Syllabus for PHYSICS 10

- Class: Tuesday, Thursday 12:10-1:30
- Instructor: Gergely Zimanyi
- Office: Phy/Geo 405, email: zimanyi@physics.ucdavis.edu; phone: 530-400-3936
- web: zimanyi.ucdavis.edu
- TA: Mikhael Semaan; email: msemaan@ucdavis.edu, OH: Wed 4pm, room 80
- Book: The New Quantum Universe (Hey/Walters, *Cambridge U. Press, 2003/2004*)
- Homework: Read the book; review the lecture slides!
- Quiz: Every Thursday in the last ten minutes. One question related to the lecture material of the week. I drop lowest grade for every one.
- Discussion session: attendance is mandatory. 2 missed disc. sect.=1 missed quiz
- Exams: One midterm, one final
- Course grade: 30%Final+30%Midterm+30%Quiz+10%Discussion session

Regrade: Within one week: first ask TA, then me. Grades on MyUCDAVIS

PHYSICS 10: A Journey into the Quantum Universe

- Many of us had the experience that we understand everyday things around us.
- We also understand mathematics and love its exactness: 2+2 is always 4.
- But how are the two REALLY related? Why do mathematical formulas guide waterfalls, the wind and the motion of every electron? Immanuel Kant
- Science is mankind's bravest attempt to bridge the gap between the exact math and the real world.
- Science still does not know why the exact formulas apply, but it shows that if one accepts nothing but the basic equations, nature's behavior can be predicted without any further assumptions, only by using mathematics. Newton
- Scientific method:
  1. Postulate law/theory – often motivated by experimental insight
  2. Derive measurable predictions
  3. Compare prediction with experimental data. If explanation incomplete:
  4. Improve law/theory to improve correspondence with experiment: PROGRESS

Example: The Evolution of Mechanics

1664: Newton: Defined what science is; Invented calculus
Time is absolute, space is absolute
Discovered mechanics of moving bodies
Discovered mechanics of celestial bodies
Success of Newton made Lamettrie declare "Man is a machine"

1905: Einstein: Special Relativity: Time is not absolute, it is what the clock shows
important at very high speeds (time tables for trains)

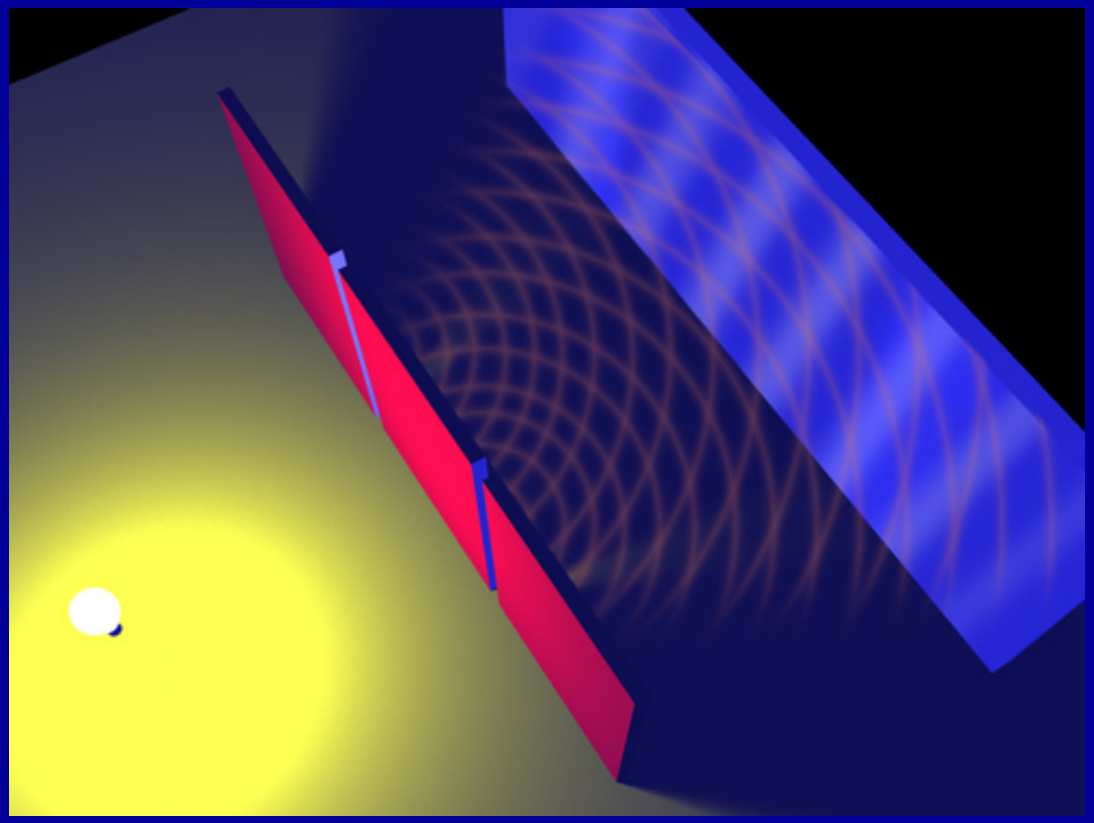
1913: Einstein: General relativity: Space is not absolute: it is curved by massive bodies
Correct theory of gravity: it is the curved space-time.
important only close to very massive bodies
(1919-1922 Eddington verified Einstein's prediction for the orbit of Mercury differing from Newton's theory during complete solstice)

1925: Heisenberg, Schroedinger: Quantum mechanics: Correction of mechanics:
particles have something wavy about them
important at very small scales

Example: The Evolution of Light I.

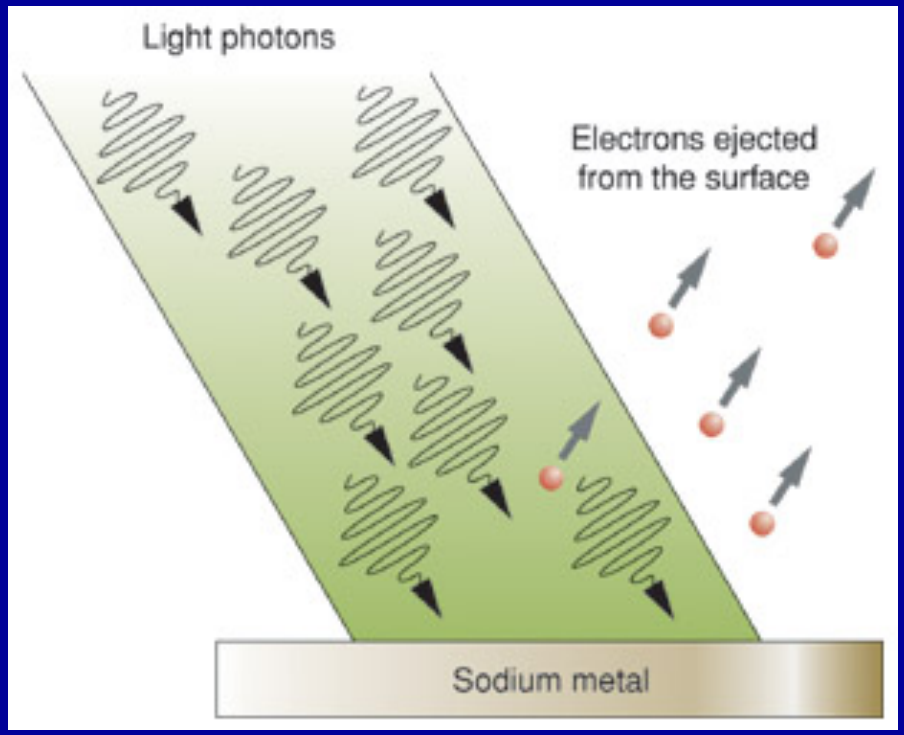
17th century: Newton: light is a stream of particles
- propagation in straight line

19th century: Young: Nope, light is all waves
- interference



Light II.

1905: Einstein: Photoelectric effect: well, it is particles after all



- Light is made up of little bundles, called "photons" because:
- # of electrons proportional to number of photons, but not the energy of electrons
- energy of electrons proportional to energy of photons, but not their number
- Light waves would knock out more electrons the higher the energy

(Nobel prize)

Light III.

1925: Heisenberg, Schroedinger, Dirac: Nope, make that particles AND waves

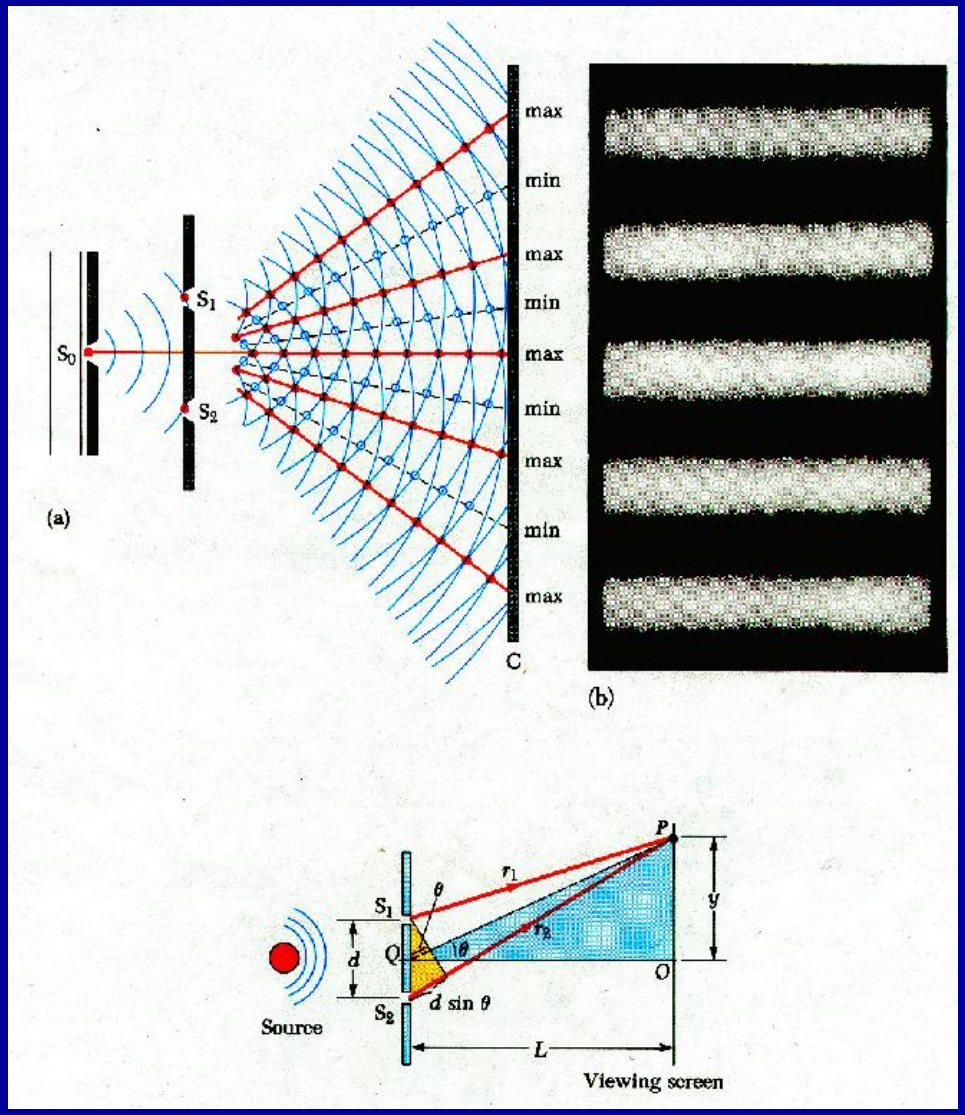
Light IV.

1925: Heisenberg, Schroedinger, Dirac: Nope, make that particles AND waves

WHAT?!?

This is the subject of this course.

Connection between light and mechanical matter: Double Slit Experiment



The analogy to water waves is complete: light is waves

I: intensity
h: height of wave

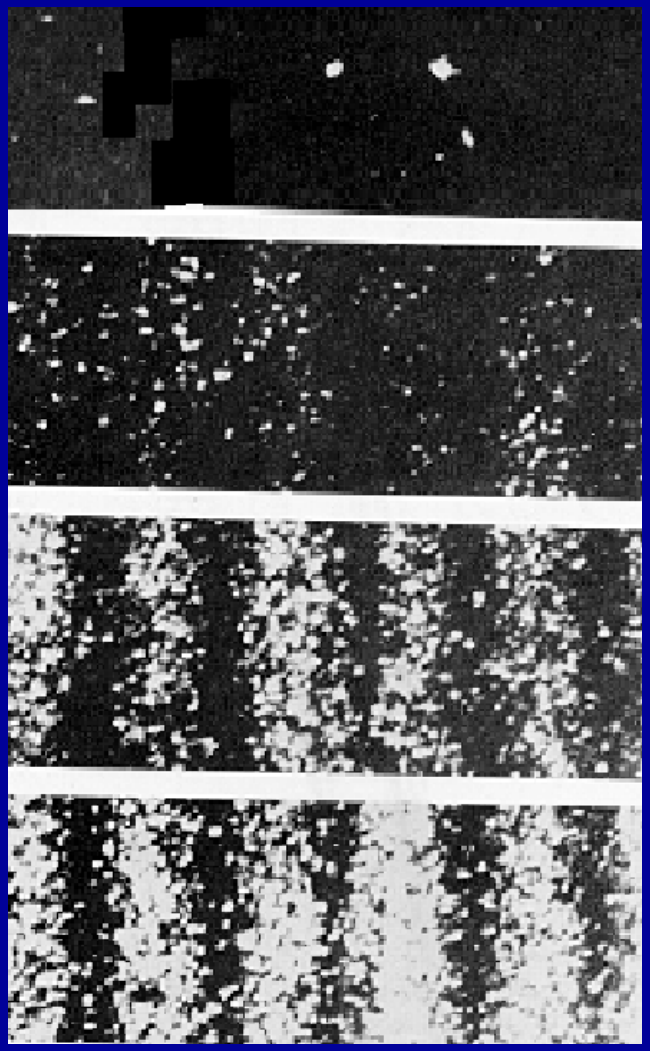
$$I = h^2$$

$$h = h_1 + h_2$$

$$I = (h_1 + h_2)^2 = h_1^{\,2} + h_2^{\,2} + 2h_1h_2 =$$

$$= I_1 + I_2 + Interference$$

Double Slit: Light is Waves and Particles

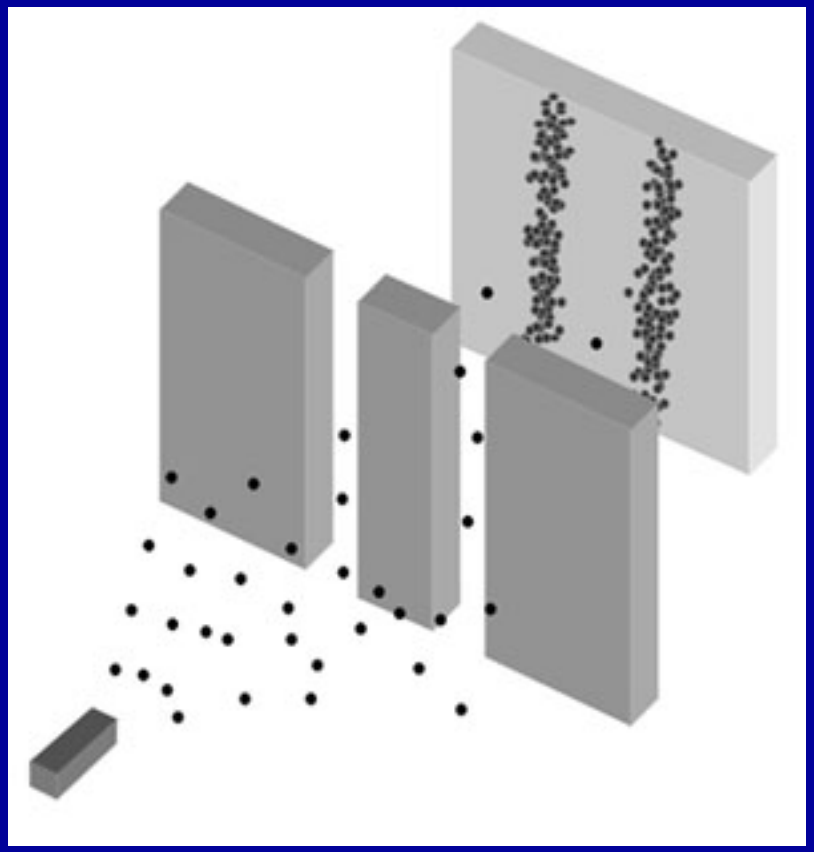


time

1. We can clearly see the individual photons absorbed on screen

2. But pattern of many photons is governed by a wave equation

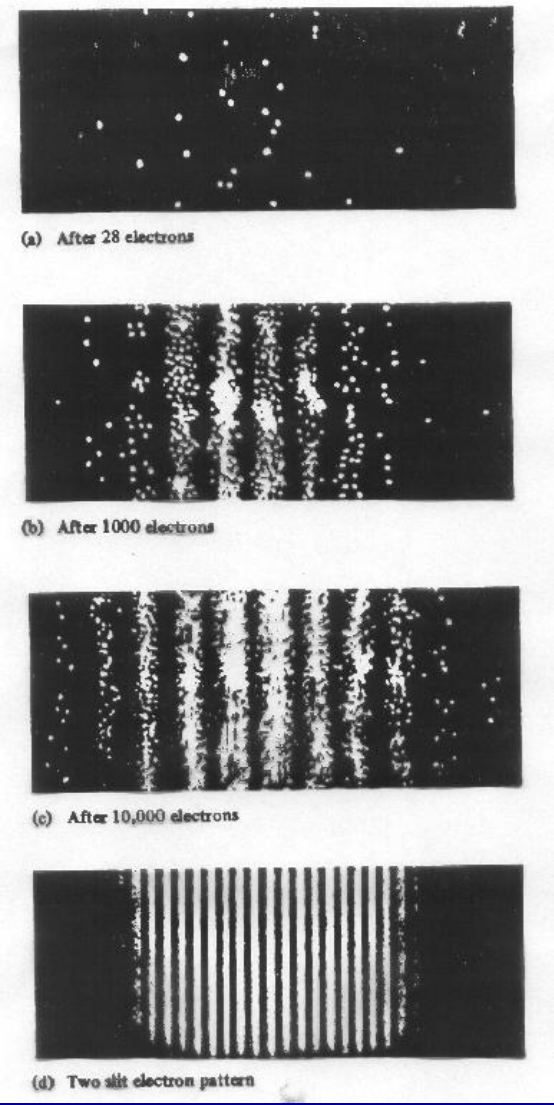
Double Slit: What would particles do?



1. We can clearly see the individual particles absorbed on screen

2. No interference, just the image of the two slits

Double Slit Experiment: Electrons are Particles and Waves



1. Electrons arrive at screen one by one
2. But the pattern of a large number of electrons is governed by a wave-like equation

Interpretation is harder: electrons do not have a “wave height”.

De Broglie: let us imagine that there is a wave associated with the electrons (Nobel prize)

The Role of Observation

1. Electrons exhibit the interference pattern in a double slit experiment:
   the electron goes through both slits simultaneously as a wave

2. But if a flashlight is aimed at the electrons to determine which slit
   it went through, then the pattern changes to the bullet pattern:

The wave nature is lost when the position is determined
(Does a falling tree make a sound when nobody is there to hear it?)

Maybe quantum particles do not have perfectly defined location on their own

Heisenberg's Uncertainty Principle I.

How to measure the location of an electron: shine light on it

Light equations: $f = c / \lambda$, c: speed of light, λ: wavelength, f: frequency

Planck: $E = h f = h c / \lambda$, h: Planck's constant

Conundrum:

1. If you want to know the location of the electron, you have to use small wavelength, because light can determine location with λ accuracy (walk barefoot in sand: grains – pebbles - boulders)

2. But small wavelength means the photon has high energy: big kick into electron, so its velocity (momentum) will be very poorly determined (wrecking ball; linebacker…)

Heisenberg's Uncertainty Principle II.

The more you know about the location, the less you know about the momentum.

and

The more you know about momentum, the less you know about location

Momentum p=mv (mass times velocity)

Cars: brick wall: good knowledge of location, little knowledge of momentum
radar gun: good knowledge of momentum, little knowledge of location

$$\Delta x \times \Delta p \approx h$$

$$h = 6 \times 10^{-34} \, Joule \sec$$

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The uncertainty is very small: do not argue with the CHP officer
based on quantum mechanics (I tried, it don't work)

The Role of Observation: Photography

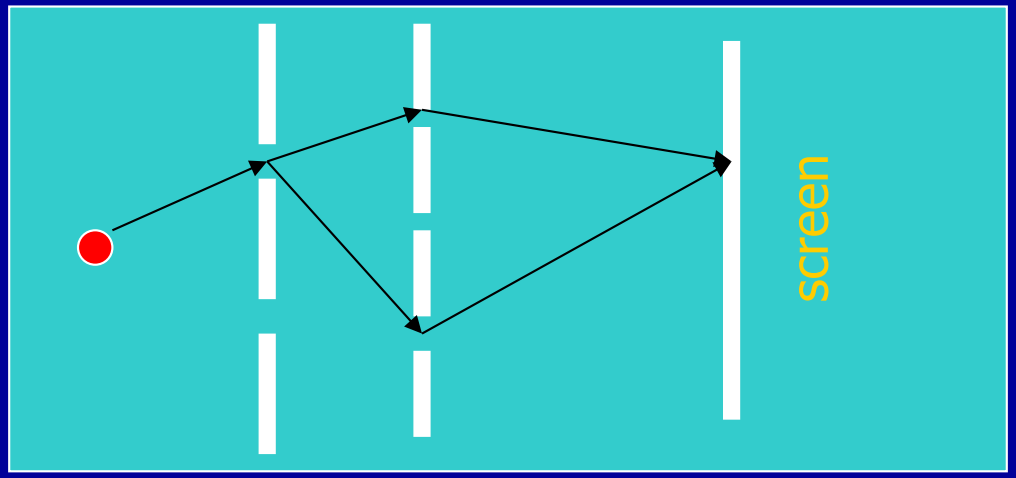
Photographs are formed point by point, as photons hit the tiny silver grains of the photographic plate, or the CCD pixels of your phone-camera.
The event of hitting the plate is the "observation" of the photon.

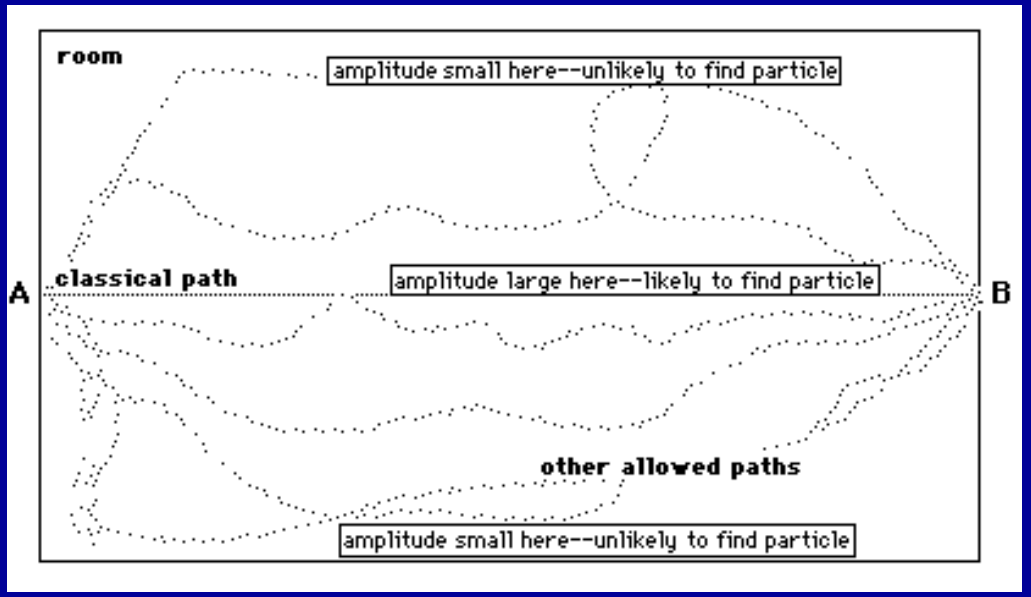
Copenhagen interpretation (Niels Bohr, similar to light):

1. The quantum waves collapse into a classical point when observed

2. The statistics/pattern of these points is governed by a wave equation

Feynman's Quantum Paths





- Quantum particles propagate from A to B by exploring all possible paths.
- Each path has a corresponding phase and amplitude/weight
- Total amplitude is sum of amplitudes along all paths
- Probability from A to B = (Total amplitude over all paths)^2

Zero point motion

Quantum roller coaster:

The car cannot sit at
the bottom. It would have
well defined momentum (p=0)
and well defined location.

It has to oscillate:
“zero point motion”

Solution of the world’s energy crisis:
Extract this zero point energy!

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IMPOSSIBLE

This would violate Heisenberg's
Uncertainty principle

Schroedinger and Matter Waves I.

1. De Broglie: all particles (electrons, protons) have a wave associated with them:

$\lambda = h/p$ (wavelength = Planck's constant/momentum)

Why wasn't this observed before? Planck's constant is tiny

Ph.D. thesis sent to Einstein. He liked the idea – the committee passed de Broglie

2. Schroedinger: moderately successful physicist
   - His prof., Debye asked him to review this wild paper of de Broglie
   - Debye said that one needs a proper equation to motivate these waves
   - Schroedinger went into a cabin in the mountains and derived his eq. in a week

Schroedinger's equation

Ingredients:

1. Energy conservation: total energy = kinetic energy + potential energy

- Roller coaster: speed is low when elevation is high
- Speed is high when elevation is low

- Classical physics $E = mv^2/2 + V = p^2/2m + V$ (V: potential energy, p=mv)

2. Quantum physics: these terms act ("operate") on de Broglie's wave :
   $E\,\psi = [p^2/2m]\,\psi + V\,\psi$

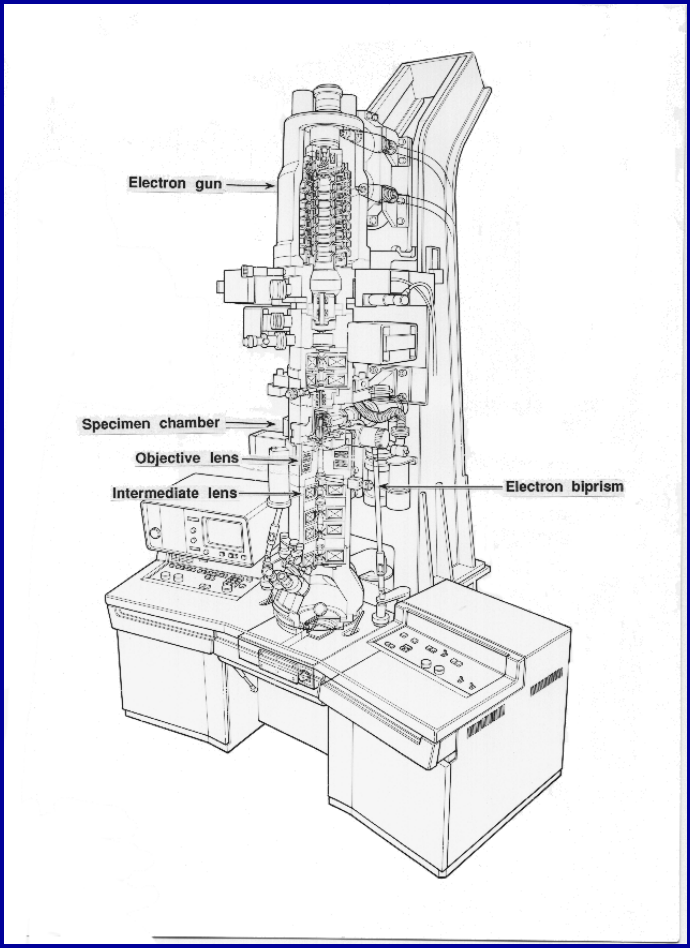
3. The momentum acts on a wave by differentiating it:
   The wavier a wave is, the higher its momentum/velocity and its derivative:
   $p\psi = i\hbar\, d\psi/dx$ (i: complex unit, $i^2=-1$, $\hbar = h/2\pi$)

4. Schroedinger's equation

$$E\,\psi = -(\hbar^2/2m)\, d^2\psi/dx^2 + V\,\psi$$

Electron Optics I.

Electrons are waves like light: we can manipulate them with lenses: electron optics



Electron Optics II.

Light cannot see (image) molecules, since wavelength is too big
Electrons can see molecules since wavelength is comparable

This is how you live: DNA

Electron Optics III.

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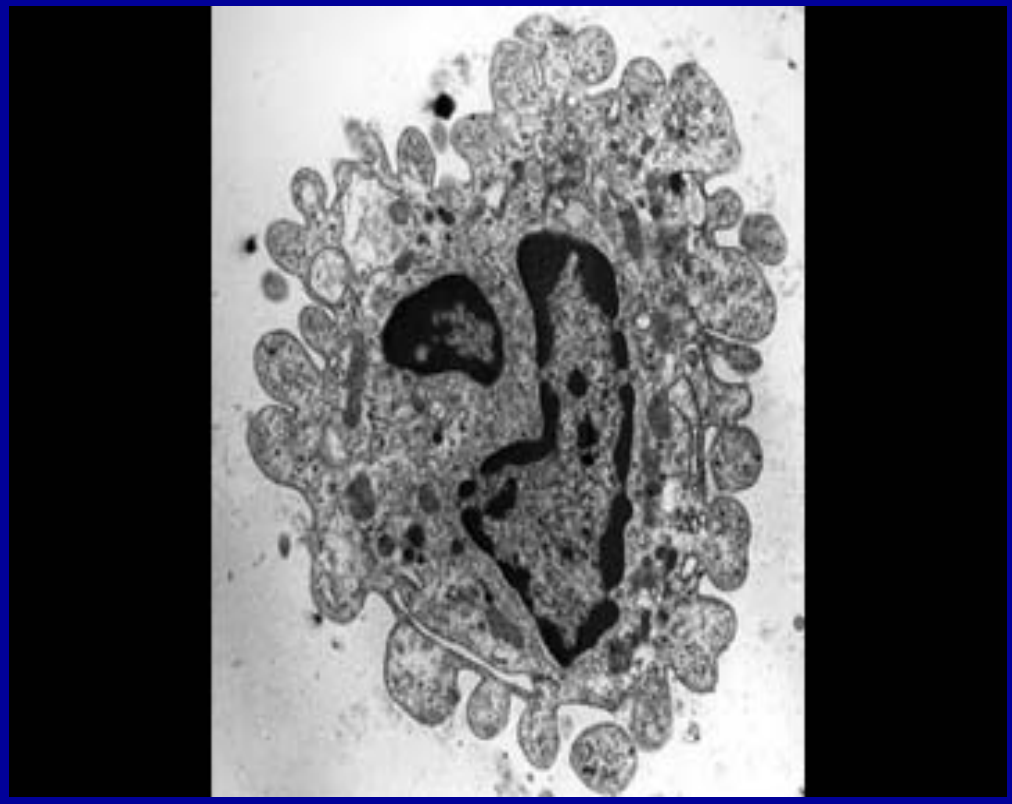

This is how you die: apoptosis