Visible Light

- Wavelengths between 400 nm and 700 nm
- Visible to humans
- Bees can see in the ultraviolet, at <400 nm

Infra-Red (IR) Radiation

- Longer wavelength (> 700 nm) than visible light – “below the red”; “heat”
- Can be detected by sensors in human skin

Ultraviolet (UV) Radiation

- Shorter wavelengths than visible light - 10 nm to 380 nm (400 nm is violet light).
- Carries more energy than visible light
UV light causes skin tanning, sunburn, formation of vitamin D, melanoma.
It can penetrate water vapour (clouds) unlike most visible light, so it is not stopped by an overcast day.
Glass absorbs UV strongly.

Microwaves
- Wavelengths of 1 mm to 30 cm (lots of overlap with both IR and radio waves)

Microwave Oven
- Creates standing waves of microwaves
- Wavelength ~ 10 cm
- Transfers energy to free water molecules
- Heating effects strongest at the antinodes

Radio Waves
- Sometimes characterized by wavelength (e.g. long wave radio channels ~ 1500 m) and sometimes by frequency (FM radio ~ 100 MHz)
- Wavelengths $\lambda = 0.1$ to $10^4$ metres
- Originate from accelerating charges through conducting wires (antenna)

Radio waves are useful because the atmosphere does not block them
Radio waves are not absorbed by the oxygen, nitrogen or water vapour in the atmosphere.
X-Rays and Gamma-Rays

• There is considerable overlap in these two categories (mostly from the historical way in which the sources were categorized)

Gamma Rays

• Gamma rays have higher frequencies (shorter wavelengths) than X-rays, and thus transmit more energy
  – They were first observed as the “gamma radiation” from radioactive decay
  – They are also observed in many objects in deep space – pulsars, black holes and supernovae are all gamma ray sources

19th Century Physics

• Newton’s Laws
• Gravitation
• Thermodynamics (heat transfer)
• Waves
• Electricity and Magnetism (Maxwell’s Equations)

But there was experimental evidence that could not be described by Classical Physics!

First Problem with Classical Physics: Blackbody Radiation

• The colour of a hot object.
• The colour observed changed with temperature
• White hot (very hot)
• Red hot (not as hot)

Observing hot objects and looking at the wavelengths of light given off, showed that there was a peak (a preferred wavelength)

The sun (5500 K – 5200 °C)
Peak colour is green-yellow
This is the same colour that our eyes are most sensitive to.
Tennis ball green
Incandescent Lightbulb

- The filament is heated by passing an electric current through it.
- It heats up and acts like a black-body
- Produces visible light
- Produces lots of infra-red (heat)
- Not very efficient

Lord Rayleigh (John William Strutt)
Used Maxwell’s equations to predict the shape of the graph and the distribution of wavelengths
The Rayleigh-Jeans theory failed!

Rayleigh-Jeans theory predicted intensity going to infinity in the ultraviolet part of the spectrum
Complete failure of 19th century physics!

Planck Model

- The German Physicist Max Planck re-calculated the blackbody radiation curves
- His model assumed that matter consisted of many atomic oscillators, each absorbing and emitting radiation
- The energy of each oscillator was quantized – constrained to certain values – like a ladder

https://www.nobelprize.org/prizes/physics/1918/summary/

- Planck’s oscillators could only oscillate at quantized energy levels
- The energy was frequency dependent

The Planck constant \( h = 6.62606876 \times 10^{-34} \text{ J.s} \)

Energy

\[ E_3 = 4 \times h \times \text{frequency} \]
\[ E_2 = 3 \times h \times \text{frequency} \]
\[ E_1 = 2 \times h \times \text{frequency} \]
\[ E_0 = 1 \times h \times \text{frequency} \]

Planck’s theory explained the true shape of the intensity curve
Planck was very worried that he had managed to find a solution by playing a mathematical trick!

By 1918, enough other evidence had been produced for him to get the Nobel Prize
Second Problem With Classical Physics: The Photoelectric Effect

- If light of an appropriate wavelength shines on a metal in a vacuum, then electrons may be emitted from the metal.
- They are known as photoelectrons (they are normal electrons, just produced by light).

UV light

An electron is emitted

http://www.youtube.com/watch?v=kcSYV8bJox8

Einstein’s Explanation

- Light consists of particles (wave packets) which have both wavelike AND particle properties.

Wave (Huygens)

Particles (Newton)

Stream of wave packets

- The individual wave packet is called a photon.

A photon collides with an electron in the metal.

The electron absorbs the energy of the photon and is emitted.

UV Photons

Photoelectron

Energy of the Photon

- Einstein calculated the energy of a single photon to be

\[ E = hf \]

Energy = Planck’s Constant \( \times \) frequency

- Uses the Planck equation
- Nobel Prize in 1921

Third Problem with Classical Physics: Spectroscopy

- A J Ångström studied the light emitted by low pressure gases in discharge tubes in 1853.
  http://www.youtube.com/watch?v=ryB-cuv8rT0

- Different gases emit different wavelengths of light (different colours).
- They do not emit all colours (which classical physics predicts should happen).

Emission Spectra

- Different gases emitted discrete wavelengths, not a continuous spectrum.
- Each gas emits a different characteristic line spectrum.
- The spectrum for hydrogen was the simplest.
• The spectrum for helium gas from a discharge tube is much more complicated and does not follow the simple formulae for hydrogen.

The Fourth Problem With Classical Physics: The Structure of the Atom
• Each atom consists of a very small nucleus, which contains most of the mass, and has a positive electrical charge.
• Around the atoms (in a cloud) are the negatively charged electrons.

• This picture is known as a “Rutherford Atom”, after Earnest Rutherford, who proposed the structure.
  • This is not stable in classical physics
  • The electron should spiral into the nucleus!
• The lifetime was predicted to be ~$10^{-8}$ seconds = 0.00000001 seconds

The Bohr Model
• The Danish physicist Niels Bohr proposed a model to explain the emission spectrum of hydrogen
• Classical physics (attraction between charged particles, and circular motion), with a quantum idea
• Electrons must remain in “stationary states” which are described by a quantum number

The electrons are in circular orbitals known as stationary states
As the radius of the orbital increases, so does the energy of the electron in the state.
The orbitals (and the radii and energy) can be described by a quantum number $n$
The Quantum Jump

- An electron in the Bohr model can make a quantum jump between states.
  - If it goes to higher energy, it emits a photon (light)
  - If it drops to lower energy, it must absorb a photon of exactly the right energy

Candlelight

- When the flame is relatively cool, the colour is dominated by the black body radiation of the hot particles produced

Fireworks

- When the flame burns hotter (more oxygen), then molecules get ionized, and start to emit their characteristic quantum emission colours
  - Tend to get more blue light emitted

- Adding different chemicals can enhance the colours produced by the emission process

The Aurora Borealis

- The Aurora is caused by charged particles from the sun trapped in the Earth’s magnetic field and spiralling towards the North or South Poles.

https://sciencenotes.org/firework-colors-chemistry/
• If charged particles hit an oxygen molecule \((O_2)\) they can excite an electron to a higher quantum state

“Collisional pumping”

Emits a photon with a wavelength of 577 nm (green)

• The colour of light emitted depends on the molecule being hit by the charged particle
• And on the particular quantum transition
• Green colours most common
• Blue and Pink rarer

Mercury Arc Lamp

• Mercury Vapour at low pressure produces a bluish light
• It also emits strongly in the ultraviolet

https://www.youtube.com/watch?v=Qi6rXUOOGiw

Fluorescent Light

• Mercury vapour used to produce ultra-violet light
• Ultraviolet light hits a coating on the inside of the bulb (a phosphor), this emits visible light

Mineralogy

• Some minerals fluoresce under ultraviolet light
Electronic Orbitals in a Solid

- Combining ~$10^{23}$ atoms together.
- The discrete energy levels are so close together, that they form a BAND.
- Note this a gap in energy, not a distance.

- If a band is full, then the electrons can’t go anywhere and can’t be used for conducting electricity.
- If a band is partly full, then the electrons can slosh about if a voltage is applied, and can move.

Metal
Conduction Band partly filled with electrons

Insulator
Valence band full
Conduction band empty
Large energy gap

Porcelain insulators

Semiconductor
Valence band full
Conduction band empty
Small energy gap

At room temperature a few electrons can jump up to the conduction band.

- Add different atoms - “doping” to create extra levels
  - n-type
    - Phosphorus (P)
    - Arsenic (As)
  - p-type
    - Boron (B)
    - Gallium (Ga)

$E_{pu}$
Conduction Band
Donor level
$E_{pu}$
Conduction Band
Acceptor level
Semiconductor Diodes

- A device which only lets current flow one way
- A p-type and an n-type semiconductor placed back-to-back

```plaintext
n-type Electron rich
p-type Electron deficient
```

Current can flow

Light Emitting Diodes

- The light emitting diode is designed so that the band gap between valence and conduction bands is of energy

\[ \Delta E = hf = \frac{hf}{c} \]

- The wavelength associated with energy is in the visible range 400 – 700 nm

LED circuit diagram symbol

- Very efficient, as they only produce light in a very narrow set of wavelengths
- Low power

- Good replacements for incandescent light bulbs, as they don’t emit in the infra-red
- 2 Watts LED equivalent to a 15 W incandescent

Photodiodes

- Some diodes are designed to be light sensors.
- Light falling on them causes an electron to be excited into the conduction band, increasing the conductivity
- These photodiodes can be made to detect many different frequencies of electromagnetic radiation (IR, visible UV being the most common)

Circuit Symbol for Photodiode

Some LEDs emit infra-red light, so invisible to the human eye

- Most TV remote controllers use an IR-LED to send the signals
Photodiodes

- The diode can be used to detect photons. Increased current when light shines on the diode
- A solar cell, which makes energy from sunlight is an example of a photodiode
- This type of operation is known as Photovoltaic Mode
- The photon energy is used to create an electron-hole pair, which increases conductivity of the device.

- Turn the array to face the sun directly – most efficient energy conversion
- Biological equivalent

- Light sources require quantum physics to show how they work