CHAPTER 29: LIGHT WAVES 03/18/19

Light is a wave – in many ways it behaves just like a wave. Light is also a particle – in many ways it behaves just like a particle. This week we study the wave properties of light. Next week we'll study the particle nature of light.

CAUSE OF REFRACTION

- Refraction is caused by the change in the speed of light from one transparent medium to another, and the wave nature of light.
- Consider two cart wheels on an axle rolling from the sidewalk to the grass at an angle. The wheel that hits the grass first slows down while the other keeps going fast, turning the wheels toward the normal.
  - FIG. 28.23
- A light wave behaves the same way when it moves from air into water for example. The portion of the wave fronts that hit the water first slow down, while the rest keeps moving fast, changing the direction of the light ray (which is always perpendicular to the wave fronts).
  - FIG. 28.24
- This provides a causal explanation for mirages (and all other refraction effects).
  - FIG. 28.25

HUYGENS' PRINCIPLE

- The wave crests that form the concentric circles of a spreading wave are called wave fronts.
- Huygens said that the wave fronts of light are the overlapped crests of tiny secondary waves – wave fronts are made up of tinier overlapping wave fronts.
- Every point on a wave front is a source of new wavelets that combine to produce the next wave front, etc.
  - ANIM: Spherical wave fronts
  - FIGS. 29.3 and 29.4
- Laws of Reflection and Refraction can be understood by looking at the wavelet makeup of an incoming plane wave.
  - FIG. 29.5
- When waves go through openings, what comes out depends on what size the opening is compared to the wavelength:
  - Opening wider than the wavelength: plane waves go through fairly unchanged except at the corners, where the waves bend into the shadow area.
  - Opening smaller than the wavelength: the opening acts as a point source of new waves that fan out on the other side of the opening. This fanning out of waves, rather than going straight through, is called *diffraction.*
  - BOOK: show Fig. 29.7

DIFFRACTION

- Light can bend by reflection and refraction – it can also be bent by diffraction.

- Light passing through an opening larger than its wavelength casts a sharp shadow. There is not much spreading out – there is little diffraction.
- When it passes through a thin slit, the sharp shadow disappears and the light spreads out like a fan to produce a pattern of lighter and darker areas.
    - FIG. 29.8: light through a big opening in poster, light through slit in poster.
    - FIG. 29.9
    - DEMO: laser through single slit
- The amount of diffraction depends on how large the wavelength of light is compared to the size of the obstruction casting the shadow.
    - Longer wavelengths diffract more - they fill in the shadows better.
    - FIG. 29.11
- Diffraction and microscopes and radio

INTERFERENCE

- Diffraction fringes of light and dark regions are caused by *interference*.
    - Interference is the adding, or superposition, of different waves. Constructive interference is crest-to-crest reinforcement; destructive interference is crest-to-trough cancellation.
    - FIG. 29.13
    - DEMO: circle interference plates
- In 1801, Thomas Young discovered that light shining through two close pinholes produced light and dark fringes on a screen through interference.
    - DEMO: Monochromatic light through two slits
    - FIGS. 29.18
- This happens because the light diffracts (fans out) through the two pinholes. Then the light from the two different sources (pinholes) travel different distances to a particular point on the screen.
    - If a crest from the light through one hole and a crest from the light through the other hole get to a point at the same time, then there is constructive interference – a bright fringe.
    - If a crest from the light through one hole and a trough from the light through the other hole get to a point at the same time, then there is destructive interference – a dark fringe.
    - FIGS. 29.17, 29.19, 29.20
    - DEMO: laser through single slit; laser through double slit

SINGLE COLOR THIN FILM INTERFERENCE

- Interference can be produced by the reflection of light from the top and bottom surfaces of a very thin film.
  - FIG. 29.23: Two pieces of glass with a thin air wedge between them
    - Light coming from a given point can reach the eye by two paths: reflecting off of the top of the air wedge and reflecting off of the bottom of the air wedge.
    - The two rays have traveled different distances. When they meet again, they can be in phase or out of phase depending on the thickness of the wedge.
    - As we look across the glass surface there will be alternating light and dark regions where the two rays are recombining in phase (constructive interference) or out of phase (destructive interference)
      - BOOK: Fig. 29.24

INTERFERENCE COLORS BY REFLECTION FROM THIN FILMS

- Colors reflected from a soap bubble or gasoline on wet pavement is caused by interference. This production of colors by interference in thin films is called *iridescence*.
  - DEMO: soap bubbles
- When a soap bubble is about the same thickness as the wavelength of light, light can interfere when it reflects off of the outer and inner surfaces of the soap film.
  - If, for example, the film is just the right thickness to cause destructive interference for green light, then when white light shines on the soap, the green light is subtracted out and the reflected light appears magenta (the complementary color of green).
  - At other places on the soap bubble where the film is thinner, what color might be canceled? If the film is thinner, then the extra distance that light travels to reflect off of the inner surface will be less than before. Therefore the light that experiences destructive interference at that point must have a shorter wavelength than green. So blue possibly would be canceled.
- The same thing happens with gasoline on a wet street.
  - FIG. 29.26
  - Why does the street have to be wet to see iridescence from gasoline? Because there has to be a second surface to reflect from, in this case the water on the street.
  - Different colors correspond to different thicknesses. Long wavelength colors are absorbed in thicker regions than short wavelength colors. Circles of different colors make up a “contour map.”

POLARIZATION

- Interference and diffraction show that light is wavelike. But is light a longitudinal wave (oscillating motion is along the direction of wave travel), or is it a transverse wave (oscillating motion is perpendicular to the direction of wave travel)?
  - The fact that light waves can be polarized shows that they are transverse.
  - *Polarization* is the alignment of transverse electric vibrations in an electromagnetic wave.
  - DEMO: shaking a rope tied at one end vertically or horizontally to produce a vertically or horizontally plane-polarized wave.
  - Plane-polarized: waves traveling along rope are confined to a single plane.
- An electron vibrating in one direction produces a plane-polarized electromagnetic wave. A vertically vibrating electron produces a vertically polarized wave. Horizontally vibrating electron produces a horizontally polarized wave.
  - FIG. 29.29
- Common lights emit unpolarized light because all of the electrons vibrate in random directions. The vibrating planes point in all directions, but all the directions can be represented by vertical and horizontal components. So unpolarized light can be thought of as having equal amounts of vertical and horizontal polarization.
  - FIG. 29.30
- Some crystals actually divide the unpolarized light into two beams polarized at right angles to each other, and then transmit one beam while absorbing the other. These crystals are put between plastic sheets to make a Polaroid filter, which converts unpolarized light into polarized light.
  - DEMO: wave on a rope through grating.
  - FIG. 29.32
  - No matter what direction a Polaroid is rotated, it will absorb 50% of unpolarized light, and the 50% that is transmitted will then be polarized in the direction of the Polaroid axis.
  - If a second Polaroid is arranged with its axis lined up with the first one, then all of the Polarized light that came through the first will also pass through the second one.
  - If a second Polaroid is arranged with its axis at right angles to the first one, none of the Polarized light that came through the first will pass through the second one.
  - DEMO: Polaroids
- A lot of light reflected from non-metallic surfaces (such as the glare from glass or water) is polarized.
  - Vibrations parallel to the surface are mostly reflected.
  - Vibrations perpendicular to the surface are transmitted, or refracted in.
  - Much like skipping flat rocks off of water: the flat surface has to be parallel to the water to skip, otherwise it will go into the water.
  - We reduce glare from the water, wet road, glass, etc. by using Polaroid sunglasses. What orientation should the polarization axis of the lens be to reduce glare best? Vertically aligned lenses block horizontally polarized glare.

CHAPTER 30: LIGHT EMISSION 03/25/19

THE OSCILLATOR MODEL FOR LIGHT TRANSMISSION

- So far, we have used an oscillator model to describe light.
    - Oscillating electrons (free electrons and those in atoms), produce EM waves.
    - This model of oscillating charges producing EM waves allowed us to understand many properties of light transmission:
        - EM spectrum, reflection, refraction, diffraction, polarization, etc.

THE PLANETARY MODEL FOR LIGHT EMISSION

- Now we need another model, the planetary atomic model, to understand the physics of light source – light *emission*.
- Light emission involves the transition of electrons from higher to lower energy states within the atom.
    - FIG. 30.1: Electrons occupy electron shells surrounding the atom.
        - Each shell is at a certain radius and represents a different energy state for the electrons in the shell.
        - Each element has its own characteristic pattern of electron shells, or energy states.
    - Because the states only have certain specific energy values, they are discrete, and are called quantum states.

EXCITATION

- DEMO: analogy of dropping a book from different heights.
- Electrons in higher orbit/shell are in a higher energy state – they have more potential energy relative to the nucleus.
- When an electron is raised to a higher energy level (state/orbit/shell), it is *excited*.
    - It usually returns to its lowest energy state quickly (like a pushed-open spring door that is released). When it drops back down, it releases its temporarily acquired energy by emitting a pulse of electromagnetic energy called a *photon*.
        - FIG. 30.2
        - A photon is a particle of light.
            - The emitted photon has energy equal to the energy transition of the jump (the difference in the energy levels).
            - The frequency of the photon is proportional to its energy:
                - $E \sim f$, $E = hf$, where h is Planck's constant.
    - DIAGRAM: draw atom with different energy levels and emitted photons.
- The frequencies of the photons (i.e. light) emitted by exited electrons in a material are determined by the pattern of different energy levels in the material. The different frequencies correspond to characteristic colors for each element.
    - "Neon" light tubes
        - DEMO: neon (red) and mercury (blue) gas discharge tubes

        - Different color “neon” lights come from different gases used in the tubes. Only red “neon” light comes from tubes that actually use neon gas (others include argon, xenon).
        - Electrons are boiled off metal electrodes located at both ends of the tube. The electrons are made to vibrate in a high voltage AC field. They smash into neon atoms, boosting the orbiting electrons into higher energy level orbits. The orbiting electrons fall back to the stable low energy state and give off photons with red light frequencies. Atoms can then be excited and de-excited again.
    - Various colors of flames from different elements being burned.
        - Atoms give off colored light characteristic of their energy spacings.
        - Sodium (salt): yellow (most street lights). Copper: green. Mercury: more blue/violet (other street lights).
- Two different models for light: oscillator for reflection, transmission; planetary for emission. Neither is supposed to show what atoms “really are,” but rather they simply give useful representations for different behavior.
    - No scientific model is “right” or “wrong.”
    - They are “useful” or “nonuseful.”
    - **All are incomplete and imperfect.**

EMISSION SPECTRA

- Every element has its own characteristic pattern of energy levels
    - Therefore it has its own characteristic set of light frequencies that it emits when excited. This set of emission frequencies is called its ***emission spectrum.***
        - BOOK: Fig. 30.5
    - The emitted frequencies of light can be separated into a viewable pattern by passing the emitted light through a prism, or better yet through a ***spectroscope***:
        - FIG. 30.4
        - Light is passed through a thin slit, then focused with a lens through a prism or diffraction grating.
        - Each color is focused at a different position according to its frequency, and forms a separate image of the slit on a screen, film, or your eye.
        - The separate colored images of the slit are called ***spectral lines***.
        - Each element has a unique pattern of spectral lines corresponding to the transitions between its energy levels – the pattern is like a fingerprint of the element.
    - DEMO: gas discharge spectra through diffraction gratings.
        - Neon (red), mercury (blue)

INCANDESCENCE

- Materials can glow when they are heated. Light produced from a heated material is called ***incandescence***.

- Incandescent light contains an infinite number of frequencies spread smoothly across the spectrum rather than a few individual separated frequencies like those from the emission spectra of gases.
    - DEMO: spectrum from an incandescent lightbulb.
    - The atoms in heated materials do not have infinite numbers of energy levels.
    - In a gas, atoms are far apart and electrons undergo energy level transitions unaffected by other atoms.
    - Closely packed atoms (like in solids or dense stars), outer electrons make transitions within their own atoms and between neighboring atoms over large distances.
        - This leads to an infinite variety of transitions and corresponding emission frequencies.
- Incandescent light depends on the temperature of the glowing object.
    - A heated object radiates energy with a wide distribution of frequencies.
        - The higher the temperature, the more high energy transitions producing high frequency radiation, or light.
        - The brightest part of the spectrum is the ***peak frequency*** of the distribution which is directly proportional to the absolute temperature (in kelvins) of the object:
            - FIG. 30.7
            - $\bar{f} \sim T$
            - ANIM: Incandescent spectrum applet
    - Incandescent objects can glow red, white, or blue.
        - Red: If the peak frequency is in the infrared, below red and other visible colors, then some of the distribution will extend in to the red part of the visible spectrum – the object will be glowing "red hot."
        - White: If the object is heated further, the peak frequency will start to move into the visible part of the spectrum. However, the distribution is so wide, that it will extend to all frequencies of visible light and therefore white light will be produced – the hotter object is now "white hot."
        - Blue: If the object is heated even further, then the peak frequency will move out of the visible range into the ultraviolet part of the spectrum. However, the wide distribution will extend into the violet and blue part of the visible range - the object is now even hotter and glows "blue hot."

CHAPTER 30: LIGHT EMISSION 03/27/19

ABSORPTION SPECTRA

- Atoms absorb light as well as emit light. They absorb light most strongly at many of the natural frequencies that are the same as the frequencies of light they emit.
- When an atom absorbs a photon, one electron is boosted to a higher energy level.
- Excited atoms of gas emit light at certain frequencies, producing an emission spectrum. What happens to a beam of white light passing through a gas?
    - The atoms of gas will absorb light of certain frequencies from the beam.
    - The absorbed light will be re-radiated (re-emitted) in all directions.
    - The non-absorbed light from the beam continues on together with only a very small portion of the re-emitted light at the absorption frequencies.
    - When the beam is spread out with a spectroscope, what will it look like?
        - ANIM: absorption spectrum
        - An almost continuous rainbow spectrum with dark lines located exactly at the absorption frequencies. There are dark lines there because only a very small amount of light at those frequencies was re-emitted in the direction of the beam. This kind of distribution is called an ***absorption spectrum***.
        - The absorption lines mostly match the emission lines of the gas. The absorption spectrum is almost exactly like the emission spectrum in reverse.
        - FIG.: http://csep10.phys.utk.edu/astr162/lect/light/absorption.html
- Incandescent light from the sun does not contain the entire full spectrum of colors. Although it appears white, there are many absorption lines in the spectrum. Why?
    - The sun (and other stars) is surrounded by an atmosphere of cooler gases. When the incandescent light from the main body of the sun passes through this atmosphere, the cooler gas atoms absorb some frequencies and produce an absorption spectrum.
        - FIG.: http://angryastronomer.blogspot.com/search/label/basics http://s94958815.onlinehome.us/angryastronomer/sunspectrumnoao.jpg
        - The location of the absorption lines reveals the chemical composition of the sun's atmosphere (just like the chemical fingerprints of emission spectra).
        - Helium was first discovered by finding new absorption lines in sunlight that didn't match the emission spectrum of any known element on Earth!

FLUORESCENCE

- Now we've seen that atoms can be excited by
    - Heating (thermal agitation)
    - Collisions (e.g. with high-speed electrons)
    - Absorbing photons
        - High frequency light energizes atoms more than low-frequency light ($E=hf$)
        - UV delivers more energy than visible light (e.g. sunburns)

- Many materials that are excited by absorbing UV light emit visible light when they de-excite. This process is called ***fluorescence***.
    - The UV light gives enough energy to boost the atom to very high energy state. This quantum jump can leapfrog over intermediate energy states.
    - When the atom de-excites, it can do so in several smaller jumps to the intermediate states rather than all in one step. The smaller jumps emit light with smaller energy (and frequency) than the UV light that was absorbed. Light with lower frequency than UV is visible.
        - FIGS. 30.10, 30.11
    - Fluorescent materials illuminated with UV light glow with visible light.
        - DEMO: Message with fluorescent crayons, fluorescent rocks
        - "Whiter-than-white" detergent dyes
        - FIG. 30.14: Fluorescent lamp tubes

PHOSPHORESCENCE

- When excited, some materials get temporarily "stuck" in a high-energy state
    - There is a time delay between excitation and de-excitation. These ***phosphorescent*** materials emit light in an afterglow that can continue for seconds, minutes, hours after excitation.
    - The prolonged excited states are called ***metastable states***.
    - DEMO: Phosphorescent powders, crayons, etc.
    - Glow-in-the-dark objects are examples of phosphorescence
        - TV screens, luminous clock dials

LASERS

- Normal, incandescent light from a lamp with many different frequencies is *incoherent*: photons with many different phases.
    - FIG. 30.15
- Even filtered light of one frequency or color, *monochromatic*, is still incoherent.
    - FIG. 30.16
- A beam of photons with the same frequency, phase and direction is *coherent*.
    - FIG. 30.17
- A laser produces a beam of coherent light.
    - LASER: Light Amplification by Stimulated Emission of Radiation
- FIG. 30.18: How a laser works
    - Atoms in an active medium (e.g. gas in a tube or a ruby crystal) are excited by an external energy source to one specific metastable state.
    - When most of the atoms are in the metastable state, one photon from a de-excitation can start a chain reaction by passing near another excited atom and stimulating it into emission exactly in phase with the first photon.
    - Light is emitted in all directions, but light that travels along the laser axis is reflected by mirrors at the ends. The reflected light continues to stimulate more emissions and the intensity of light resonating between the mirrors builds up, or amplifies.
    - The mirror on one end is only partially reflecting, so with every pass, some light escapes and forms the laser beam.

CHAPTER 31: LIGHT QUANTA 04/01/19

- Classical physics deals with two separate categories of phenomena:
  - Particles (e.g. Newton's laws of motion – Newtonian Mechanics)
  - Waves (e.g. Maxwell's laws of electromagnetism)
  - They are mutually exclusive and characterized by absolute predictability.
- Quantum physics came along around 1900 to describe the physics of the submicroscopic domain where classical rules of physics don't apply.
  - Things are grainy, or quantized (e.g. light energy comes in discrete packages of specific size called photons)
  - Particles and waves merge into one composite phenomenon.
  - The basic rules deal with probabilities, not certainties.

QUANTIZATION OF LIGHT AND PLANCK'S CONSTANT

- In quantum physics, energy is quantized much the same as electric charge is quantized – it only comes in discrete amounts, not a continuous, smooth range of values.
  - The energy in a laser beam is a whole-number multiple of a single lowest value of energy – one quantum of energy.
  - The quantum of electromagnetic radiation, including visible light, is the photon.
- The energy of a photon is $E=hf$ where f is the frequency of the light and h is Planck's constant.
  - h is a fundamental constant of nature – the single number resulting from dividing any photon's energy by its frequency.
    - It sets the lower limit on the smallness of things, e.g. the smallest amount of energy that can be converted into light with frequency f is $E=hf$.
  - The frequency of UV radiation is a million times greater than that of microwave radiation. Therefore UV photons can deliver a million times more energy to molecules in living cells than microwave radiation can. Which one do you think can cause sunburns?

PHOTOELECTRIC EFFECT

- Light can eject electrons from a metal surface. This is called the ***photoelectric effect*** and it was observed before quantum physics appeared.
  - DRAW: FIGS. 31.2, 31.3 et.al.
  - There is no time lag between turning on the light and ejection of the first electrons no matter what the brightness or frequency of the light source is.
  - The effect happens easily with high-frequency light, but not easily (or not at all) with low frequency light.
  - The maximum energy of the ejected electrons is unaffected by the brightness of the light, but increases with increasing frequency of the light.
  - The rate that electrons are ejected is proportional to the brightness of the light.
- These observations could not be understood with the wave model of light.

- Einstein came up with a quantized, particle-like model for light which explained the photoelectric effect completely.
    - One photon of light is completely absorbed by each ejected electron.
    - It's all-or-nothing so there is no time delay even for dim light sources.
    - Higher frequency (higher energy) photons can deliver enough energy to eject an electron, and the greater the photon energy, the greater the kinetic energy of the ejected electron.
    - More photons (brighter light) can eject more electrons.

WAVE-PARTICLE DUALITY

- Optical photographic images
    - We understand the formation of images in terms of light waves spreading from a point on an object, refracted through lenses onto a focal plane.
    - We understand the film exposure and development in terms of light particles – photons.
        - Film consists of grains of silver halide crystals, each containing 10^{10} silver atoms.
        - Each absorbed photon gives up its energy to a single atom, and the energy activates surrounding crystals.
        - Many photons activate many grains, one at a time.
        - BOOK: FIG. 31.4
- Double-slit experiment
    - Remember the interference pattern formed by passing monochromatic light through two narrow, closely-spaced slits.
        - BOOK: FIG. 31.5
    - If the light source is dimmed to send out just one photon at a time, we still get the interference pattern after many photons go through the barrier one at a time!
        - BOOK: FIG. 31.6
    - If we cover one slit, we get the single-slit diffraction pattern – photons hit places on the screen that they didn't hit when both slits were open!
        - BOOK: FIG. 31.7
    - The individual photons don't "know" if there is a second slit or not. Each photon has both particle **and** wave properties.
        - Photons are emitted or absorbed like particles.
        - Photons travel like waves. Even though a photon is one particle, it has a probability of being anywhere that the light wave would extend.

PARTICLES AS WAVES

- Material particles with mass also have both wave and particle properties.
- All particles no matter how big or small have a wavelength inversely proportional to their momenta: *Wavelength=h/momentum*.
    - Bodies with macroscopic masses and ordinary speeds have wavelengths so small that wave effect such as interference and diffraction are completely negligible: e.g. bullets don't diffract.

  - Subatomic particles are so small, that diffraction and interference can be very evident.
    - BOOK: FIG. 31.11

UNCERTAINTY PRINCIPLE

- The act of measuring something affects the quantity being measured.
  - A cool thermometer placed in a hot cup of coffee changes the temperature of the coffee.
    - This type of uncertainty can be corrected for.
- Quantum uncertainties are much more fundamental to the nature of matter, space, and time and they are unavoidable.
  - Waves occupy some space and time, and trying to locate or squeeze them to a point in space or time changes what they are.
  - Waves are inherently "fuzzy" objects that lead to fuzzy quantum measurements.
- The measurement of a baseball's speed and position is limited by the precision of the measurement apparatus.
- The measurement of an electron's speed and position is limited by quantum uncertainty.
  - A single photon hitting an electron can change its motion unpredictably.
  - To locate an electron precisely, one needs to use very short wavelength light, but short wavelength light is high energy and therefore would greatly alter the electron's motion.
  - To minimize the effect on the electron's motion, one would use less energetic light, but then the light would have longer wavelength and the electron's position would not be measured as precisely.
  - You have considerable uncertainty in either the position, momentum, or both.
- ***Heisenberg Uncertainty Principle:***
  - $\Delta p \Delta x \geq h/2\pi$: Δp is the uncertainty in momentum and Δx is the uncertainty in position.
  - $\Delta E \Delta t \geq h/2\pi$: ΔE is the uncertainty in energy and Δt is the uncertainty in time.
  - $h/2\pi$ is the lower limit on uncertainty.

CHAPTER 32: THE ATOM AND THE QUANTUM 04/03/19

BOHR MODEL OF THE ATOM

- FIG. 32.8: Planetary model (1913)
  - Applied theory of quantum physics to the atom.
  - Electrons have orbits of fixed energy around the nucleus (energy states).
  - According to classical physics, orbiting electrons would continuously emit radiation, losing energy causing them to spiral into the nucleus.
  - In Bohr's model, light is only emitted when an electron makes a quantum jump from a higher to a lower energy state: $E=hf$ (E is energy difference of the two levels, f is frequency of emitted light, h is Planck's constant.
  - Solved the mystery of patterns in atomic emission and absorption spectra.
    - FIG. 32.10
  - Radii of orbits are determined by amount of electric charge in the nucleus.
    - Higher number elements have more positive charge in the nucleus, and can therefore pull the electrons into tighter orbits.
    - Therefore each element has a unique set of possible orbits, unique set of possible energy level transitions, unique set of possible frequencies that it can emit, unique pattern of spectral lines.

EXPLANATION OF QUANTIZED ENERGY LEVELS: ELECTRON WAVES

- The idea that electrons could only have certain energy levels was confusing to everyone including Bohr.
  - The electron was thought to be a particle like a planet orbiting the sun.
  - Discrete energy levels for electrons were understood by considering the electron to be a wave.
- de Broglie's Matter Waves
  - A wave is associated with every particle
  - The wavelength is inversely proportional to the particle's momentum.
- Discrete values for the radii of Bohr orbits are due to standing electron waves.
  - A standing wave is one that closes in on itself constructively.
    - DEMO: standing wave on a spring
    - FIGS. 32.12, 32.13: Electron wave in an orbit with a circumference equal to a whole number multiple of the electron wavelength.
    - Electron standing waves are not flat circular orbits, but rather, spherical or elliptical shells.
  - The electron is not thought of as a particle at a point, but rather as having its mass and charge spread out into the standing wave.

QUANTUM MECHANICS

- In the modern wave model of the atom, the waves don't just spread out around the nucleus, but also in and out, spreading out in three dimensions to form an "electron cloud."
  - FIG. 32.14: The cloud is not made up of pulverized electrons scattered through space. It is a cloud of probability representing places where the electron *could* be.

    - This probability cloud model is described by quantum mechanics – the physics of the motion of very small particles.
- Schrödinger formulated a new kind of quantum mechanics very different from Newton's mechanics in Classical Physics:

Classical Physics	Quantum Physics
|	|
Newtonian Mechanics	Quantum Mechanics
|	|
Newton's equation	Schrödinger's equation
|	|
$F=ma$	$\left(-\frac{\hbar^2}{2m}\nabla^2+V\right)\psi=i\hbar\frac{\partial\psi}{\partial t}$
|	|
Material objects	Mathematical entities (matter wave amplitude or *wave function*, ψ)
|	|
Deterministic (where it *will* be)	Probabilistic (where it *could* be)

    - ψ: *wave function*: represents the possibilities that can occur. It contains the information about where the electron *possibly* is: anywhere from the center of the nucleus to a large radial distance away.
    - $|\psi|^2$: *probability density function*: gives the probability for each of the possibilities represented by ψ. It tells where the electron *probably* is: a very small chance that it is inside the nucleus momentarily, a very large chance that it is near an average distance equal to the Bohr orbital radius.
        - It is a 3-dimensional map of the regions of high and low probabilities. This map is the electron cloud of probability.
        - FIG. 32.15. Bohr (planetary) → de Broglie (matter waves) → Schrödinger (quantum mechanics probability cloud).

CORRESPONDENCE PRINCIPLE

- For a new theory to be valid, it must account for the verified results of the old theory. This ***correspondence principle*** was first stated by Bohr.
- The new theory must overlap and agree with the old theory in the region, or domain where the results of the old theory have been verified.
    - For example, when Quantum Mechanics is applied to large, macroscopic systems where classical physics theories are successful, the results are virtually identical to those of classical physics. Quantum and classical physics blend when the de Broglie wavelength is small compared to the size of the system or particle.
    - Only at the submicroscopic level do quantum and classical physics differ significantly, because classical physics was not developed to deal with that domain.