

Skating 1

Skating

Turn off all electronic devices

Skating 2

Observations about Skating

- When you're at rest on a level surface,
 - without a push, you remain stationary
 - with a push, you start moving that direction
- When you're moving on a level surface,
 - without a push, you coast steady & straight
 - with a push, you change direction or speed

Skating 3

4 Questions about Skating

- Why does a stationary skater remain stationary?
- Why does a moving skater continue moving?
- Why does a skater need ice or wheels to skate?
- How does a skater start or stop moving?

Skating 4

Question 1

- Why does a stationary skater remain stationary?
- Related Questions:
 - What keeps the dishes in place on a table?
 - If I pull the tablecloth, what will happen?
 - Does the speed at which I pull matter?

Skating 5

Physics Concept

- **Inertia** (just the first part)
 - A body at rest tends to remain at rest

Skating 6

Question 2

- Why does a moving skater continue moving?
- Related questions:
 - What keeps a moving banana moving?
 - Can I slice a moving banana in midair?

Rayleigh Scattering

- Rayleigh scattering occurs when
 - passing sunlight electrically polarizes tiny particles in the air.
 - That alternating polarization acts as a source of light waves,
 - so air particles scatter light—they absorb and then reemit it.
- Air particles are too small to be good antennas for light,
 - so long-wavelengths (reds) scatter poorly
 - while shorter-wavelengths (violets) scatter better.
- Rayleigh scattered sunlight is bluish in appearance
- The missing blue light reddens the solar disk itself
 - particularly at sunrise and sunset

Question 3

- How does a rainbow break sunlight into colors?

Light and Refraction

- Sunlight slows while it passes through matter
 - Light waves electrically polarize matter
 - That polarization delays the light wave's passage
 - Each material has an “index of refraction”—the factor by which it reduces light's speed.
- When light changes speed at an interface,
 - it bends toward the perpendicular if it slows down
 - it bends away from the perpendicular if it speeds up

Light and Reflection

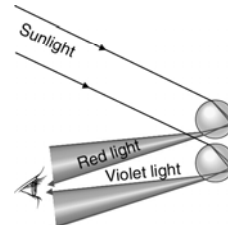
- Light polarizes different materials differently,
 - which affects both how fast light travels in them and
 - relationship between its electric & magnetic fields.
- Changes in how light travels causes reflections
 - Sunlight partially reflects from most surfaces
 - Sunlight reflects almost completely from metals

Light and Dispersion

- The different colors of light in sunlight
 - have different frequencies
 - and polarize a material slightly differently,
 - so they travel at slightly different speeds.
 - Violet light usually travels slower than red
- Refraction (bending) depends speed change
 - so violet light usually bends more than red

Rainbows

- Occur when sunlight encounters water droplets
 - and undergoes refraction, reflection, and dispersion.

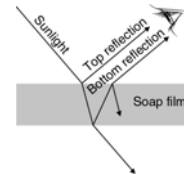


Question 4

- Why are soap bubbles and oil films so colorful?

Light and Interference

- Overlapping waves superpose and may interfere
- Light following different paths can interfere
 - constructively if fields point in the same direction
 - or destructively if fields point in opposite directions.
- The two reflections from a soap or oil film interfere
- Different colors often interfere differently



Question 5

- Why do polarizing sunglasses reduce glare?

Reflection of Polarized Light

- Angled reflections depend on polarization
- When light's electric field is parallel to a surface
 - there is a large fluctuating surface polarization
 - and thus a strong reflection.
- When electric field is perpendicular to a surface
 - there is a small fluctuating surface polarization
 - and thus a weak reflection.
- Glare is mostly polarized parallel to the surface

Polarization and Sunlight

- Polarizing sunglasses
 - block horizontally polarized light
 - and thus block glare from horizontal surfaces.
- Rayleigh scattering has polarizing effects,
 - so much of the blue sky is polarized light, too.

Summary about Sunlight

- Sunlight is thermal light at about 5800 K
- It undergoes Rayleigh scattering in the air
- It bends and reflects from raindrops
- It interferes colorfully in soap and oil films
- It reflects in a polarizing fashion from surfaces

Discharge Lamps

Observations about Discharge Lamps

- They often take a few moments to turn on
- They come in a variety of colors, including white
- They are often whiter than incandescent bulbs
- They last longer than incandescent bulbs
- They sometimes hum loudly
- They flicker before they fail completely

4 Questions about Discharge Lamps

- Why phase out incandescent lamps?
- How can colored lights mix so we see white?
- How can white light be produced without heat?
- How do gas discharge lamps produce their light?

Question 1

- Why phase out incandescent lamps?

Shortcomings of Thermal Light

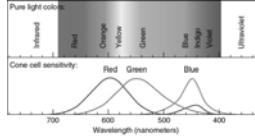
- Incandescent lamps are reddish and inefficient
- Filament temperature is too low, thus too red
 - The temperature of sunlight is 5800 K
 - The temperature of an incandescent lamp is 2700 K
- An incandescent lamp
 - emits mostly invisible infrared light,
 - so less than 10% of its thermal power is visible light.

Question 2

- How can colored lights mix so we see white?

Seeing in Color

- We have three groups of light-sensing cone cells
 - Their peak responses are to red, green, and blue light
 - Those are therefore the primary colors of light
- When the primaries mix, we see other colors
- When the primaries mix evenly, we see white

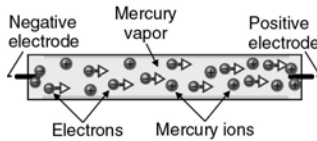


Question 3

- How can white light be produced without heat?

Fluorescent Lamps (Part 1)

- Fluorescent tubes
 - contain low density gas and metal electrodes,
 - which inject free electric charges into the gas
 - to form a plasma—a gas of charged particles
 - and electric fields cause current to flow in the plasma.



Fluorescent Lamps (Part 2)

- Collisions in the plasma cause
 - electronic excitation in the gas atoms
 - and occasionally ionize the gas atoms,
 - which helps to sustain the plasma.
- Excited atoms emit light through fluorescence
- Fluorescence is part of quantum physics

Quantum Physics of Atoms

- In an atom,
 - the negative electrons “orbit” the positive nucleus
 - and form standing waves known as orbitals.
 - Each orbital can have at most two electrons in it
- An electron in a specific orbital has a total energy,
 - that is the sum of its kinetic and potential energies.
- An atom’s electrons
 - are normally in lowest energy orbitals – the ground state
 - but can shift to higher energy orbitals – excited states.

Atoms and Light

- Electron orbitals are standing waves:
 - they do not change with time
 - they involve no charge motion
 - they do not emit (or absorb) light.
- While an electron is changing orbitals,
 - there is charge motion and acceleration,
 - so the electron can emit (or absorb) light.
- Such orbital changes are called radiative transitions

Skating 367

Light from Atoms

- The wave/particle duality applies to light:
 - Light travels as a wave (diffuse rippling fields)
 - but is emitted or absorbed as a particle (a photon).
- An atom's orbitals differ by specific energies
 - These energy differences set the photon energies,
 - so an atom has a specific spectrum of photons.

Skating 368

Photons, Energy, and Color

- Photon's frequency is proportional to its energy
Photon energy = Planck constant · frequency
- and its frequency · wavelength = speed of light.
- Each photon emitted by an atom has
 - a specific energy,
 - a specific frequency,
 - a specific wavelength (in vacuum),
 - and a specific color when we see it with our eyes.

Skating 369

Atomic Fluorescence

- Excited atoms lose energy via radiative transitions
- During a transition, electrons shift to lower orbitals
- Photon energy is the difference in orbital energies
 - Small energy differences → infrared (IR) photons
 - Moderate energy differences → red photons
 - Big energy differences → blue photons
 - Even bigger energy differences → ultraviolet (UV) photons
- Each atom typically has a bright "resonance line"
- Mercury's resonance line is at 254 nm, in the UV

Skating 370

Phosphors

- A mercury discharge emits mostly UV light
- A phosphor can convert UV light to visible
 - by absorbing a UV photon
 - and emitting a less-energetic visible photon.
 - The missing energy usually becomes thermal energy.
- Fluorescent lamps use white-emitting phosphors
 - They imitate thermal whites at 2700 K, 5800 K, etc.
- Specialty lamps use colored light-emitters
 - Blue, green, yellow, orange, red, violet, etc.

Skating 371

Fluorescent Lamps (Part 3)

- Starting a discharge requires electrons in the gas
- Those electrons can be injected into the gas by
 - heated filaments with special coatings
 - or by high voltages
- Once discharge starts, it can sustain the plasma
- Starting the discharge damages the electrodes
 - Atoms are sputtered off the electrodes
 - Damage limits the number of times a lamp can start

Skating 372

Fluorescent Lamps (Part 4)

- Gas discharges are electrically unstable
 - Gas is initially insulating
 - Once discharge is started, gas become a conductor
 - The more current it carries, the better it conducts
 - Current tends to skyrocket out of control
- Stabilizing discharge requires ballast
 - Inductor ballast (old, 60 Hz, tend to hum)
 - Electronic ballast (new, high-frequency, silent)

Question 4

- How do gas discharge lamps produce their light?

Low-Pressure Discharge Lamps

- Mercury gas has its resonance line in the UV
 - Low-pressure mercury lamps emit mostly UV light
- Some gases have resonance lines in the visible
- Low-pressure sodium vapor discharge lamps
 - emit sodium's yellow-orange resonance light,
 - so they are highly energy efficient
 - but extremely monochromatic and hard on the eyes.

Pressure Broadening

- High pressures broaden each spectral line
 - Collisions occur during photon emissions,
 - so frequency and wavelength become smeared out.
 - Collision energy shifts the photon energy

Radiation Trapping

- Radiation trapping occurs at high atom densities
 - Atoms emit resonance radiation very efficiently
 - Atoms also absorb resonance radiation efficiently
 - Resonance radiation photons are trapped in the gas
 - Energy must escape discharge via other transitions

High-Pressure Discharge Lamps

- At higher pressures, new spectral lines appear
- High-pressure sodium vapor discharge lamps
 - emit a richer spectrum of yellow-orange colors,
 - are still quite energy efficient,
 - but are less monochromatic and easier on the eyes.
- High-pressure mercury discharge lamps
 - emit a rich, bluish-white spectrum,
 - with good energy efficiency.
 - Adding metal-halides adds red to improve whiteness.

Summary about Discharge Lamps

- Thermal light sources are energy inefficient
- Discharge lamps produce more light, less heat
- They carefully assemble their visible spectra
- They use atomic fluorescence to create light
- Some include phosphors to alter colors

Lasers and LEDs

Observations about Lasers and LEDs

- Lasers and LEDs often have pure colors
- Lasers produce narrow beams of intense light
- Lasers are dangerous to eyes
- Reflected laser light has a funny speckled look

3 Questions about Lasers and LEDs

- How does laser light differ from regular light?
- How does a laser produce coherent light?
- How does an LED produce its light?

Question 1

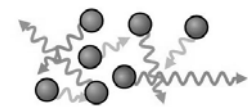
- How does laser light differ from regular light?

Light: Photons and Waves

- Electrons obey the Pauli exclusion principle
 - Each wave mode can have only one unique electron.
 - That result gives structure to atoms and materials
- Photons don't obey the Pauli exclusion principle
 - Each wave mode can have many photons
 - A radio wave has many photons in a single wave
- Most light sources produce photons randomly
 - Each photon usually has its own wave mode
 - But laser light is an exception!

Spontaneous Emission

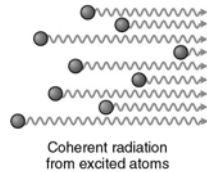
- Excited atoms normally emit light spontaneously
- These photons are uncorrelated and independent
- Each photon has its own wave mode
- These independent waves are incoherent light



Incoherent radiation from excited atoms

Stimulated Emission

- Excited atoms can be stimulated into duplicating passing light
- These photons are correlated and identical
- The photons all have the same wave mode
- This single, giant wave is coherent light

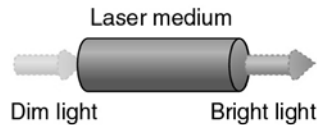


Question 2

- How does a laser produce coherent light?

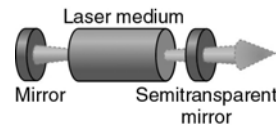
Laser Amplification

- Light can be amplified using stimulated emission
 - Excited atom-like systems can act as a laser medium
 - That medium will duplicate any photons that have the right wavelength, polarization, and orientation
 - This duplication is perfect: the photons are true clones
- This light amplification is the basis for lasers



Laser Oscillation

- A laser medium can amplify its own light
 - A laser medium in a resonator acts as an oscillator
 - It duplicates its one of its own spontaneous photons
 - Duplicated photons leak from semitransparent mirror
- The photons from this oscillator are identical



Properties of Laser Light

- Coherent – identical photons
- Controllable wavelength/frequency – colors
- Controllable spatial structure – narrow beams
- Controllable temporal structure – short pulses
- Energy storage and retrieval – intense pulses
- Giant interference effects
- But apart from all this, laser light is still just light

Examples of Lasers

- Gas lasers (powered by discharges)
 - Helium-neon lasers (red, green, yellow)
 - Carbon dioxide lasers (infrared)
- Solid state lasers (powered by current or light)
 - Diode lasers (red, blue, infrared)
 - Ruby lasers (red)
 - Nd:YAG lasers (infrared)
 - Ti:Sapphire lasers (infrared)

Skating 391

Question 3

- How does an LED produce its light?

Skating 392

Light-Emitting Diodes

- LEDs are Light-Emitting Diodes
 - They conduct current only in one direction
 - Each charge releases energy on crossing pn-junction
 - That energy is often emitted as a photon of light
- For LEDs to emit higher-energy photons,
 - they must be designed to have larger band gaps
 - they must be supplied with larger voltage drops
- Laser diodes are LEDs that can amplify light.

Skating 393

Summary about Lasers and LEDs

- Lasers produce coherent light by amplification
- Coherent light contains many identical photons
- Laser amplifiers and oscillators are common
- LEDs are incoherent, light-emitting diodes

Skating 394

Cameras

Skating 395

Observations about Cameras

- They record a scene on an image sensor
- Good cameras need focusing, cheap ones don't
- Many cameras have zoom lenses
- Some cameras have bigger lenses than others
- They have ratings like focal length and f-number

Skating 396

6 Questions about Cameras

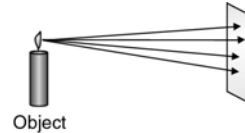
- Why does a camera need a lens?
- Why do most camera lenses need focusing?
- Why are lenses telephoto or wide-angle?
- Why do fancy lens's have internal apertures?
- Why is a good camera lens so complex inside?
- How does the image sensor respond to light?

Question 1

- Why does a camera need a lens?

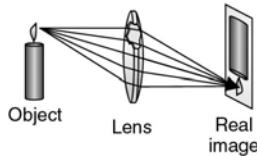
Light from an Object

- An illuminated object reflects or scatters light
 - You see the object via reflected or scattered light
 - The object's light produces diffuse illumination
 - You can't tell what the object looks like from this diffuse illumination



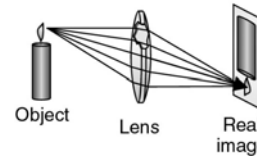
Converging Lenses

- A converging lens bends light rays via refraction
 - Light rays that were spreading now converge
 - Rays from a common point on an object converge to a common point on the far side of the lens



Real Images

- An image forms in space on far side of the lens
 - The image is a pattern of light in space that exactly resembles the object, except for size and orientation
 - The image is "real" – you can put your hand in it

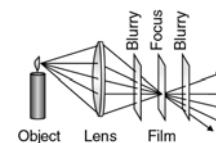


Question 2

- Why do most camera lenses need focusing?

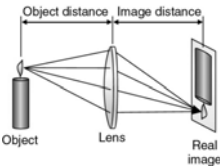
Lenses and Image Sensor

- The sensor records the pattern of light it receives
- If you put the sensor in a real image, it will record a pattern of light that looks just like the object
- For a good photograph, the real image should be sharply focused on the image sensor and its size should match the image sensor.



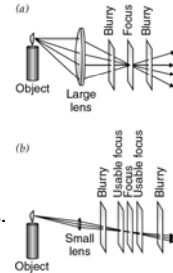
Focusing

- The farther the object,
 - the less diverging its light as that light enters the lens
 - the more converging that light after it leaves the lens
 - and the nearer to the lens the real image forms.
- Different objects form real images at different distances from the lens.
- Lens-to-sensor distance must match lens-to-image distance.



Lens Diameter and Focusing

- Larger lens gathers more light
 - so the image is brighter
 - but focus is more critical
 - and there is less depth of focus.
- Smaller lens gathers less light
 - so the image is dimmer
 - but focus is less critical
 - and there is more depth of focus.

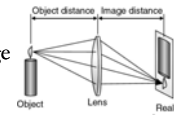


Question 3

- Why are lenses telephoto or wide-angle?

Focal Length

- Focal length measures lens's converging ability
 - Long focal length: weak lens, long image distance
 - Short focal length: strong lens, short image distance
 - Behavior accurately described by the lens equation:
- Larger image distance, then bigger image
 - Long focal length: big dim image
 - Short focal length: small bright image



Wide Angle vs Telephoto

- Wide-angle lens converges rays strongly,
 - so they focus close to the lens
 - and form a bright, small image near the lens.
 - Small diameter lenses are usually adequate.
- Telephoto lens converges rays weakly,
 - so they focus far from the lens
 - and form a dim, large image far from lens.
 - Large diameter lenses are usually necessary.

Question 4

- Why do fancy lenses have internal apertures?

Aperture or f-number

- f-number is focal length over lens diameter
 - and characterizes the brightness of the image.
- A large f-number lens produces a dim image
 - with a large depth of field/focus (focus is forgiving).
- A small f-number lens produces a bright image
 - with a small depth of field/focus (focus is critical).
- Fancy lenses have adjustable f-numbers,
 - to control both image brightness and depth of focus.

Question 5

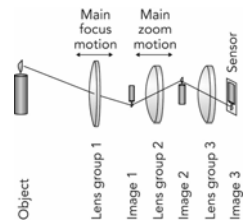
- Why is a good camera lens so complex inside?

Lens Flaws

- Dispersion → different colors focus differently
 - Use low-dispersion glass (fluoride glasses)
 - Use multi-piece lenses or “achromats”
- Reflections → fog in photographic images
 - Use antireflection coatings
- Spherical aberration → imperfect focus
- Poor focusing off axis → coma distortions
- Spherical focus projected on flat film → Astigmatism
 - Use aspheric lenses

Zoom Lenses

- A zoom lens typically has three images overall
- Its first lens group produces the first image
- Its second and third lens groups project a resized real image onto the image sensor.



Question 6

- How does the image sensor respond to light?

Black and White Film

- Light exposure creates a latent image
 - Silver bromide grains absorb photons (a silver salt)
 - Photon energy separates salt into silver and bromine
 - If a 4 atom silver cluster forms → grain will develop
 - Gold sensitization lowers threshold to 2 silver atoms
- Development turns exposed salt grains to silver
- Silver particle is misshapen and appears black
- Film forms a negative image of exposing object

Skating 415

Color Film

- Sensitizers and filters yield three latent images
 - Sensitizers and filters are built into the film
 - Latent images are sandwiched together in the film
 - Layers record red, green, and blue light respectively
- During development, colored dyes are produced
 - Spent developer causes dye molecules to form
 - Red : cyan, blue : yellow, green : magenta
- Dyes form a negative image of exposing object

Skating 416

Digital Cameras

- Instead of film, use CCD imaging chip
- Chip is divided into tiny squares or pixels
- Each photon causes a charge transfer in its pixel
- After exposure, the pixels retain a charge image
- Charge is shifted out of pixels using MOSFETs
- Camera obtains and saves image

Skating 417

Summary about Cameras

- They use converging lenses to form real images
- Lens focal length sets image size
- Lens f-number sets image brightness
- The image sensor records the pattern of light

Skating 418

Optical Recording and Communications

Skating 419

Observations about Optical Recording and Communications

- Optical disks can store lots of audio or video
- That audio or video is of the highest quality
- Optical disks continue to play perfectly for years
- Playback of optical disks involves lasers
- Lasers and fibers are used in communication

Skating 420

5 Questions about Optical Recording and Communication

- How is information represented digitally?
- How is information recorded on an optical disk?
- How is information read from an optical disk?
- How can light carry information long distances?
- Why does light follow an optical fiber's bends?

Question 1

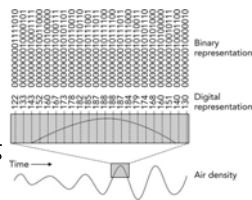
- How is information represented digitally?

Review of Digital Representation

- Audio or video info is a sequence of numbers
- Each number can be represented digitally
 - by putting specific symbols in a set of digits.
 - Digital representations often involve binary digits,
 - which can each hold only two symbols: 0 and 1.
 - Each symbol is a discrete value of a physical quantity
- Digital representations have
 - good noise-immunity
 - and permit error correction (elimination of noise).

Digital Audio

- The air pressure in sound is measured thousands of times per second
- Each measurement is represented digitally using about 16 binary digits, each a 0 or a 1.

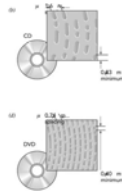


Question 2

- How is information recorded on an optical disk?

Structure of CDs and DVDs

- These disks have spiral tracks in reflective layers
- Each track contains pits and flats
- Digital symbols consist of the lengths of the pits and flats
- The track structure is made as small as can be detected by the playback system, so as to maximize the density of information.



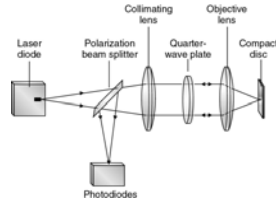
Question 3

- How is information read from an optical disk?

Skating 427

Playback Techniques

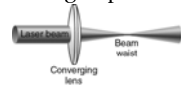
- Laser light is focused on the shiny layer
- Reflection is weaker from a pit than from a flat
- Reflected light is directed to photodiodes
- Reflected light intensity indicates pits or flats



Skating 428

Playback Issues

- Light must hit pits perfectly
 - Feedback optimizes the position of the light spot
- Light must hit only one pit
 - Use laser light—a single wave
 - Use a converging lens to focus that wave to a spot
- The wave forms a “waist”—its minimum width
 - Wave limits on focusing are known as diffraction
 - Waist can't be much smaller than a wavelength
 - so pit size can't be much smaller than a wavelength.



Skating 429

Advantages of Digital Recording

- Freedom from noise and media damage issues
 - Digital representation avoids information loss
 - Error correction ensures clean information
 - Surface contamination doesn't matter (much)
- High information density
- Data compression is possible
- Perfect, loss-less copies are possible

Skating 430

Question 4

- How can light carry information long distances?

Skating 431

Optical Communication

- Both analog and digital representations possible
- Analog representation
 - often involves AM modulation of the light
 - and is often used for remote process monitoring.
- Digital representation
 - often uses pulses with discrete amplitudes as symbols
 - and provides noise-immunity, error correction, compression, and channel-sharing.

Skating 432

Transmission Techniques

- Light in air: direct line-of-sight
 - Infrared remote controls
 - Infrared computer links
- Light in optical fibers: arbitrary paths
 - Optical cables and networks

Skating 433

The Components of Optical Communications

- Transmitters
 - Incandescent lamps (poor performance)
 - Light Emitting Diodes (adequate performance)
 - Laser Diodes (high performance)
- Receivers
 - Photoresistive cells (poor performance)
 - Photodiodes (high performance)
- Conduits
 - Optical Fibers (ranging from poor to high performance)

Skating 434

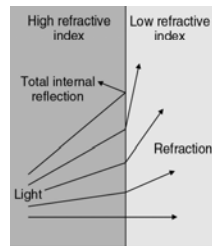
Question 5

- Why does light follow an optical fiber's bends?

Skating 435

Total Internal Reflection

- As light enters a material with a lower index of refraction, it bends away from the perpendicular
- If that bend exceeds 90° , the light reflects instead
- That reflection is perfect: total internal reflection



Skating 436

Optical Fibers

- An optical fiber consists of a high-index glass core in a low-index glass sheath
- When light tries to leave the core at a shallow angle, it experiences total internal reflection
- Light bounces endlessly through the core and emerges from the end of the fiber
- If the glass is pure and perfect enough, the light may travel for many kilometers through the fiber

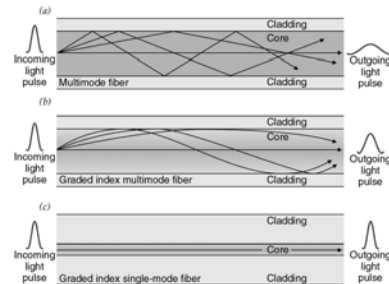
Skating 437

Communication Issues

- Information is sent as a stream of digital symbols
 - Those symbols are usually pulses of light
 - If pulses spread out and overlap, information is lost
- To keep pulses from spreading in time
 - all the light must follow a single path through fiber
 - all frequencies of light must travel at the same speed
- The fiber's structure and materials are critical
- To limit possible paths, use a "single mode" fiber

Skating 438

Optical Fiber Types



Skating 439

Communication Issues

- To limit frequency-related spreading of pulses
 - minimize dispersion with monochromatic laser light
 - in low-dispersion glass at its optimal wavelength.
- Since light attenuates as it passes through fiber
 - use low-loss glass
 - and amplify the light periodically,
 - using fiber laser amplifiers.
- Systems using different colors can share a fiber!

Skating 440

Summary about Optical Recording and Communication

- Optical disks store information as pits and flats
- Focused laser light reads that information
- Digital representations allow perfect playback
- Optical fibers carry information as light

Skating 441

Nuclear Weapons

Skating 442

Observations about Nuclear Weapons

- They release enormous amounts of energy
- They produce incredible temperatures
- They produce radioactive fallout
- They are relatively difficult to make
- They use chain reactions

Skating 443

3 Questions about Nuclear Weapons

- Where is nuclear energy stored in atoms?
- Why are some atomic nuclei unstable?
- How does a nuclear chain reaction work?

Skating 444

Question 1

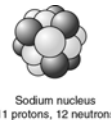
- Where is nuclear energy stored in atoms?

Atomic Nuclei

- Atoms are usually electrically neutral
 - They must have as many + charges as – charges
 - Each electron must be matched by a + charge
- At the center of an atom is its nucleus
 - Extremely small (1/100,000th of atom's diameter)
 - Contains most of the atom's mass
 - Also contains most of the atom's potential energy
 - Evidence is related to: $E=mc^2$

Structure of Nucleus

- Nucleus contains two kinds of nucleons
 - Protons are positively charged
 - Neutrons are electrically neutral
- Two forces are active in a nucleus
 - Electrostatic repulsion between protons
 - Nuclear force attraction between touching nucleons
- At short distances, the nuclear force dominates
- At long distances, the electric force dominates



Question 2

- Why are some atomic nuclei unstable?

Nuclear Stability

- The nucleons in a nucleus are in equilibrium
- To be classically stable, that equilibrium must be stable
- To be quantum-mechanically stable, that equilibrium must also be the overall potential energy minimum
- Quantum mechanics and the Heisenberg uncertainty principle allow the nucleons to “try out” arrangements that are quite different from their equilibrium positions
- If they find a path to a new, lower-potential-energy equilibrium, the nucleus may fall apart

Radioactivity

- Large nuclei have two possible problems:
 - Too many protons: too much electrostatic potential
 - Too many neutrons: isolated neutrons are unstable
- Balance between protons and neutrons is tricky
- Large nuclei tend to fall apart spontaneously
- These breakups are known as radioactive decay
 - and can include a splitting process called fission

Question 3

- How does a nuclear chain reaction work?

Skating 457

Nuclear Reactors

Skating 458

Observations about Nuclear Reactors

- They provide enormous amounts of energy
- They consume nuclear fuel
- They produce radioactive waste
- Their nuclear fuel can be reprocessed
- They have safety issues

Skating 459

4 Questions about Nuclear Reactors

- How can a nuclear reactor use natural uranium?
- How do thermal fission reactors work?
- How can a fission chain reaction be controlled?
- How can a nuclear reactor be made safe?

Skating 460

Question 1

- How can a nuclear reactor use natural uranium?

Skating 461

About Uranium

- Uranium-235 (^{235}U) is
 - radioactive – fissions and emits neutrons
 - fissionable – breaks when hit by neutrons
 - a rare fraction of natural uranium (0.72%)
- Uranium-238 (^{238}U) is
 - radioactive – emits helium nuclei, some fissions
 - nonfissionable – absorbs fast neutrons without fission
 - a common fraction of natural uranium (99.27%)

Skating 462

Problem with Natural Uranium

- Fissioning uranium nuclei emit fast neutrons
 - Fast neutrons can fission ^{235}U ,
 - but fast neutrons are strongly absorbed by ^{238}U .
- Natural uranium
 - contains mostly ^{238}U , with some ^{235}U ,
 - so chain reactions won't work in natural uranium

Skating 463

Thermal Neutrons

- Fission neutrons can be slowed to thermal speeds
 - Slow neutrons can fission ^{235}U ,
 - but slow neutrons don't interact with ^{238}U .
- A ^{235}U chain reaction can occur in natural uranium if its neutrons are slowed by a moderator
- Moderator nuclei
 - are small nuclei that don't absorb colliding neutrons
 - but extract energy and momentum from the neutrons

Skating 464

Question 2

- How do thermal fission reactors work?

Skating 465

Thermal Fission Reactors

- Reactor core contains large amount of uranium
- Uranium is natural or slightly enriched
- Moderator is interspersed throughout core
- Moderator slows neutrons to thermal speeds
- Nuclear chain reaction occurs only among ^{235}U

Skating 466

Choosing Moderators

- Hydrogen nuclei (protons)
 - Good mass match with neutrons
 - Excellent energy and momentum transfer
 - Slight possibility of absorbing neutron
- Deuterium nuclei (heavy hydrogen isotope)
 - Decent mass match with neutron
 - Good energy and momentum transfer
 - No absorption of neutrons

Skating 467

More about Moderators

- Carbon
 - Adequate mass match with neutron
 - Adequate energy and momentum transfer
 - Little absorption of neutrons
- Choosing a moderator
 - Deuterium is best, but it's rare (used as water)
 - Hydrogen is next best (used as heavy water)
 - Carbon is acceptable and a convenient solid

Skating 468

Question 3

- How can a fission chain reaction be controlled?

Skating 469

Thermal Fission Chain Reaction

- Critical mass is governed by
 - size and structure of reactor core
 - type of nuclear fuel (extent of ^{235}U enrichment)
 - location and quality of moderator
 - positions of neutron-absorbing control rods

Skating 470

Controlling Chain Reactions (Part 1)

- Critical mass governs chain reaction rate
 - Below it, fission rate diminish with each generation
 - Above it, fission rate increases with each generation
 - Generation rate of prompt neutrons is very short
 - Controlling prompt-neutron fission is difficult!
- Delayed neutrons make reaction controllable
 - Some fissions produce short-lived radioactive nuclei
 - These radioactive nuclei emit neutrons after a while
 - Delayed neutrons contribute to the chain reactions

Skating 471

Controlling Chain Reactions (Part 2)

- There are two different critical masses
 - Prompt critical: prompt neutrons sustain chain reaction
 - Delayed critical: prompt and delayed neutrons required
- Reactors operate
 - Below prompt critical mass
 - Above delayed critical mass
- Control rods govern the fission rate

Skating 472

Using Nuclear Reactors

- Nuclear reactor releases thermal power
 - Fissions release thermal energy in the reactor core
 - That thermal energy is extracted by a coolant
 - The coolant is used to power a heat engine
 - That heat engine produces electrical power

Skating 473

Question 4

- How can a nuclear reactor be made safe?

Skating 474

Long Term Safety Issues

- Fission reactors produce
 - radioactive nuclei (from fissions)
 - plutonium (from neutron capture by ^{238}U)
- Radioactive nuclei are a radiation hazard
 - They must be sequestered securely for eons
- Plutonium is a nuclear proliferation hazard
 - It can be used as a nuclear fuel in reactors
 - but it can also be used in weapons.

Short Term Safety Issues

- To avoid catastrophes,
 - chain reactions must never get out of control
 - reactors must never overheat
- Reactors must be designed so that they are
 - stable—chain reaction stops if overheating occurs
 - redundant—no single failure can cause a disaster
 - easy to quench—chain reaction stops immediately

Nuclear Accidents

- Windscale Pile 1 (Britain)
 - Carbon moderator burned while being annealed
- Three Mile Island (US)
 - Cooling pump failed and core overheated (while off)
- Chernobyl Reactor 4 (USSR)
 - Coolant boiled in overmoderated graphite reactor
 - Exceeded prompt critical and partially vaporized
- Tokia-mura Accident (Japan)
 - Critical mass was reached while processing uranium

Summary about Nuclear Reactors

- They can use natural or slightly enriched uranium
- They slow fission neutrons using a moderator
- They control the chain reaction carefully
- They produce radioactive waste and plutonium

Medical Imaging and Radiation

Observations About Medical Imaging and Radiation

- They manage to work right through your skin
- Imaging involves radiation of various sorts
- Some imaging radiation is itself hazardous
- Radiation can make you well, sick, or neither
- Some radiation involves radioactivity
- Some radiation involves accelerators

5 Questions about Medical Imaging and Radiation

- How are X-rays produced?
- Why do X-rays image bones rather than tissue?
- How does CT scanning create a 3D image?
- How do gamma-rays kill cancerous tissue?
- Why does MRI image tissue, not bone?

Question 1

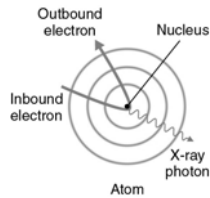
- How are X-rays produced?

X-rays

- Are short-wavelength electromagnetic waves
- Each X-ray photon has a large amount of energy,
 - enough to do severe chemical damage to molecules
 - or to knock particles out of atoms.
- X-rays are produced by very energetic events,
 - such as rapid electron acceleration near a nucleus
 - or a radiative transition in a highly excited atom.

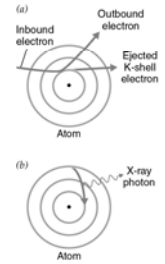
Bremsstrahlung X-rays

- When a fast-moving electron whips around a massive nucleus,
 - that electron accelerates rapidly
 - and may emit much of its energy as an X-ray photon.



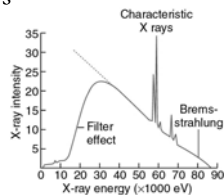
Characteristic X-rays

- When a fast-moving electron hits a massive nucleus,
 - it may knock an electron out of a tightly bound orbital
 - and leave the atom (now an ion) in a high-energy state.
 - That atom then undergoes a radiative transition to a lower-energy state
 - and emits an X-ray photon.



Producing X-rays

- Accelerate electrons to 10kV - 100kV
- Let electrons hit heavy atoms
- Some X-rays emitted via bremsstrahlung and some as characteristic X-rays
- An X-ray tube filters away the lowest energy photons, because they're useless and cause skin burns.



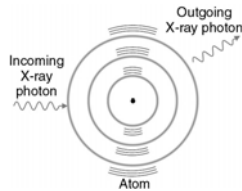
Question 2

- Why do X-rays image bones rather than tissue?

Skating 487

X-rays and Matter

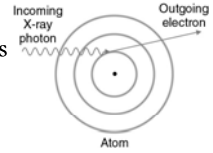
- X-rays interact with atoms via
 - Rayleigh scattering
 - Photoelectric effect
- Rayleigh scattering is what makes the sky blue
 - An atom temporarily absorbs a photon and then reemits it
 - This “scattered” photon travels in a new direction



Skating 488

Photoelectric Effect

- In this effect, an X-ray causes a radiative transition that ejects an electron from an atom
- The ejected electron’s energy is the difference between the X-ray photon’s energy and the energy needed to remove the electron from the atom
- Effect is strongest when ejected electron energy is low, so it requires atoms with many-electrons



Skating 489

X-ray Imaging

- An atom that blocks X-rays casts a shadow
 - Many-electron atoms produce strong shadows
 - Few-electron atoms cast essentially no shadows
- X-ray imaging observes shadows of large atoms
- Unfortunately, all atoms Rayleigh scatter X-rays,
 - causing a distracting haze
 - that can be filtered away by collimating structures.

Skating 490

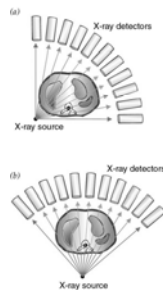
Question 3

- How does CT scanning create a 3D image?

Skating 491

CT Scanning

- Many separate X-ray images are used to produce CT database
 - X-rays from different angles mix shadows differently
- Computer can recreate original 3-D by analyzing database
- Computer typically plots cross sections of the body



Skating 492

Question 4

- How do gamma-rays kill cancerous tissue?

Skating 493

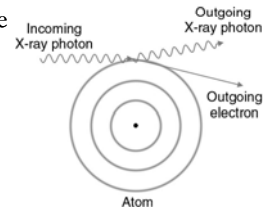
Gamma Rays

- Gamma-rays are extremely high energy photons
- They are produced by
 - radiative transitions within atomic nuclei and
 - particle accelerators (high-energy bremsstrahlung).

Skating 494

Gamma-rays and Matter

- Gamma rays interact with individual charges
 - via Compton scattering (electron-photon collisions)
 - and electron-positron pair production.
- “Pair production” is the conversion of energy (a photon) into matter (an electron and an anti-electron).



Skating 495

Radiation Therapy

- Gamma rays are highly penetrating in tissue
 - Little Rayleigh scattering and photoelectric effect
- Gamma ray events are Compton or Pair Prod,
 - each of which damages many molecules
 - and often kills cells.
- Approaching tumors from many angles minimizes collateral damage to healthy tissue

Skating 496

Question 5

- Why does MRI image tissue, not bone?

Skating 497

MRI Imaging (Part 1)

- Nuclear Magnetic Resonance (NMR)
 - Hydrogen nuclei are protons
 - Protons are magnetic—they are tiny dipole magnets
 - Because of quantum physics, protons have only two observable orientations: “spin-up” and “spin-down.”
 - In a magnetic field, spin-up and spin-down protons have different energies
 - A radio-wave photon with the correct frequency (and thus the correct energy) can flip a proton’s spin.

Skating 498

MRI Imaging (Part 2)

- Magnetic resonance imaging is based on NMR
 - The person enters a carefully designed magnetic field
 - That magnetic field varies slightly with location
 - The radio-wave frequency needed to flip a proton depends on that proton’s exact location (and field).
 - Using complicated magnetic fields and radio-wave pulses, you can image a person’s hydrogen atoms.
- MRI images hydrogen and its tissue environment.

Summary about Medical Imaging and Radiation

- X-rays and gamma-rays are high energy photons
- X-rays scatter from heavy atoms, for imaging.
- Gamma-rays disrupt cells, for therapy.
- MRI detects and locates hydrogen nuclei.