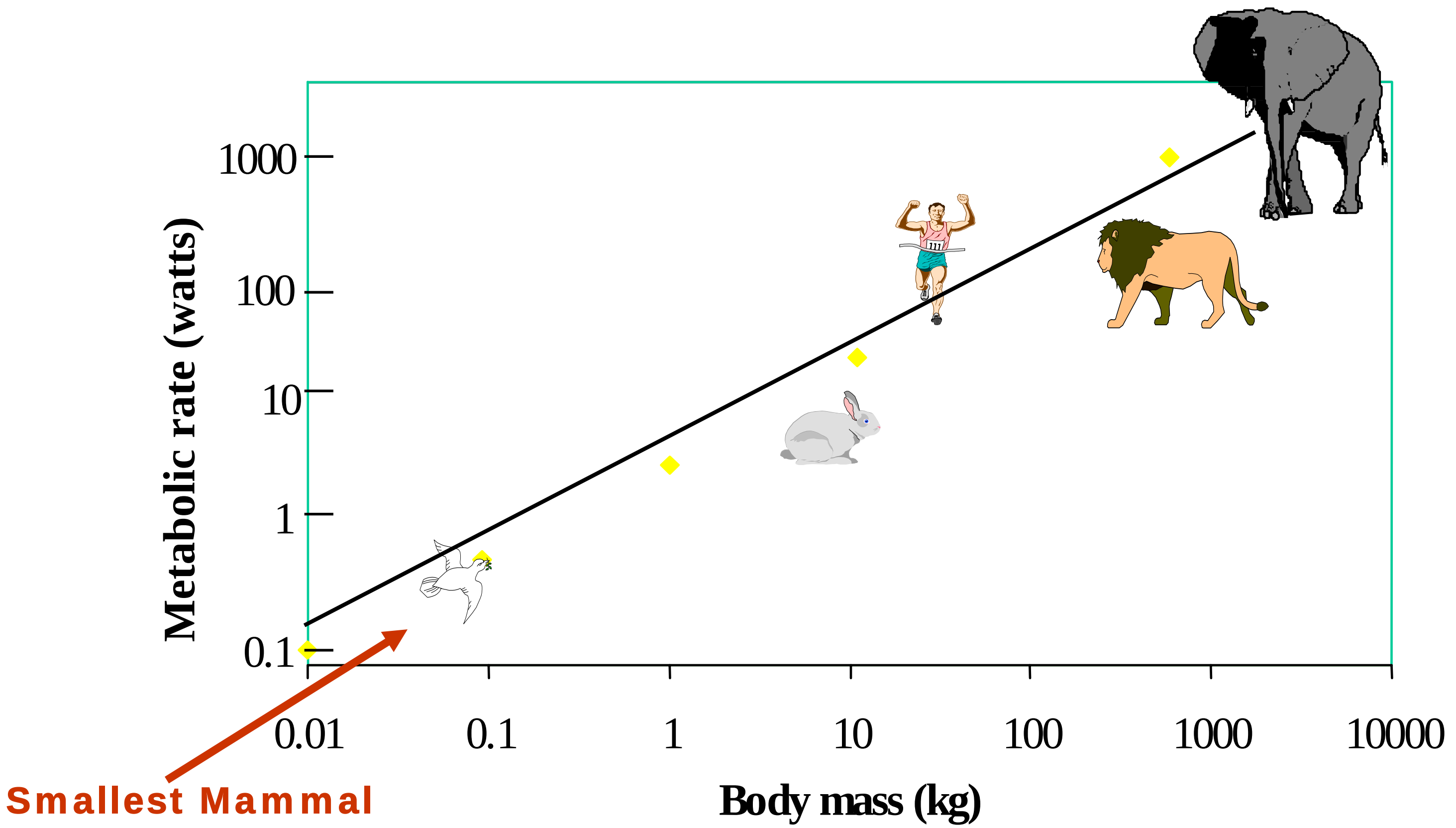
(III) Surface ~ (volume)$^{2/3}$
or $S \sim V^{2/3}$

Scaling laws deal with the structural and functional consequences of changes in size or scale among otherwise similar (isometric) structures/organisms.

Linear extrapolation of length comes easy to us, but we are quickly at a loss when considering the implications that shrinking of length has on surface area to volume ratios (S/V) and on the relative strength of external forces.
: weight scales as l^3 and surface tension as l.

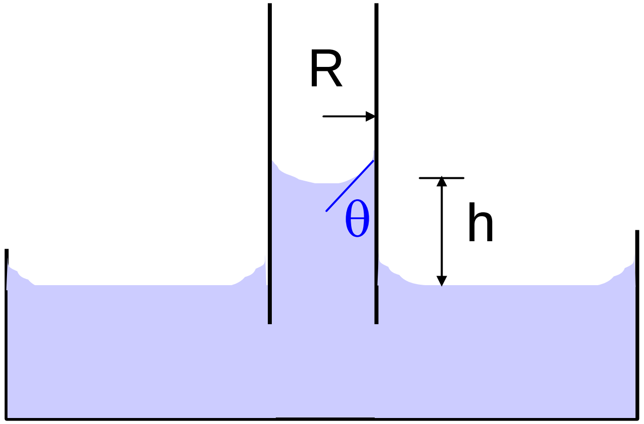
Animal Size

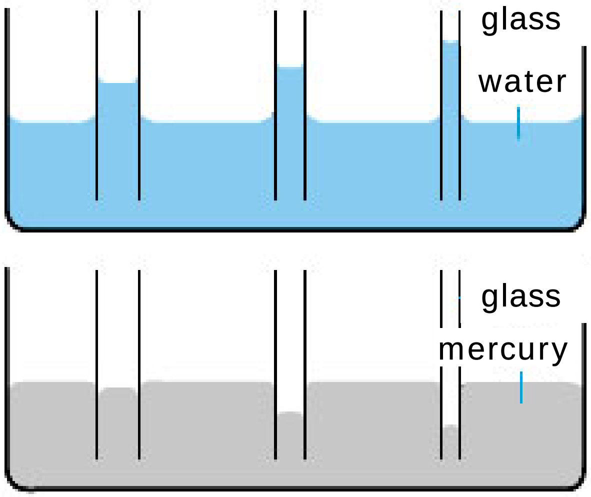
(D'Arcy Thompson: "On Growth and Form" and Knut Schmidt-Nielsen: "Why is Animal Size so Important?")



Small mammals must keep on eating to stay warm ((heat loss ~ l^2 and heat generation (through eating) is ~ l^3))---insects avoid this problem by being cold blooded.

Nano Physics – Capillarity (Surface tension)





- Young-Laplace equation

$$\Delta P = \frac{2\gamma}{R}\cos\theta,\ h = \frac{2\gamma}{\rho g R}\cos\theta$$

- Laplace pressure vs. Gravity
- Example

\- Water/Glass (θ = 0º, γ = 72 mN/m, R = 50 nm, ρ = 1000 Kg/m^3, g = 9.8 m/s^2)

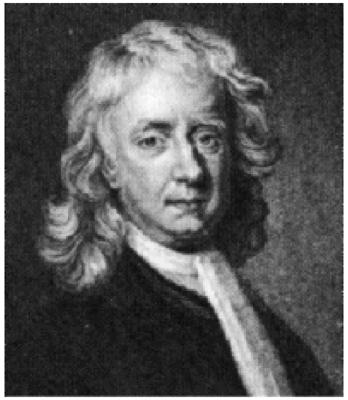
$\Rightarrow \Delta P$ = 2.88×106 N/m^2 (Pa) = 28.4 atm

$\Rightarrow$ h = 294 m !!

Nano Physics – Quantum Effect

Described by Newton's Law of Motion (17th century)

- Successful for explaining the motions of objects and planets
- In the end of 19th century, experimental evidences accumulated showing that classical mechanics failed when applied to very small particles.



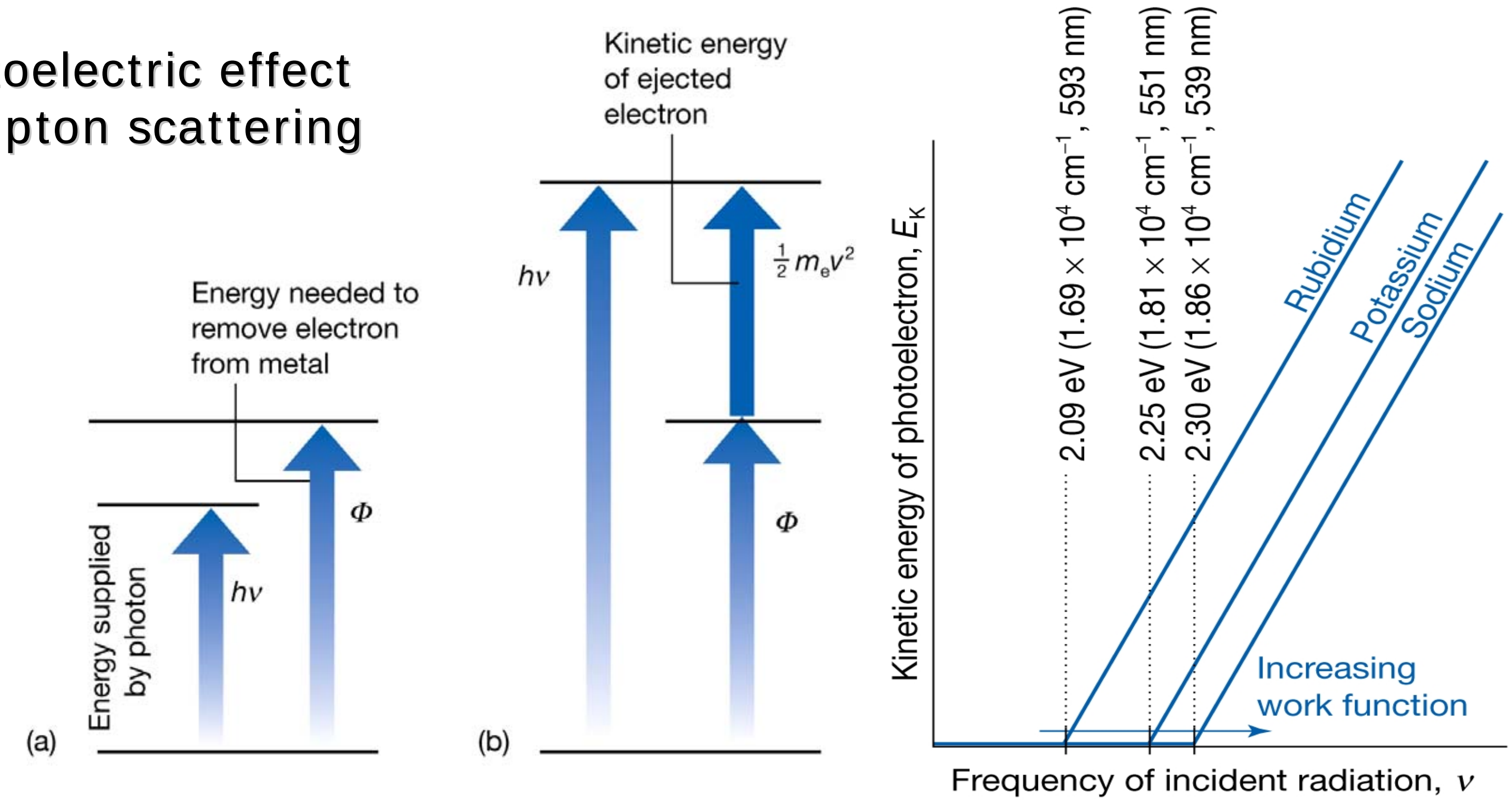
Sir Isaac Newton

At the nanoscale—a nanometer is a billionth of a meter or 1,000 times smaller than the diameter of a human hair—materials behave differently than they do in their larger, bulk form. In this size regime, the laws of quantum mechanics predominate.

Wave – Particle Duality

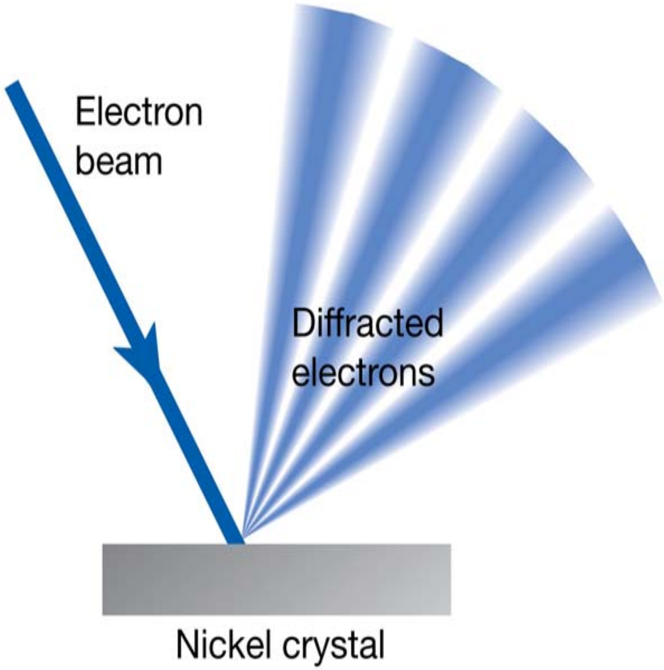
– Evidence for Particle character of wave

- Photoelectric effect
- Compton scattering

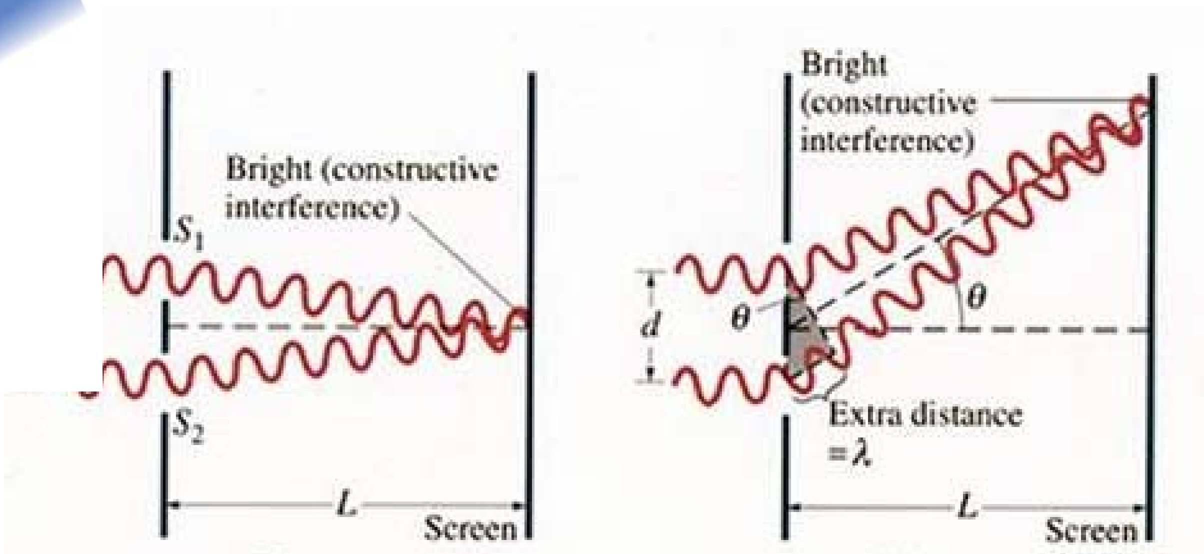


Wave – Particle Duality

– Evidence for wave character of particle



- Electron diffraction,
- Iinterference of matter waves



Nano Physics – Quantum Effect

*-Light and matter exhibit **wave-particle duality***

*-Relation between wave and particle properties given by the **de Broglie relations***

In his thesis in 1923, Prince Louis V. de Broglie suggested that mass particles should have wave properties similar to electromagnetic radiation.

Louis V. de Broglie
(1892-1987)

If a light-wave could also act like a particle, why shouldn't matter-particles also act like waves?

*The wavelength of a matter wave is called the **de Broglie wavelength:***

$$\boxed{\lambda = \frac{h}{p}}$$

Nano Physics – Quantum Effect

- *In quantum mechanics, the wave-particle duality is explained as follows: every system and particle is described by wave functions which encode the probability distributions of all measurable variables. The position of the particle is one such variable. Before an observation is made the position of the particle is described in terms of probability waves which can interfere with each other.*
- *After measurement the position of the particle collapses to one location, the probability of each location determined by the wave probability function.*
- *In fact according to quantum mechanics the physical world is probabilistic and not deterministic*
- *The future is not completely determined by the past*
- *Leaves room for free will philosophically*
- *Differs from Newtonian mechanics which is deterministic*

Why Nano Physics?

- ***Nano Physics unveils new information on***

(1) Physical properties such as density, strength, isotropy…

(2) Electrical properties such as conductivity, resistivity…

(3) Thermal properties such as thermal conductivity, emissivity…

(4) Optical properties such as transparency, photoefficiency…

(5) Biological properties such as sensitivity, toxicity…

Nano Physics – Schrödinger Wave Equation

Take it easy~

Erwin Schrödinger (1887-1961)

A careful analysis of the process of observation in atomic physics has shown that the subatomic particles have no meaning as isolated entities, but can only be understood as interconnections between the preparation of an experiment and the subsequent measurement.

- Erwin Schrödinger

I think it is safe to say that no one understands quantum mechanics. Do not keep saying to yourself, if you can possibly avoid it, "But how can it be like that?" because you will get "down the drain" into a blind alley from which nobody has yet escaped. Nobody knows how it can be like that.

- Richard Feynman

Those who are not shocked when they first come across quantum mechanics cannot possibly have understood it.

- Niels Bohr

Nano Physics – Schrödinger Wave Equation

Macroscopic

Classical mechanics (Newtonian mechanics)

$$\mathbf{F} = m\mathbf{a} = m\mathbf{r}$$

Microscopic

Quantum mechanics

?

1926, Erwin Schrödinger (Austria)

- Describe a particle with wave function
- Wave function has full information about the particle

Nano Physics – Schrödinger Wave Equation

Why we cannot apply the classical mechanics to Nano scale ?

HEISENBERG UNCERTAINTY PRINCIPLE

$$\Delta x \Delta p \geq \frac{h}{2\pi}$$

Δx **: *Uncertainty in measurement of particle location***

Δp **: *Uncertainty in measurement of particle momentum***

In Classical mechanics Δx ***= 0***

But, $\frac{h}{2\pi}$ ***≠ 0***

So, we cannot apply the classical mechanics to Nano scale

Nano Physics – Schrödinger Wave Equation

Starting of Schrödinger Wave Equation
: Conservation of Energy

$$U(x)+\frac{p^2}{2m}=E \longleftarrow K=\frac{1}{2}mv^2=\frac{p^2}{2m}$$

$$p=-i\frac{\partial}{\partial x},\quad x=x,\quad E=i\frac{\partial}{\partial t}$$

$$\boxed{i\frac{\partial}{\partial t}\Psi(x,t)=-\frac{{}^{2}}{2m}\frac{\partial^2}{\partial x^2}\Psi(x,t)}$$

Time independent Schrödinger equation for a particle in one dimension

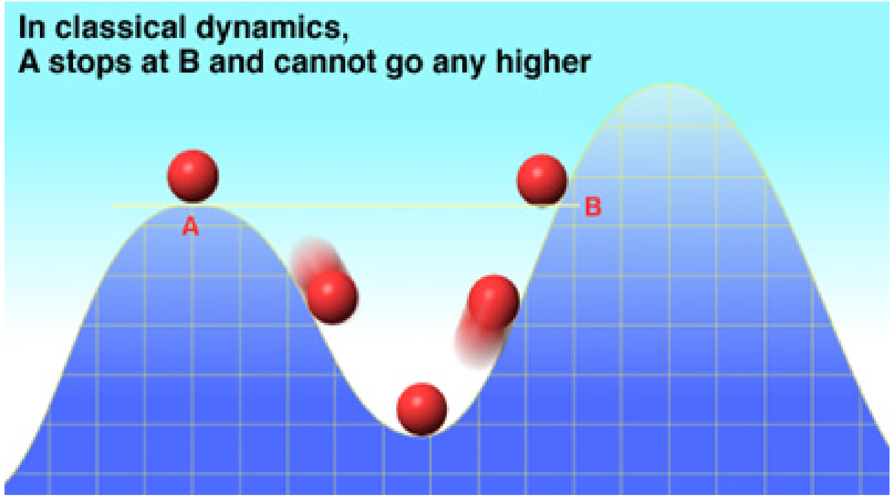
The Wave function

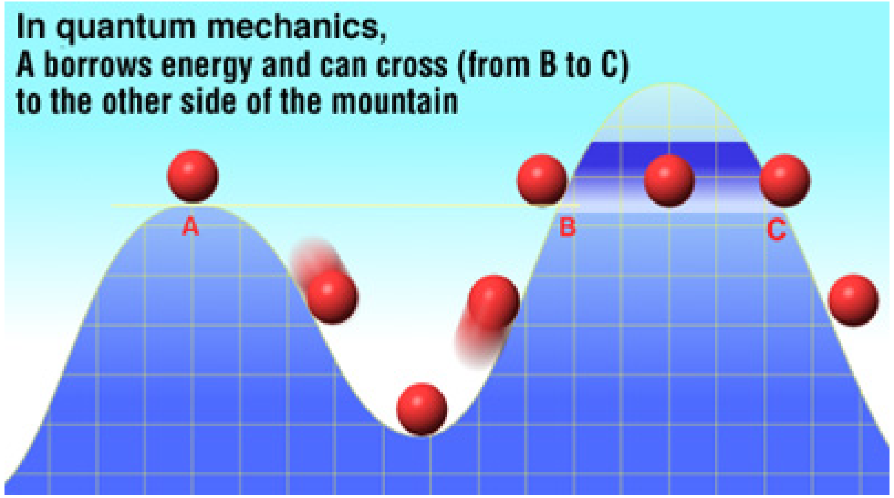
- *Contains all the dynamic information about the system*
- *Born made analogy with the wave theory of light (square of the amplitude is interpreted as intensity – finding probability of photons)*

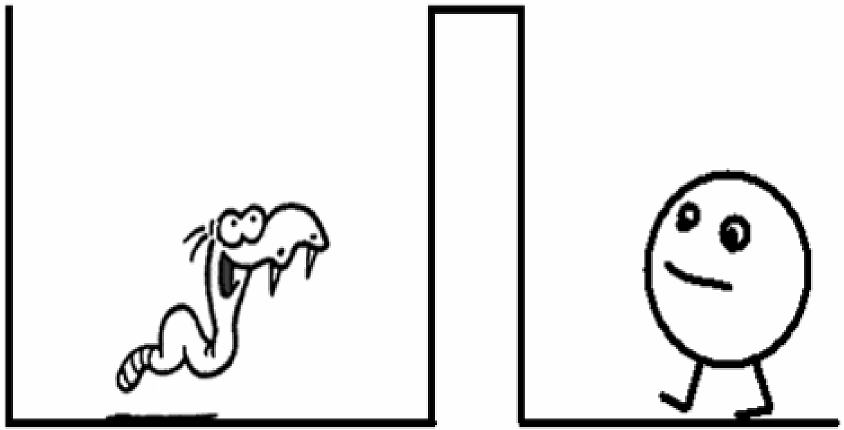
Max Born

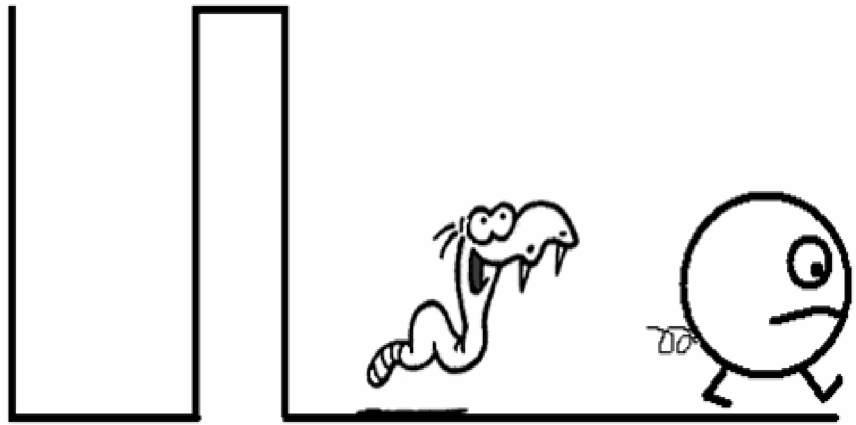
Schrödinger Wave Equation is the momentum equation in Nano-scale !!

Nano Physics – Tunnel Effect

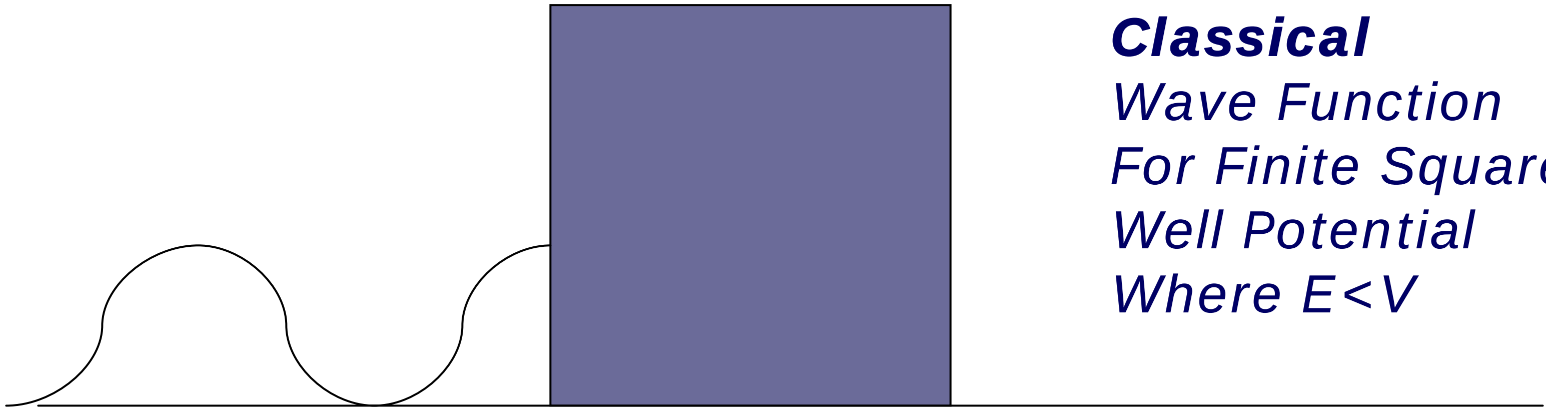








Nano Physics – Tunnel Effect

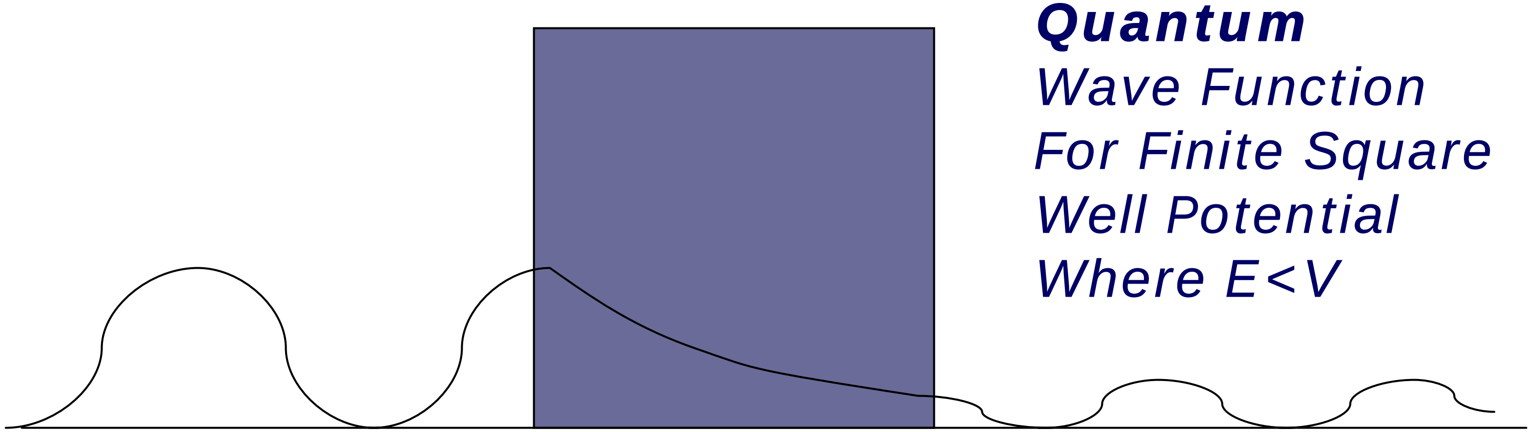


Classical
Wave Function
For Finite Square
Well Potential
Where E<V

Classically, when an object hits a potential that it doesn’t have enough energy to pass, it will never go though that potential wall, it always bounces back.

If you throw a ball at a wall, it will bounce back at you.

Nano Physics – Tunnel Effect



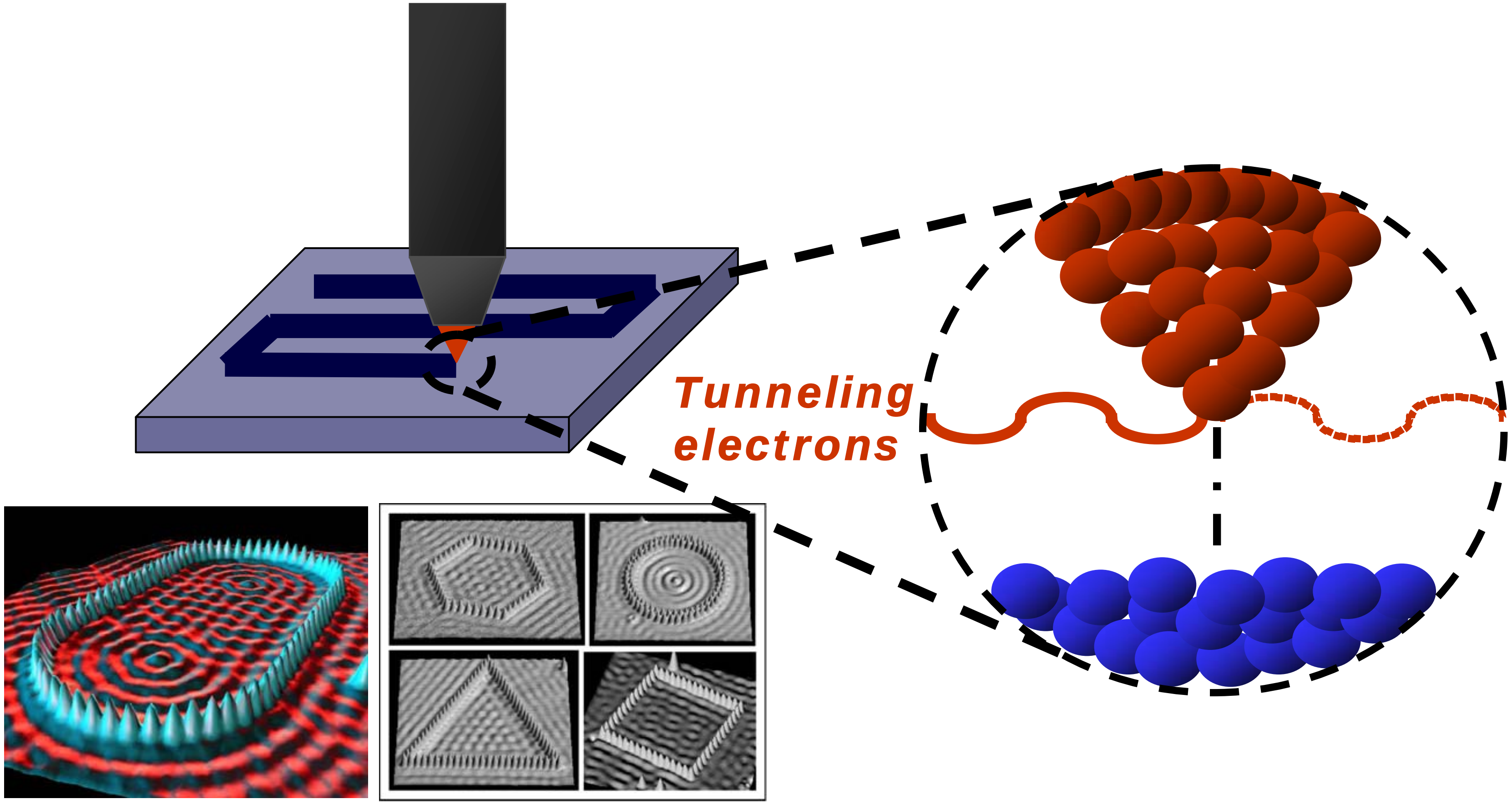
Quantum
Wave Function
For Finite Square
Well Potential
Where E<V

In quantum mechanics when a particle hits a potential that it doesn't have enough energy to pass, when inside the square well, the wave function dies off exponentially.

If the well is short enough, there will be a noticeable probability of finding the particle on the other side.

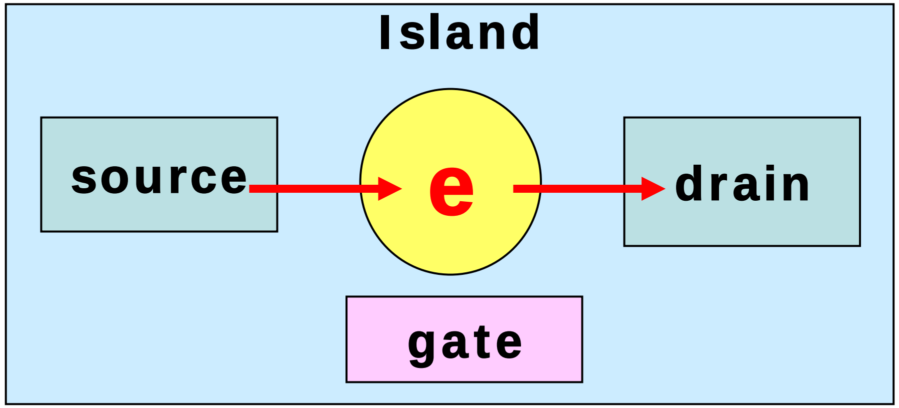
Nano Physics – Tunnel Effect

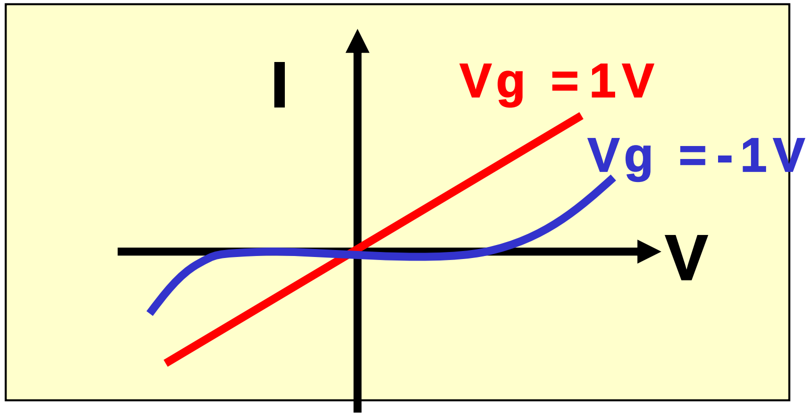
Application of Tunnel Effect
: Scanning Tunneling Microscopy



Nano Physics – Single Electron Effect

Example of Single Electron Effect
– Single Electron Transistor





Single Electron Transistor

- Island potential is capacitively controlled by the gate.
- Coulomb blockade is overcome by changing the gate voltage

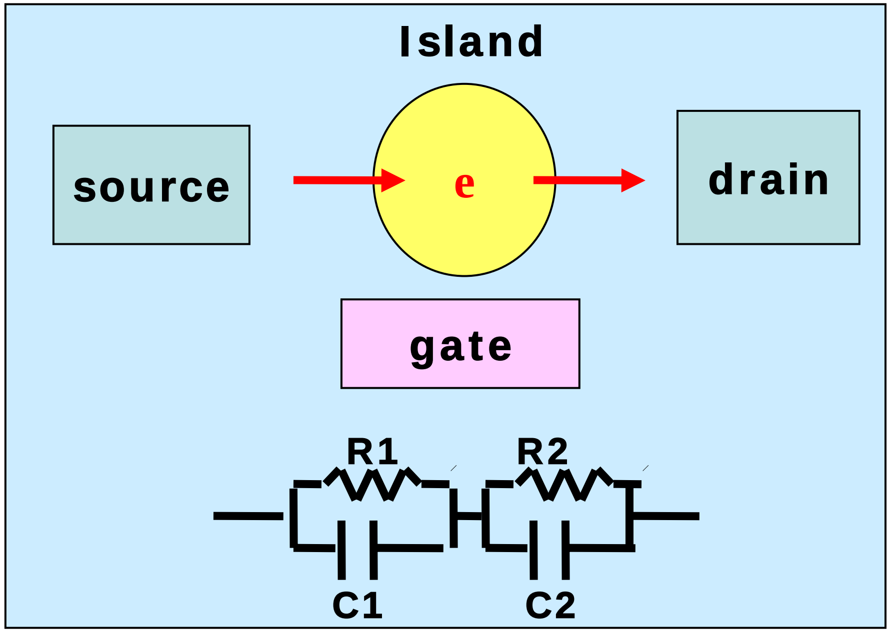
Advantage

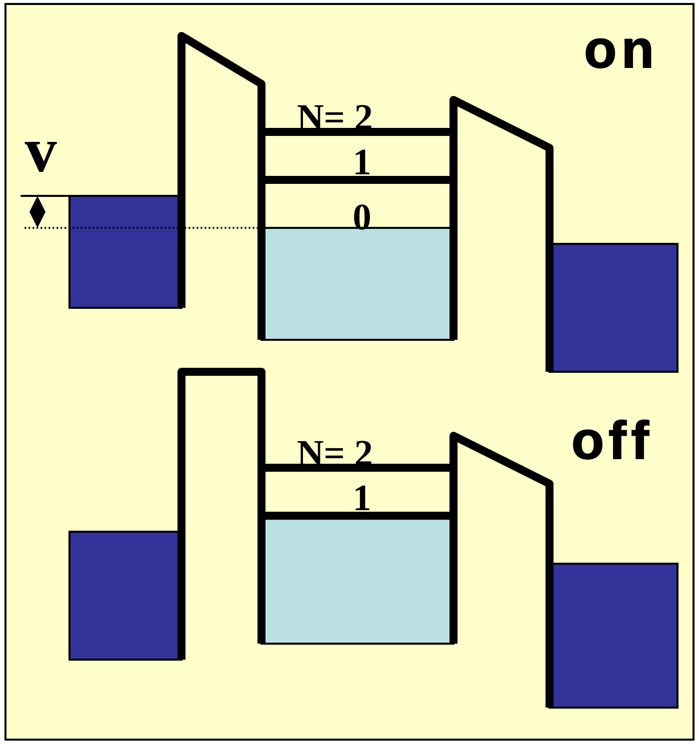
- ultra low power operation
- fast

Nano Physics – Single Electron Effect

Example of Single Electron Effect
– Single Electron Transistor

Coulomb Blockade Effect





Quantum tunneling of electron between source and drain can be blocked by coulomb Blockade Effect