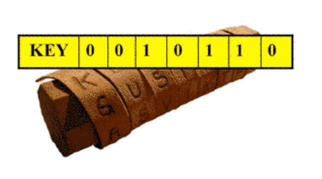
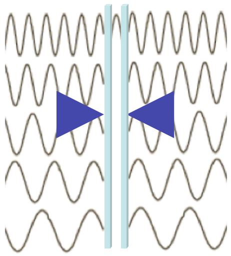
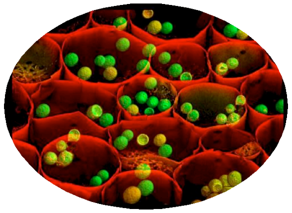
Light Meets Matter: Atoms and Lasers



Martin Plenio - Clocks and Entanglement

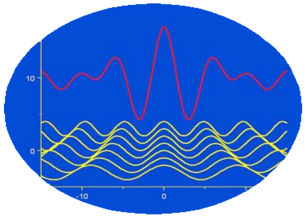
Peter Knight - Quanta and Non-Classicality





Yaron Silberberg - Lasers and Microscopy

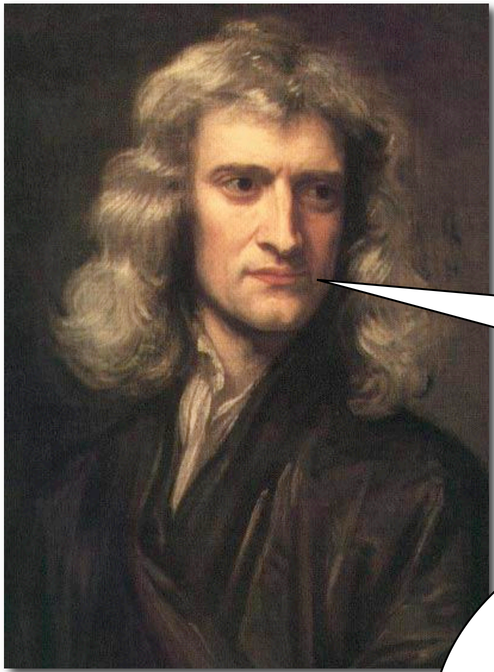
Paul Corkum - Attosecond Science



Steve Brehmer - Mayo High School
Rochester, Minnesota

What is light?

In the late 1600's Newton explained many of the properties of light by assuming it was made of particles.



"Tis true, that from my theory I argue the corporeity of light; but I do it without any absolute positiveness..."

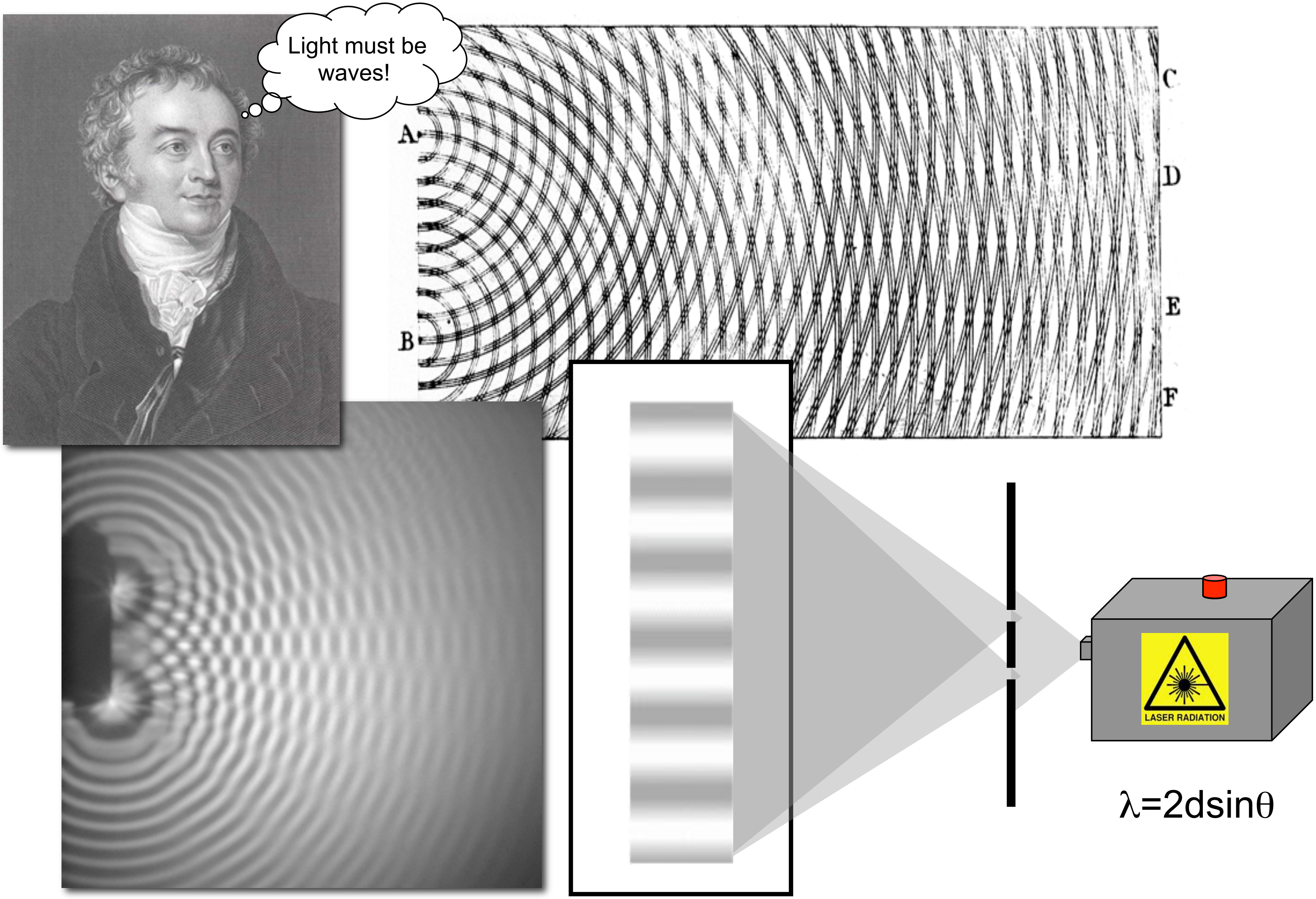
"The waves on the surface of stagnating water, passing by the sides of a broad obstacle which stops part of them, bend afterwards and dilate themselves gradually into the quiet water behind the obstacle. But light is never known to follow crooked passages, nor to bend into the shadow."

Because of Newton's enormous prestige, his support of the particle theory of light tended to suppress other points of view.

In 1678 Christian Huygens argued that light was a pulse traveling through a medium, or as we would say, a wave.

I'm thinking waves.

In 1803 Thomas Young's double slit experiment showed that, much like water waves, light diffracts and produces an interference pattern.



$\lambda = 2d\sin\theta$

"…it seems we have strong reason to conclude that light itself is an electromagnetic disturbance in the form of waves propagated through the electromagnetic field according to electromagnetic laws."

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

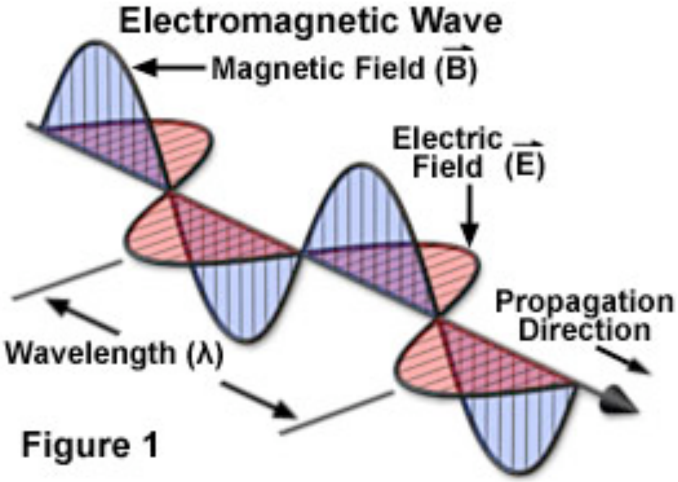
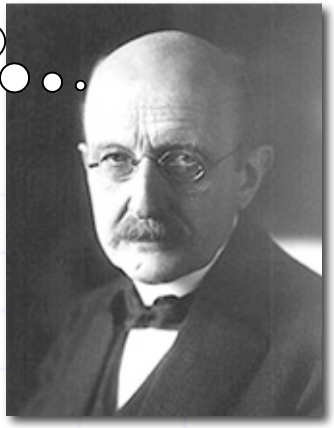


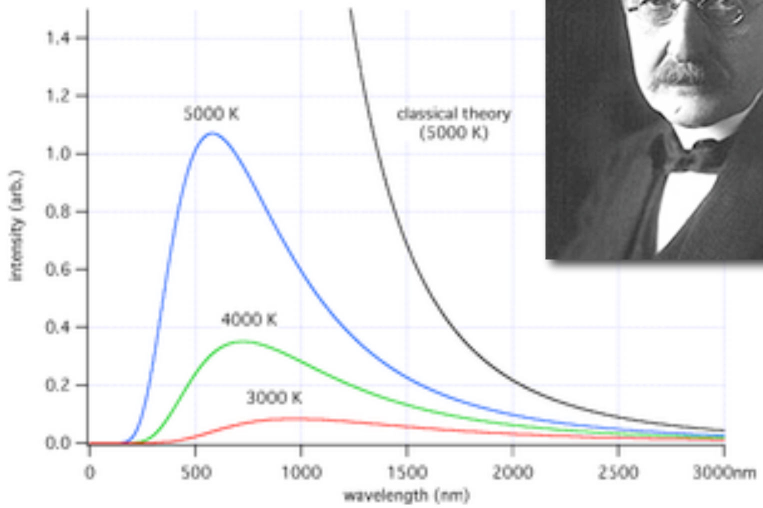
Figure 1

In the 1860's Maxwell, building on Faraday's work, developed a mathematical model of electromagnetism. He was able to show that these electromagnetic waves travel at the speed of light.

I don’t like that!



In 1900 Max Planck was able to explain the spectrum of a “blackbody” radiator by assuming that light energy is quantized. That quantum of light energy was later named a photon.

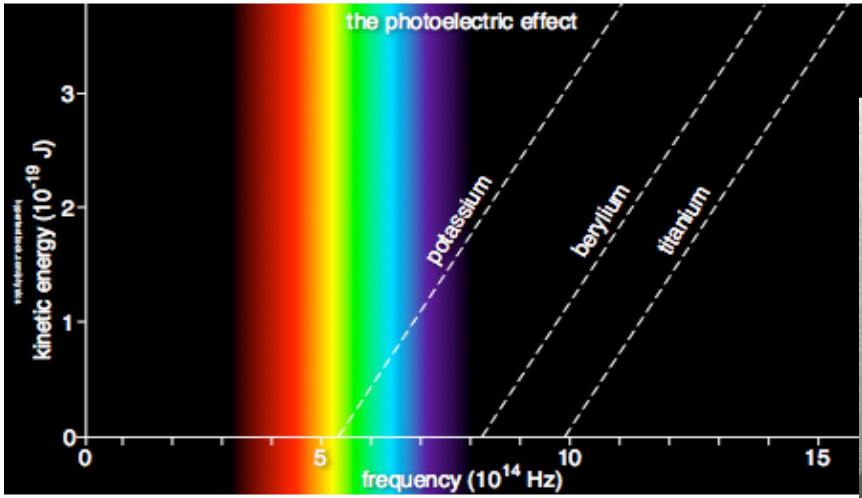


$$E=hf$$

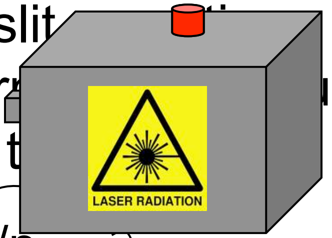
$$E=hf+\phi$$

That quantum
of light energy
seems
particle-like!

A few years later, in 1905, Einstein used Planck’s idea to explain the photoelectric effect.



In 1909 G.I. Taylor experimented with a very dim light source. His work, and many modern experiments show that even though only one photon passes through a double slit an interference patter uced - one "particle" at a t



$\lambda=h/p$

"It would seem that the basic idea of the quantum theory is the impossibility of imagining an isolated quantity of energy without associating with it a certain frequency."

Louis de Broglie, in 1923, reasoned that if light waves could behave like particles then particles should have a wavelength.

$n\lambda=2d\sin\theta$

Soon after, an experiment by C. J. Davisson and L. H. Germer showed that electrons could produce interference patterns just like those produced by light.

$$\Delta p \, \Delta x \geq \frac{1}{2} \hbar$$

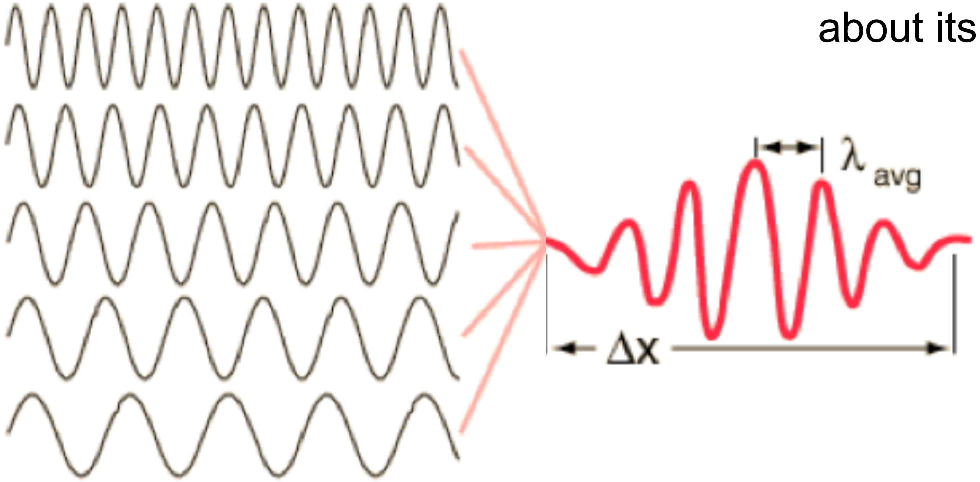
Heisenberg's Uncertainty Principle helps us examine the dual nature of light, electrons, and other particles.

$p=\lambda/h$

If we know the wavelength we are certain about the momentum.

But, because a wave is spread out in space, we are uncertain about its position.

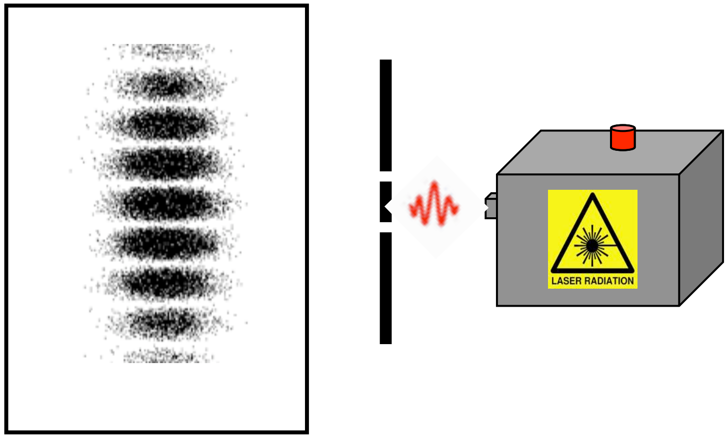
If we add together many wavelengths...



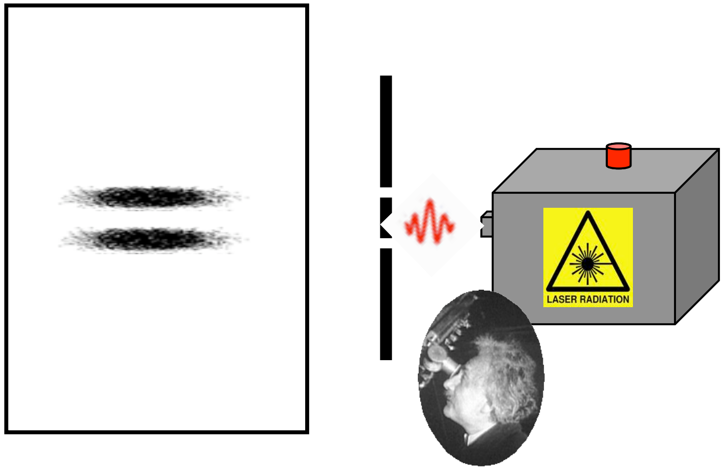
We are uncertain about the momentum.

But, we are now more certain about position.

Photons striking a double slit, one at a time, produce interference.

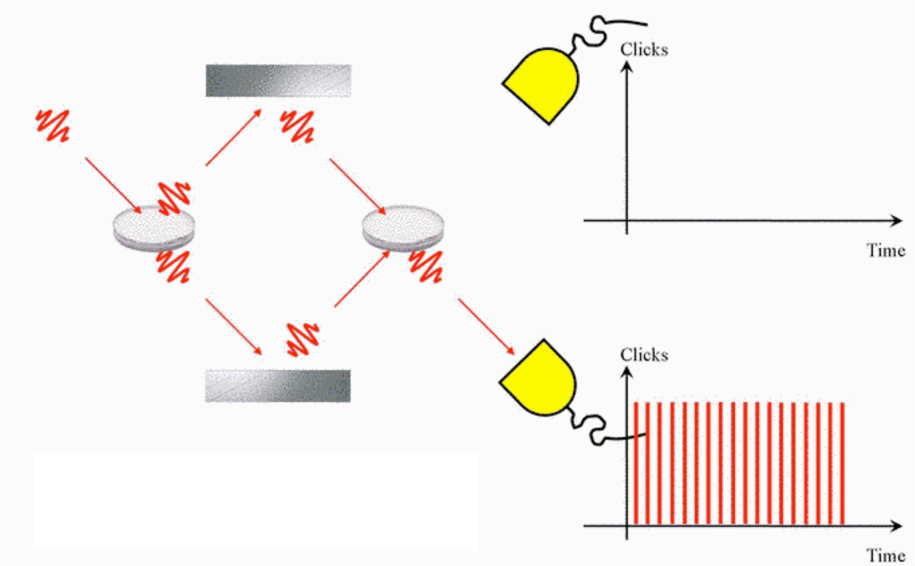


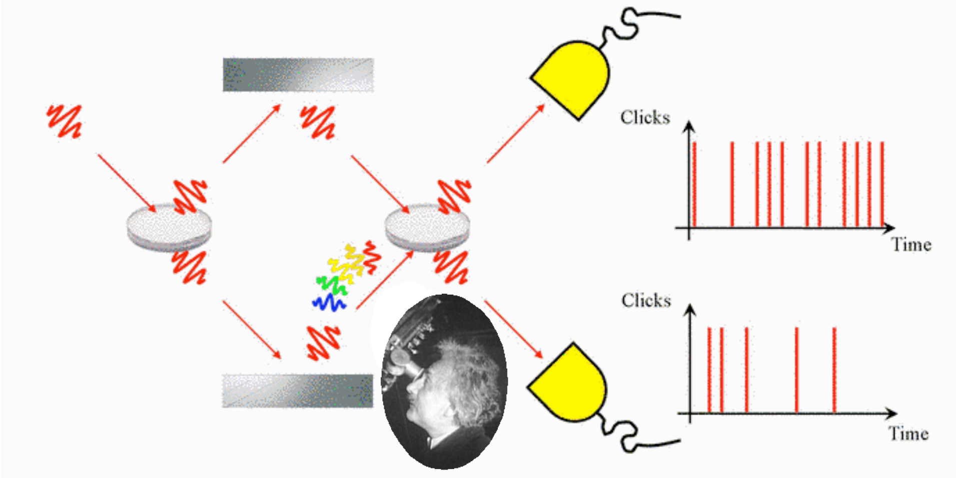
If we observe which slit the photon chooses…



the interference pattern disappears.

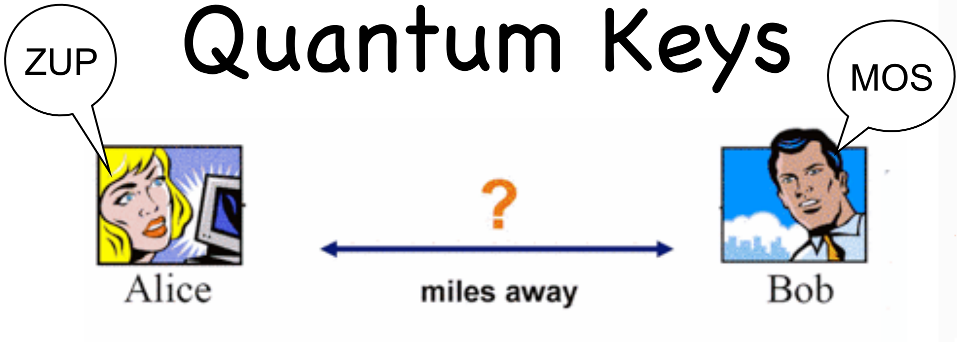
A similar experiment can be done with beam splitters and mirrors.



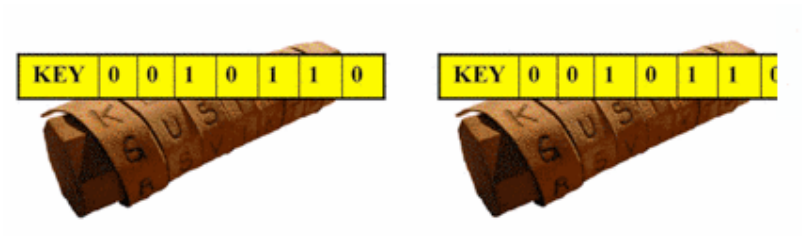


We can tell when someone is watching.

Quantum Keys



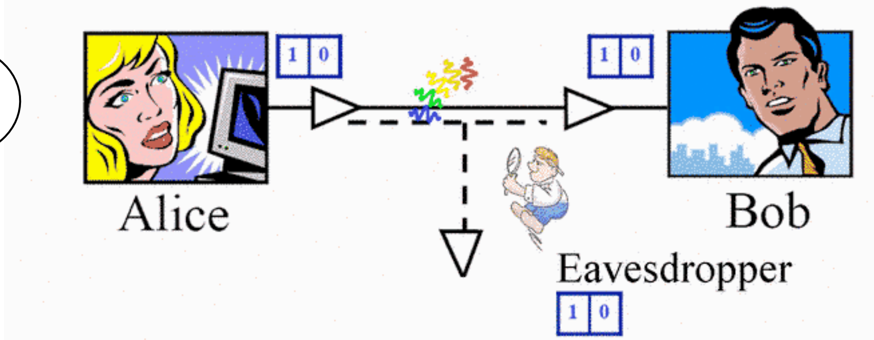
How can Alice and Bob know that their communications will remain private?



When evolving freely, quantum systems exhibit wave character.

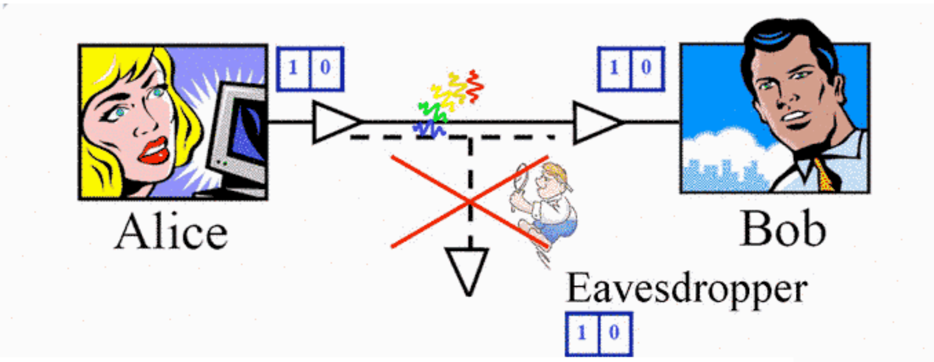
When measured, quantum systems exhibit particle character.

Measurements that acquire information perturb the quantum system.



Eve may measure a classical signal without detection.

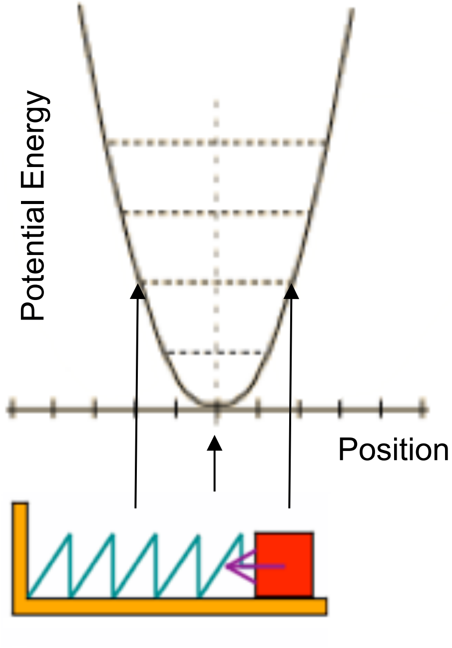
We do not know how much Eve has learnt about the key!



Eve's measurements of a quantum signal causes perturbation and can be detected.

Potential energy for a classical harmonic oscillator is continuous and can have a value of zero.

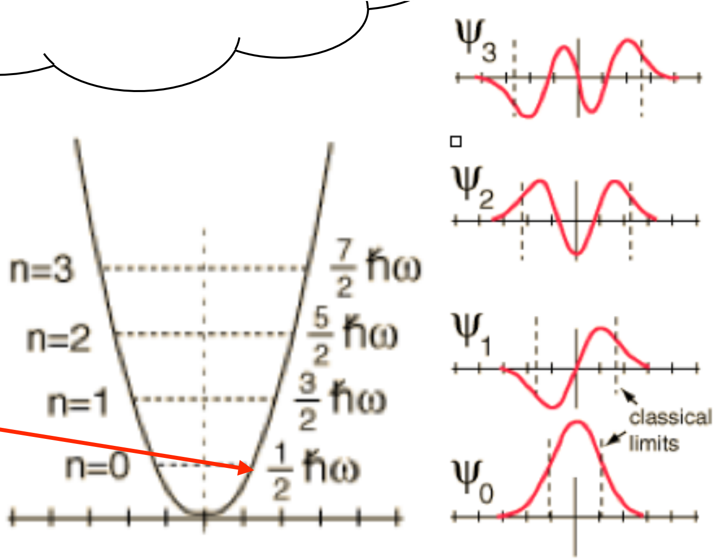
Schrödinger's equation was published in 1926. The solution of this equation for a particular particle and the forces acting on that particle is called the wave function (Ψ).



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

Quantized energy levels

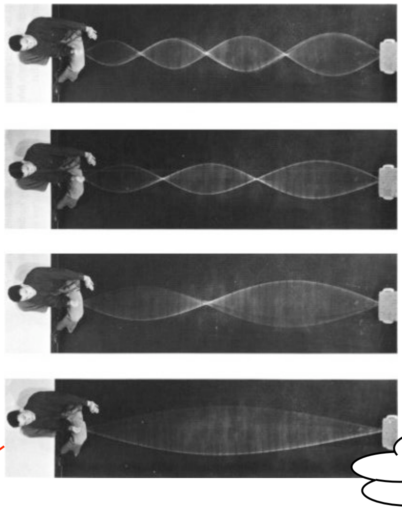
Zero-point energy



Maxwell showed that oscillating electric charge produces an electromagnetic wave.

Unlike the classic oscillator, this system has a minimum energy or “zero-point” energy.

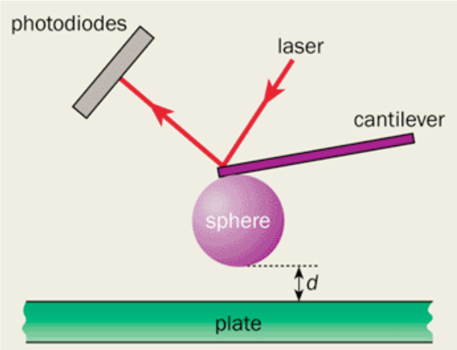
A vibrating rope between two fixed points can only produce standing waves that are a multiple of 1/2 λ.

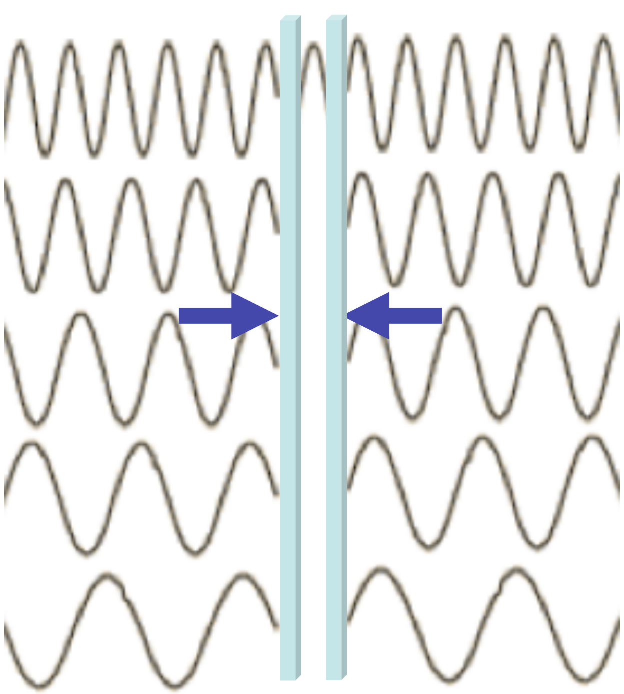


Because of the zero point energy even a complete vacuum is filled with waves of every wavelength…

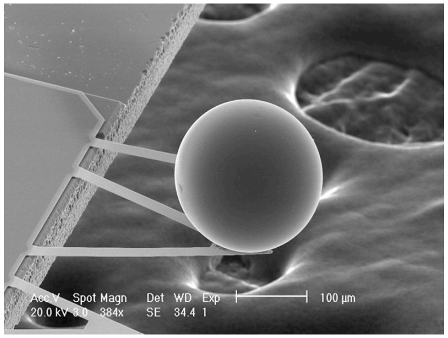
but only certain wavelengths can exist between two closely spaced mirrors in the vacuum.

$F = \pi hc/480\ d^4$

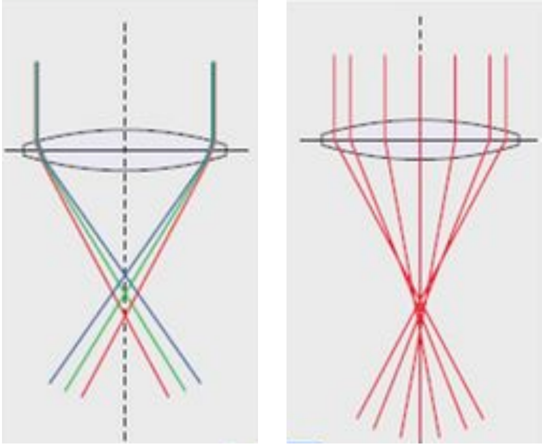


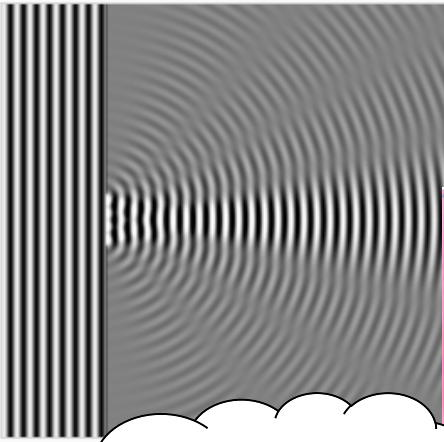


In 1948 Hendrick Casimir predicted that these two mirrors would be pushed together because of the difference in energy.

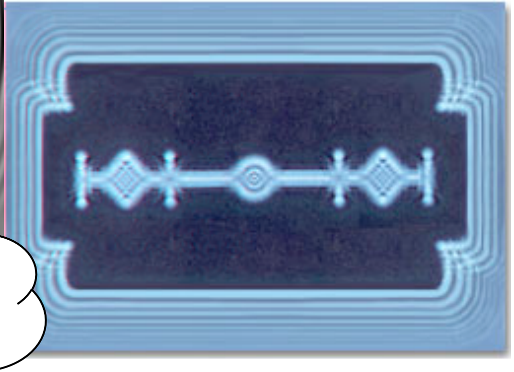


Once you have designed optics to correct for aberrations caused by the lenses…





diffraction still limits the size of objects we can resolve. The smaller the object the shorter the wave-length required.



$$d = \frac{\lambda}{2n\sin(\theta)}$$

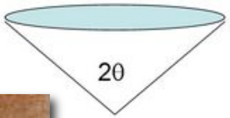


Figure 1

Ernst Abbe (1840–1905)

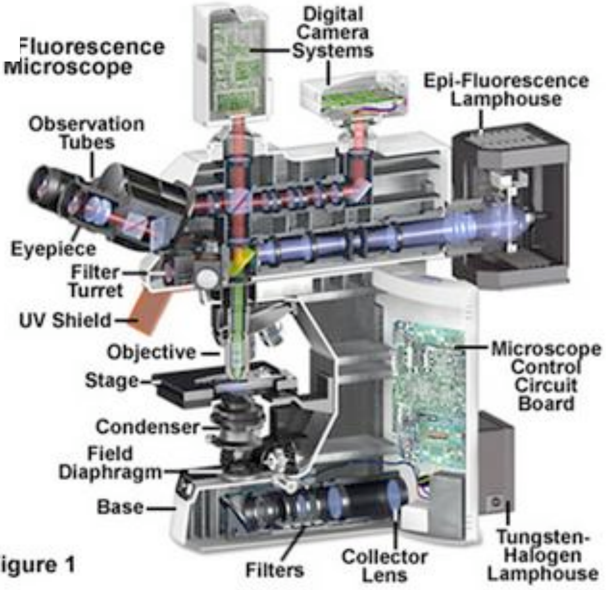
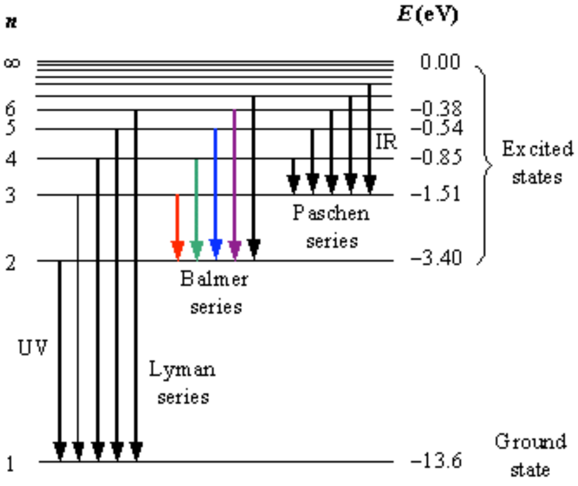
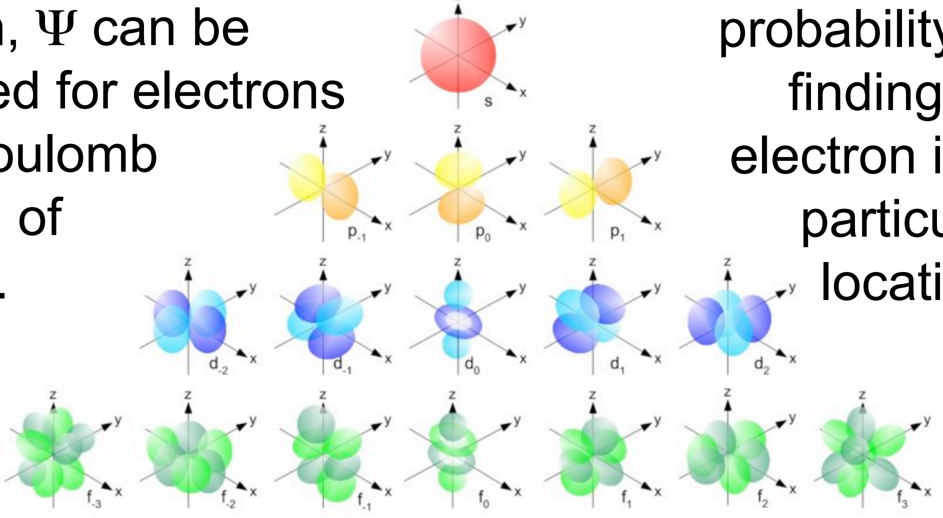


Figure 1



Using Schrödinger's wave equation, Ψ can be calculated for electrons in the Coulomb potential of an atom.

Ψ^2 gives us the probability of finding an electron in a particular location.



These calculations show discrete energy levels similar to the calculations for a harmonic oscillator.

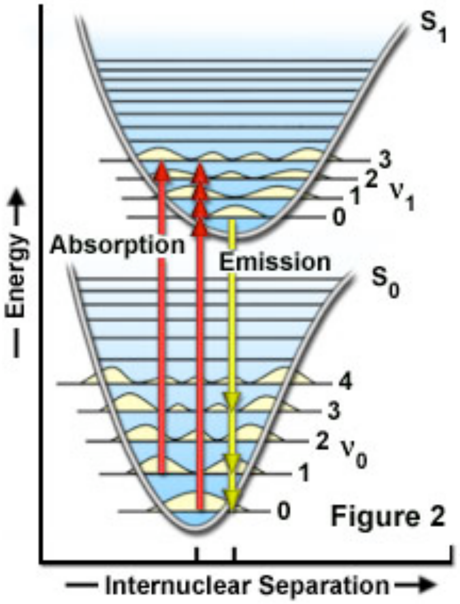
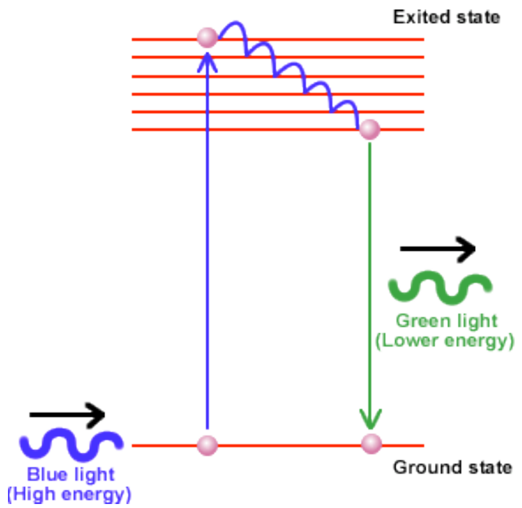
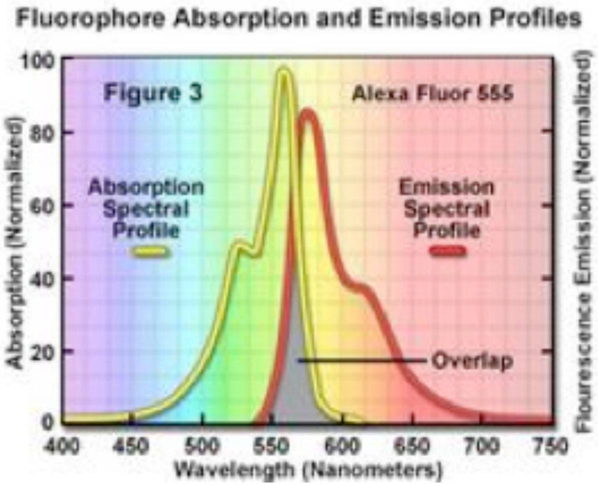


Figure 2

An electron is excited to a higher energy when a photon is absorbed and gives off a photon when it relaxes to a lower energy.

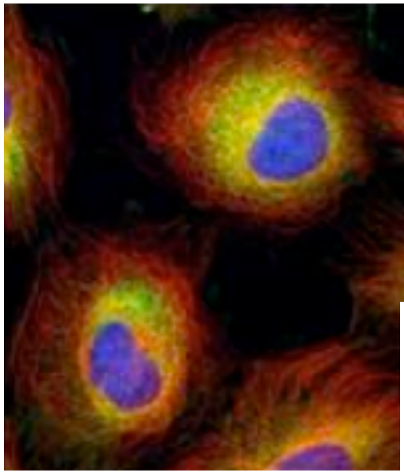


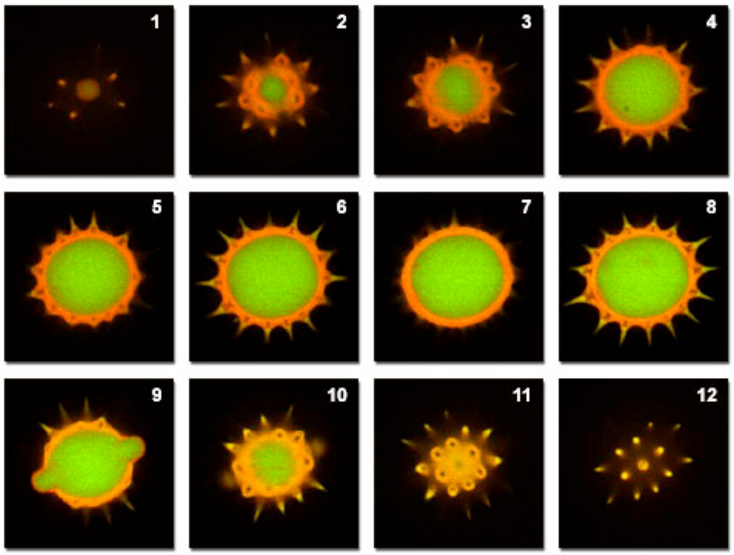
An atom fluoresces when a short λ photon excites the atom and a longer λ photon is given off.

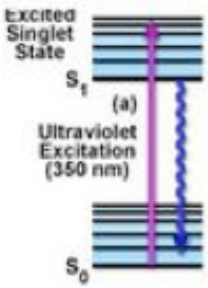


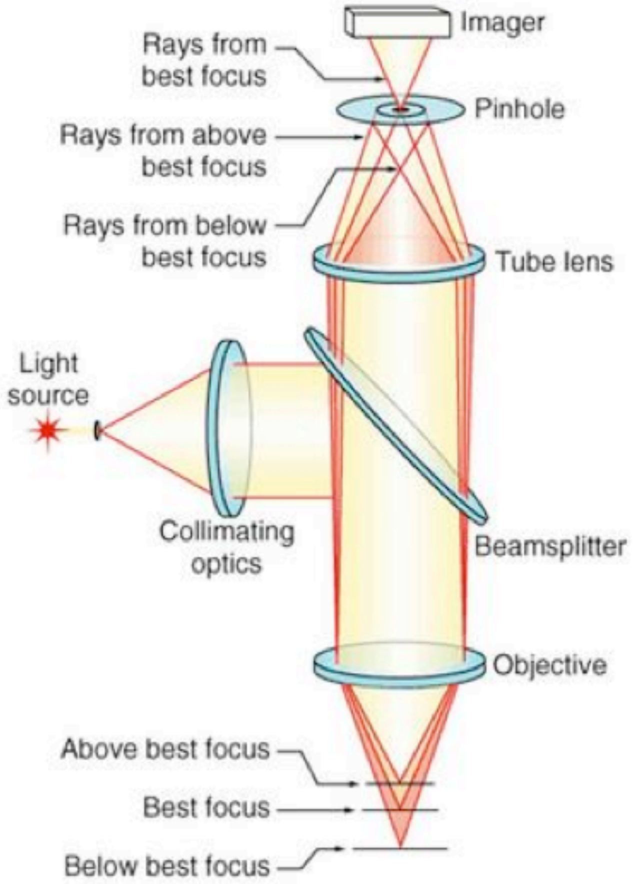
Labeling specific parts of the object with a substance that fluoresces helps bring out details in the image.

A confocal microscope uses a point source (laser) to cause one small spot to fluoresce at a time. You create an image by scanning across the object.

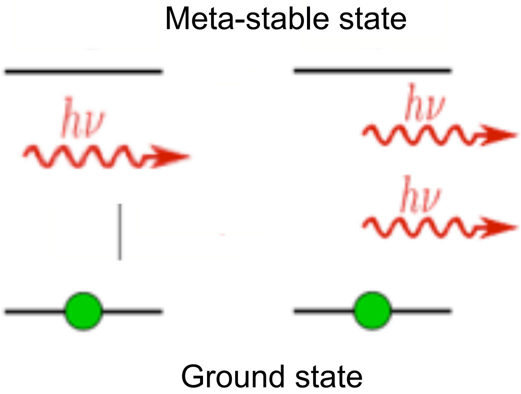








Energy is “pumped” into the medium, exciting electrons to the metastable state.



An electron drops to the ground state and produces a photon.

That photon interacts with another excited electron causing it to drop.

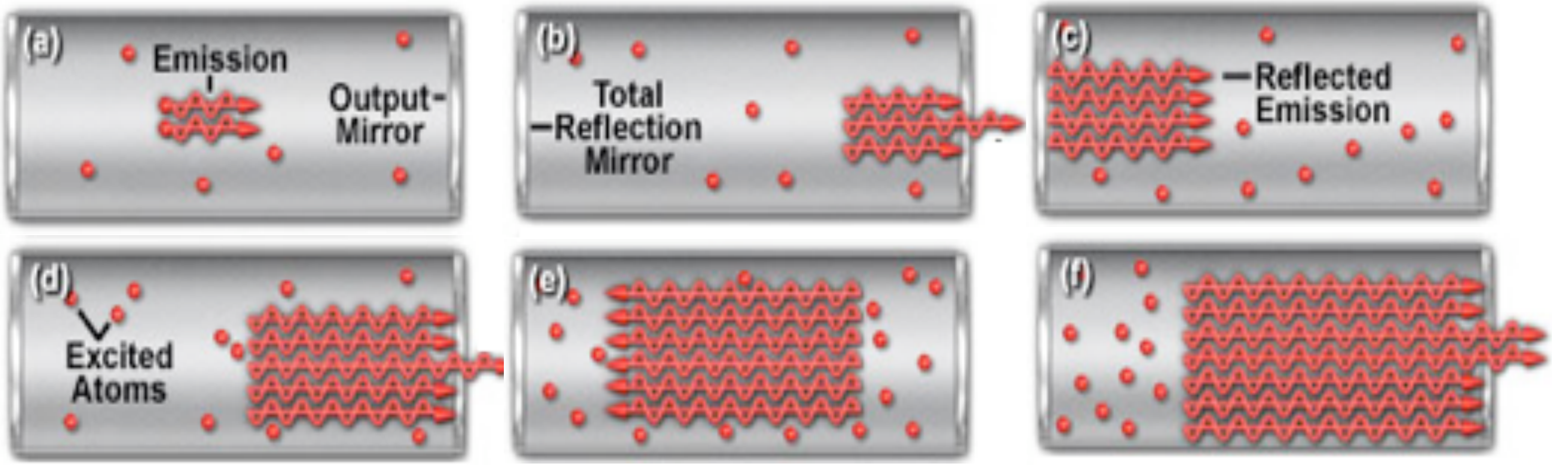
Coherent

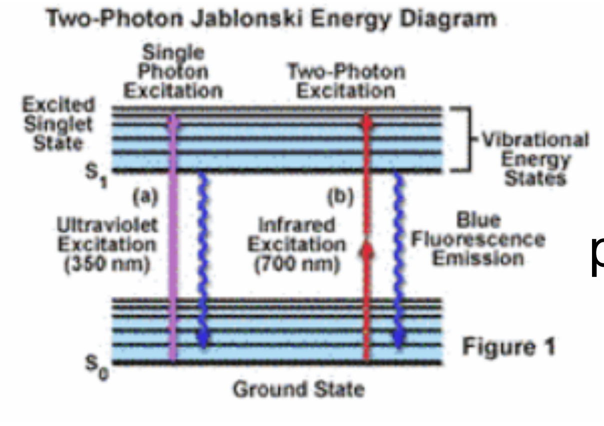
Collimated

Monochromatic

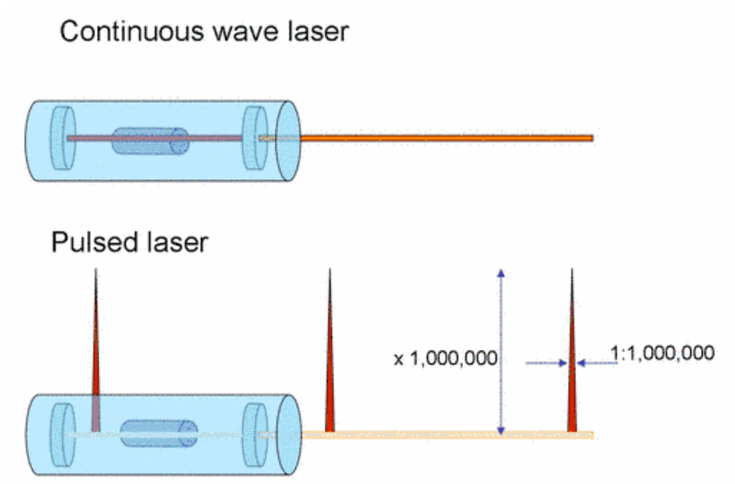
A second photon is produced by stimulated emission.

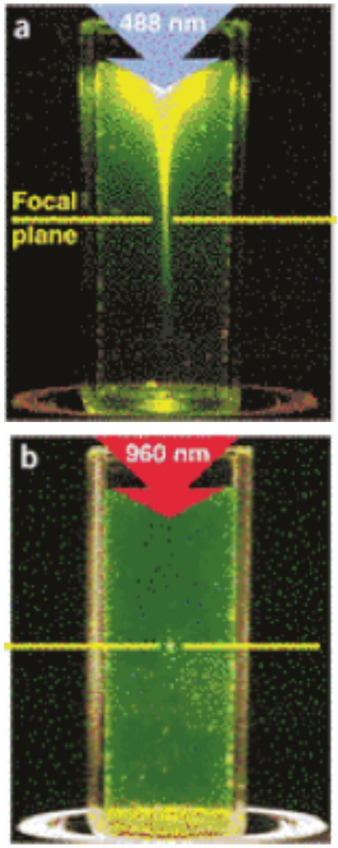
Those photons reflect and continue to stimulate more photons.



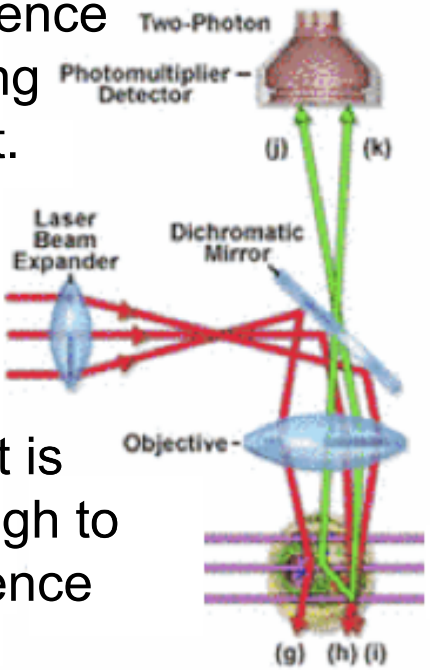


If you have a very intense light, two photons can induce a single fluorescence.

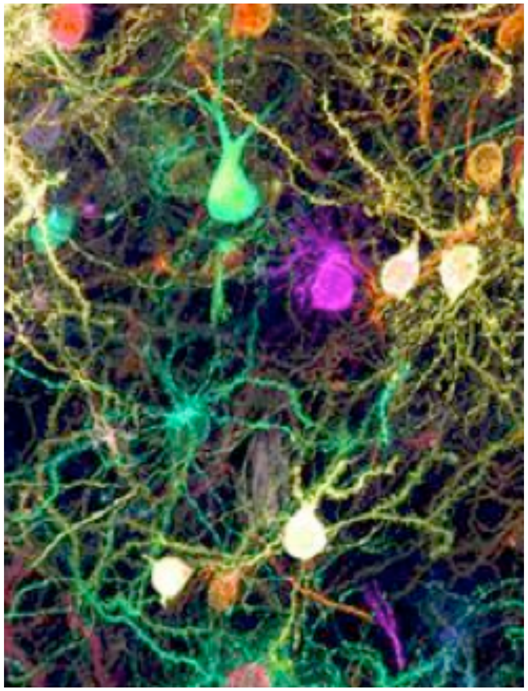




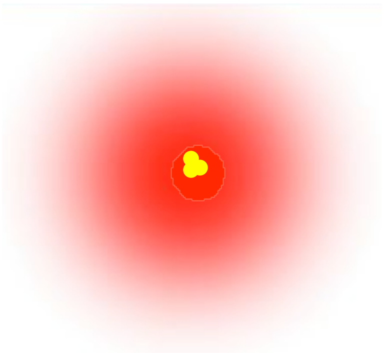
In single photon excitation, fluorescence is produced all along the path of the light.



In two-photon excitation the light is only intense enough to produce fluorescence at the focal point.

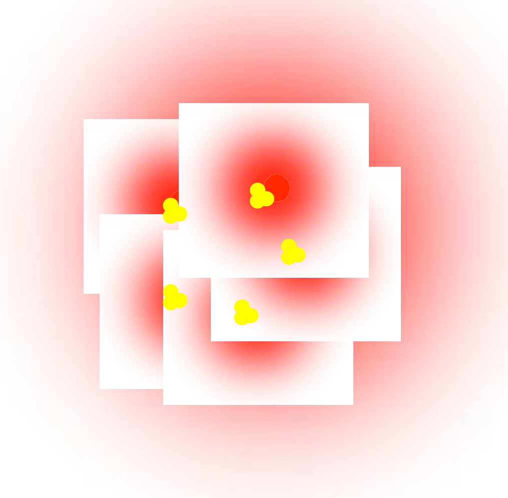


Can we break the diffraction limit?

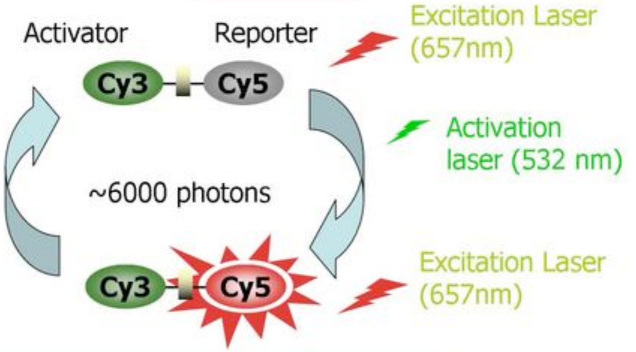


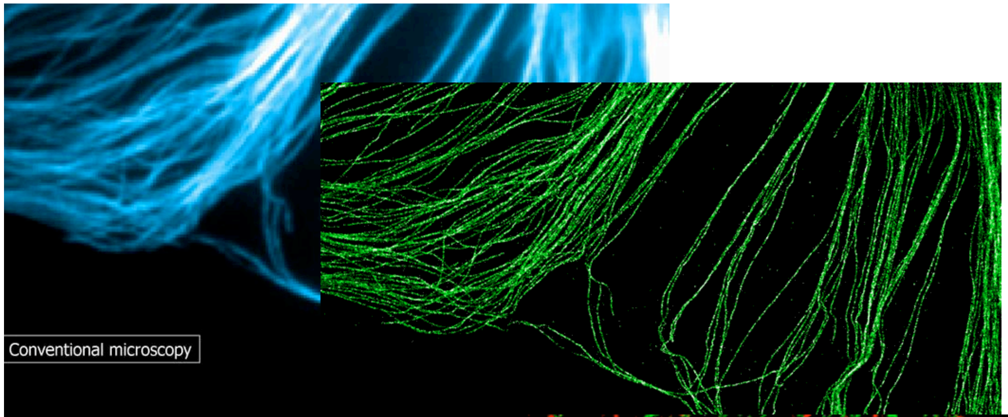
Because of diffraction a molecule might look like this.

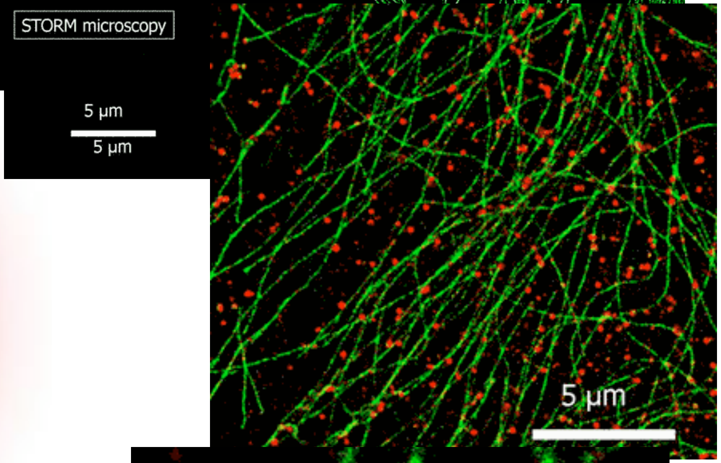
But we would have a pretty good idea of its location.

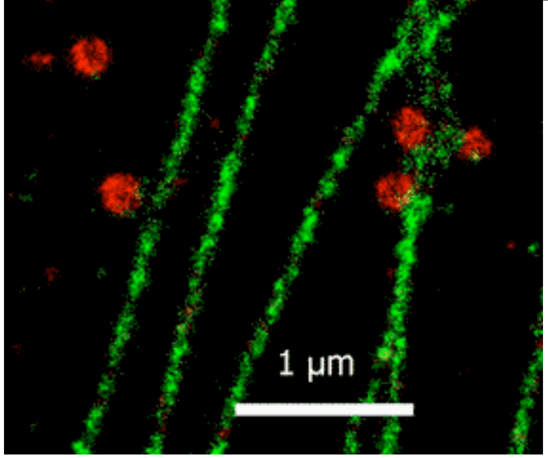


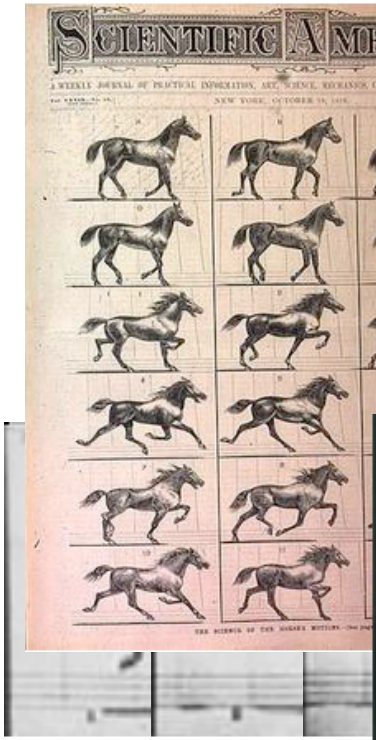
If we have many molecules in the same location we will not be able to resolve them…
unless we can turn them on one molecule at a time.





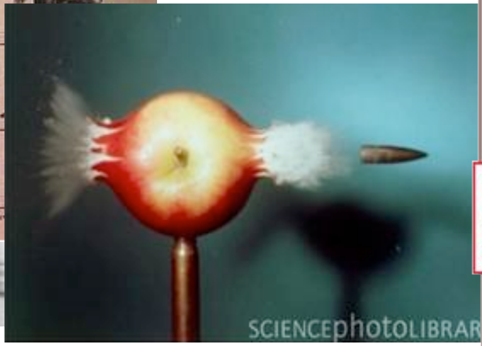


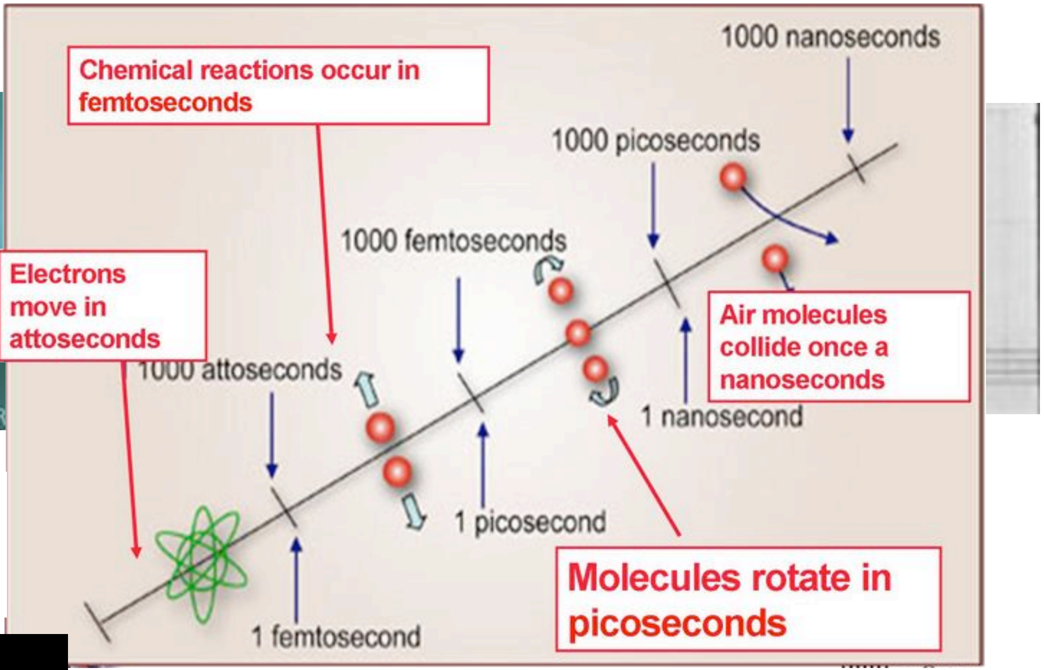




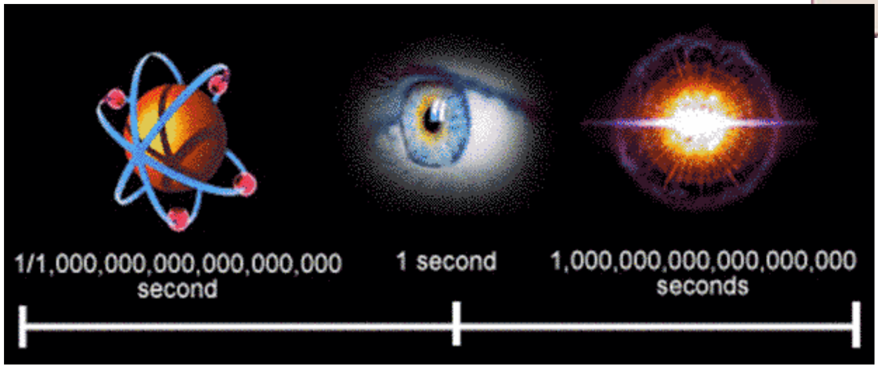
Eadweard Muybridge froze the motion of a horse in 1878 - a millisecond event.

If we wish to examine electrons we must take “pictures” at the attosecond level.

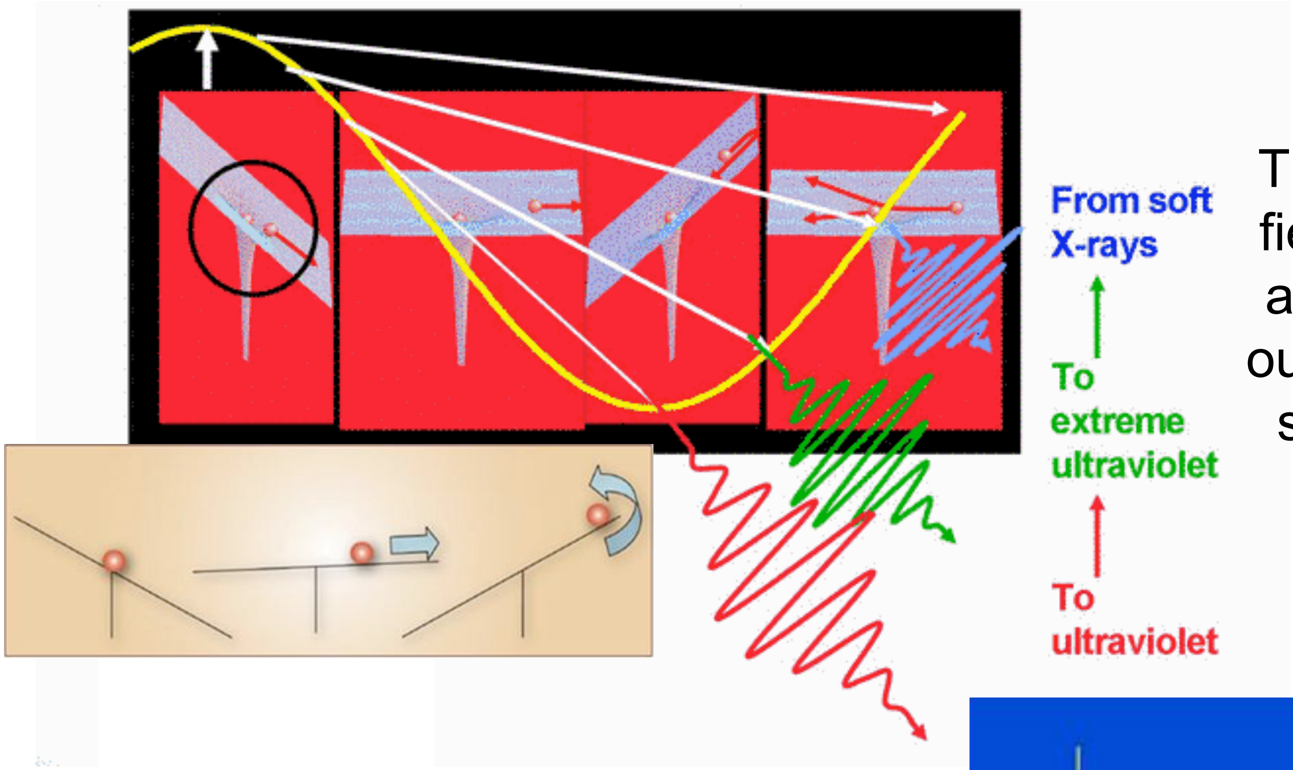




Harold Edgerton stopped a bullet at the microsecond time scale.

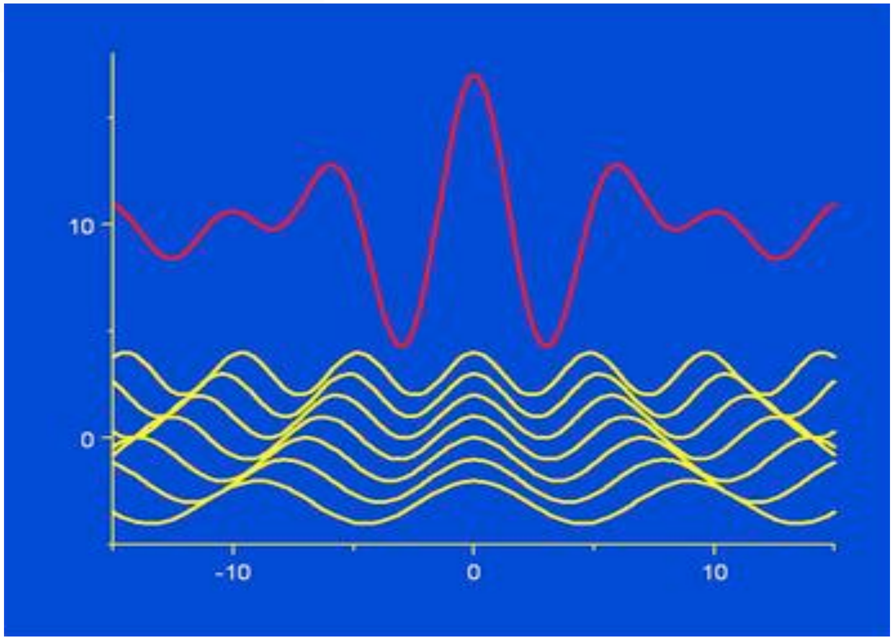


One attosecond is to 1/2 second as 1/2 second is to the age of the universe.

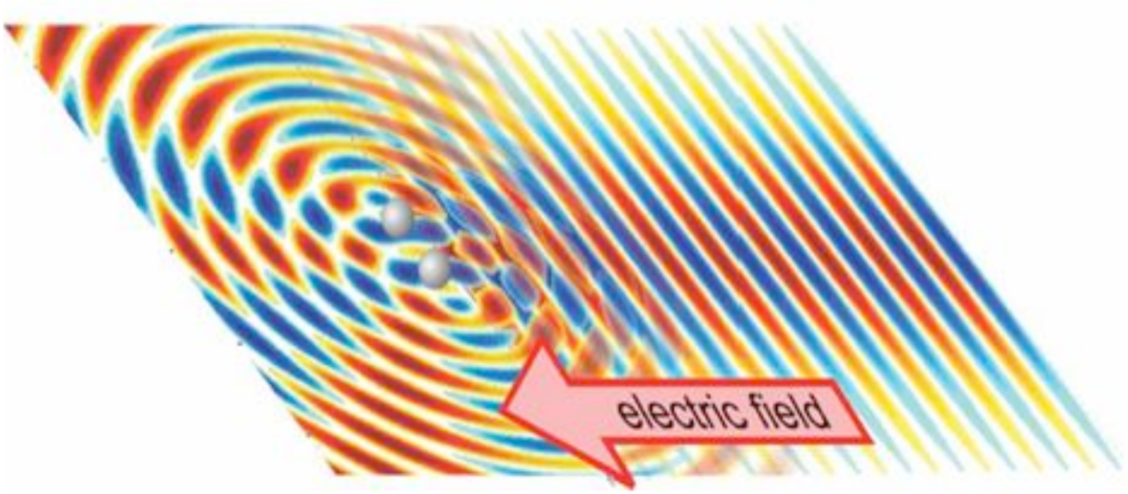


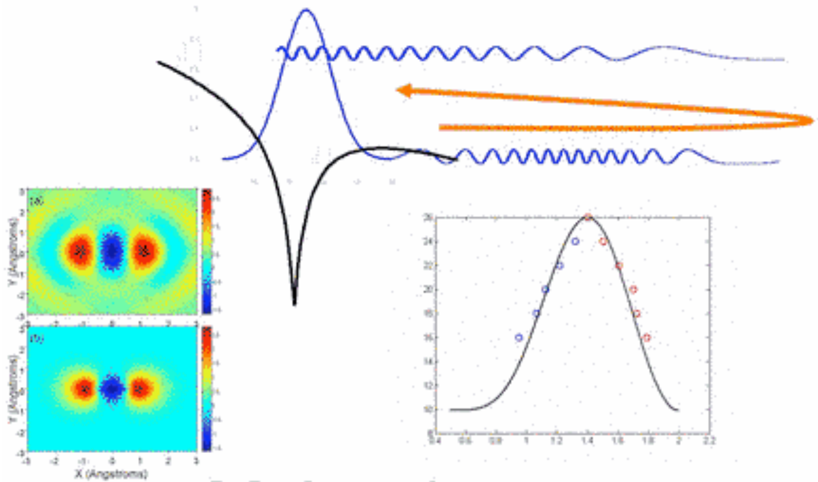
The alternating electric field of laser beam can accelerate an electron out of an atom and then send it crashing back into the atom.

The frequencies of light produced as the electron accelerates can interfere to produce a very short pulse of light.



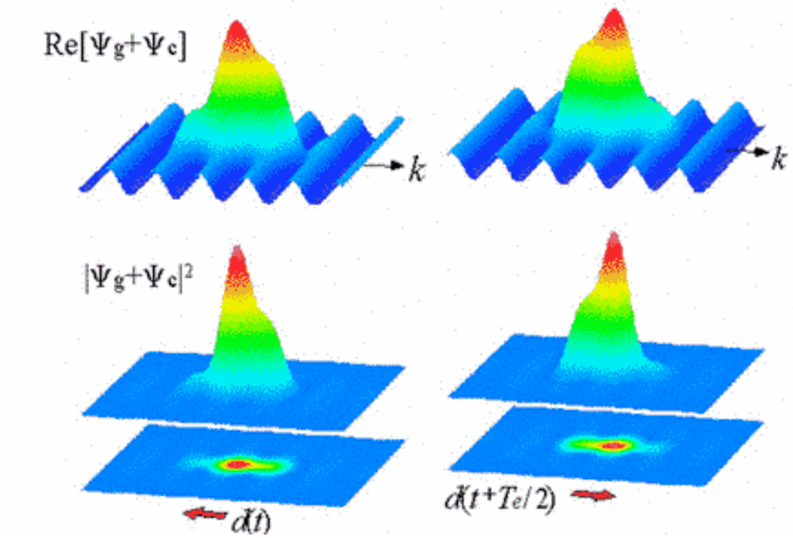
These pulses of light, interfering with the electron itself, can tell you everything you can know about the electron's wave function.



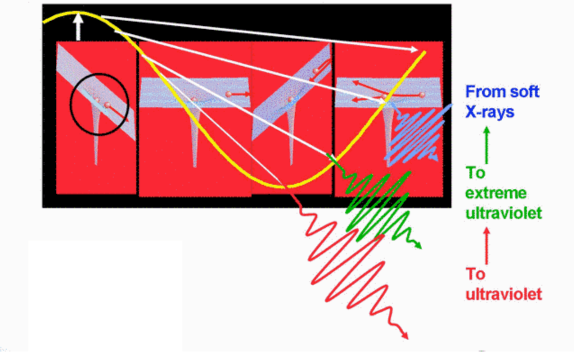


Molecular interferometer

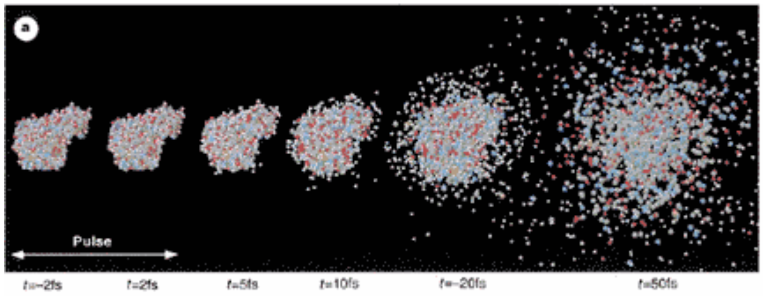
Now, movies of atoms moving and bonds breaking are possible.

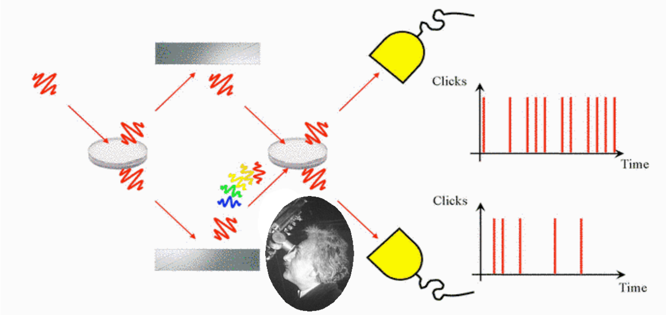


Understanding the Photon…

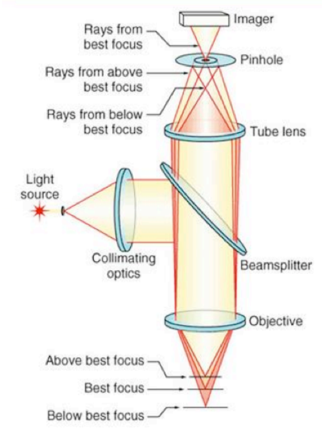


Molecular movies

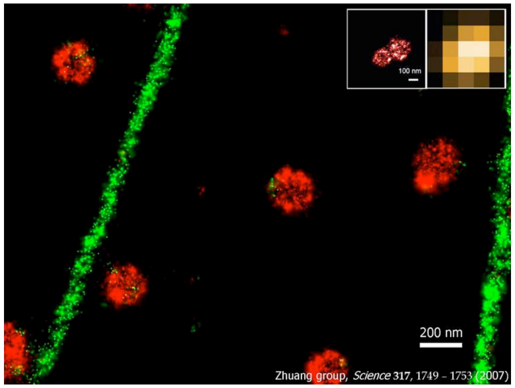




Improved solar panels



Images that defy the diffraction limit

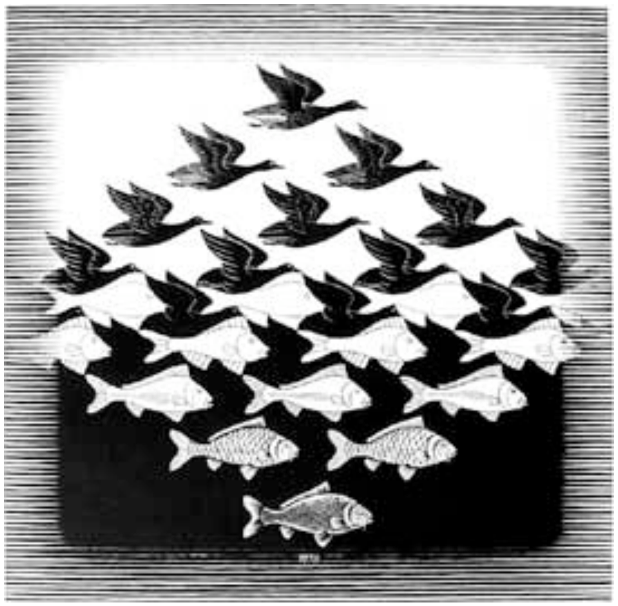


Zhuang group, *Science* 317, 1749 – 1753 (2007)

Problem Set

1. Young's experiment is performed with blue-green light of wavelength 500 nm. If the slits are 120 mm apart, and the viewing screen is 5.40 m from the slits, how far apart are the bright fringes near the center of the interference pattern? 2.25 mm
2. The cosmic background radiation follows a black body curve. If the radiation peaks at a wavelength of 2.2 mm, what is our temperature? 2.6 K If the universe was 2970 K 379000 years after the big bang when the universe became transparent to electromagnetic radiation, what was the peak wavelength of the curve? 976 nm
3. Photoelectrons are ejected from the surface of sodium metal when illuminated. The stopping potential for the ejected electrons is 5.0 V, and the sodium work function is 2.2 eV. What is the wavelength of the incident light? 170 nm
4. If you double the kinetic energy of a nonrelativistic particle, what happens to its de Broglie wavelength? Cut by a factor of $(1/2)^{0.5}$ What if you double its speed? Cut by a factor of 1/2
5. If we assume the sun's emission rate is 3.9×10^{26} W and that all of its light has a single wavelength of 550 nm, at what rate does it emit photons? 1×10^{45} photons/s
6. In a tube television electrons are accelerated through a 25.0 kV potential difference. If they are nonrelativistic, what is their de Broglie wavelength? 7.75 pm
7. How far would a beam of light travel in 1 μs? 900 m In 1 attosecond? 0.30 nm

8. Discuss M.C. Escher's print and its relationship to the dual nature of light and Heisenberg Uncertainty Principle.



9. The Uncertainty in the position of an electron is 50 pm or about the radius of a hydrogen atom. What is the uncertainty in the measurement of the momentum for that electron? 2.1×10^{-21} kgm/s

10. Starting with the idea that an electron is a wave, prove that $E_n = n^2h^2/8mL^2$ for an electron trapped as a standing wave in a one-dimensional box. Assume the length of the box is L and that m is the mass of the electron (hint: use de Broglie's equation and find momentum in terms of kinetic energy).

11. What would be the smallest diameter object you might expect to resolve with a microscope if the wavelength of light being used is 500 nm, the index of refraction is 1.4 and the total angle seen by the lens is 5°? 2×10^{-6} m = 2 μm

12. A pulsed laser emitting 694.4 nm light produces a 12 ps, 0.150 J pulse. What is the length of the pulse? 3.60 mm How many photons are emitted during each pulse? 5.24×10^{17} photons

13. The diagram at the right shows the energy levels in a substance. What wavelength of light is required to excite the electron. 4.29 μm What wavelength of light is emitted? 0.100 μm