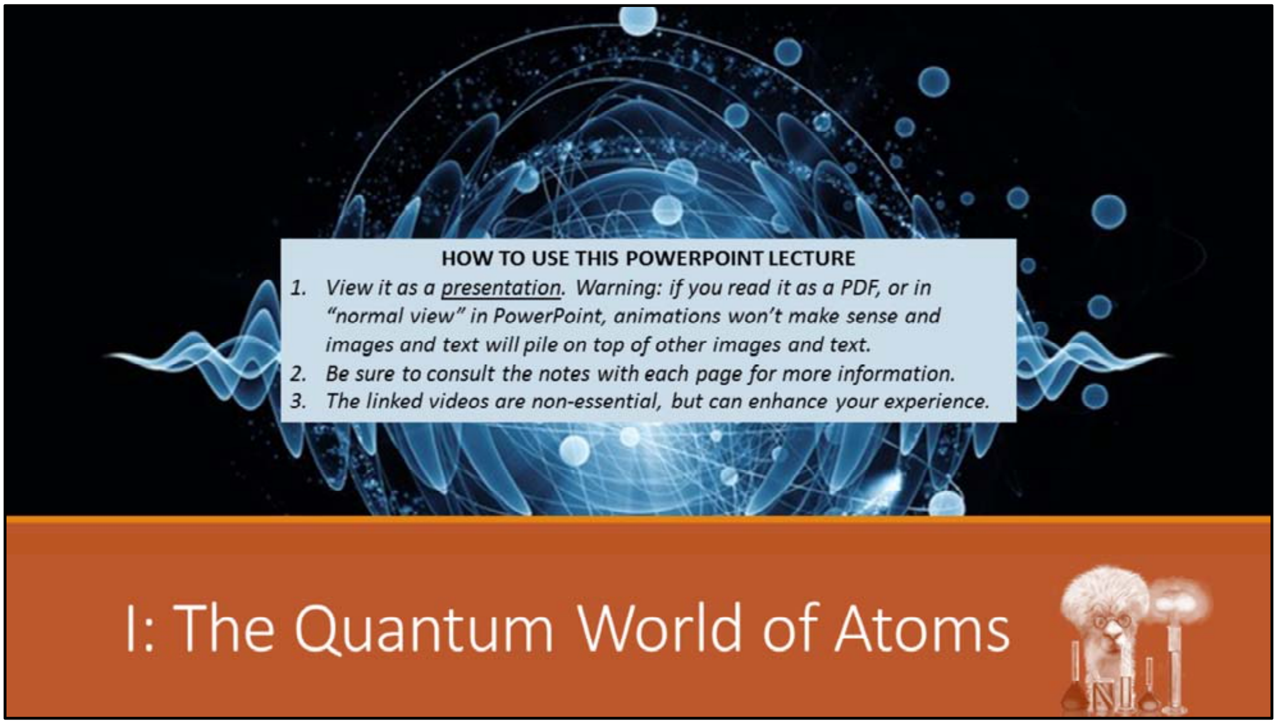
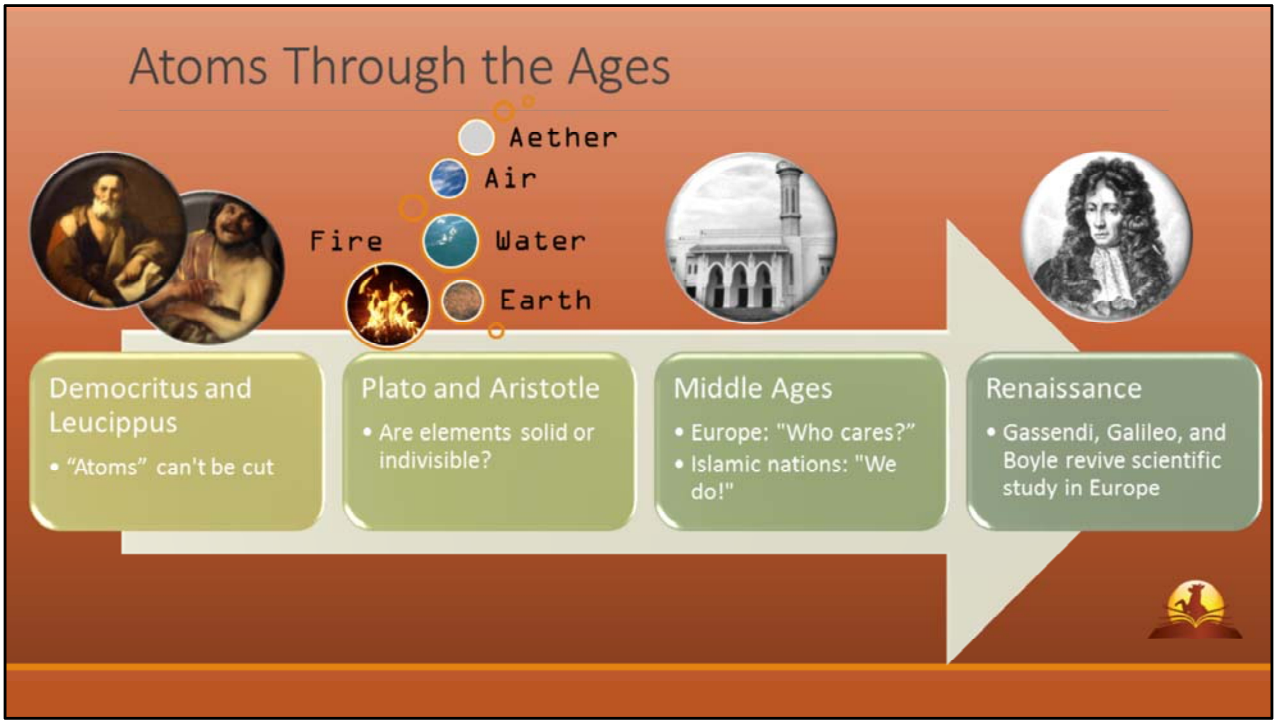
SCIENCE

An Introduction to Atomic and Nuclear Physics

DEMIDEC POWERPOINT LECTURE 2016


HOW TO USE THIS POWERPOINT LECTURE
1. View it as a presentation. Warning: if you read it as a PDF, or in "normal view" in PowerPoint, animations won't make sense and images and text will pile on top of other images and text.
2. Be sure to consult the notes with each page for more information.
3. The linked videos are non-essential, but can enhance your experience.
I: The Quantum World of Atoms



- **Democritus** and **Leucippus** made earliest references to "atoms" (5th century BCE).
  - "Atom" comes from the Greek word *atomos*, meaning "unable to be cut."
- **Plato** and **Aristotle** believed that fire, water, earth, air, and aether (an invisible medium) composed all elements. ***[Click 1]***
  - Plato believed that geometric solids formed elements, depending on the physical properties of each element.
  - Aristotle believed elements were continuous and indivisible, made of different proportions of these 5 substances.
    - This view represents **anti-atomist thinking.**
- Middle Ages ***[Click 2]***
  - European scientific research declined.
  - Islamic scientific research rose, as part of the Islamic Golden Age.
    - These scientists attempted to reconcile Greek thoughts about atoms with the Asharite school of religion.
- Renaissance ***[Click 3]***
  - European interest returns during the Renaissance, with the help of:
    - **Pierre Gassendi,** a Catholic priest who reconciled atomist thoughts with Church teachings.
    - **Galilei Galileo,** who promoted the existence of atoms.
    - **Robert Boyle,** who promoted corpuscular theory.

- Isaac Newton advocated corpuscular theory in his 1704 publication, *Opticks.*
- **Corpuscular theory** advocated that **corpuscles** were divisible particles that altered the characteristics of other matter.

- These competing theories existed simultaneously until about 200 years ago, because scientists couldn’t experimentally verify the existence of atoms.

https://upload.wikimedia.org/wikipedia/commons/2/2e/Hendrik_ter_Brugghen_-_Democritus.jpg
Hendrick ter Brugghen [Public domain], via Wikimedia Commons

https://upload.wikimedia.org/wikipedia/commons/c/c8/Leucippe_%28portrait%29.jpg
See page for author [Public domain], via Wikimedia Commons

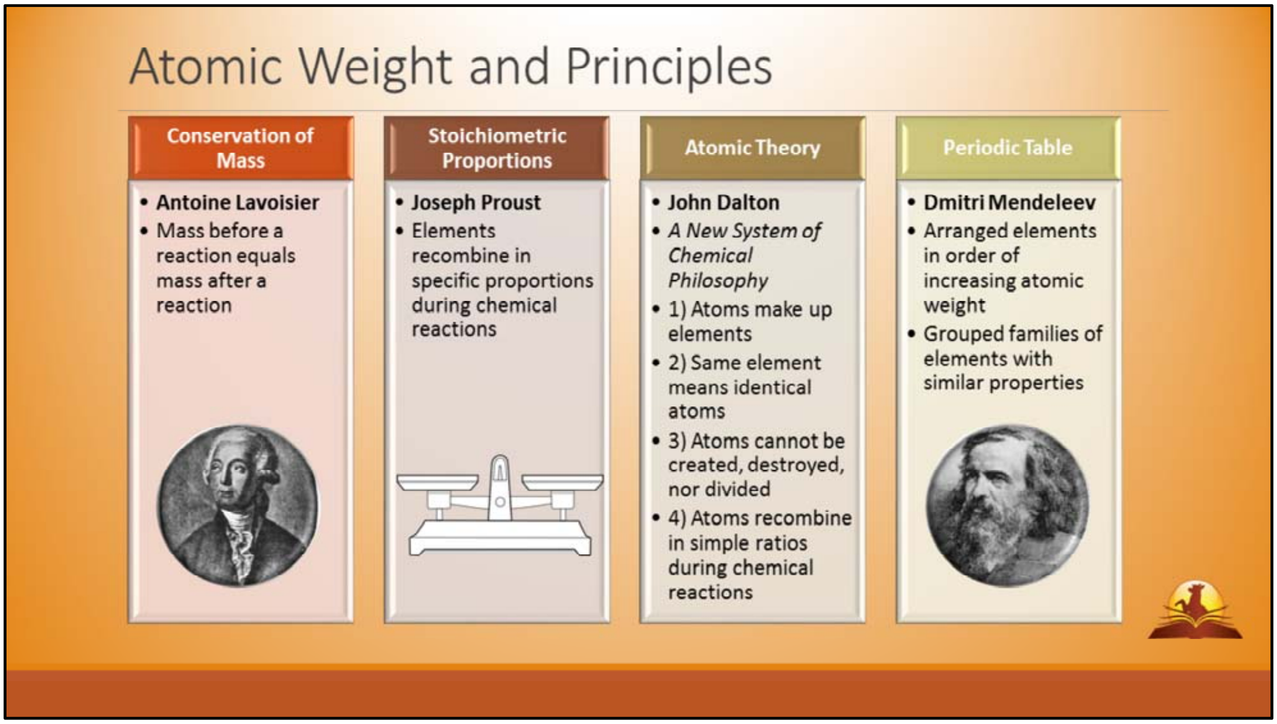
https://upload.wikimedia.org/wikipedia/commons/e/e3/Firetora.jpg
By MyName (Pedroserafin) (Own work) [Public domain], via Wikimedia Commons

https://commons.wikimedia.org/wiki/File:Andisol.jpg#filelinks

https://commons.wikimedia.org/wiki/File:Cirrus_over_Warsaw,_June_26,_2005.jpg

https://upload.wikimedia.org/wikipedia/commons/8/8e/Mosislsol2.jpg
By Courtesy Hiram A. Ruiz (http://lcweb2.loc.gov/frd/cs/somalia/so02_05a.jpg) [Public domain], via Wikimedia Commons

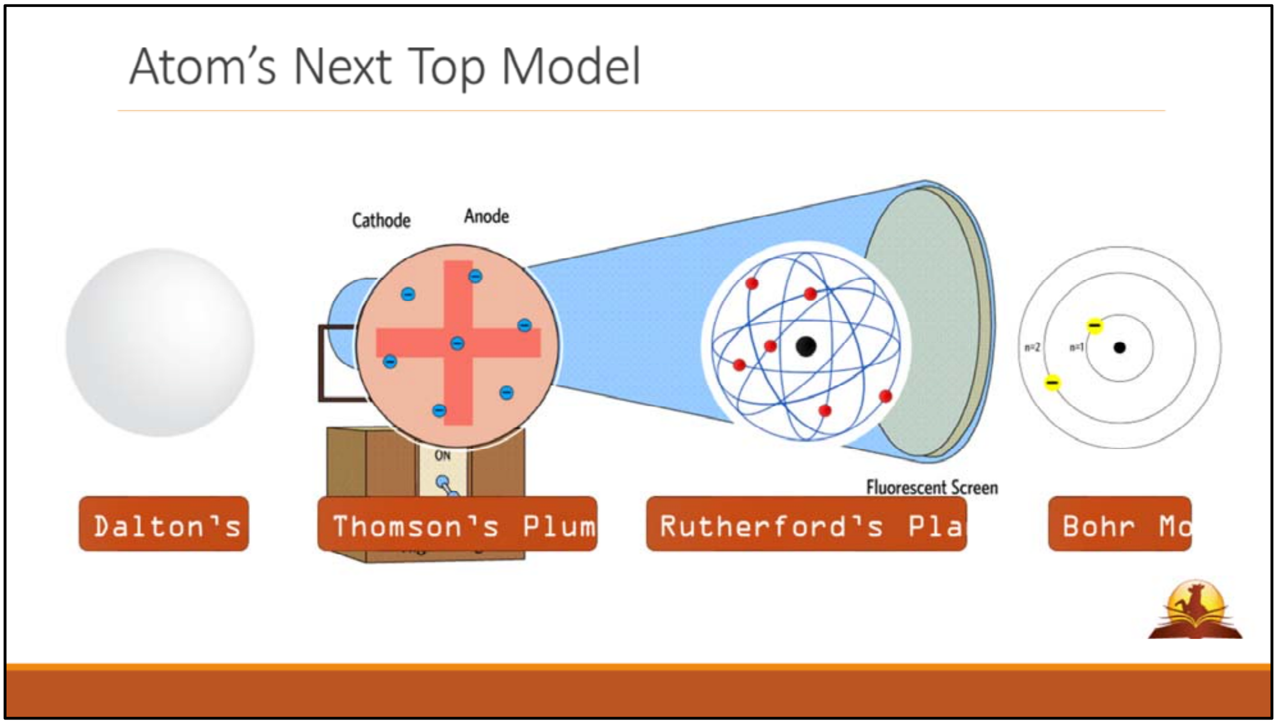
https://upload.wikimedia.org/wikipedia/commons/5/5a/Portrait_of_The_Honourable_Robert_Boyle_%281627_-_1691%29_Wellcome_M0002557.jpg
See page for author [CC BY 4.0 (http://creativecommons.org/licenses/by/4.0)], via Wikimedia Commons



- The study of **atomic weight** played a valuable role in early experiments regarding the nature of atoms
- **Antoine Lavoisier** discovered the **Law of the Conservation of Mass,** which stated that the mass of all atoms involved in a reaction remains constant.
- **Joseph Proust** confirmed that reactions were the recombination of atoms in **specific proportions.**
- **John Dalton** examined the masses of elements that combined during chemical reactions
    - Dalton published his **atomic theory principles** in *A New System of Chemical Philosophy* (1808), which included:
        - 1) Elements are made up of atoms.
        - 2) Atoms of the same element are identical to one another.
        - 3) Atoms cannot be created, destroyed, or divided.
        - 4) Atoms recombine in simple ratios during reactions.
- **Dmitri Mendeleev** created the first periodic table in 1864, arranging the 64 known elements based on increasing atomic weight.
    - Mendeleev noticed that groups of elements had similar properties.

https://upload.wikimedia.org/wikipedia/commons/7/7e/Lavoisier.jpg
By David (University of Texas , Austin) [Public domain], via Wikimedia Commons

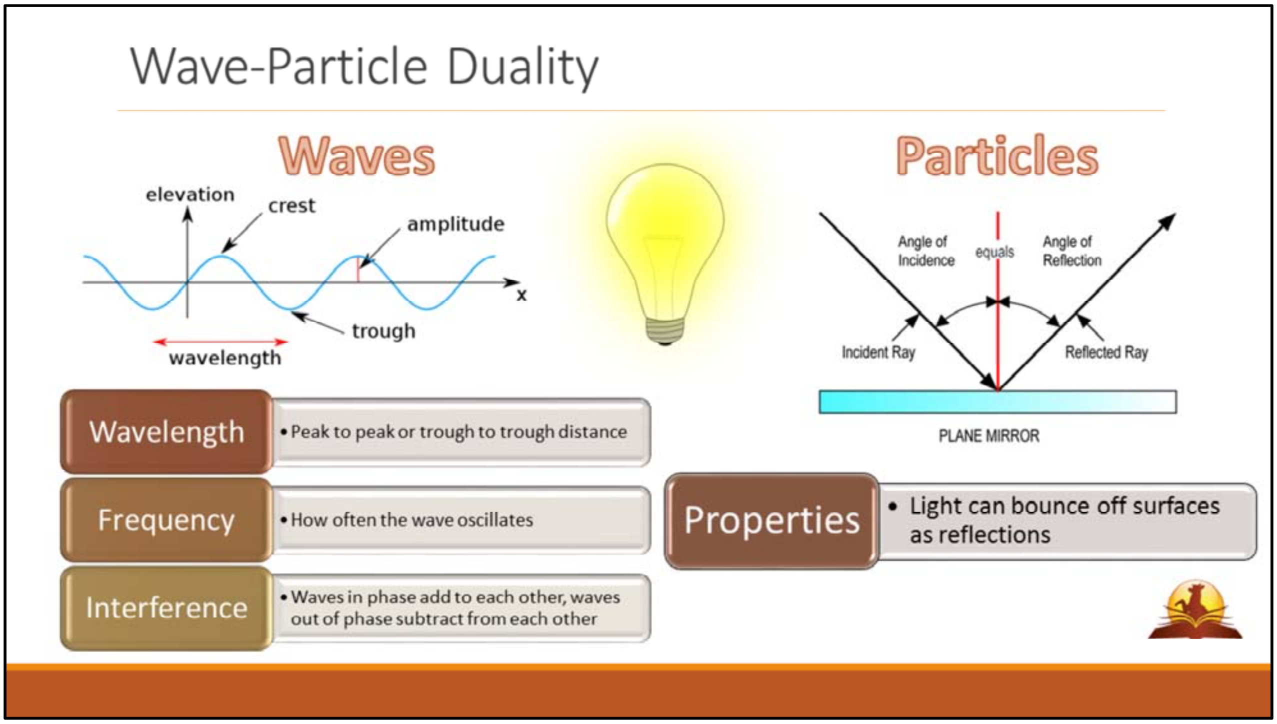
https://upload.wikimedia.org/wikipedia/commons/4/4b/%D0%94%D0%BC%D0%B8%D1%82%D1%80%D0%B8%D0%B9_%D0%98%D0%B2%D0%B0%D0%BD%D0%BE%D0%B2%D0%B8%D1%87_%D0%9C%D0%B5%D0%BD%D0%B4%D0%B5%D0%BB%D0%B5%D0%B5%D0%B2_3.jpg



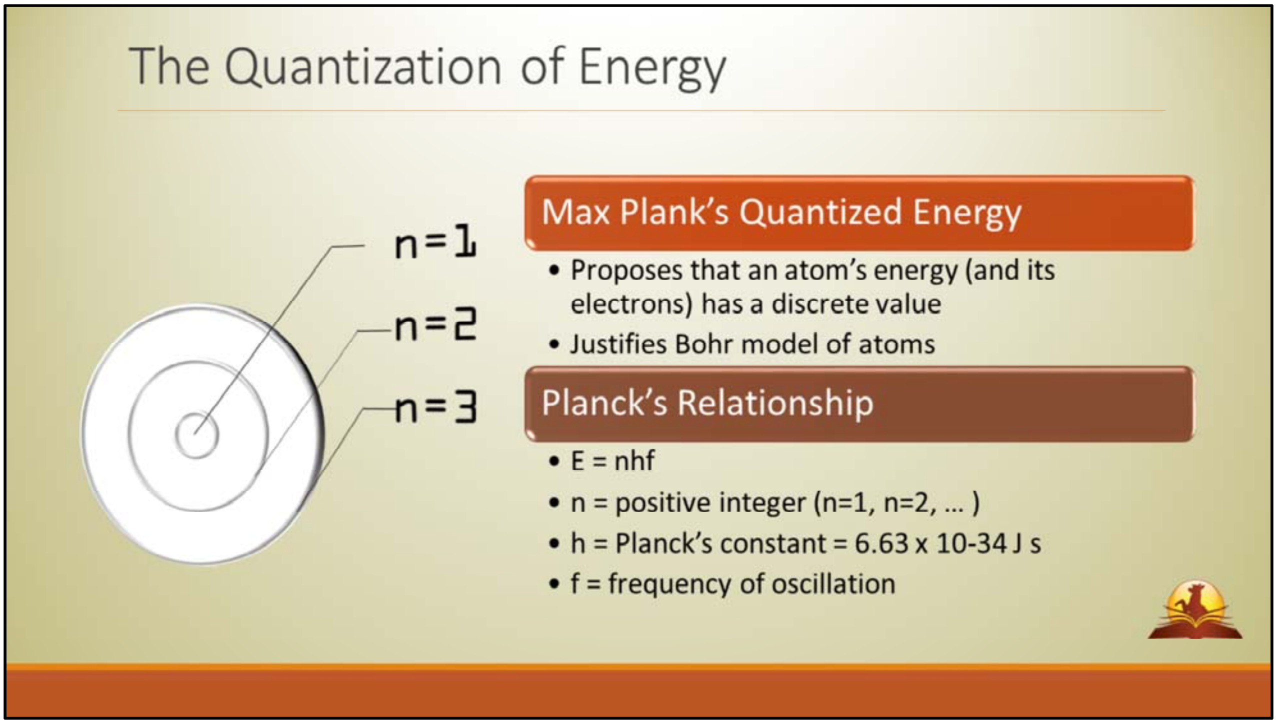
- In a **Cathode ray,** applying voltage across the ends of glass tubes evacuated with air causes the positive end to glow.
    - The **ray of electrons** passes from the cathode (negatively charged end) to the anode (positively charged end).
    - The cathode ray resulted in later experiments that led to advances in atomic models.
- In **Dalton's model**, electrons had not yet been discovered, so the atom was simply a particle with no charge.
- **JJ Thomson's Plum Pudding model** (1897) started when Thomson measured the mass of cathode ray particles and discovered that their mass was 1800 times less massive than H-atom.
    - Thomson proposed that an atom was a **positively charged sphere** with **electrons** interspersed throughout.
    - The name came from the fact that electrons in the model resembled the plums or raisins in plum pudding.
- **Rutherford B. Hayes' Planetary Model** began with a gold foil experiment (with Hans Geiger and Ernest Marsden).
    - When they shot positively charged particles at gold foil, the particles mostly went through, but a small amount deflected the nucleus by a wide angle.

    - To support the Plum Pudding Model, some particles would have deflected, but only at a small angle.
    - Hayes concluded that the **positively charged nucleus was small** and **negatively charged electrons orbit** around it like a planet.
- In **Niels Bohr's model,** electrons occupy a certain energy level away from the nucleus.

https://upload.wikimedia.org/wikipedia/commons/9/98/Modelo_atomico_de_rutherford.png
By Thalia Inga (Own work) [CC BY-SA 3.0 (http://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons



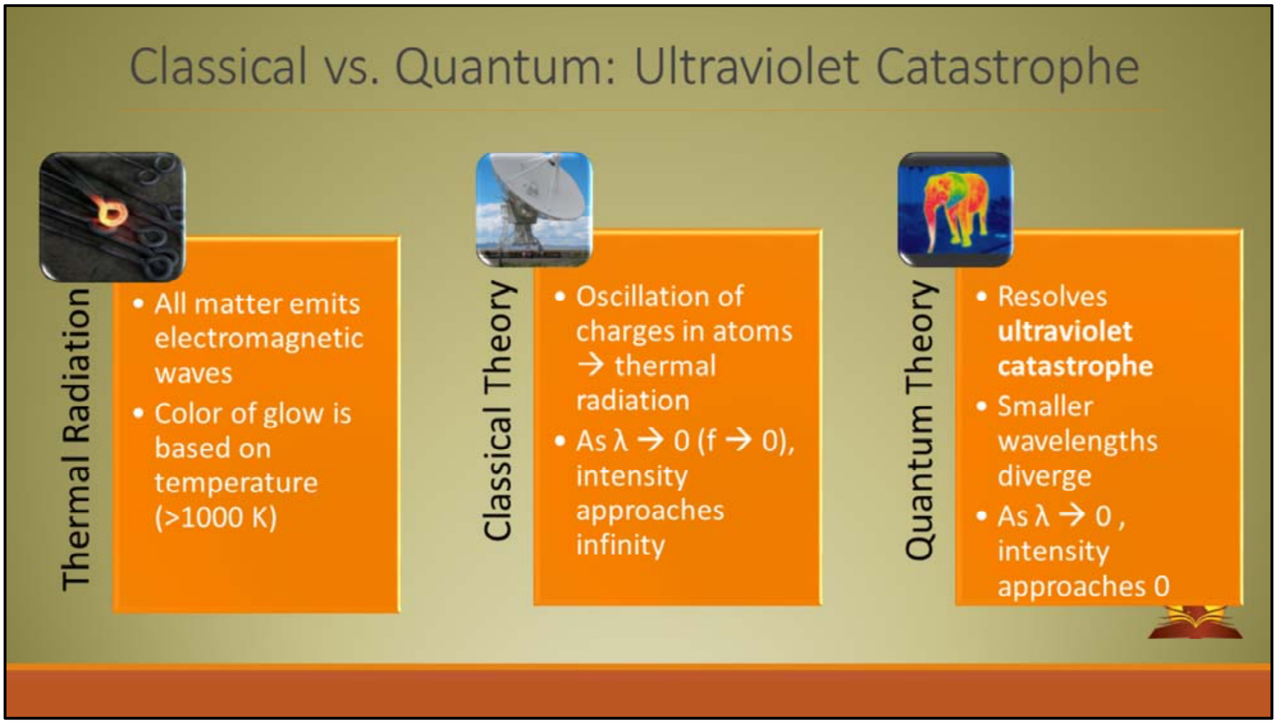
- Light exhibits **both wave and particle characteristics** depending on the experiment, called **wave-particle duality**.
- Isaac Newton proposed light as a **particle** in his 1704 *Opticks***.**
    - He believed that light functioned like a ball, bouncing off smooth surfaces to give reflections.
- In order to explain diffraction, Christian Huygens proposed light was a **wave*.***
    - Diffraction occurs when light **curves around corners and apertures.**
- In discussing the properties of light, we use the following terms:
    - **Wavelength**: trough to trough or peak to peak length
    - **Frequency**: frequency of oscillation (measured in Hz, or vibrations per unit time)
    - Wavelength and frequency are related inversely.
    - **Constructive interference**: waves in phase add to each other
    - **Destructive interference**: waves out of phase subtract from each other



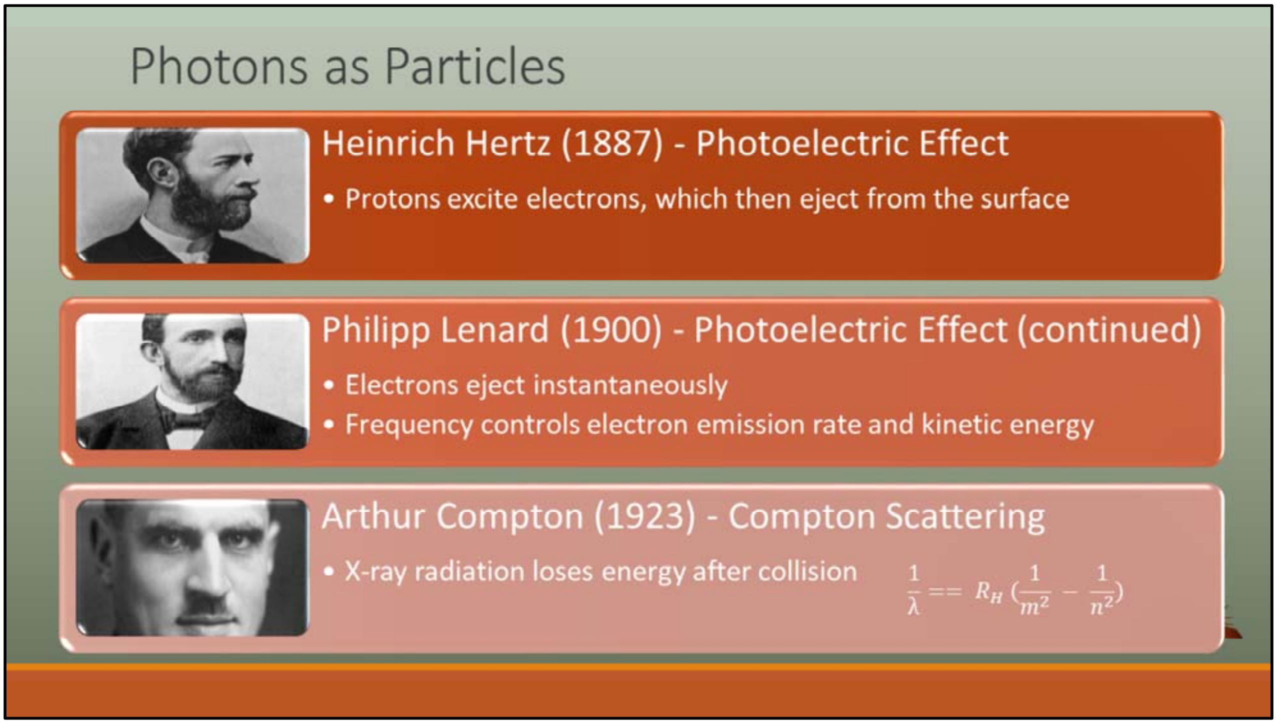
- The **energy** of atoms (and electrons) is **quantized.**
  - Quantization describes the situation in which values represent **discrete multiples** of a fundamental unit of energy called **quanta**.
    - There can be no values in between the quanta.
  - This theory explains why electrons can only occupy specific energy levels away from the nucleus.
- Max Planck proposed the quantization of energy in 1900.
  - The equation **E = nhf** determines the relationship, in which n refers to the **energy levels in Bohr's model.**

https://upload.wikimedia.org/wikipedia/commons/a/a2/Ebohr1.png
By The original uploader was Lacatosias at English Wikipedia Later versions were uploaded by Kripkenstein at en.wikipedia. (Transferred from en.wikipedia to Commons.) [GFDL (http://www.gnu.org/copyleft/fdl.html) or CC-BY-SA-3.0 (http://creativecommons.org/licenses/by-sa/3.0/)], via Wikimedia Commons

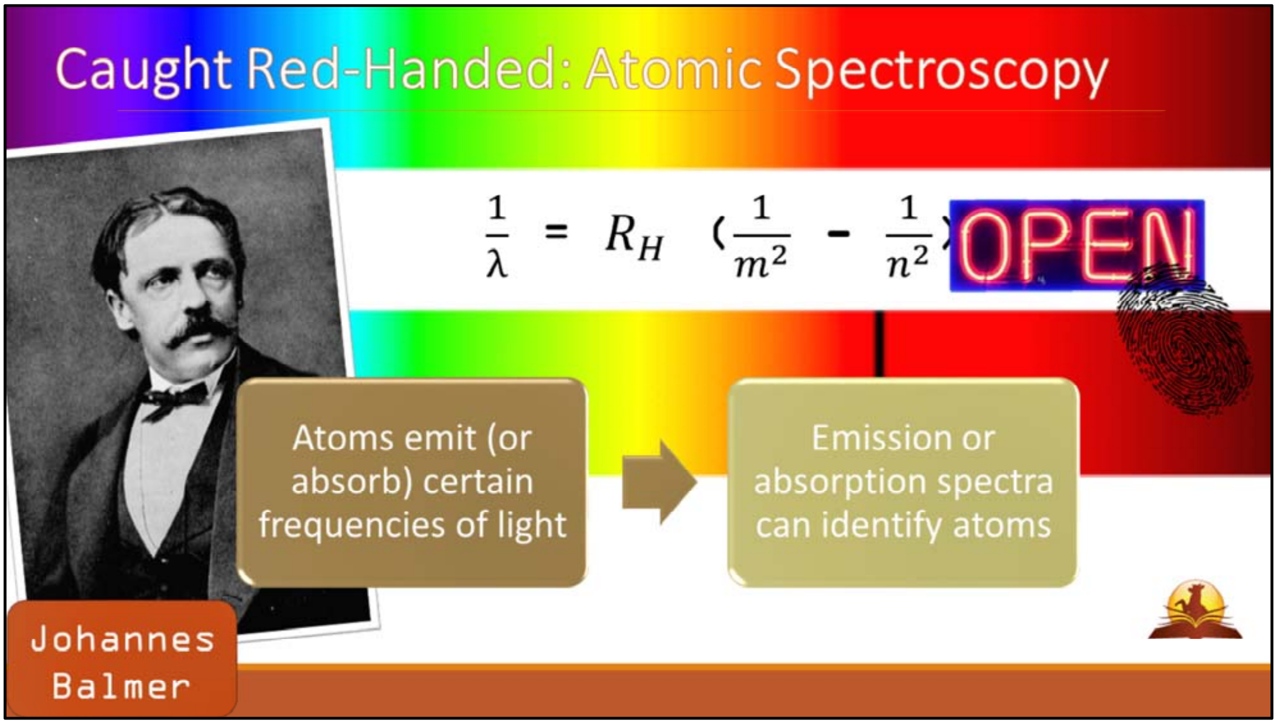
https://upload.wikimedia.org/wikipedia/commons/b/b8/Double_slit_experiment_%28destructiv_waves%29.svg
By Daniel Edler (Own work) [GFDL (http://www.gnu.org/copyleft/fdl.html) or CC BY-SA 3.0 (http://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons



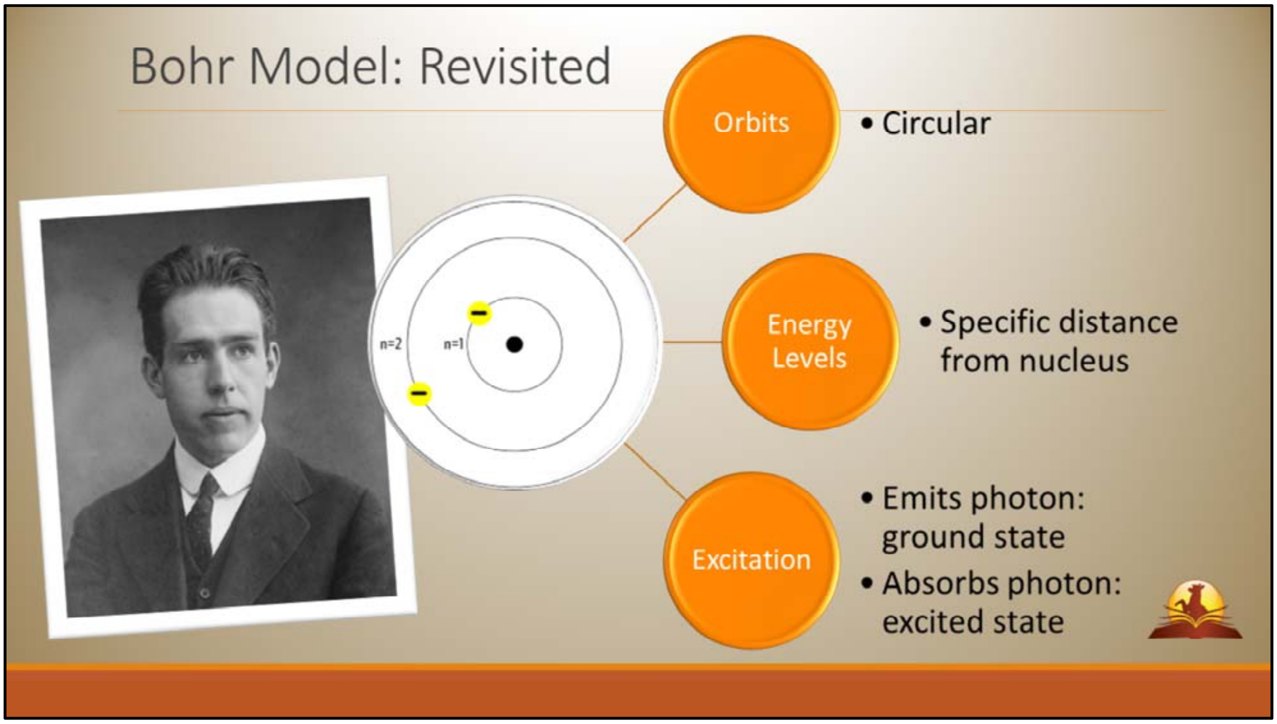
- According to **thermal radiation** principles**,** all matter that has a temperature above 0° K radiates electromagnetic (EM) waves.
  - Normally, matter does not get hot enough for us to feel these waves.
  - Sufficiently hot objects can cause us to experience heat radiating from the object as well as a color glow.
- In **classical theory,** oscillating atoms emit thermal radiation.
  - As oscillation increases, the charges moving within the matter act like antennas to produce EM radiation.
- A theoretical object called a **blackbody** absorbs all radiation and emits EM waves to remain in thermal equilibrium.
  - Basically, the blackbody converts all incoming radiation energy into EM waves, rather than using it to increase the temperature of object.
  - Scientists developed this idea to help explain the intensities of thermal radiation.
- Classical mechanics would predict that small wavelengths would emit EM waves at a higher intensity, but actually, the intensity approaches 0.
  - This phenomenon is known as **ultraviolet catastrophe,** because ultraviolet light has a low wavelength.
  - This observation also supports the position that light is a wave.



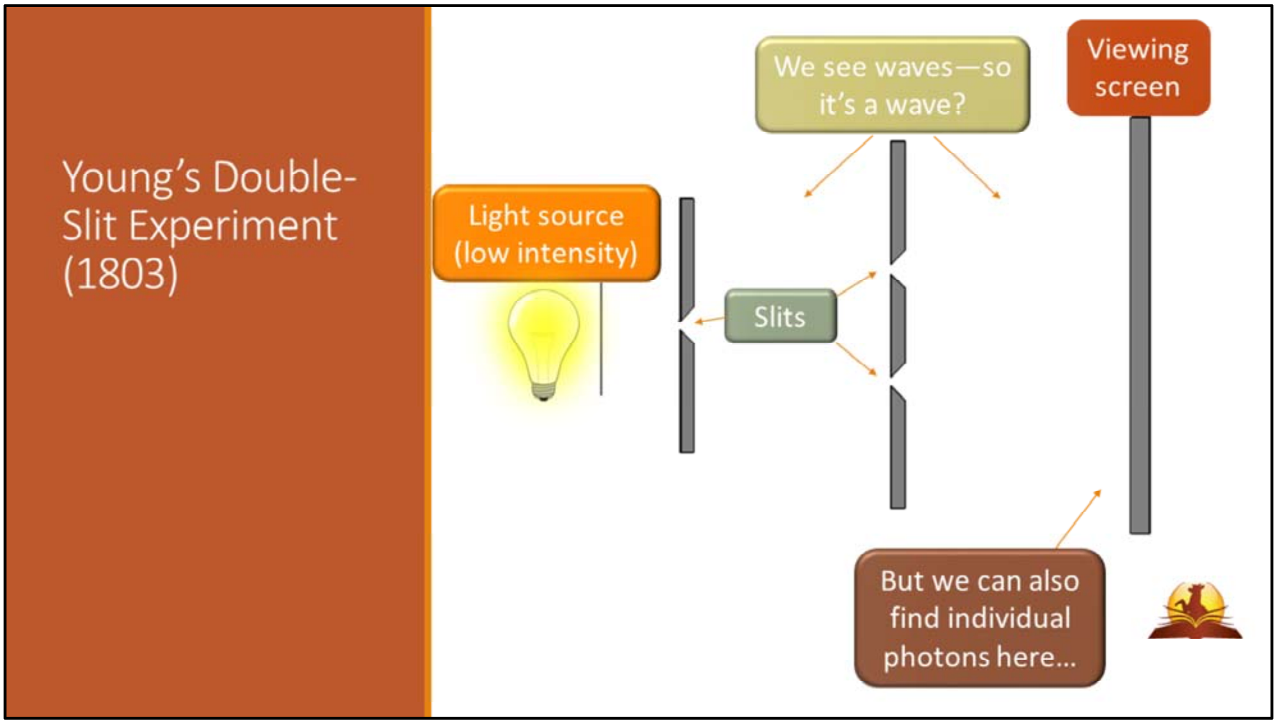
- **Heinrich Hertz** (1887) **illuminated metals with UV light** and discovered that they tended to produce sparks (electrons).
  - The emission of electrons from the surfaces of matter when illuminated by photons is the **photoelectric effect.**
- **Philipp Lenard** (1900) investigated photoelectric effect with charged plates that measured the energy of the emitted electrons.
  - He also experimented with **photons of varying intensity and frequency.**
  - Lenard made four observations that **contradicted classical theory**:
    - 1) Electrons were emitted instantaneously, where classical theory predicted a time delay.
    - 2) Light below a certain frequency did not eject electrons regardless of intensity.
    - 3) Increasing the intensity of light did not cause electrons to be ejected with greater kinetic energy.
    - 4) Increasing the frequency of light resulted in the emission of higher-energy electrons.
- **Arthur Compton** (1923) observed that **x-ray radiation collided with and scattered off of free electrons,** as well as **losing energy and shifting frequency.**
  - He named this effect **Compton scattering**
- All of these findings supported the view of light as particles.



- **Atomic spectroscopy** involves the analysis of spectral lines to identify a chemical.
- Atoms emit and absorb certain frequencies of light.
    - Therefore, observing which frequencies an atom absorbs or emits can identify a specific chemical like a fingerprint**.**
    - A spectroscope, a prism that separates the light that a collection of atoms emits, creates an **emission spectrum.**
    - By passing white light through a collection of atoms and observing which frequencies they absorb, scientists can create an **absorption spectrum.**
        - **Johann Balmer** created the first absorption spectrum in 1885.
    - Johannes Rydberg simplified the expression, in the formula above.



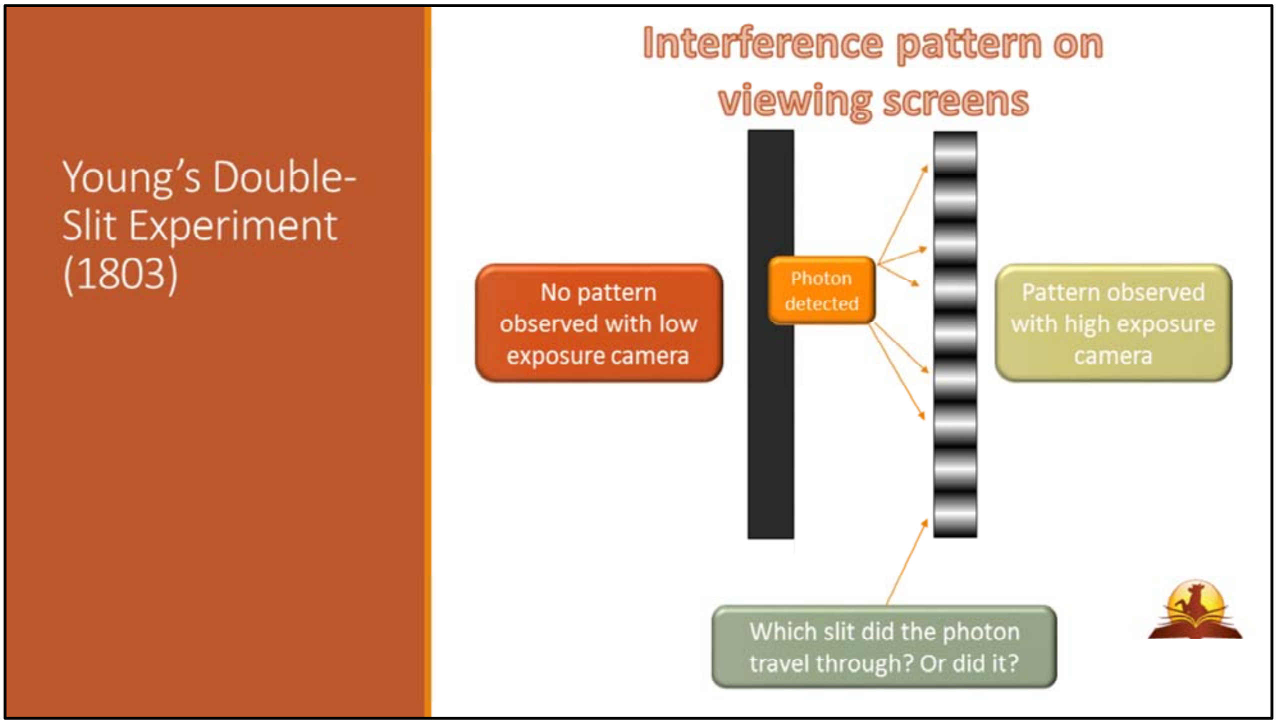
- **Niels Bohr** proposed the **Bohr model** in 1913.
  - The model attempted to **explain why hydrogen atoms emit quantized energy.**
  - Assumptions:
    - 1) Electrons revolve in **circular orbits** around the nucleus.
    - 2) Electrons **orbit at specific distances** away from the nucleus, called **energy levels.**
      - Electrons do not radiate energy as a result of their orbit. (This concept violated classical physics at the time.)
    - 3) Electrons **rise and drop energy levels by absorbing or emitting photons.**
      - This concept modified **Rutherford's planetary model** by limiting the angular momentum of electrons to h/ 2 pi.



In Thomas Young's Double Slit experiment in 1803, light passed through two thin parallel slits and produced a pattern of bright and dark fringes on the screen.

- Due to alternating constructive and destructive interference, these observations could only be explained by treating light as a wave.
- However, detecting the photon on the viewing screen could only be explained by treating light as a particle.

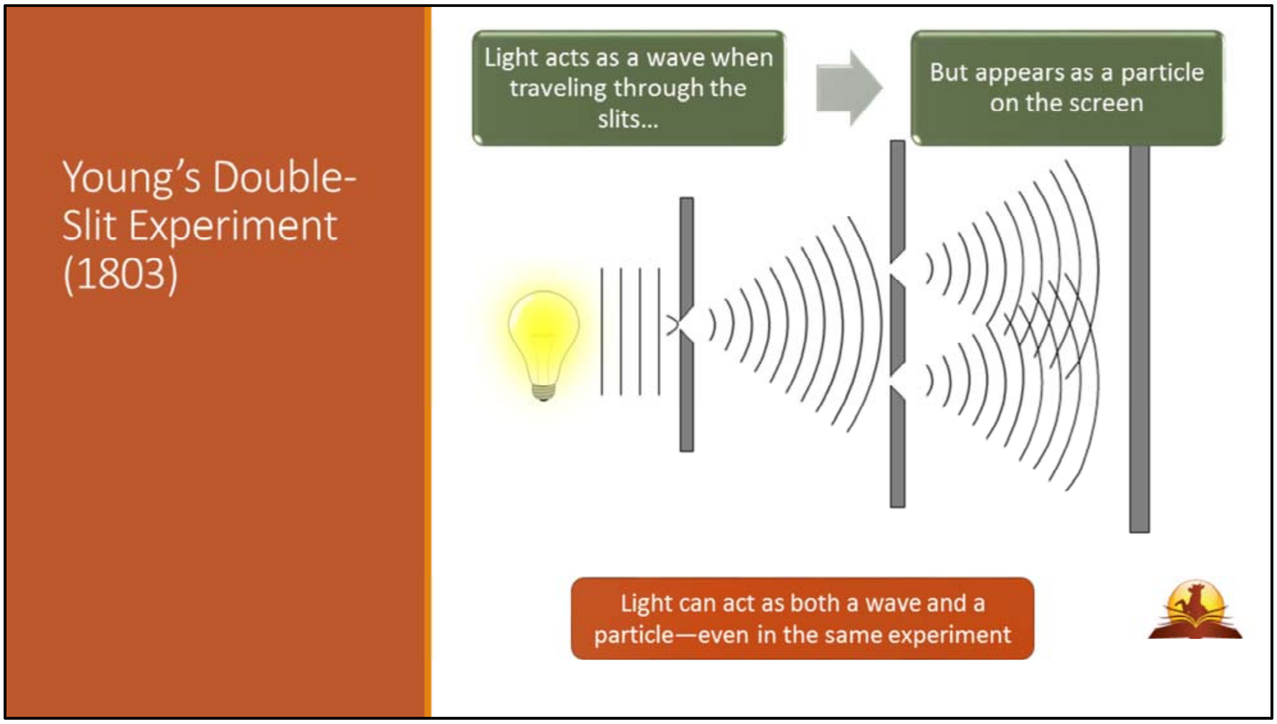
- So, we're right back where we started: light exhibits both wave and particle properties.



In Thomas Young's Double Slit experiment in 1803, light passed through two thin parallel slits and produced a pattern of bright and dark fringes on the screen.

- Due to alternating constructive and destructive interference, these observations could only be explained by treating light as a wave.
- However, detecting the photon on the viewing screen could only be explained by treating light as a particle.

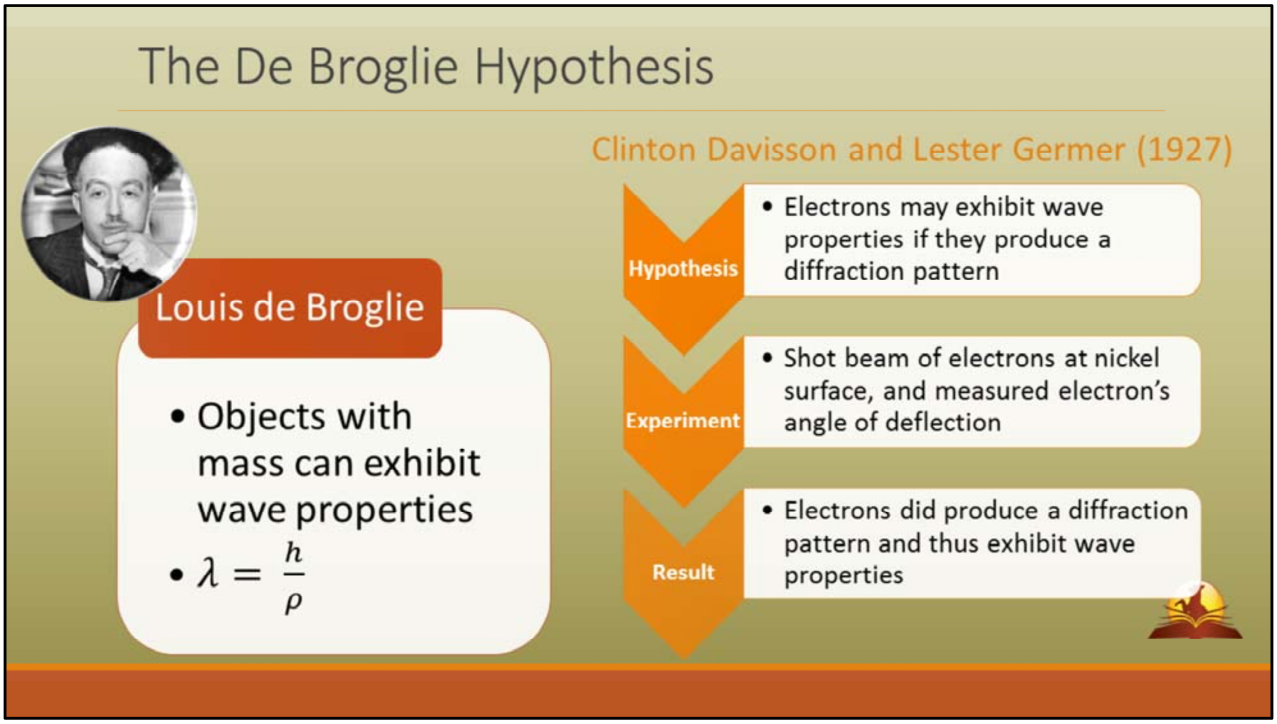
- So, we're right back where we started: light exhibits both wave and particle properties.



In Thomas Young's Double Slit experiment in 1803, light passed through two thin parallel slits and produced a pattern of bright and dark fringes on the screen.

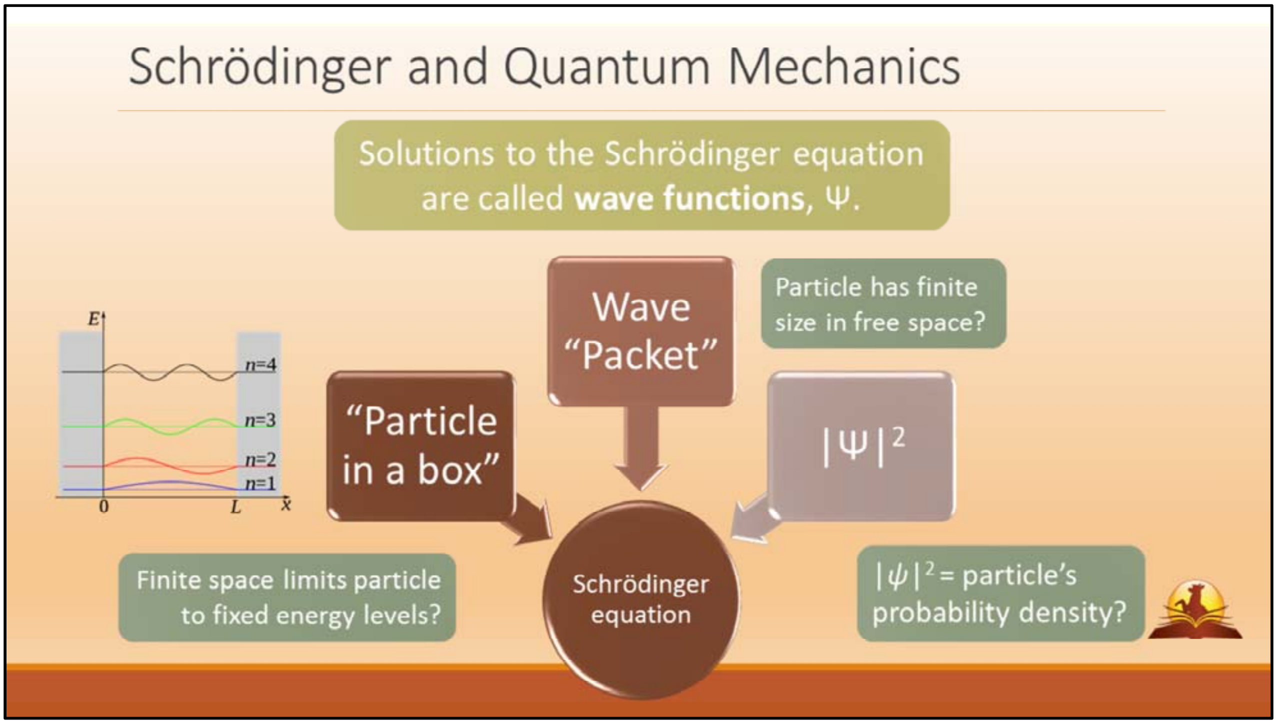
- Due to alternating constructive and destructive interference, these observations could only be explained by treating light as a wave.
- However, detecting the photon on the viewing screen could only be explained by treating light as a particle.

- So, we're right back where we started: light exhibits both wave and particle properties.



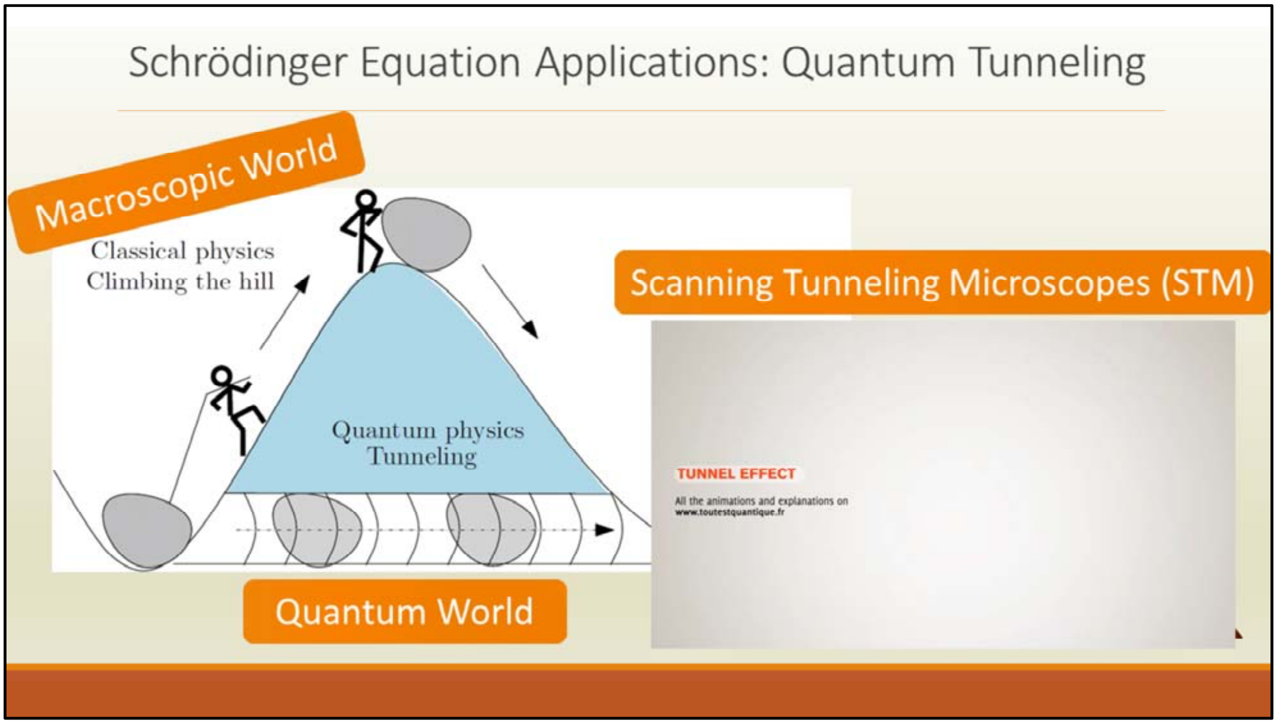
- **Louis de Broglie** (1924) proposed that **matter exhibits wave-like properties** in addition to particle-like properties, even though it has mass.
    - This hypothesis was similar to the wave-particle duality explanation of light.
- De Broglie's hypothesis can be mathematically summarized as:
    - $\boldsymbol{\lambda = \frac{h}{\rho}}$
    - λ – wavelength, h – Planck's constant (6.63 x 10^{-34} J * s), ρ – momentum (mass x velocity)
- De Broglie's hypothesis provided **justification for the Bohr model,** in that an **electron's angular momentum is quantized** because their energy levels relate to waves with **specific frequencies.**
- **Clinton Davisson** and **Lester Germer of Bell Labs** experimentally verified the theory in 1927.
    - Originally, Davisson and Germer wanted to determine the roughness of a nickel surface, and which properties of electrons would affect their interaction with a nickel surface.
    - However, the results of their experiment actually confirmed the De Broglie hypothesis, even though that's not what they had set out to do.
    - If the **beam of electrons** they fired at the crystalline nickel target **produced a diffraction pattern** then it would confirm that electrons exhibit wave

characteristics—because only waves diffract.
    - They shot the beam of electrons at the nickel target and **measured the electron's angle of deflection.**
    - They saw that the electrons did produce a diffraction pattern, thus **confirming that they exhibited wave properties.**
- **The implications of De Broglie's hypothesis** included:
    - The invention of transmission electron microscopes (TEM), which accelerate electrons to have a kinetic energy of 100 keV and a de Broglie wavelength of 0.0037 nm.
        - These microscopes allow us to **examine sample details smaller than the wavelength of visible light** (400 – 700 nm).
    - The knowledge that **objects as massive as cars also produce wavelengths.**
        - However, because they are so **massive** and **h is so small**, the wavelengths they produce are **too small to detect** (trillionth of a trillionth the size of an atom).



- **Quantum mechanics** describe **physics at the atomic level,** where quantum effects are relevant.
- The **Schrödinger equation** describes de Broglie's "matter waves" (1925).
  - Scientists generally accept the Schrödinger equation because it **matches with experimental data.**
  - **Wave functions** describe potential solutions to the Schrödinger equation.
- **Solutions** to the equation have **wave properties,** such as amplitude and wavelength.
  - One dimensional solutions include:
    - "**Particle in a box"**
      - Imagine a **particle confined to a finite space,** bounded by **infinite potential walls.**
      - The **energy the particle can take is quantized** and depends on the **mass of the particle and the dimensions of the box.**
    - **Wave "packet"** ***[Click 2]***
      - Imagine a **particle traveling through space without any external forces** acting upon it.
      - The wave function ascribed to the particle has **finite size and propagates forward** as the particle travels.
- **Max Born** proposed that the **absolute square of the wave function** is the **particle's probability density.**

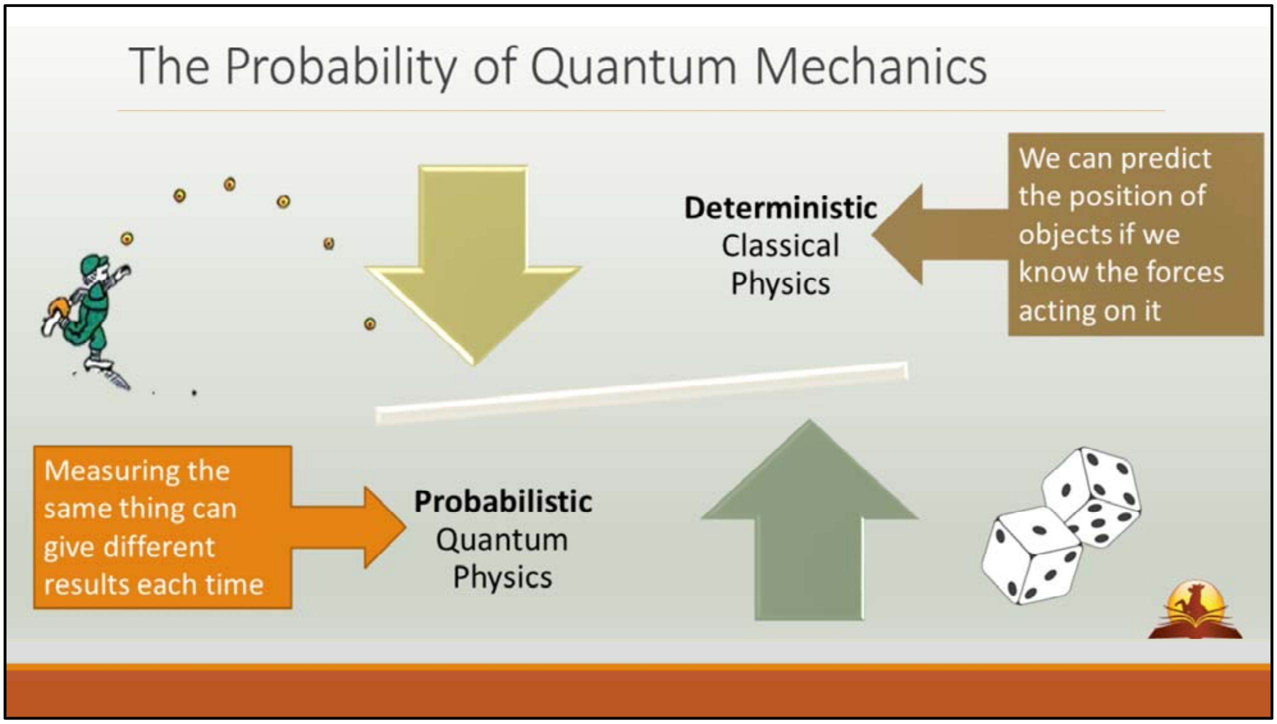
- In other words, the probability that a particle is detected within a certain volume at a given point in time.



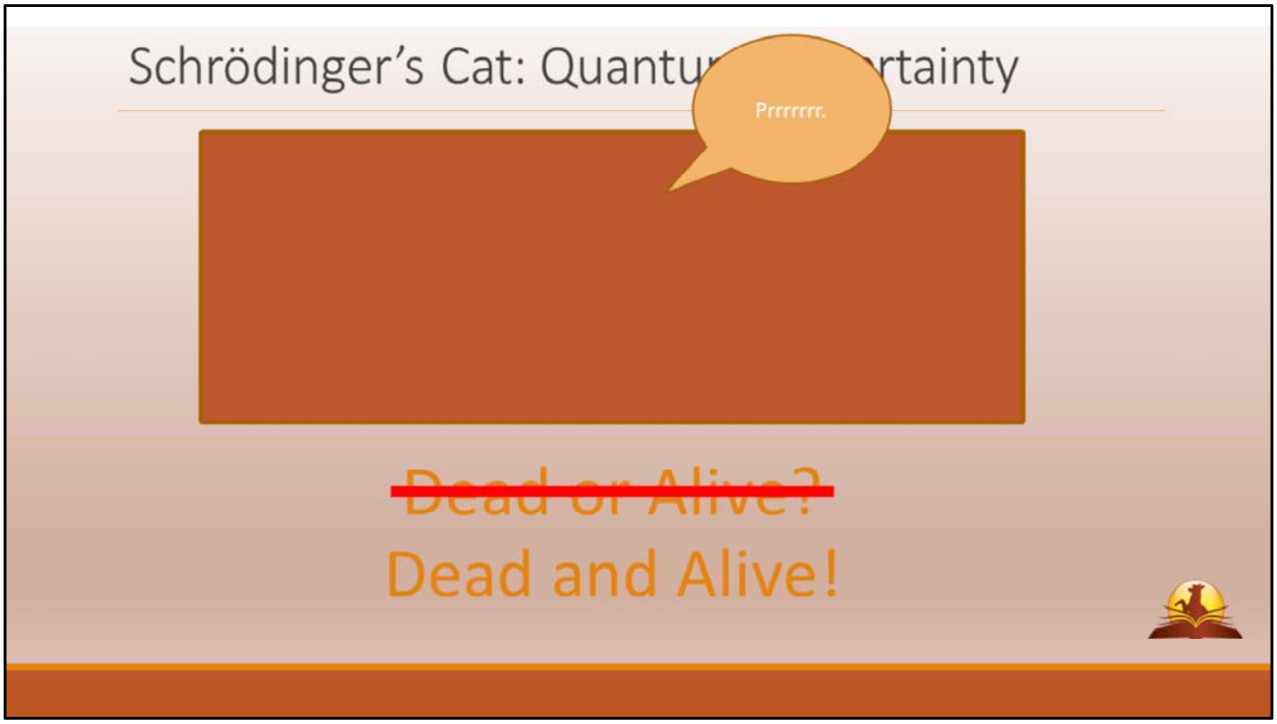
- **Quantum tunneling** is a consequence of the Schrödinger equation.
  - In the macroscopic world:
    - Objects want to occupy the lowest energy state, but cannot reach that lower energy state without being provided enough energy.
    - Example: Rolling a ball from the base of the hill (lower energy state) to the top of a hill (higher energy state) requires giving the ball enough energy.
    - If the ball doesn't receive enough energy, it will never make it to the top of the hill and on to the other side.
  - In the quantum world:
    - A particle has a very low but non-zero probability of being found on the other side of the hill.
    - It bypasses the energy required to reach the other side as seen in the macroscopic example.
    - The probability at which this occurs depends on the width of the barrier and the energy of its wave.
- Quantum tunneling has applications in technology.
  - **Scanning Tunneling Microscopes (STM)**
    - A voltage is applied to a surface to create a barrier for the surface's electrons.

- A conducting tip is brought close and electrons from the sample tunnel across to it if the tip is close enough.
- By measuring the current due to electrons tunneling to the tip, an STM can map out the surface of samples with resolution of about 0.1 nm.

Credit: “Quantum Tunneling: Macroscopic vs. Microscopic”
https://techforspace.com/blog/en-En/space/physics/quantum-tunneling-in-technology/

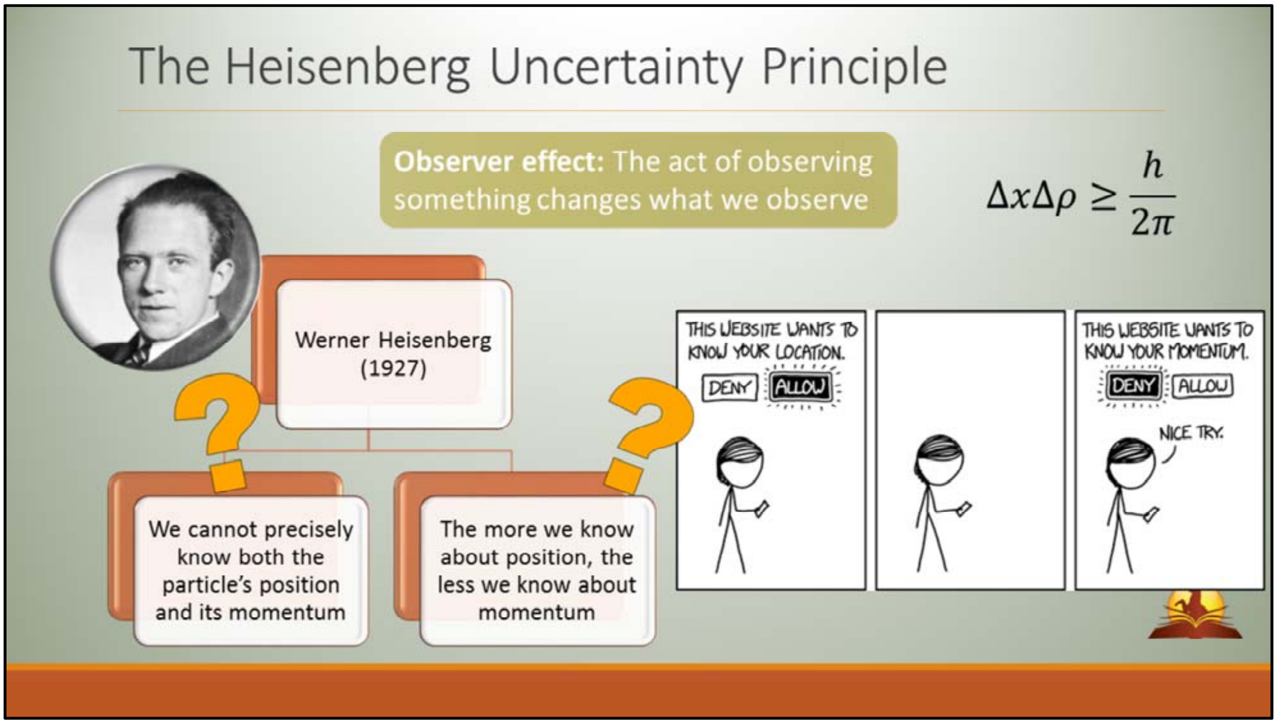


The sub-microscopic world is **probabilistic:** Measuring the same thing can give different results each time!
The macroscopic world is **deterministic:** We can predict the position of objects if we know the forces acting on it!



The Schrödinger's Cat thought experiment imagines that you place a cat, a vial of poison, and a radioactive source and Geiger counter in a sealed box. There is a 50% probability that radioactive source will decay and trigger a release of the poison; there is a chance that it won't. According to quantum uncertainty, until you open the box to discover the outcome, the cat is both alive and dead at the same time.

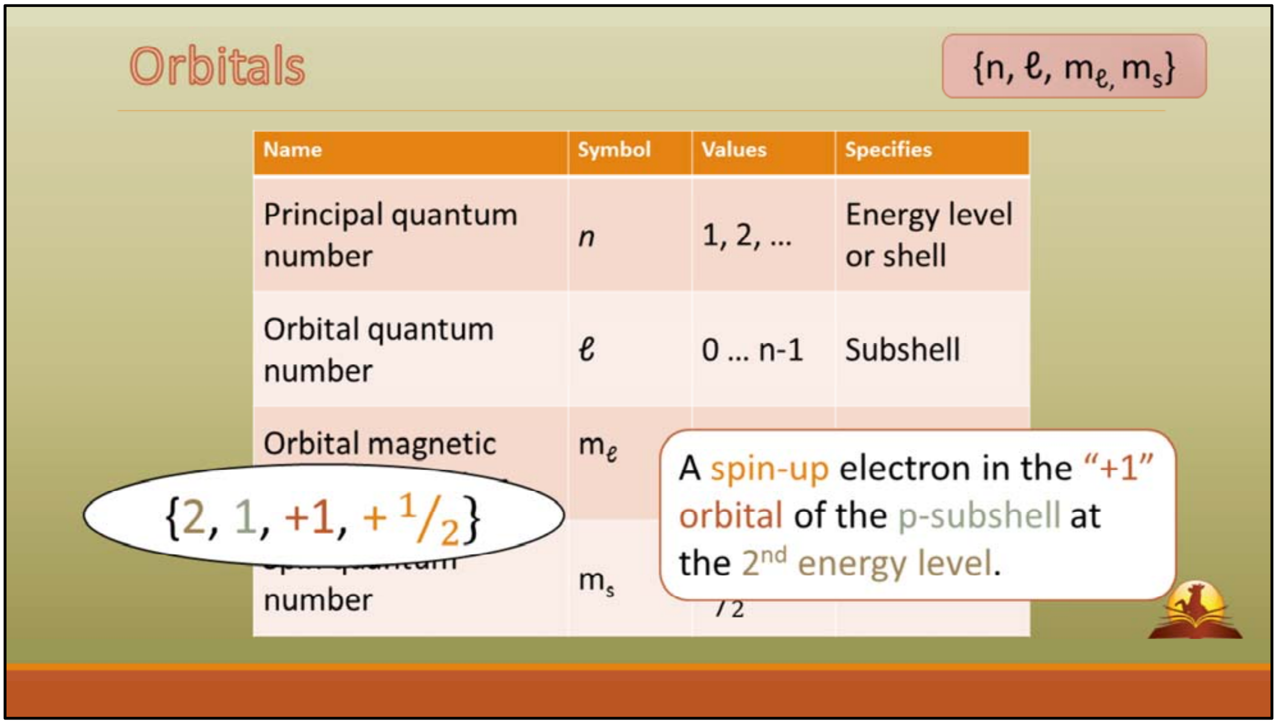
Credit: https://www.youtube.com/watch?v=uWMTOrux0LM



- The **observer effect**
  - At the quantum level, **how we measure things** often **affects the measurement** we end up getting.
  - At the macroscopic level, the **sheer size/scale** of what we measure means that our **observance doesn't appreciably affect the measurement** we get.
  - Example: the impact of photons bouncing off an electron causes a greater effect than photons bouncing off a car and into our eye.
- German theoretical physicist **Werner Heisenberg** proposed **Heisenberg Uncertainty Principle.**
  - Mathematically represented by $\Delta \boldsymbol{x} \Delta \boldsymbol{\rho} \geq \frac{\boldsymbol{h}}{\boldsymbol{2\pi}}$ where:
    - $\Delta x = uncertainty\ in\ position; \Delta \rho = uncertainty\ in\ momentum; h = Planck's\ constant$ (6.63 x 10−34 J $*$ s)
  - We **cannot simultaneously know the precise location and momentum** of a particle at the quantum level.
    - There is an **inverse relationship between the precision of our knowledge of a particle's position and momentum**, the more we know about one, the less we know about the other.
- Because of the small value of Planck's constant, the Heisenberg Uncertainty Principle,

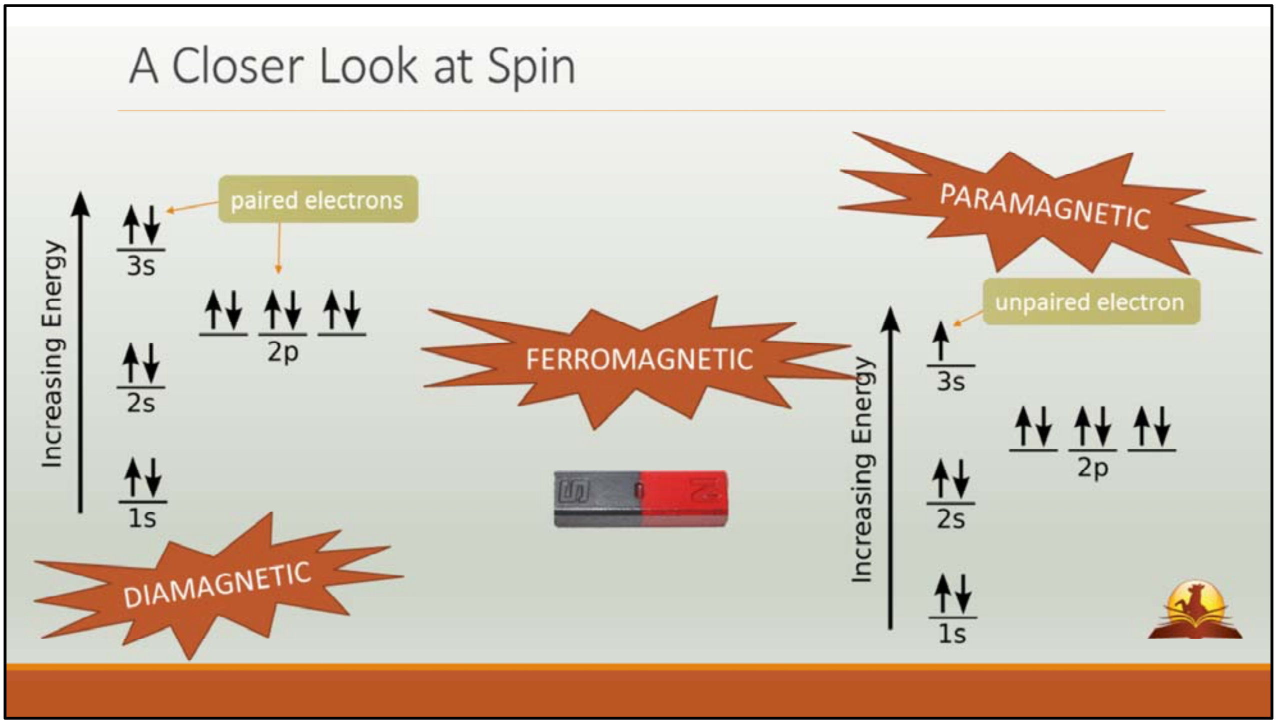
like the observer effect, is not significantly noticeable in the macroscopic world.

Credit: “Werner Heisenberg” By Bundesarchiv_Bild183-R57262,_Werner_Heisenberg.jpg: Unknown derivative work: Quartl (Bundesarchiv_Bild183-R57262,_Werner_Heisenberg.jpg) [CC BY-SA 3.0 de (http://creativecommons.org/licenses/by-sa/3.0/de/deed.en)], via Wikimedia Commons
Credit: “Location Sharing”
https://www.explainxkcd.com/wiki/images/a/ae/location_sharing.png



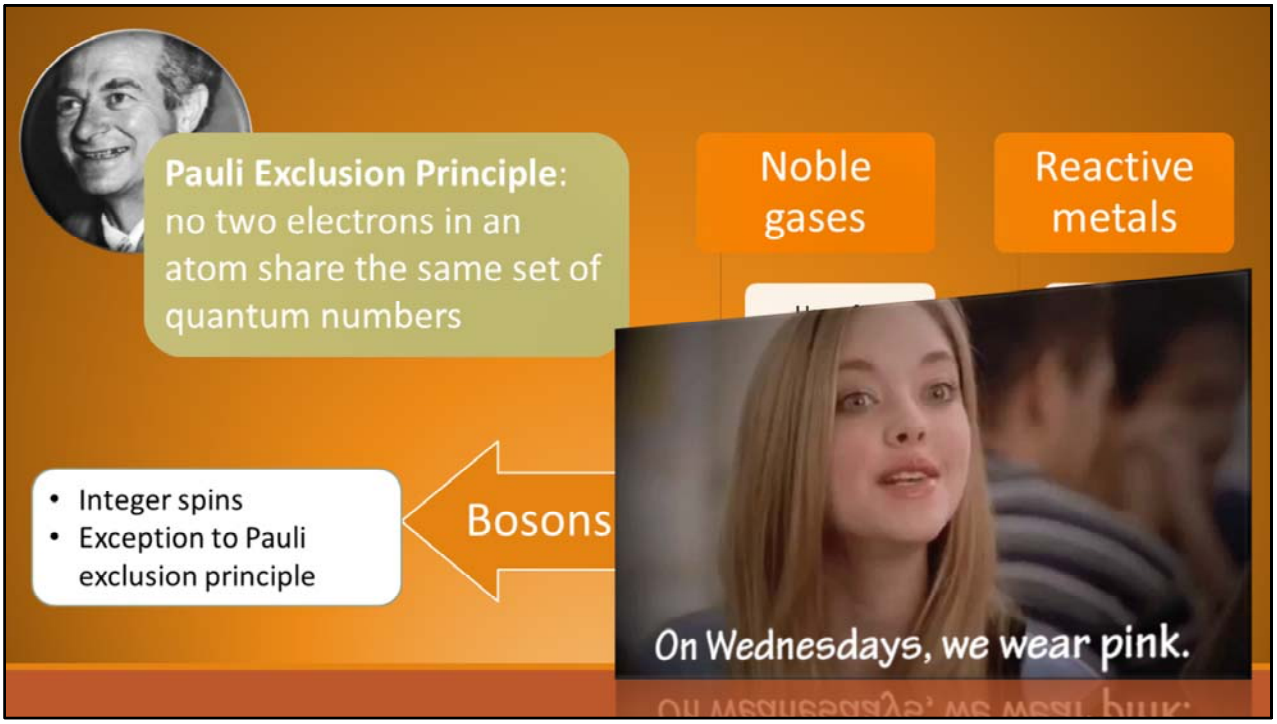
- Electrons of atoms are described using wave functions from Schrödinger's equation.
  - The **three quantum numbers** n, l, and m_l are **solutions to wave functions** in three dimensions.
- The **principal quantum number**, n, is the same n as in the Bohr model.
  - It is used to describe the **energy level** of an electron in an atom.
  - Electrons with the same n are said to be occupying the same electron shell.
- The **orbital quantum number**, l, can take on any integer value from 0 to n-1.
  - Electrons with the same n and l are said to be in the same **subshell.**
  - The subshell symbols s, p, d, and f correspond to l = 0, 1, 2, and 3, respectively.
- The **orbital magnetic quantum number** m_l can take on integer values from –l to l.
  - In the presence of a magnetic field, electrons with different m_l have their energies shifted slightly differently.
  - This observation is called the **Zeeman effect.**
- **The spin quantum number** will be explained in the next slide**.**
- Here is an example of how one could describe an electron using these four quantum numbers.

Credit: "Erwin Schrodinger" By Nobel foundation [Public domain], via Wikimedia Commons



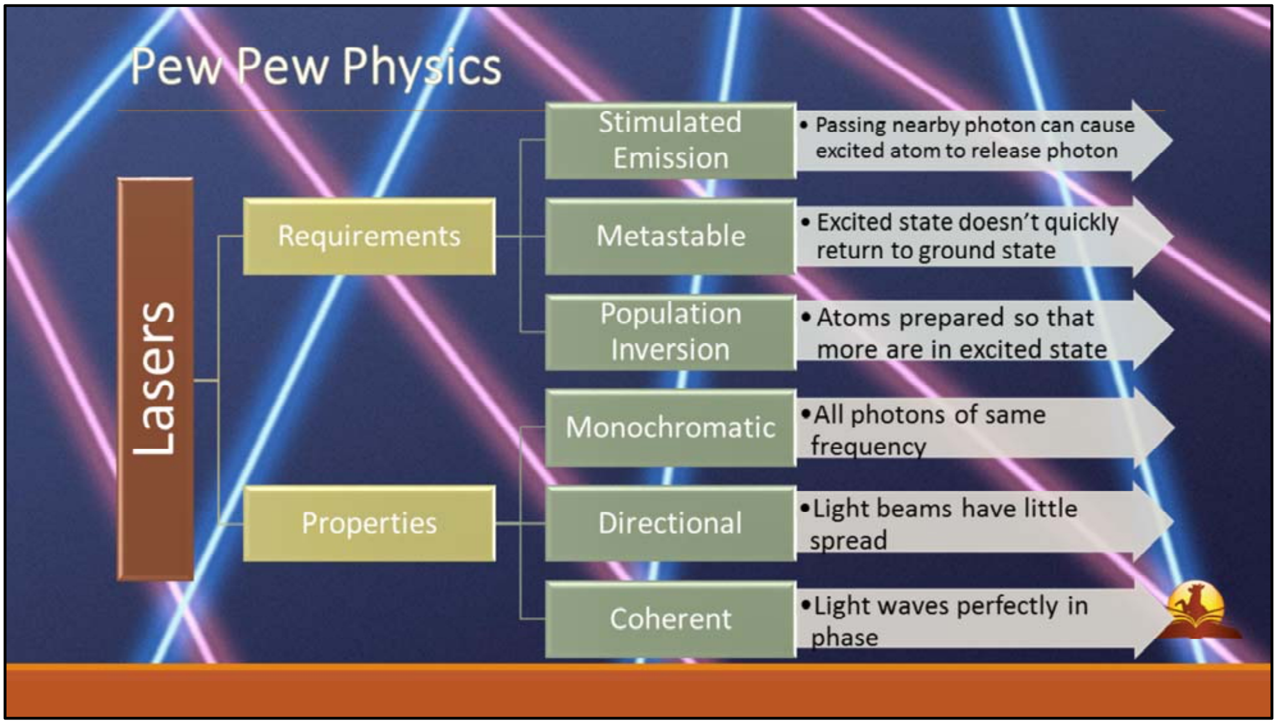
- An electron's **spin** doesn't refer to an actual spin like a top, but to its **angular momentum.**
- Here is the electron configuration of Magnesium that shows all its electrons as either spin-up or spin-down.
  - Notice how all electrons in Magnesium are paired up.
  - Magnesium is **diamagnetic because all electron spins are paired.**
    - Diamagnetic atoms have **no magnetic moment** and are **repelled** when exposed to a magnetic field
- Now we look at the electron configuration of Sodium.
  - Notice how an electron in the 3s orbital is unpaired.
  - Sodium is **paramagnetic** because there is **at least one unpaired electron.**
    - Paramagnetic atoms have an **intrinsic magnetic moment** and are **attracted** to magnetic fields.
- **Ferromagnetic** atoms have **at least one unpaired electron that aligns with each other even without magnetic field present.**
  - These atoms have magnetic properties that make them useful as **permanent magnets.**
  - Above the **Curie temperature,** however, these atoms lose their magnetic properties.

Credit: “Electron configuration of sodium” By CK-12 Foundation (raster), Adrignola (vector) (File:High School Chemistry.pdf, page 365) [Public domain], via Wikimedia Commons
Credit: “Electron configuration of magnesium” By CK-12 Foundation (raster), Adrignola (vector) (File:High School Chemistry.pdf, page 366) [Public domain], via Wikimedia Commons
Credit: “Top” By Clara E. Atwood - A Book of Nursery Rhymes, Public Domain, https://commons.wikimedia.org/w/index.php?curid=8536787



- The **Pauli Exclusion Principle** states that **no two electrons** in an atom can **share the same set of quantum numbers.**
  - Therefore, each electron in an atom has a unique set of four quantum numbers*.*
- Electrons follow a **"stacking rule"** as they are added to atoms. Each additional electron will occupy the **lowest energy unoccupied orbital** before pairing up in the same orbital*.*
  - This effect explains how certain atoms have their properties*.*
  - Non-reactive elements have fully paired electron shells, while reactive ones have unpaired electrons.
- The Pauli exclusion principle only applies to a class called **fermions.**
  - Fermions, such as electrons, have **half-integer spin values** such as +1/2 and -1/2*.*
  - Bosons have **integer spin values** and can have electrons share the same set of quantum numbers.
  - The **"Bose-Einstein condensate"** was a new state of matter proposed by Satyendra Bose and Albert Einstein in 1924.
  - In 1995, Carl Wieman and Eric Cornell experimentally composed a gas of bosons that were cooled to near 0 K.

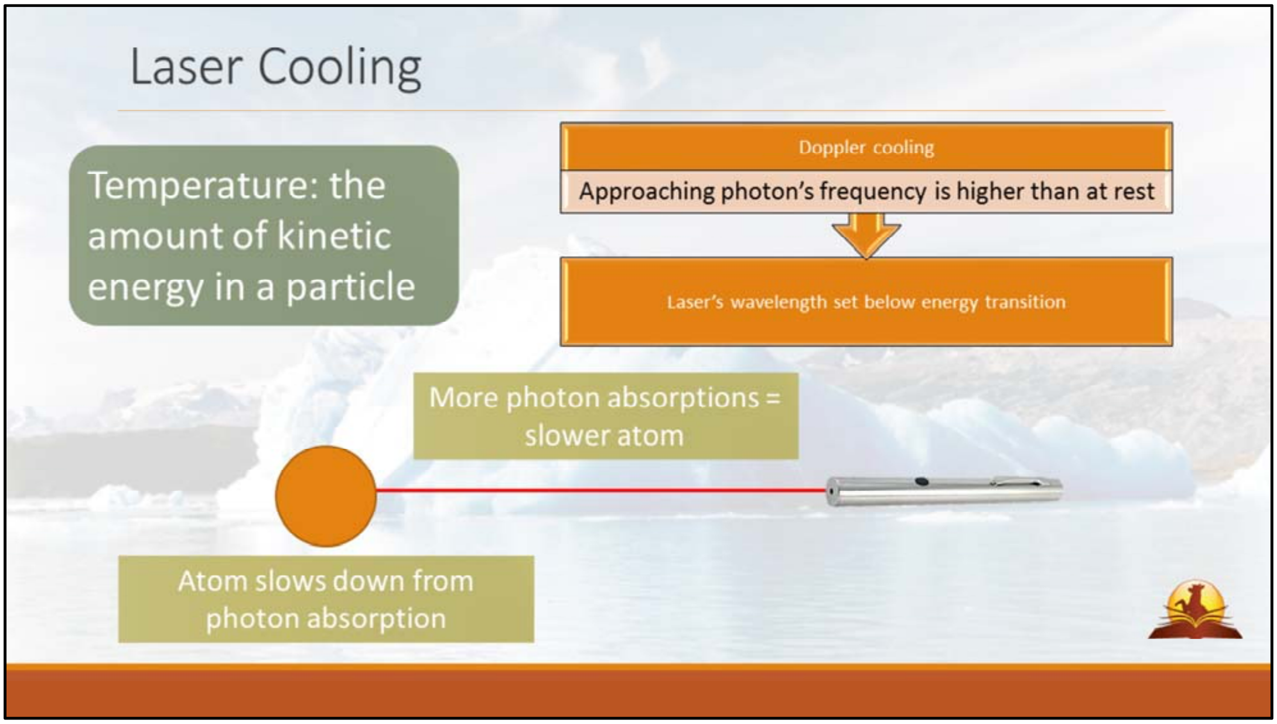
Credit: "Linus Pauling" By US-Gov., Library of Congress, biographical file - www.loc.gov...235_pop.htmlReproduction Number: LC-USZ62-76925PAULING, LINUS, photograph (no date found on item, ca. 1954)Location: Biographical filewww.loc.gov download address, Public Domain, https://commons.wikimedia.org/w/index.php?curid=540732



- Laser technology relies on atomic physics.
  - What are the requirements for laser operation?
    - **Stimulated emission**
      - Electric field from **passing photon** causes excited atom to **emit a photon.**
      - Passing photon and emitted photon oscillate **in precise synchrony**—the same frequency as an excited electron.
      - If a reflective "cavity" **contains and amplifies** this emitted light, we get a **focused beam known as a laser.**
    - **Metastable**
      - The excited state must not return quickly to ground state.
      - **Stimulated emission must take place,** rather than spontaneous emission.
    - **Population inversion** prepares atoms so that **more atoms are excited** than in the ground state.
      - This process is used to **sustain chain reaction** of stimulated emission.
  - What are the properties of lasers?
    - **Monochromatic**
      - All the emitted photons **match frequency** with the passing

photon due to stimulated emission.

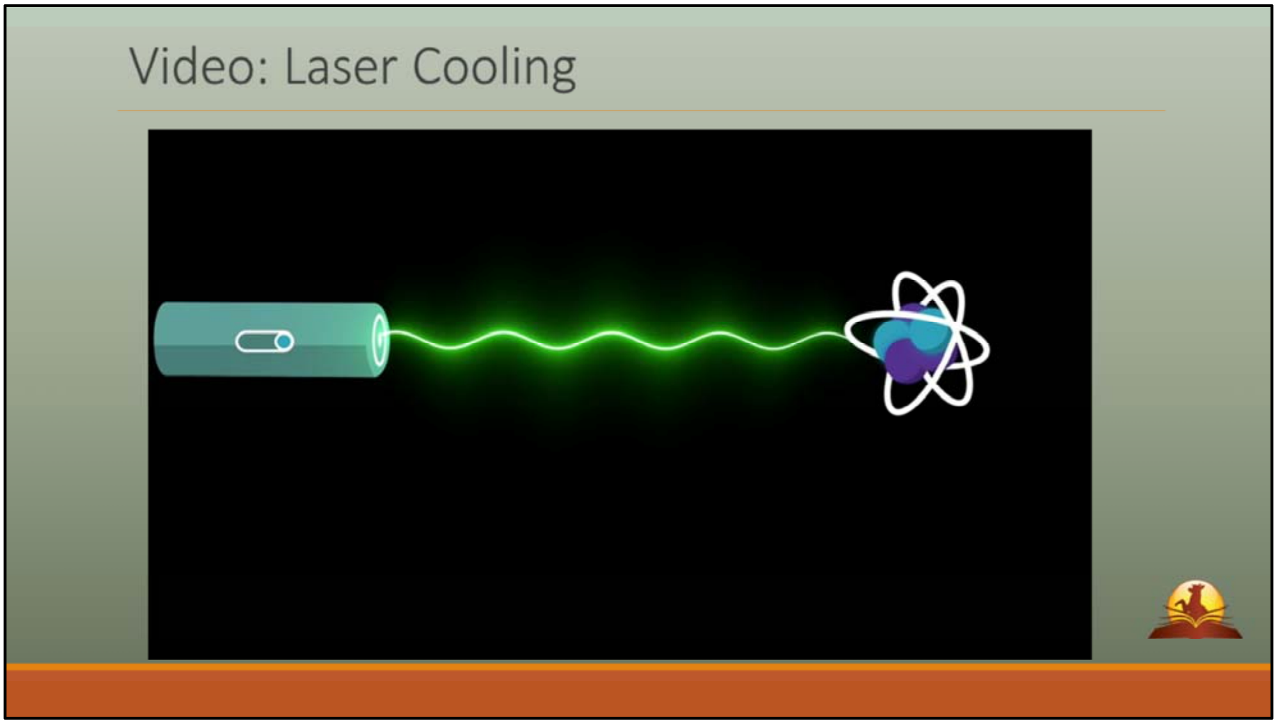
    - **Directional**
        - Precise alignment of “reflective cavity” ensures that there is **little spread in the light.**
    - **Coherent**
        - The light waves of a laser are perfectly **in phase,** meaning the peaks and troughs **align perfectly.**
- “LASER” is an **acronym** for Light Amplification by Stimulated Emission of Radiation.
    - Some of the most common lasers today are **Helium-Neon lasers.**
        - Helium atoms are excited by a current and collide with Ne to excite them to release **632.8 nm radiation (red light).**



- What is temperature?
  - Temperature is the **amount of kinetic energy** of a substance's particles
- The atoms of **colder** objects have **lower kinetic energy** than those of warmer objects ***[Click 1]***
- So how do we slow down atoms to lower their temperature? ***[Click 2]***
  - When atoms **absorb photons**, they **"recoil"** in the opposite direction because of the **conservation of momentum** ***[Click 3]***
  - After enough "recoils," the atom is **slowed down** by the impact of incoming photons ***[Click 4]***
  - But how come the atoms don't start speeding up in the opposite direction from the impact of photons?
    - **Doppler cooling** causes a photon's **frequency to be higher** when it is being **approached** ***[Click 5]***
    - Therefore, the **wavelength** of laser is set to be **slightly below the energy transition** of the atom so only **approaching atoms absorb photons** and are slowed
    - Atoms **not approaching or at rest** cannot absorb photons because their **energy transitions do not match the photon's frequency**

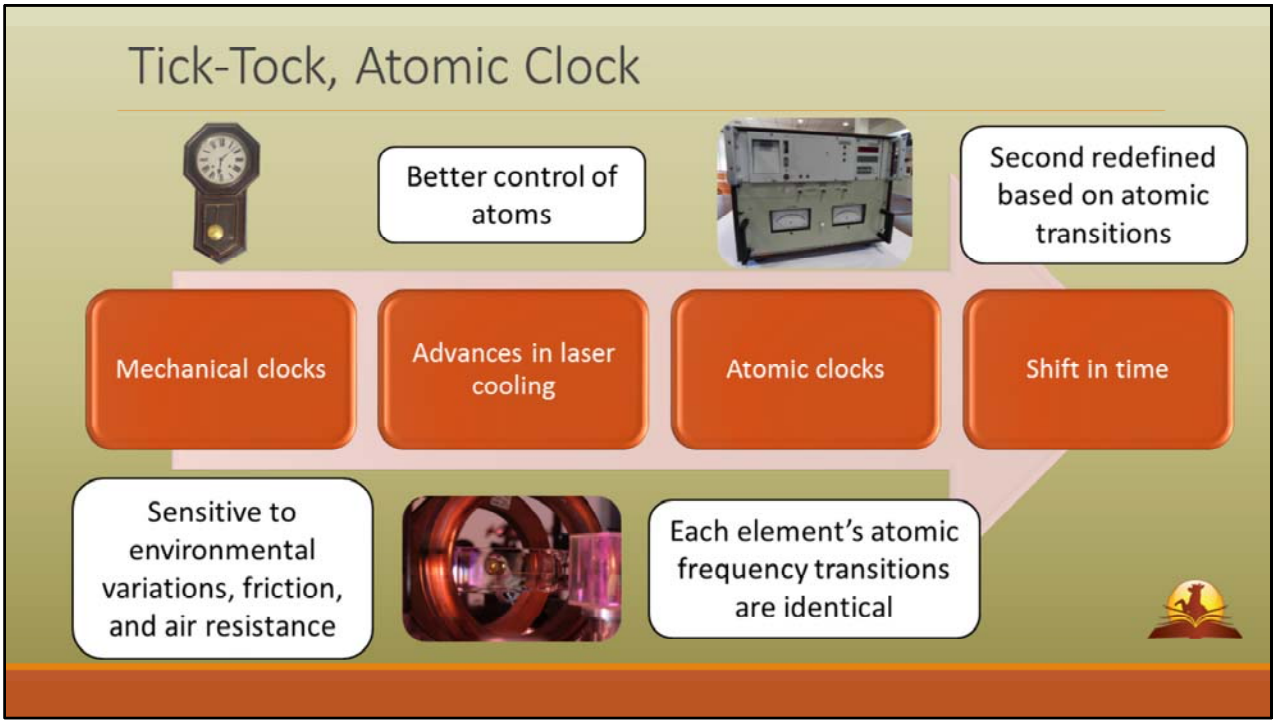
PHOTO: Iceberg, CC BY-SA 3.0,

https://commons.wikimedia.org/w/index.php?curid=229593



Note: the h-bar in the video that talks about the Heisenberg Uncertainty Principle is shorthand for h/2! So, h-bar/pi is the same as h/2pi

Credit: https://www.youtube.com/watch?v=hFkiMWrA2Bc

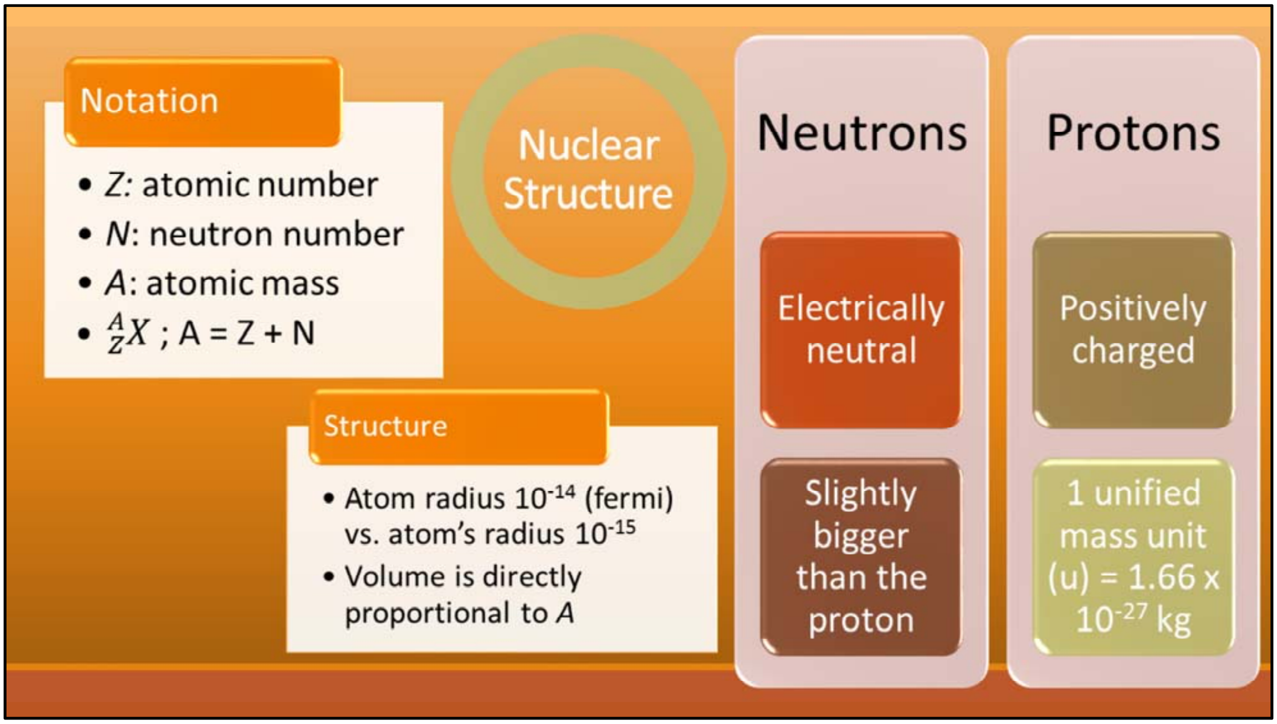


- Better control over atoms led to innovations in timekeeping.
- Early **mechanical clocks** were too unreliable for precise timekeeping.
  - Mechanical means (like the swinging of pendulum) were **sensitive to environmental variations and energy dissipation.**
- With advances in **laser cooling**, we had the ability to better control atoms.
- These advances allowed us to build **atomic clocks.**
  - Atomic clocks rely on the fact that **frequencies of atomic transitions are identical** for all atoms of the same element.
  - The first cesium atomic clock in 1955 only lost one **second every 300 years.**
  - Today, cesium clocks are accurate to within one **second every 300 million years.**
- The precision of atomic transitions allow us to accurately define the **second.**
  - The **National Institute of Standards and Technology (NIST)** defines it as:
  - 1 second = **9,192,631,770 oscillations of radiation** emitted from transitions of **cesium-133** ground state

Credit: "Pendulum clock" By $500 Av.kumar85 at en.wikipedia (Transferred from en.wikipedia to Commons.) [Public domain], from Wikimedia Commons
Credit: "Laser cooling" By Tomasz Kawalec (Own work) [CC BY-SA 4.0 (http://creativecommons.org/licenses/by-sa/4.0)], via Wikimedia Commons
Credit: "Atomic clock" By ESO (http://www.eso.org/public/images/ann13092a/) [CC BY 4.0

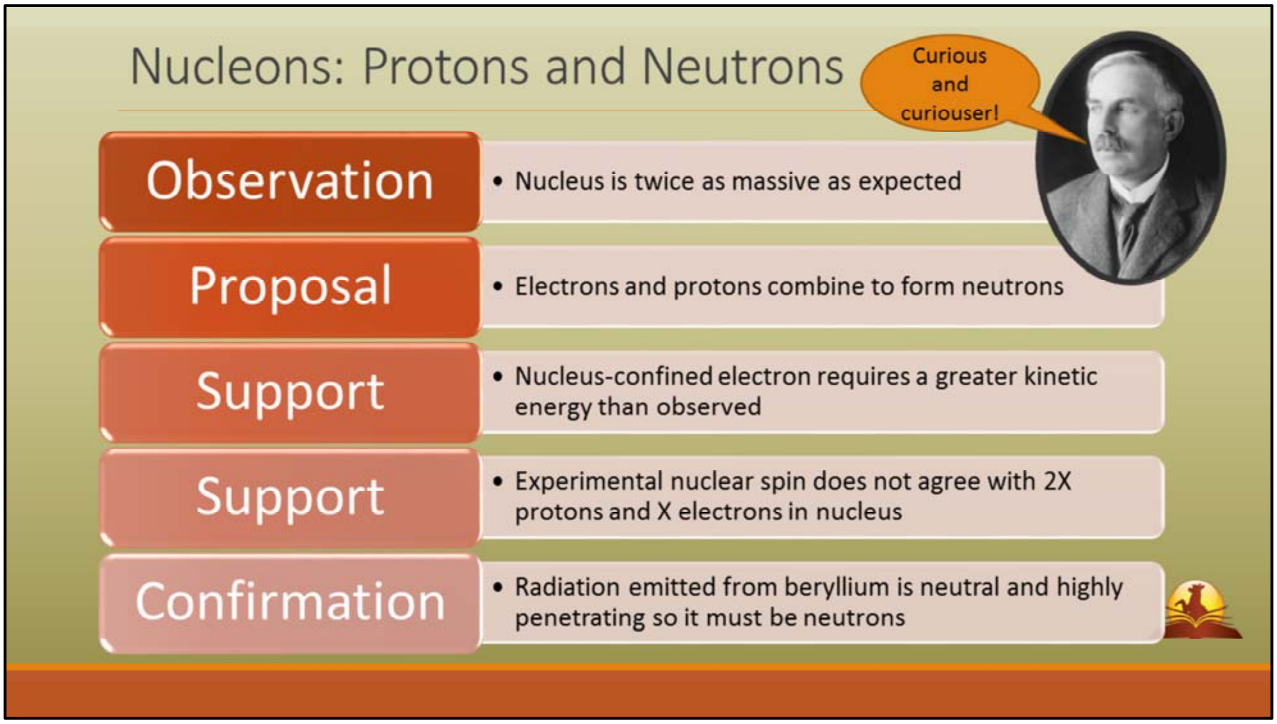
(http://creativecommons.org/licenses/by/4.0)], via Wikimedia Commons

II: An Atomic Look at Radioactivity



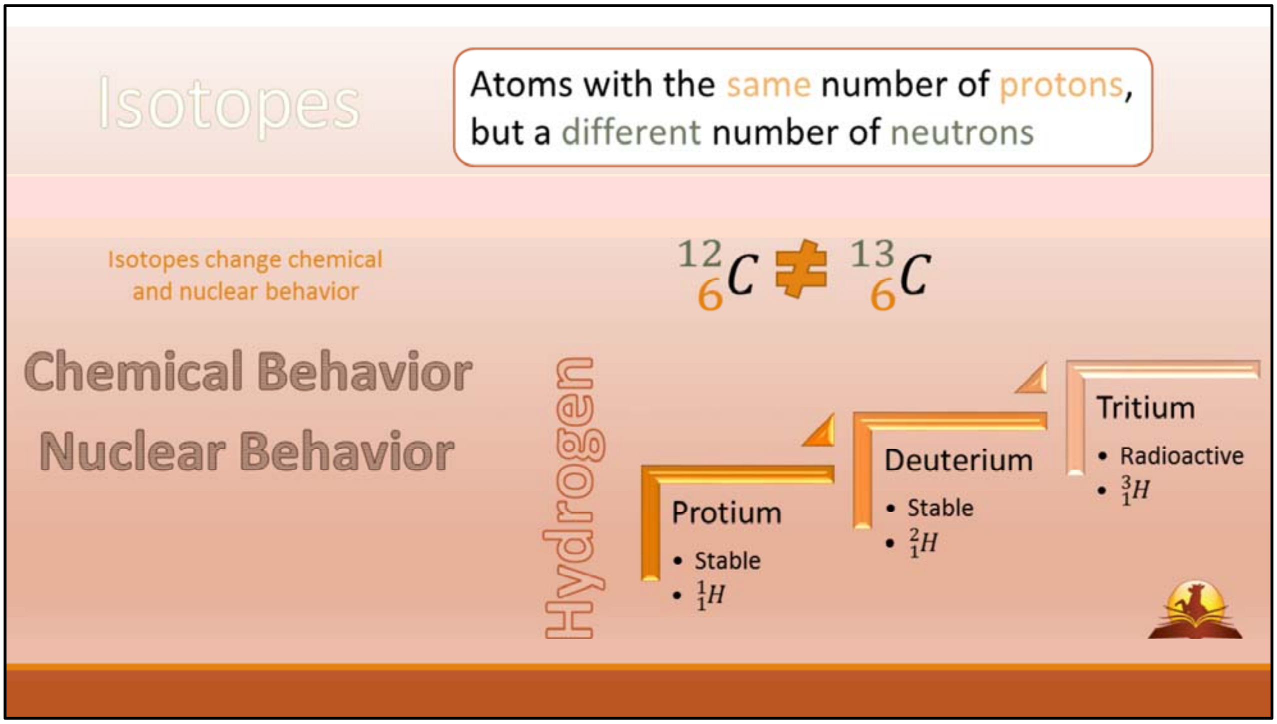
- In order to understand how the **nucleus** behaves, we need to study its **structure.**
  - The nucleus contains particles known as **neutrons** and **protons.**
  - **Neutrons** are **electrically neutral** and slightly **more massive** than protons**.**
  - **Protons** are **positively charged** and have a **mass of 1 unified mass unit**.
    - A unified mass unit is 1/12 the mass of a carbon-12 atom
  - The **number of protons** denotes the identity of the element and uses the symbol **Z** for its **atomic number.**
  - The **number of neutrons** is called the **neutron number (N).**
  - The **atomic mass, A,** is equal to the number of protons plus the number of neutrons.
    - Do not confuse the **atomic mass** with the **relative atomic mass** on the periodic table.
    - The relative atomic mass is the **weighted average mass of all isotopes** of an element.
  - To refer to a specific nucleus, we use the notation:
    - $^A_Z\boldsymbol{X}$, where element X has A atomic mass and Z protons.
    - The **atomic number can be omitted** because the identity of element X also gives the number of protons.
- The size of the nucleus (known as a **fermi**) is about **100,000** times smaller than the diameter of the rest of the atom**.**

- The **radius of the nucleus** is given by the formula $r = r_0A^{1/3}$.
- Since the volume of a sphere is proportional to r^3, the **volume of the nucleus** is **directly proportional to *A***.

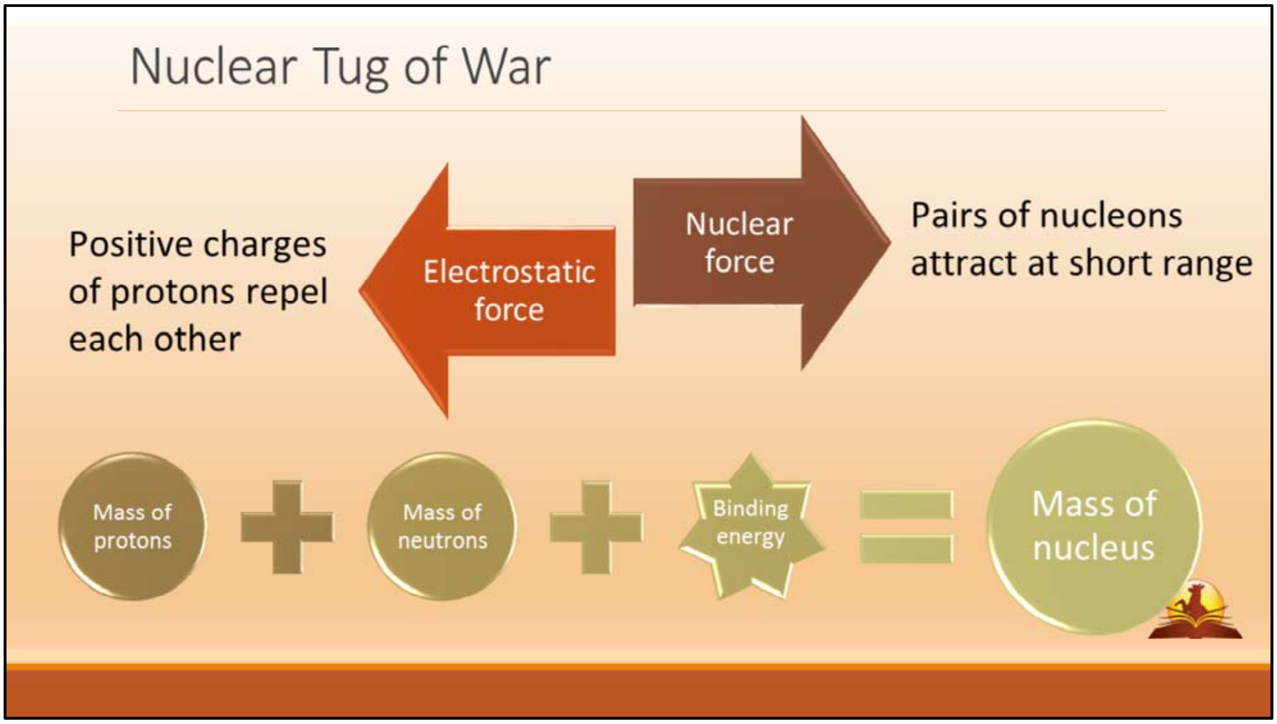


- **Ernest Rutherford** scattered particles off nitrogen gas and discovered **hydrogen nuclei** being emitted (1917)**.**
  - He repeated this experiment for **heavier atoms** and got the same result.
  - This result led Rutherford to propose that the hydrogen nuclei is a **"fundamental building block"** for all atoms, though the hydrogen nuclei is later discovered to just be a **proton**.
- The discovery of **neutrons** required a bit more support and ingenuity.
  - **Rutherford** noticed that **nuclei** tended to be **twice as massive as expected** given their charge**.**
  - He proposed that the nucleus contained **additional protons** that combined with electrons to form **neutrons (1920).**
  - Two **problems with the idea that electrons were in the nucleus**
    - The **Heisenberg Uncertainty Principle** predicts that an electron should have a **minimum kinetic energy** to be confined to the nucleus**.**
      - Minimum energy predicted was greater than the actual experimental energy measured.
    - The observation of **nuclear spin** did not agree with the presence of electrons in nucleus**.**
      - Nitrogen-14 has a nuclear spin of 1.
      - 14 protons and 7 electrons (both spin-1/2) cannot combine to

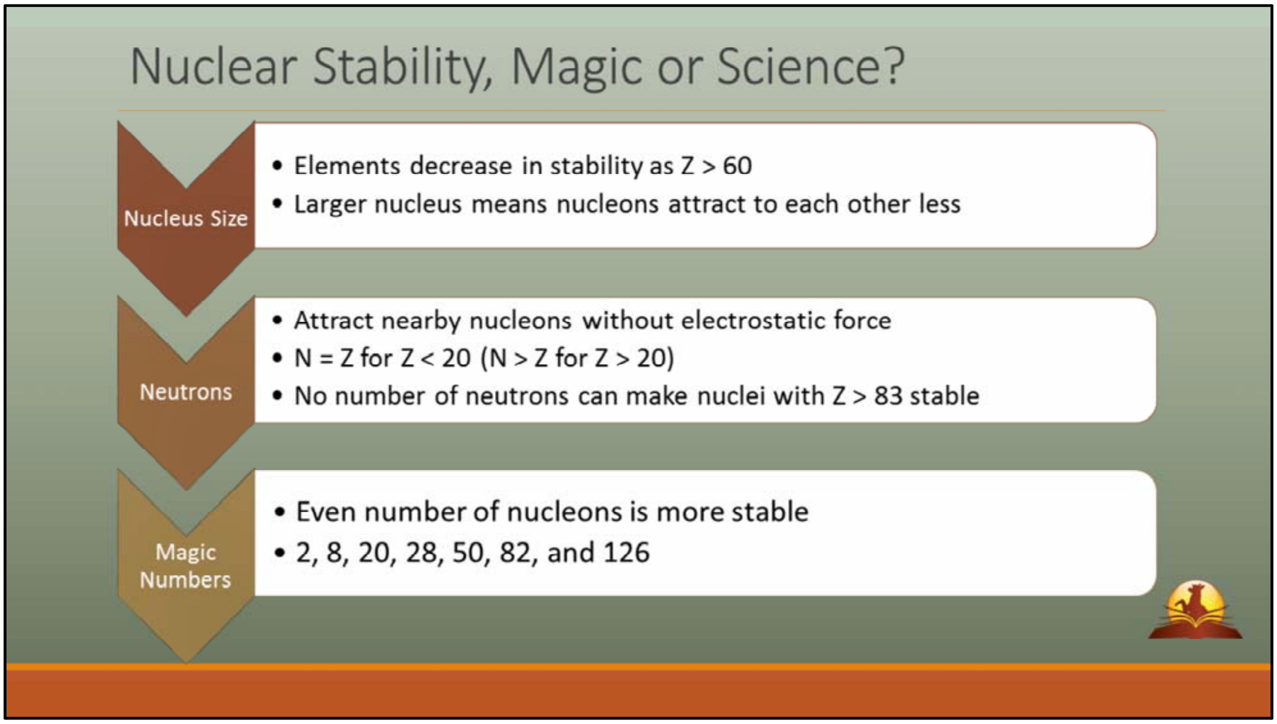
    have spin 1.
    - Therefore, electrons cannot be in the nucleus.
- **Confirmation** of neutrons' existence came with **James Chadwick** and **beryllium.**
  - In 1930, Chadwick discovered that beryllium emitted high-energy radiation when collided with alpha particles.
  - Radiation was **highly penetrating** and had **no electric charge.**
  - It couldn't be **high energy photons,** because it did not exhibit other expected properties of photons.
  - Therefore, this radiation was confirmed to be the **neutron** in 1932.



- **Isotopes** are atoms with the **same number of protons**, but a **different number of neutrons**
  - In other words, the **atomic numbers** of isotopes are the same, but the **atomic masses** of isotopes are different*.*
- Isotopes have differing effects on **chemical** and **nuclear behavior.**
  - Chemical behavior refers to how an atom behaves in **chemical reactions** (that is, the identity of elements do not change). Neutron number has little effect on chemical behavior.
  - Nuclear behavior refers to how a nucleus behaves in **nuclear reactions** (that is, the identity of elements change). Neutron numbers affect nuclear stability.
- Not all isotopes occur naturally or in the same abundance*.*
  - The three isotopes of hydrogen are **protium, deuterium, and tritium.**
  - Protium: a single proton orbited by a single electron
    - Most abundant isotope (**99.99% abundance**)
    - Stable
  - Deuterium: a proton and a neutron with a single electron
    - Stable
  - Tritium: a proton and two neutrons with a single electron
    - Radioactive

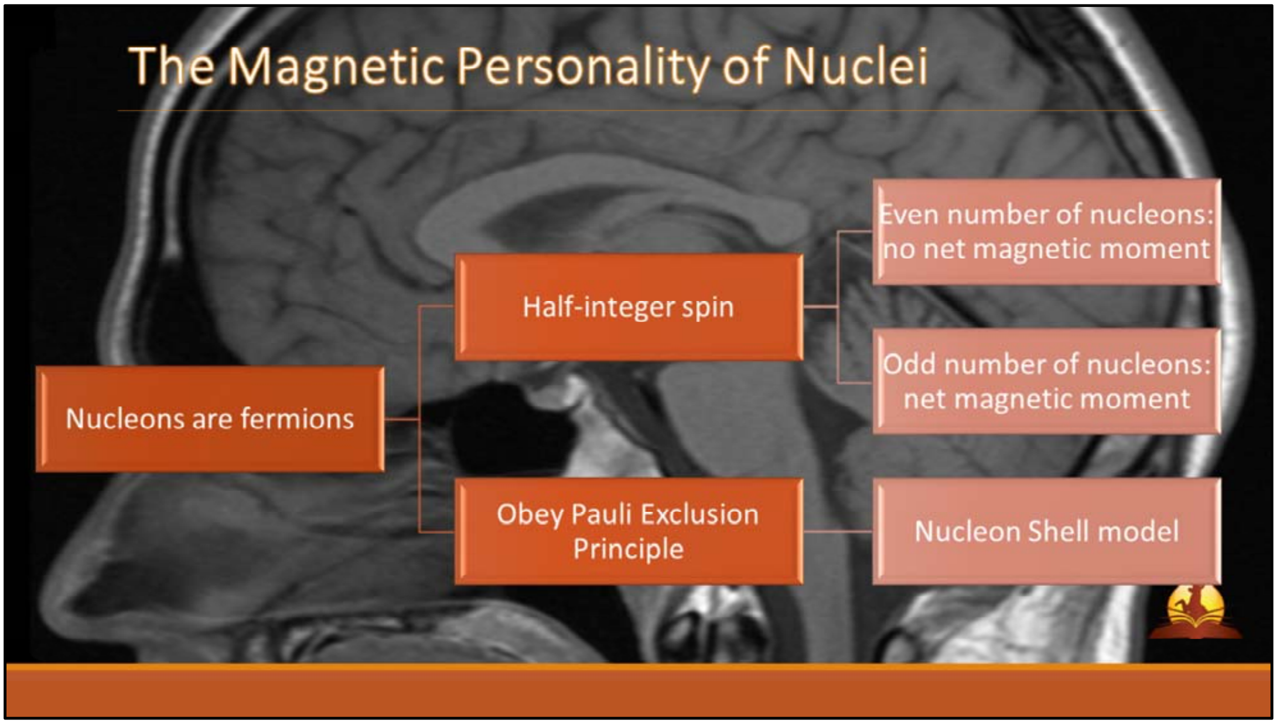


- The mass of a nucleus' constituent parts (its nucleons) does not add up to its total mass.
  - The binding energy also contributes to the mass of the nucleus.
- The energy required to keep nucleus intact is equivalent to mass by $E = mc^2$.



- **Binding energy** can be used as a measurement of nuclear stability.
  - The **higher** the binding energy, the **more stable** the nucleus.
- What are some factors that affect nuclear stability?
  - **T**he larger the **nucleus size**, the more unstable the nucleus**.**
    - Because nuclear force is short range, the larger the nucleus becomes, the less nucleons are attracted to each other**.**
  - **Neutrons** attract nearby nucleons through nuclear force without contributing electrostatic force***.***
    - For light atoms ($Z < 20$), the number of neutrons equals the number of protons**.**
    - For heavy atoms, the number of neutrons is greater than the number of protons.
    - No number of protons can make elements with $Z > 83$ stable.
  - **Magic numbers**
    - Nuclei with **even number** of nucleons are more stable than classical effects predict**.**
    - Nuclei with a **magic number** of protons and/or neutrons are more stable.
      - Nuclei with a magic number of both protons and neutrons are "**doubly magic**."

    - Ex. Helium-4 has 2 neutrons and 2 protons.
- These numbers correspond to the number of nucleons required to fill each nucleon “shell.”

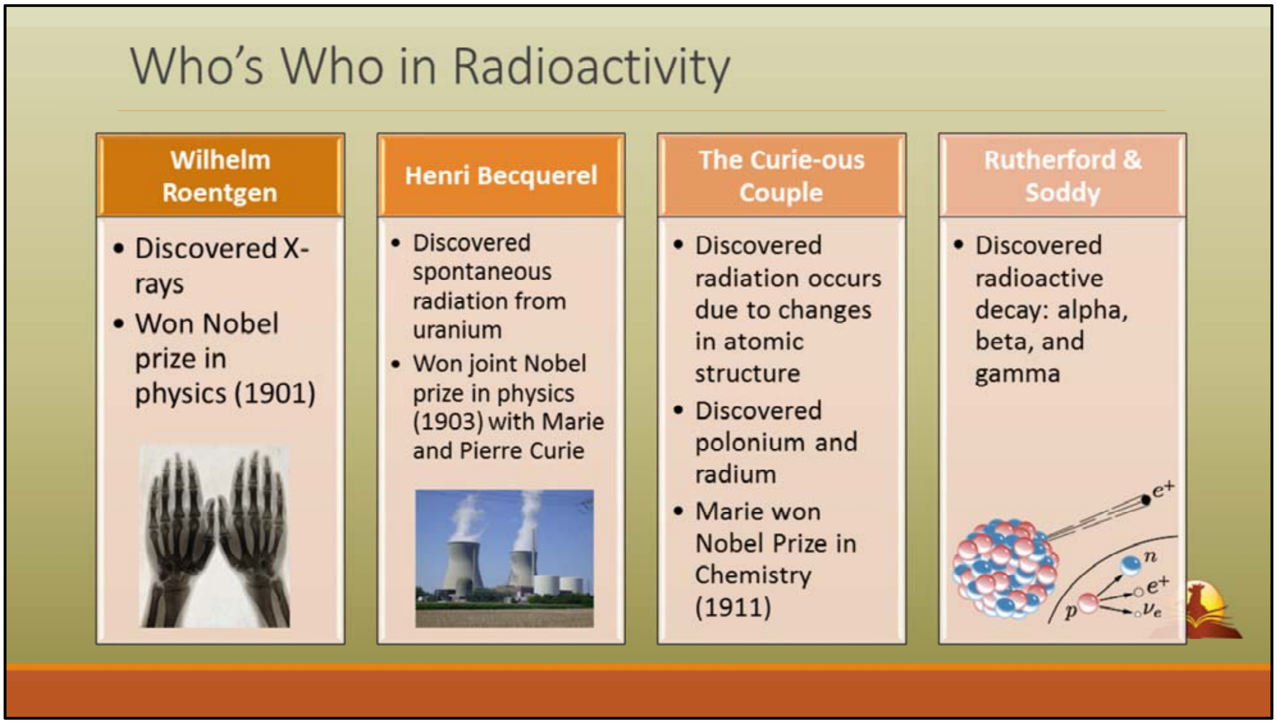


- Nucleons are **fermions**, thus:
    - Nucleons must obey the **Pauli Exclusion Principle.**
        - They have energy levels (shells) similar to that of electrons.
        - The **shell model** is similar to the orbital electron shell model proposed by Maria Geoppert Mayer and Eugene Wigner (1949).
    - Nucleons have **half-integer spin.**
        - Therefore, they have an intrinsic net magnetic moment.
            - **An even number of nucleons** means no net magnetic moment, because nucleons with opposite spin pair up and cancel out.
            - **An odd number of nucleons** means net magnetic moment.
- Even nuclei also have magnetic properties.
    - Applying an **external magnetic field** causes the magnetic moments of nuclei to either **align against (higher energy)** or **with (lower energy)** the field.
    - The nucleus can oscillate between these two states if another magnetic field is applied.
    - This **oscillation between states** is the basis of **MRI** technology, which

functions through:

- Strong magnetic field applied to patient
- Hydrogen nuclei aligned in water
- Radio waves applied to specific points to be imaged
- Waves knock nuclei out of alignment
- Waves removed and unaligned nuclei release energy
- Energy signal is detected to create image

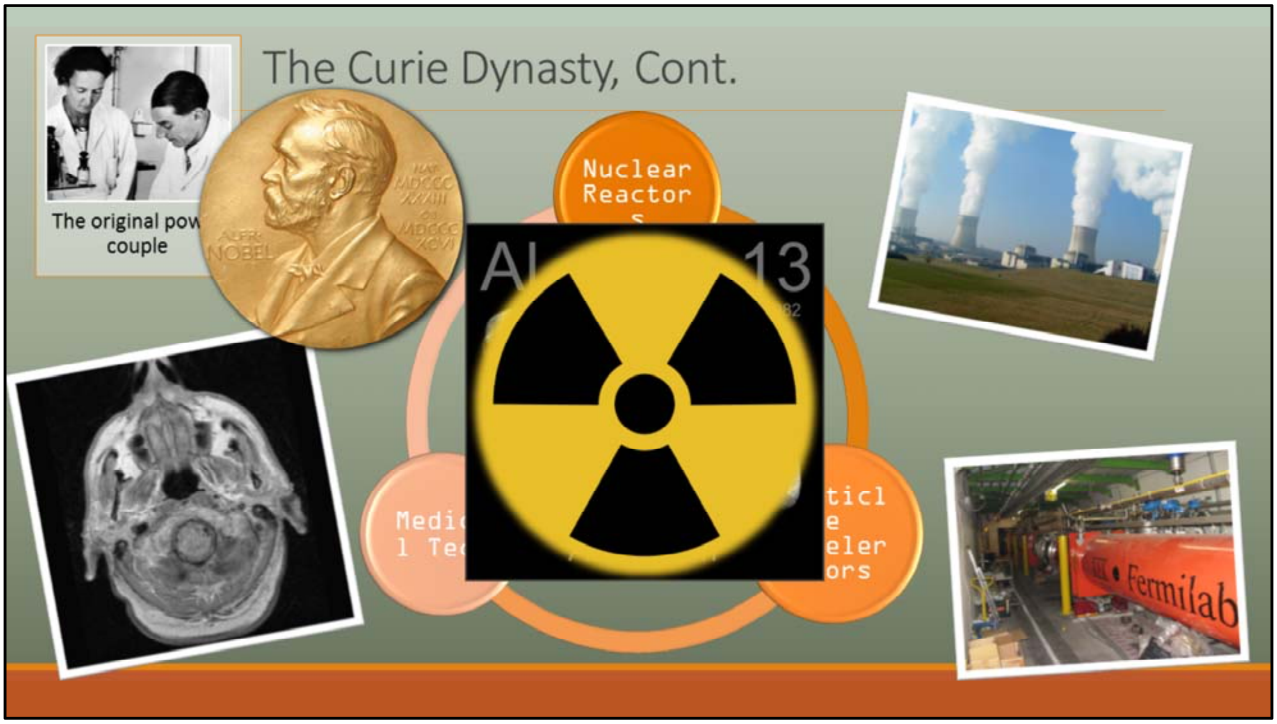
- Applying external magnetic field aligns a nucleus' magnetic field, and the MRI image is created from de-alignment of nuclei.



- **Wilhelm Roentgen** (1895)
    - Discovers **x-rays** while conducting experiments using cathode ray tubes
    - Realizes X-rays could not be blocked by cloth, paper, or books
    - Nobel Prize in Physics (1901)
- **Henri Becquerel**
    - Crystals of uranium salt emit **spontaneous radiation**
    - "Radioactive" means isotopes that spontaneously transform into other elements
    - Awarded Noble Prize in Physics (1903) alongside **Marie and Pierre Curie**
- **Marie and Pierre Curie**
    - Discovered that **radiation depends on amount** of uranium (a radioactive substance)
    - Radiation results from changes in **atomic structure**
    - Discovery of **polonium** (July 1898) and **radium** (later that year)
    - Nobel Prize in Chemistry (1911) to Marie Curie, who was the only person to win two Noble Prizes in science
    - Marie **dies from aplastic anemia** (1934) from constant exposure to radiation
- **Ernest Rutherford and Frederick Soddy**
    - Conclude that radioactivity is unstable elements transforming into more stable ones
    - Discovered **radioactive decay**: alpha, beta, gamma

- Process by which elements transform into others to be more stable
- Each type of radiation exhibited different properties, discussed next

Credit: “X-ray” See page for author [CC BY 4.0 (http://creativecommons.org/licenses/by/4.0)], via Wikimedia Commons
Credit: “Radioactive decay” By Master-m1000 [Public domain], via Wikimedia Commons
Credit: “Nuclear Power Plant” By Felix König (Eigenes Werk (own work) - Samsung S750) [GFDL (http://www.gnu.org/copyleft/fdl.html) or CC BY-SA 3.0 (http://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons



- Irene Joliot-Curie (daughter of Marie and Pierre Curie) and her husband Frederic discover how to induce radioactivity.
  - This induction allowed for the construction of **nuclear reactors**, **particle accelerators,** and **innovations in medical technology.**
  - Induced radioactivity was achieved through the synthesis of **radioactive phosphorous-30** from the bombardment of **aluminum** with **alpha particles.**
  - Induced radioactivity allowed for the easier synthesis of radioactive isotopes rather than laboriously extracting them from natural sources.
  - Awarded the Nobel Prize in Chemistry (1935)

Created synthesis of radioactive phosphorous by bombarding aluminum with alpha particles

Synthesis not extraction!

Credit: “Nuclear power plant” By Stefan Kühn (Own work) [GFDL (http://www.gnu.org/copyleft/fdl.html), CC-BY-SA-3.0 (http://creativecommons.org/licenses/by-sa/3.0/) or CC BY-SA 2.5-2.0-1.0 (http://creativecommons.org/licenses/by-sa/2.5-2.0-1.0)], via Wikimedia Commons
Credit: “Large Hadron Collider” By gamsiz (Flickr) [CC BY 2.0

Interpreting Nuclear Reactions

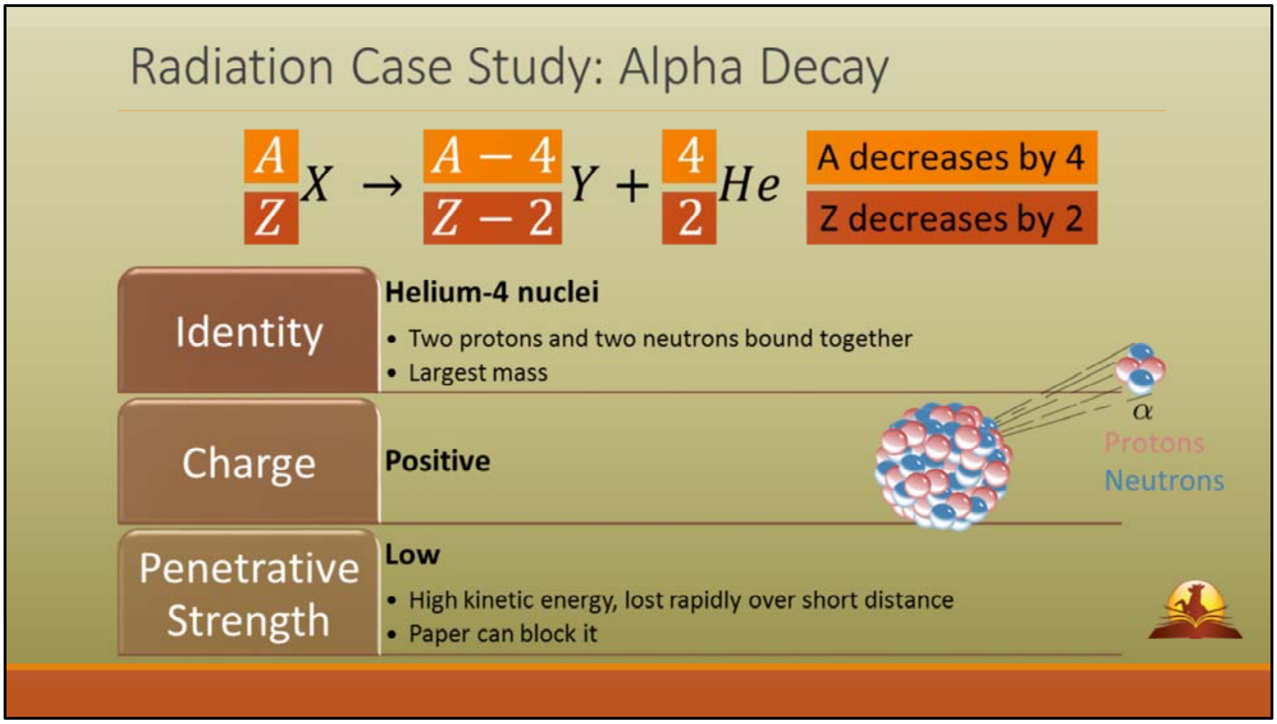
Nuclear reactions show the **transformation** of nuclei

$$^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}.$$

Parent nucleus

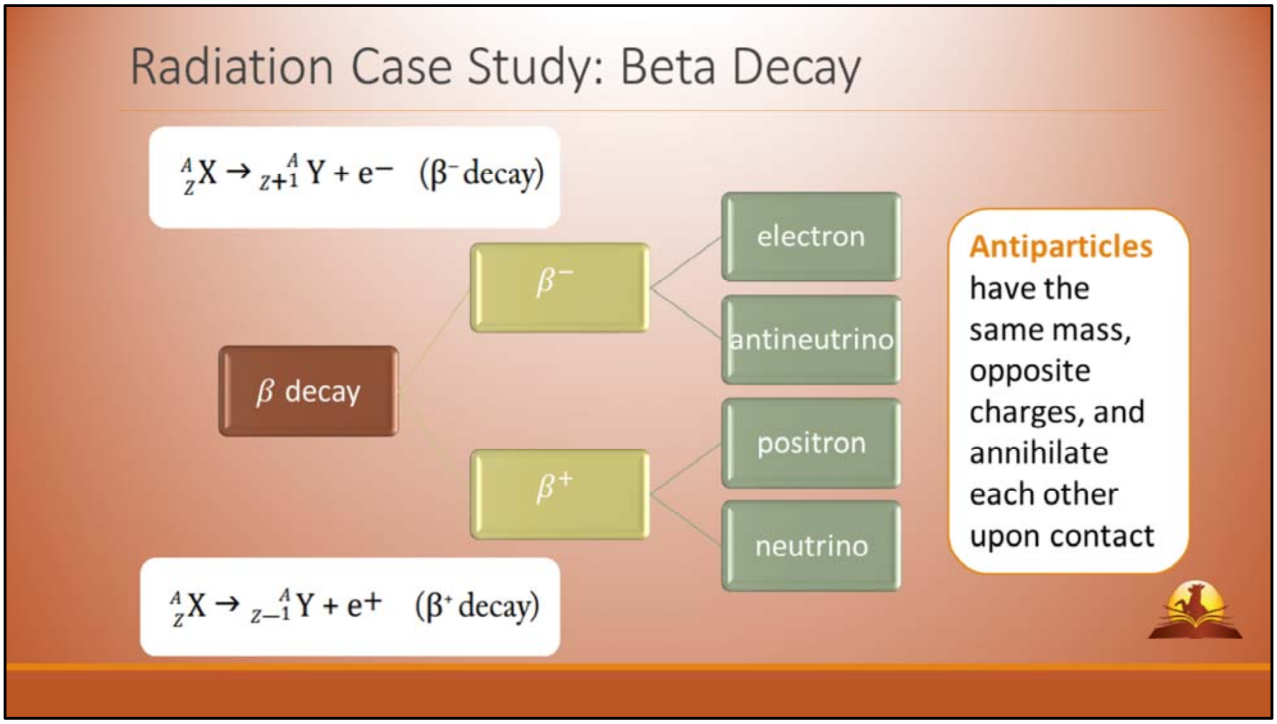
Daughter nucleus

- Equal atomic numbers
  - Equal atomic mass

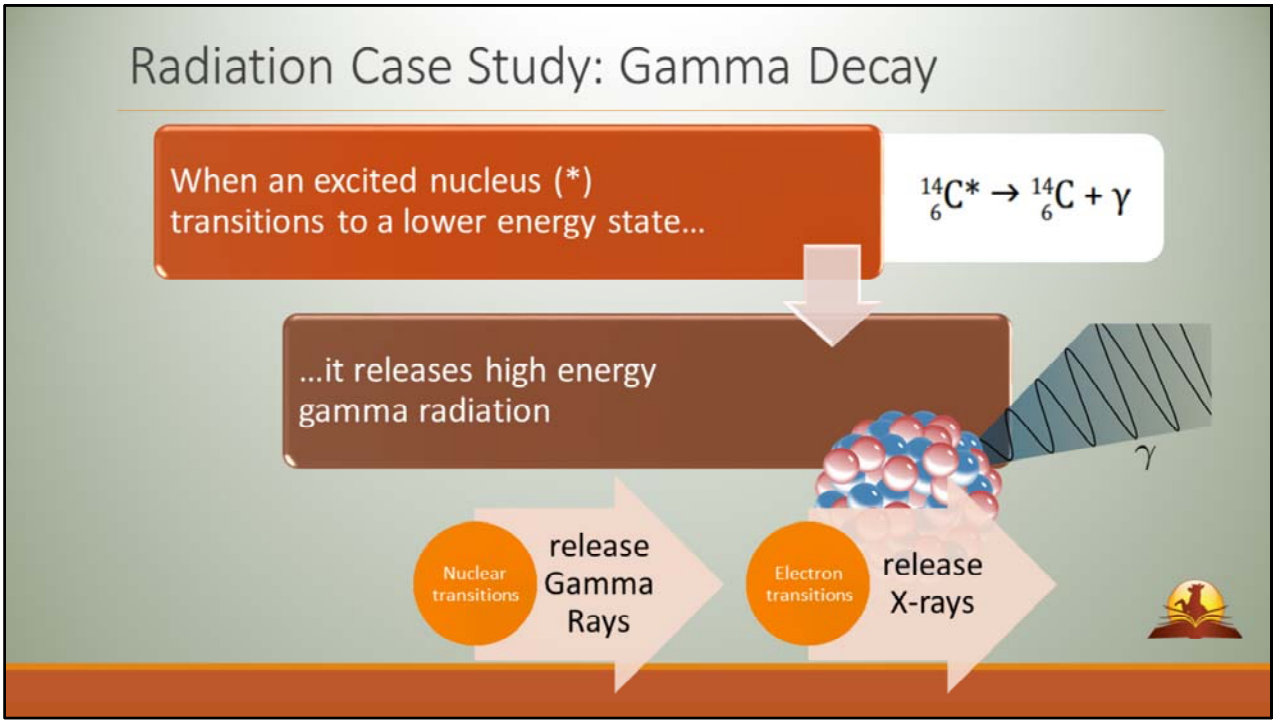


- **Alpha decay** is most common among **heavier atoms.**
  - Tellurium (Z=52) is the lightest element that undergoes alpha decay.
- Why alpha decay instead of releasing individual protons and neutrons?
  - **High binding energy** of alpha particle makes it **less massive than its individual parts.**
  - Most of the binding energy of the alpha particle is carried away by **kinetic energy,** which explains why alpha particle emission is so **fast** (5% the speed of light!).
    - **Large mass** is the reason it **loses its energy** over a **short distance.**

Credit: "Alpha decay" By Inductiveload [Public domain], via Wikimedia Commons, https://commons.wikimedia.org/wiki/File%3AAlpha_Decay.svg

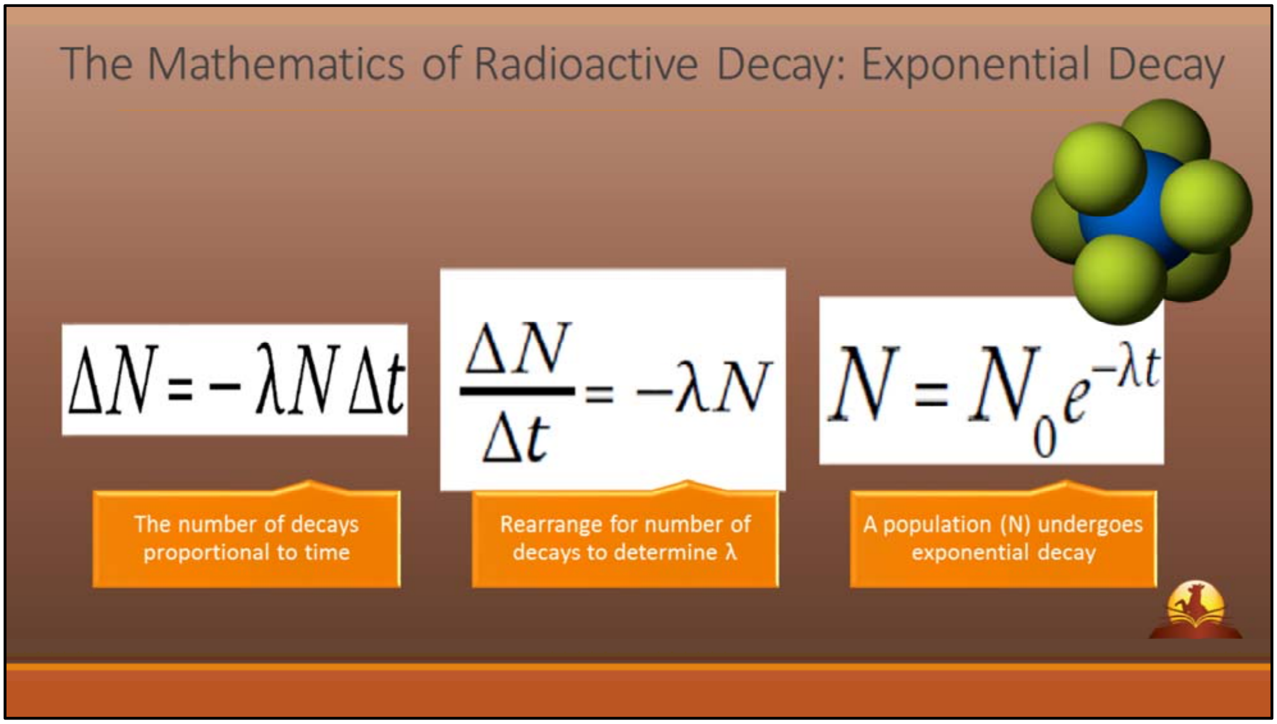


- In **beta decay**, A does not change but Z increases or decreases by 1 to maintain charge.
  - There are two types of beta decay:
    - **Beta-minus decay** results in the emission of an **electron and antineutrino.**
    - **Beta-plus decay** results in the emission of a **positron and neutrino.**
- Electrons and positrons are known as **anti-particles.** Neutrinos and antineutrinos also function as anti-particles.
- The electrons emitted during beta-minus decay come from the nucleus.
  - An electron is created in the nucleus when a neutron is converted into a proton.
- Positrons have extremely short lifetimes because they are annihilated upon contact with electrons.
- The neutrino's existence was hypothesized to explain discrepancies in energy and momentum during beta decay.
- Enrico Fermi's neutrino: **"little neutral one"**
  - No charge
  - Small mass
  - ½ spin (fermion)
  - Weak interaction with matter



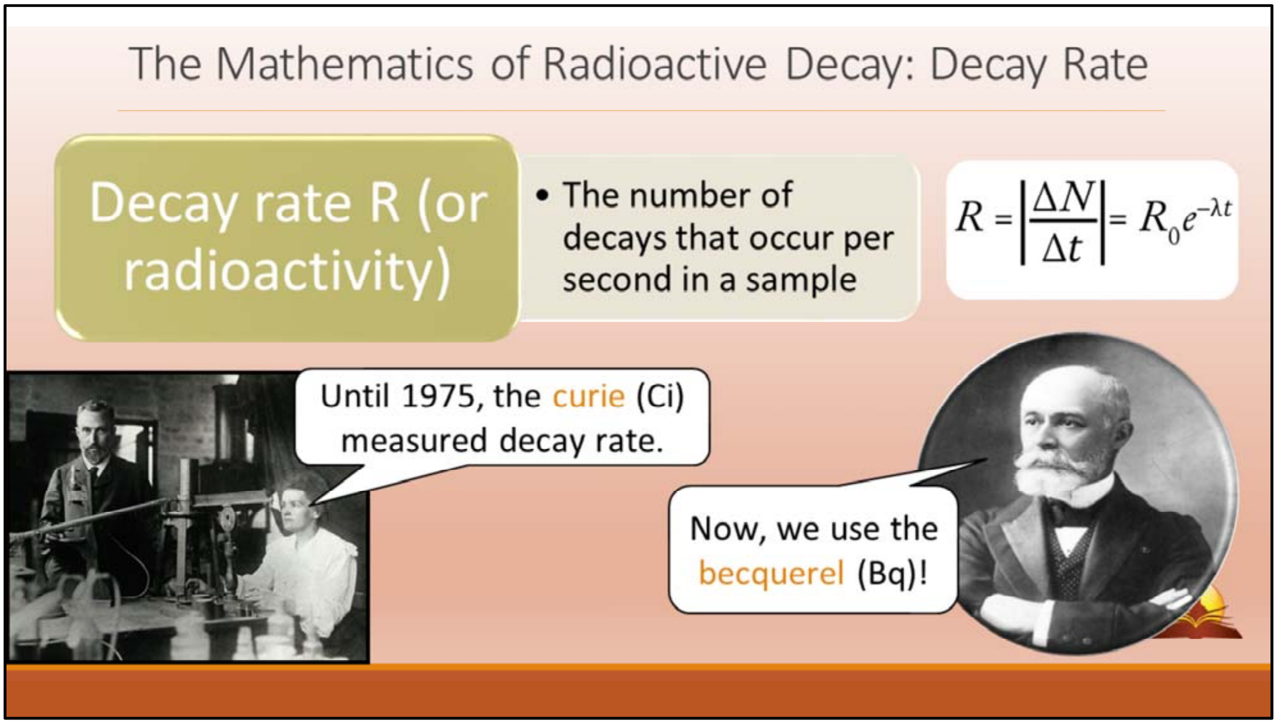
- Nuclei are excited when they…
  - …collide with another particle.
  - …have just undergone alpha or beta decay.
- The transition between an excited nucleus (*) to a lower energy state releases high energy **gamma radiation.**
- **Gamma Rays**
  - Higher energy radiation
  - Released from nuclear transitions
- **X-rays**
  - Lower energy radiation (but still high)
  - Released from electron transitions

Credit: "Gamma decay" By Inductiveload [Public domain], via Wikimedia Commons, https://commons.wikimedia.org/wiki/File%3AGamma_Decay.svg



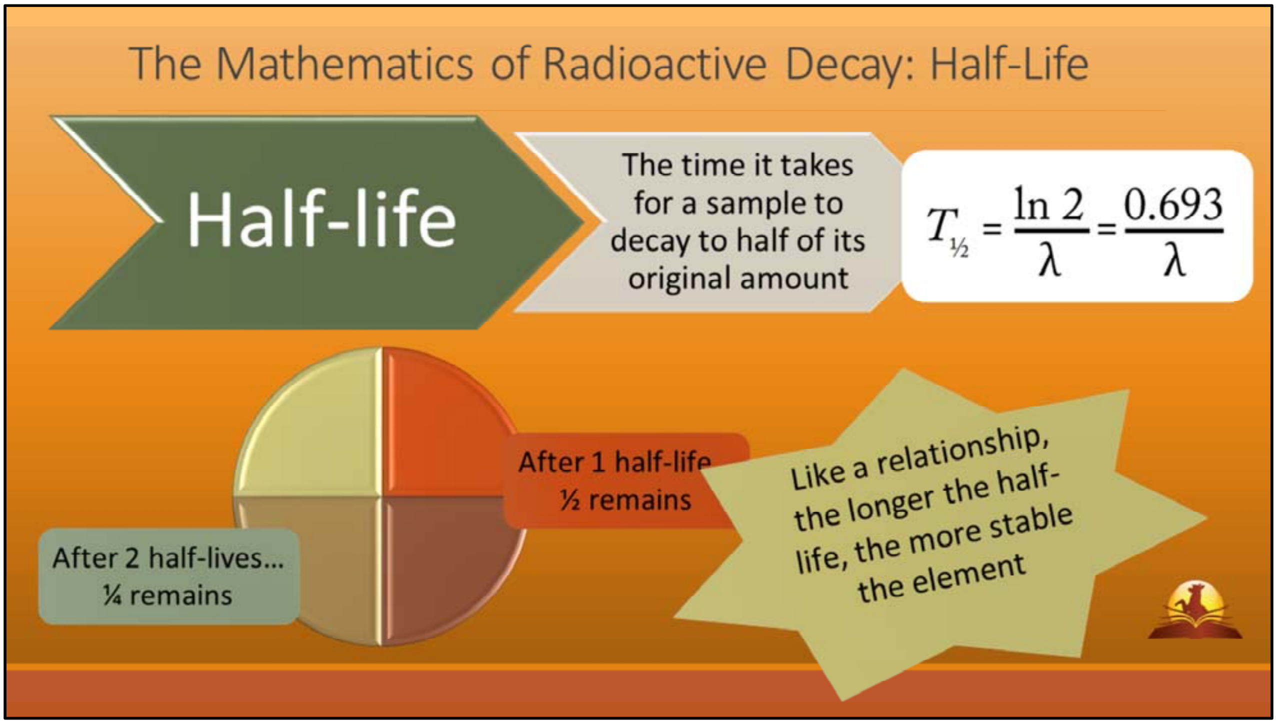
- **Radioactive decay** takes place randomly.
  - It is impossible to determine the actual rate of decay, but it is possible to probabilistically describe the nuclei in a sample after a given time period.
- The number of decays (ΔN) that occurs in a radioactive sample over a given time period (Δt) is proportional to Δt and *N* (the number of remaining parent nuclei).
- λ, the **decay constant**, is the characteristic of a given isotope.
- A population that follows the rate relationship goes under **exponential decay.**
  - *N* refers to the number of parent nuclei remaining at time *t*, and N_0 is the number at *t* 0.
- Decay refers to both the decreasing size of the population of a parent atom as well as a process that changes the characteristic and behavior of atomic nuclei.

Credits: "Uranium hexafluoride" by Ivanlul (Own work) [Public domain], via Wikimedia Commons



- The **decay rate** or **radioactivity** refers to the amount of decays that occur per second in a radioactive sample.
  - It is defined by the equation R = $|\Delta N/\Delta t| = R_o e^{-\lambda t}$ where R is radioactivity, R_o is the initial decay rate at t=0, λ is the decay constant, and t is time.
- The standard unit of decay rate, up until 1975, was the **curie (Ci)**, named after the scientists Pierre and Marie Curie.
  - 1 Ci = 3.7 x 10^{10} decay/s
- The standard unit today is the **becquerel (Bq)**, named after Henri Becquerel.
  - 1 Bq = 1 decay/s
  - Some scientists continue to use millicuries or microcuries as measurements today.

Credit: “Pierre and Marie Curie” by See page for author [Public domain], via Wikimedia Commons; https://commons.wikimedia.org/wiki/File%3APierre_and_Marie_Curie.jpg
Credit: “Henri Becquerel” by Library of Congress, Public Domain, https://commons.wikimedia.org/w/index.php?curid=6776646

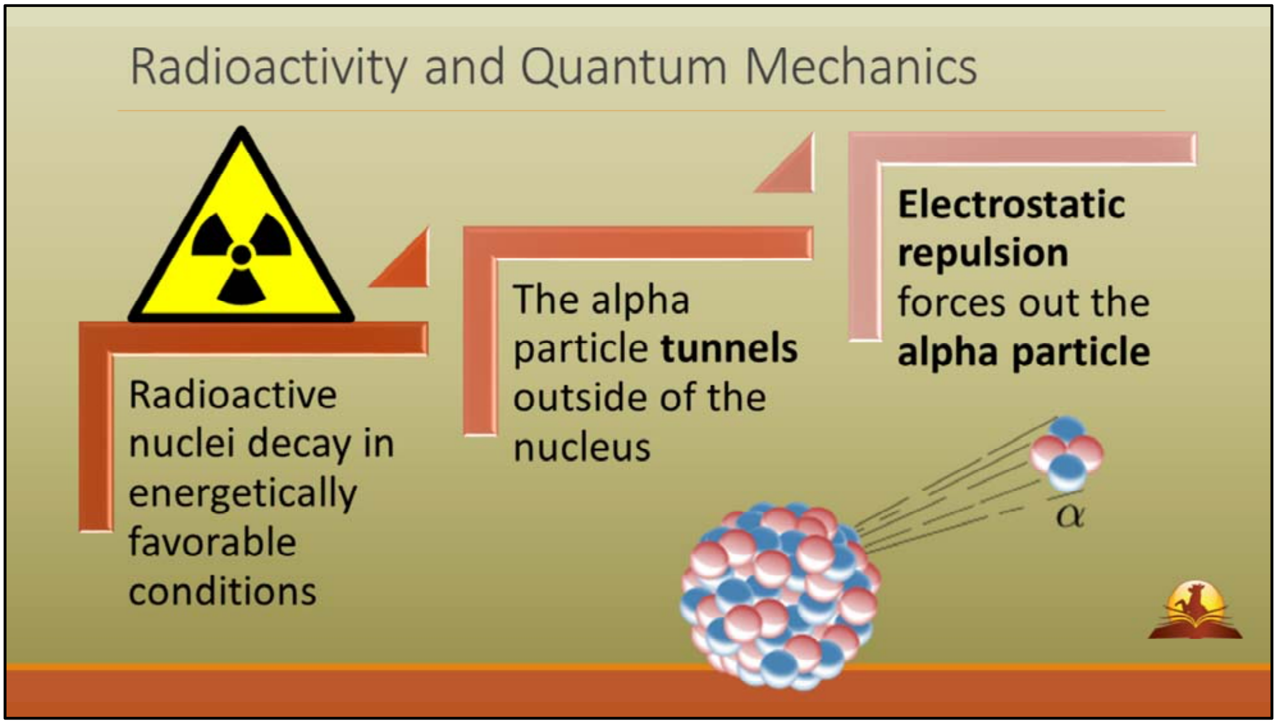


• The decay rate of an isotope is commonly described by its **half-life**, which is the time it takes for a given sample to decay to half of its original amount.

- In other words, given a sample of nuclei:
  - after 1 half-life, 50% of the nuclei remains
  - after 2 half-lives, 25% of the nuclei remains
  - after 3 half-lives, 12.5% of the nuclei remains
  - and so on…

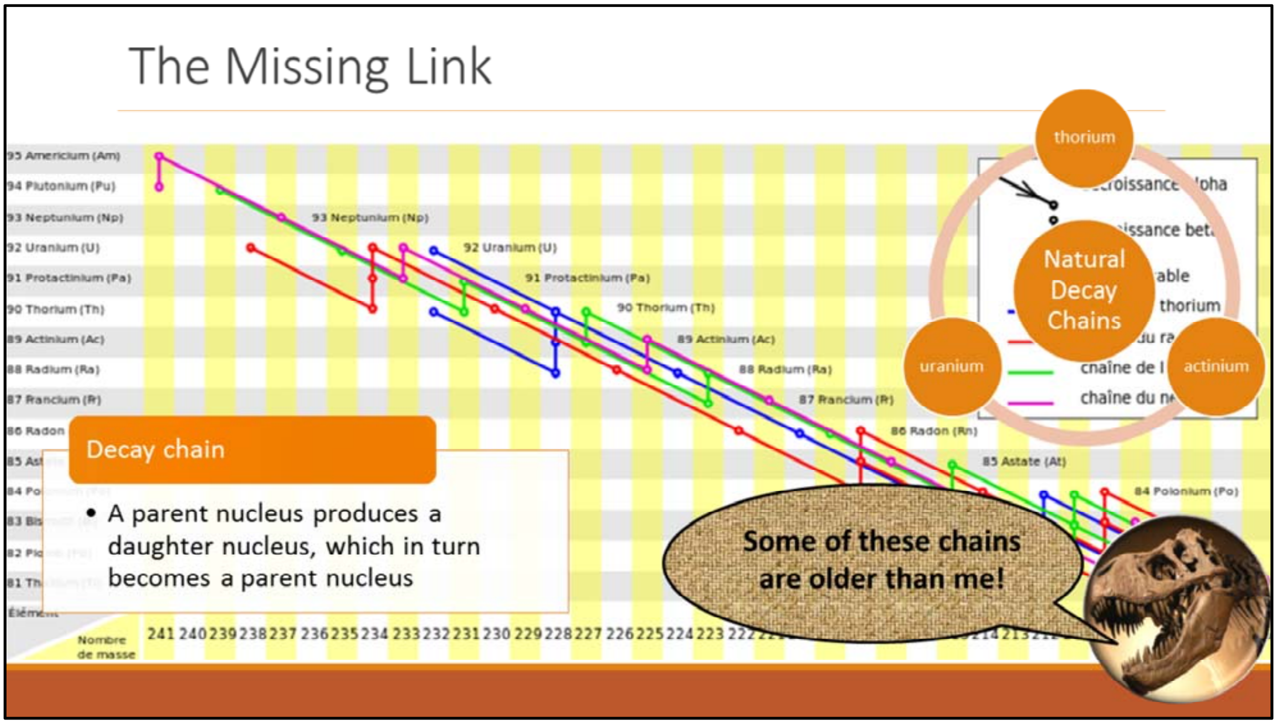
•Half-lives range from extremely small values to extremely large values.

- i.e. The half-life of ^{4}H is ~10^{-22} seconds while the half-life of ^{128}Te is ~10^{24} years
- Longer half-lives usually mean that the isotope has more stability.



- **Radioactive nuclei** undergo spontaneous decay if a process is **energetically favorable.**
  - It is necessary for the total mass of the particles post-decay to be less than the mass of the particle prior to decay.
- **Quantum mechanical principles** explain why it takes so long for decay to occur.
  - An **alpha particle** has a wave function for its position.
  - The **Coulomb force** and **nuclear force** prevent the particle from leaving the nucleus.
  - Part of the **alpha particle's** wave function strays from the nucleus, and as a result there is a chance that the particle will **tunnel** outside of the nucleus. Outside the range of the nuclear force, the particle would then be propelled outward as a result of **electrostatic repulsion**.
- The likelihood of **tunneling** depends on the height and width of the **potential barrier.**
  - The height and width is determined by the charge of the nucleus and its shape.
  - The greater the probability of tunneling, the shorter the half-life.

Credit: "Alpha Decay" by Inductiveload [Public domain], via Wikimedia Commons
Credit: "Radioactive Symbol" by Yann (fr:Image:Radioactivité.png) [Public domain], via Wikimedia Commons



•Some nuclei decay in a chain, in which the daughter nuclei becomes the parent nuclei of the next link in the chain.

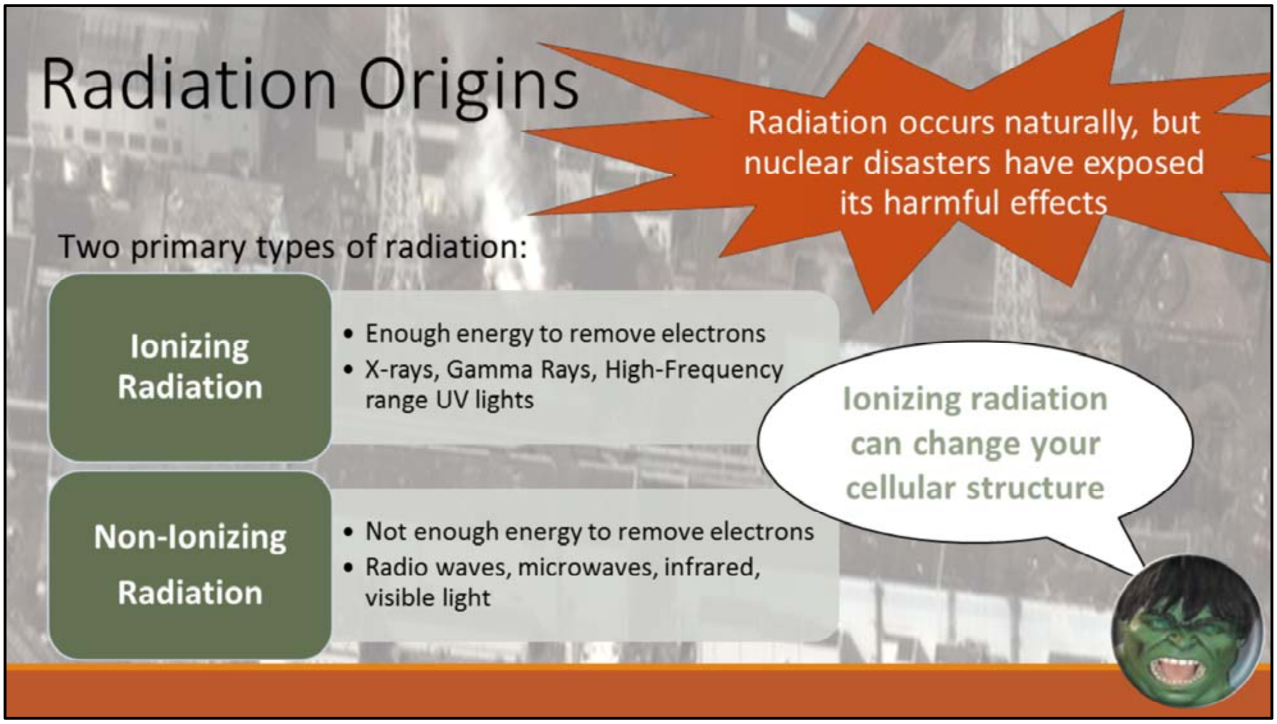
•Each decay in the **decay chain** has its own half-life.

•The naturally occurring chains are **thorium, uranium, and actinium.**

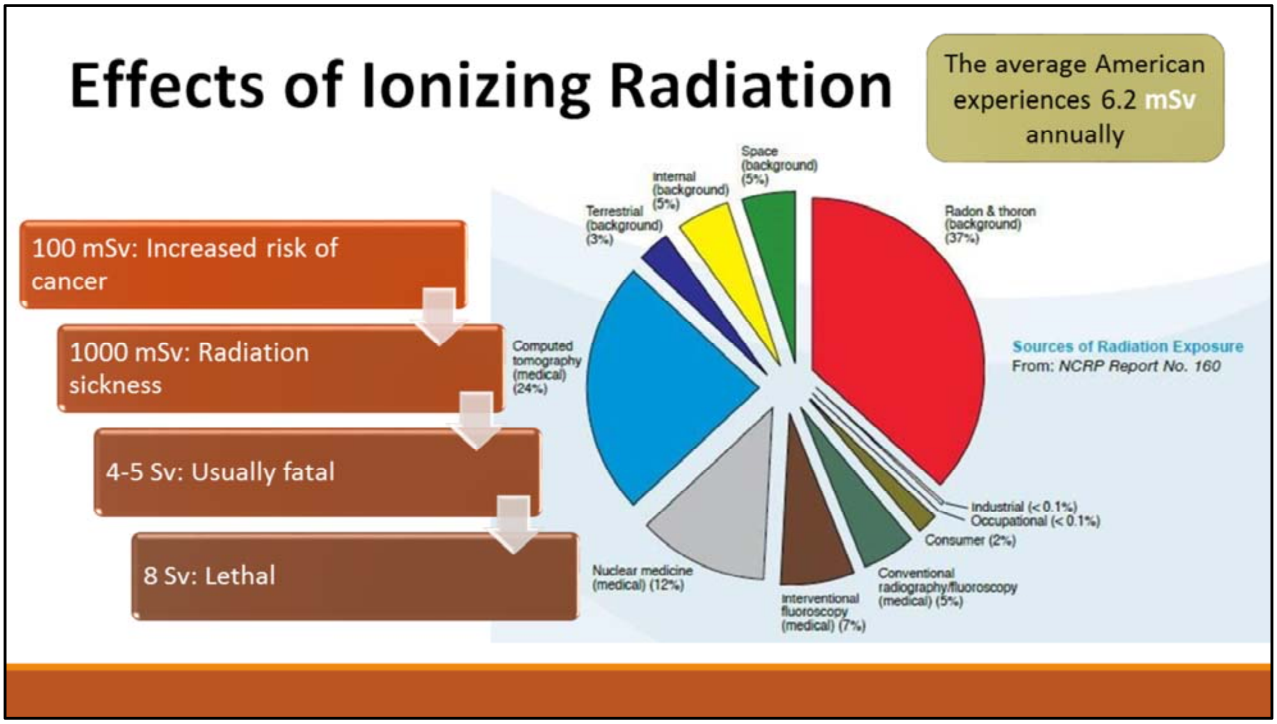
•The chain can split towards the end, because decay can occur differently

•Isotopes with a relatively short half-life can be part of a much longer chain, and these isotopes are “replenished” over time.

Credit: “Palais de la Decouverte Tyrannosaurus Rex“ by Copyright © 2005 David Monniaux (Own work) [GFDL (http://www.gnu.org/copyleft/fdl.html) or CC-BY-SA-3.0 (http://creativecommons.org/licenses/by-sa/3.0/)], via Wikimedia Commons
Credit: “Radioactive decay chains diagram” by User:Johantheghost [CC BY-SA 3.0 (http://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons



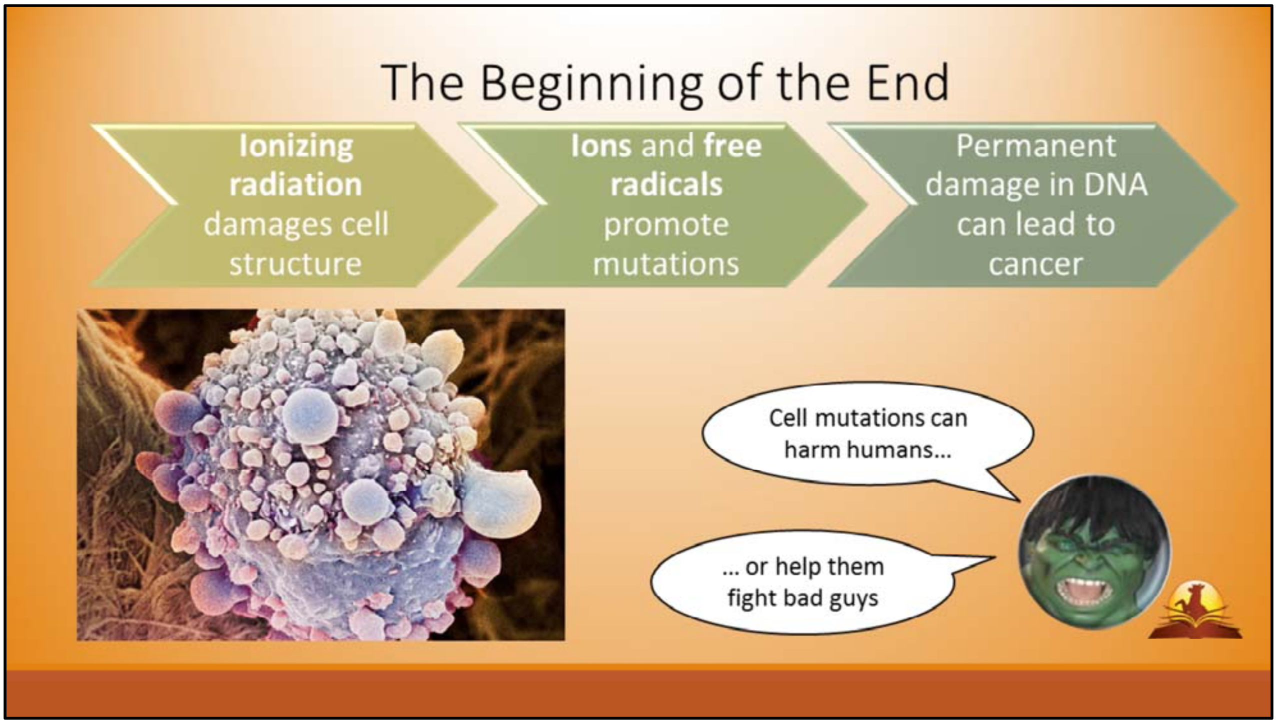
- The **Fukushima nuclear disaster** was the largest nuclear disaster since **Chernobyl.**
  - The disaster required the evacuation of over half a million people from the area.
- Radiation attracts significant negative attention in the media, however, not all radiation is harmful.
- Radiation has been naturally occurring since the dawn of time.
- Radiation can be either **ionizing** or **non-ionizing.**
  - Ionization energy varies between different atoms and molecules. Radiation is generally considered ionizing if it has more photon energy than 10-33 eV.
  - **Ionizing radiation** includes X-rays, gamma rays, and high-frequency range UV lights.
  - **Non-Ionizing radiation** includes radio waves, microwaves, infrared, and visible light.



- Radiation can kill humans.
- We measure ionizing radiation using sieverts (Sv).
  - It is 1 joule of energy into 1 kg of absorbing material.
- Small amounts of sieverts can be absorbed by the human body with few risks
- In the United States the average person takes in 6.2 mSv a year, half from natural sources and half from artificial ones
  - Very little of this radiation exposure stems from industrial sources.
  - Radon is the largest natural source of background radiation.
    - Radon is usually a heavy gas, and is sometimes found in homes. People can use kits to detect it.
- Cosmic rays contain high energy radiation.
  - The atmosphere shields us from most of these rays.
  - The higher above sea level, the greater the exposure to cosmic rays.

- In the United States, rem is also used to measure radiation (100 rems = 1 Sv).

Credit: https: “Pie chart”, https://www.epa.gov/radiation



•Cells are carefully structured.
- •**Ionizing radiation** damages their structure by stripping away electrons.
- •By creating **ions** and **free radicals** in organisms the radiation can spur mutations.

•**Ionizing radiation** can lead to permanent damage in DNA.
- •This exposure can result in cancer.
- •**Gamma rays** are the most damaging to living organisms, because they penetrate most .
- •**Alpha rays** are the second most damaging, and can cause internal damage.

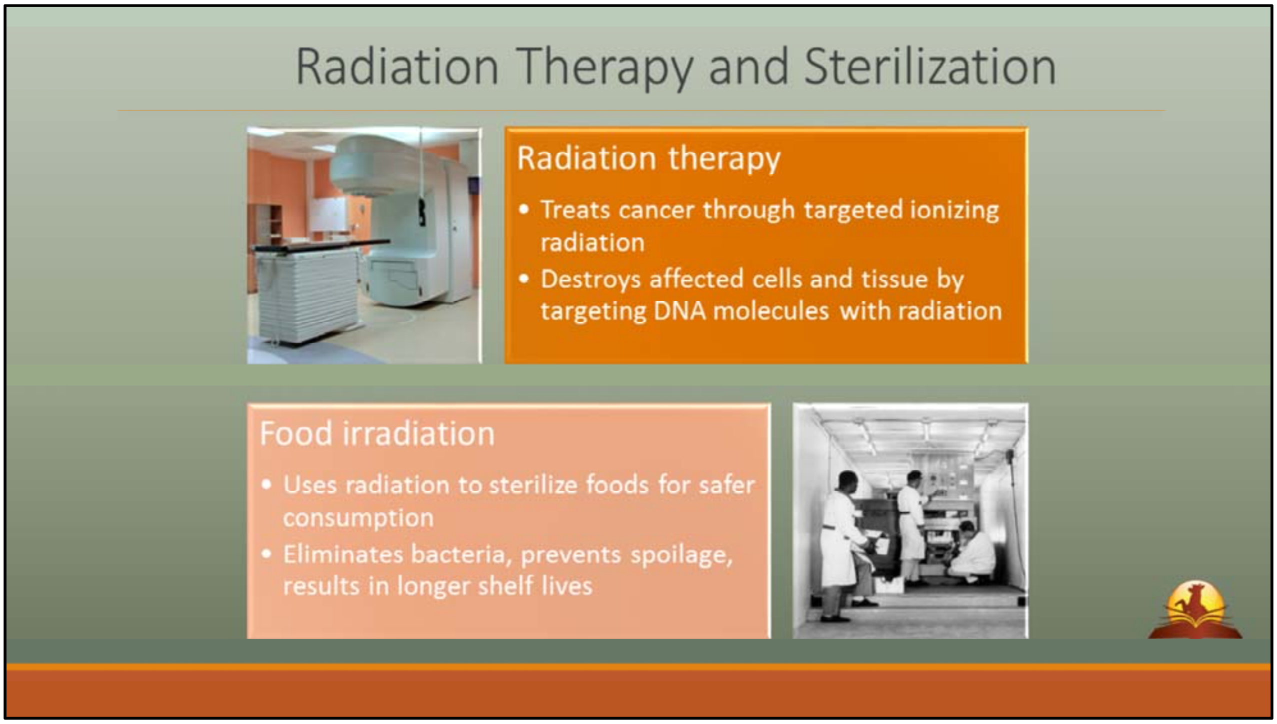
Image: a cancerous pancreatic cell

Four ways of detecting radiation:

- Geiger Counter
  - Low pressure tube filled with inert gas surrounding a positively charged wire.
  - Electrons are knocked loose by high-energy particles upon exposure to radiation.
    - Electrons then move to the wire through attraction and, as a result, trigger an electric pulse that leads a click in the counter.
  - Geiger counters are usually optimized for handheld use.
- Scintillation Counter
  - Similar to a Geiger Counter, it provides a electric pulse when radiation is detected.
  - It relies on a scintillating material, such as NaI crystal.
    - Scintillating material is easily excited by incident radiation, which leads to emission of photons. Photons can then be captured for the pulse effect.
- Cloud Chamber
  - A sealed chamber filled with water or alcohol vapor
    - Radiation passing through leaves a trail of ions.
    - Vapor is cooled leaving cloud-like trails that make the radiation visible.
- Bubble Chamber
  - Invented by American physicist Donald Glaser in 1952

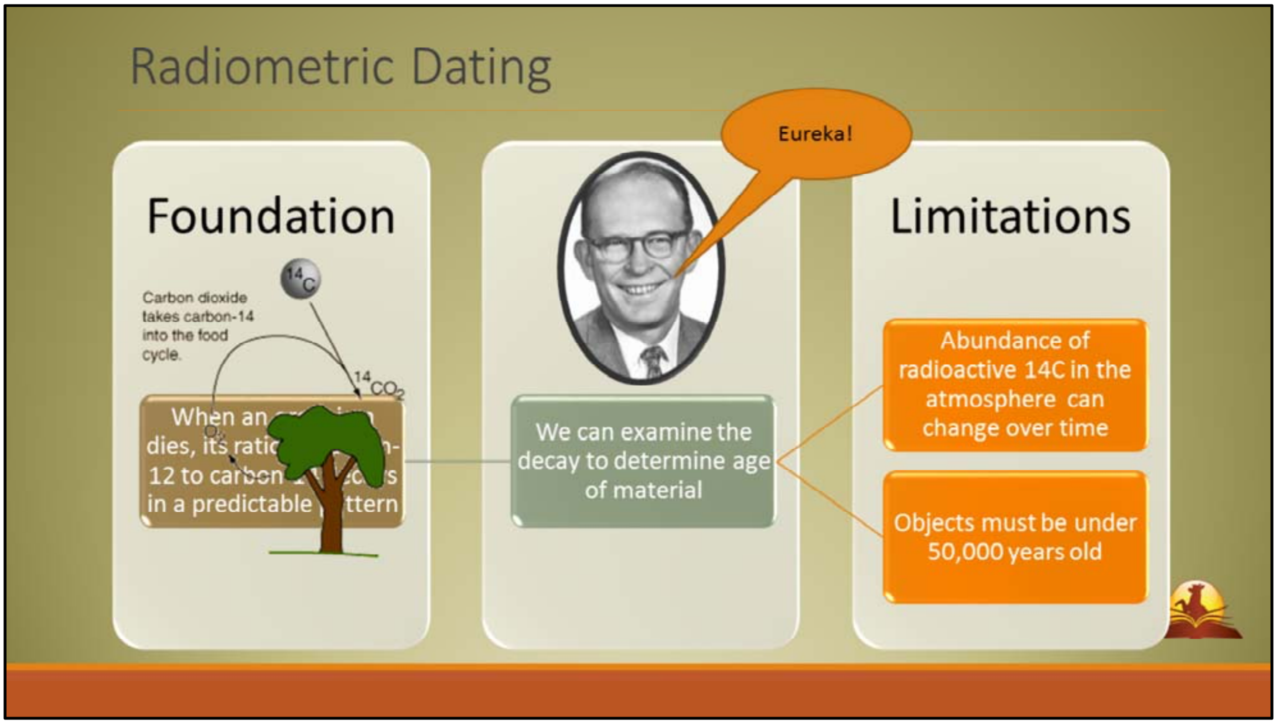
- Contains liquid H heated to just below boiling
- Pressure suddenly drops when a particle enters, and bubbles form behind the particle, then cameras capture the particle trail.

Credit: “Geiger Counter” By real name: Matylda Sęk pl.wiki: Cygaretka commons: Cygaretka (Own work) [GFDL (http://www.gnu.org/copyleft/fdl.html) or CC BY-SA 3.0 (http://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons
Credit: “Scintillation Counter” By Linda Bartlett, National Cancer Institute (source exact image source) [Public domain or Public domain], via Wikimedia Commons
Credit: “Cloud Chamber” By Cloudylabs (Own work) [CC BY-SA 3.0 (http://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons
Credit: “Bubble Chamber” By Mark Williamson (Own work) [GFDL (http://www.gnu.org/copyleft/fdl.html) or CC BY-SA 4.0-3.0-2.5-2.0-1.0 (http://creativecommons.org/licenses/by-sa/4.0-3.0-2.5-2.0-1.0)], via Wikimedia Commons



- **Radiation therapy** harnesses the power of radiation for the treatment of cancer.
  - It kills cancerous cells by targeting the affected cells' DNA.
    - This method faces the challenge of having to single out affected cells.
      - Techniques like aiming low-intensity beams at multiple angles have been developed to counteract this challenge.
    - Gamma radiation is the most common form of radiation used, though beta radiation is used to treat skin cancer and tumors that are closer to the surface.
- **Food irradiation** is the sterilization of food through radiation.
  - Small doses of gamma rays from radioactive cobalt-60 can be used to kill unwanted inhabitants (like insects, microbes, and parasites) without affecting the quality of food.
  - This method can affect the taste of the food, but it does not make the food radioactive.
    - This method is approved by U.S. Food and Drug Administration.

Credit: "Radiation Therapy" By Ntligent (Own work) [CC BY-SA 3.0 (http://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons
Credit: "Food Irradiation" By ENERGY.GOV - HD.6B.452, Public Domain, https://commons.wikimedia.org/w/index.php?curid=35935165



•**Radiometric dating**, or **radioactive dating**, refers to the technique of determining the age of a certain material from its decay.

- •The most common form is carbon dating.
  - •Three naturally occurring isotopes of carbon exist: carbon-12, carbon-13, and carbon-14 (unstable).
    - •Carbon-14 undergoes beta decay to become nitrogen-14.
  - • Living organisms maintain a constant ratio of carbon-14 to carbon-12 through respiration, as carbon dioxide is exhaled in the process.
    - •Upon death, this ratio decreases due to radioactive decay of the carbon-14, and the ratio can then be examined to determine age.
  - •American physical chemist Willard Libby developed this technique in the 1940s, winning a Nobel Prize in Chemistry for his discovery in 1960.
  - •Some limitations to this technique exist:
    - •Changes in the abundance of carbon-14 in the atmosphere over time can limit the accuracy of carbon dating.
      - •Fluctuations in the magnetic fields of the Earth and sun are the main cause of changes in the amount of carbon-14.
    - •The half-life of carbon-14 (5,730 years) is another limitation.
      - •This technique is thus limited to objects that are under 50,000 years old.

- Isotopes with longer half-lives, like uranium, can be used to date rocks and other geological features.

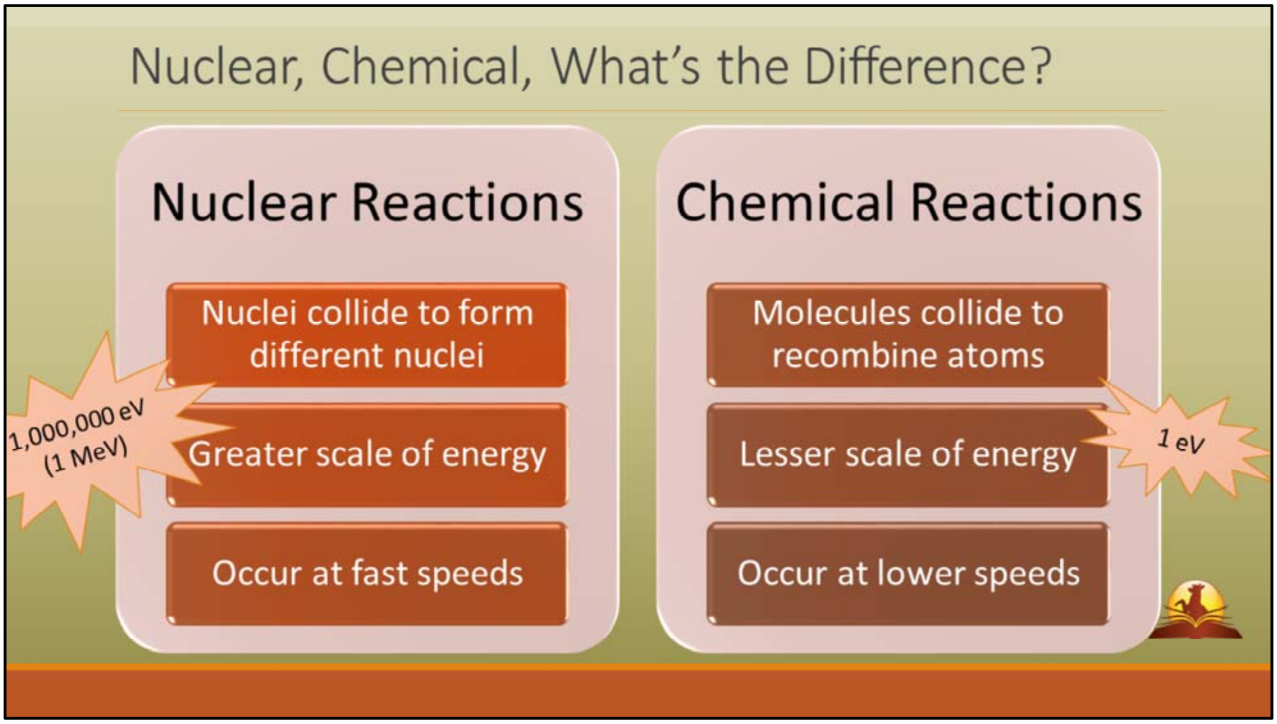
Credit: “Carbon Cycle” at http://hyperphysics.phy-astr.gsu.edu/hbase/nuclear/imgnuc/cdate2.gif

- **Smoke detectors** are a common household item that is actually a source of radioactivity.
  - Trace amounts of amercium-237 is present in the device (~ 1 microgram; which is not enough to have harmful effects).
  - The americium-237 undergoes alpha decay to become neputunium-237.
  - When smoke enters the detector and absorbs alpha particles, the current flow is decreased and the alarm is triggered.
  - Alpha particles create a weak current.
- **Radioactive tracers** are used in the analysis of chemical interactions in reactions or flow in a system.
  - Medicine:
    - Radioactive iodine is utilized to create a tracer (^{127}I is made into ^{131}I) for a patient to ingest. The buildup of iodine is measured to analyze thyroid function.
    - Tracers can be used to assess location of hemorrhages or tumors as well.
  - Agriculture
    - Tracers used in fertilizers can study how various nutrients affect plants.
  - Automobiles
    - Tracers can study the wear of pistons and other parts of the engine with radioactive material.

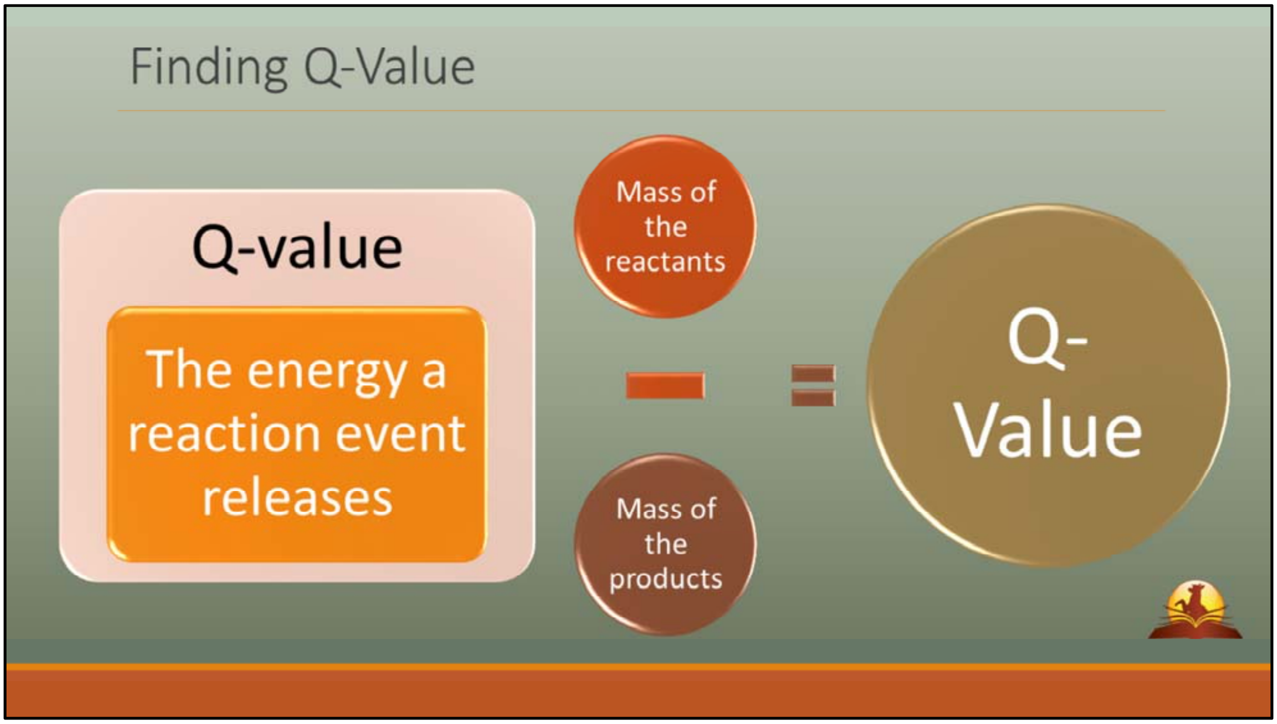
    <u>Enrichment fact</u>: When radiation was first discovered, it was considered a panacea for many illnesses.

Credit: "Smoke Detector" By Tumi-1983 (Own work) [GFDL (http://www.gnu.org/copyleft/fdl.html) or CC BY-SA 3.0 (http://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons
Credit: "Use of Radioactive Tracer on Brain" at https://www.sciencenews.org/sites/default/files/main/articles/notebook_50yrs_petscan.jpg

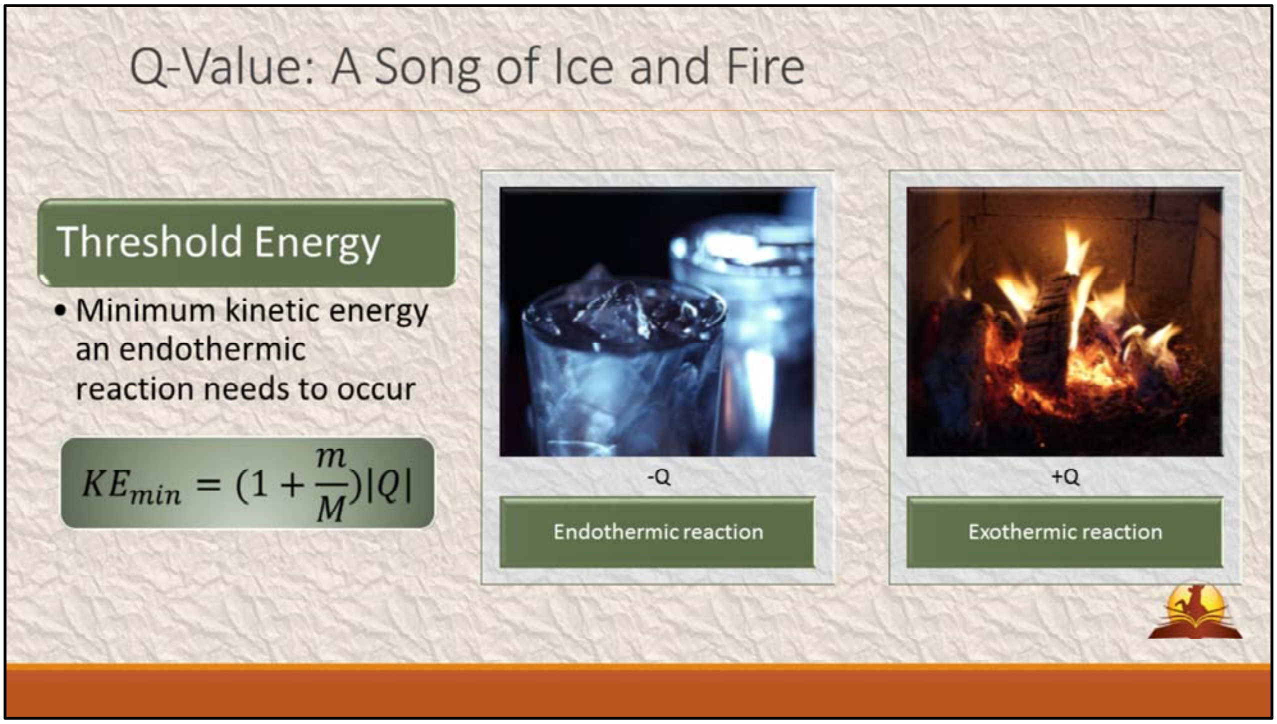
This section covers nuclear fission and fusion and how it affected the 20th century and beyond.



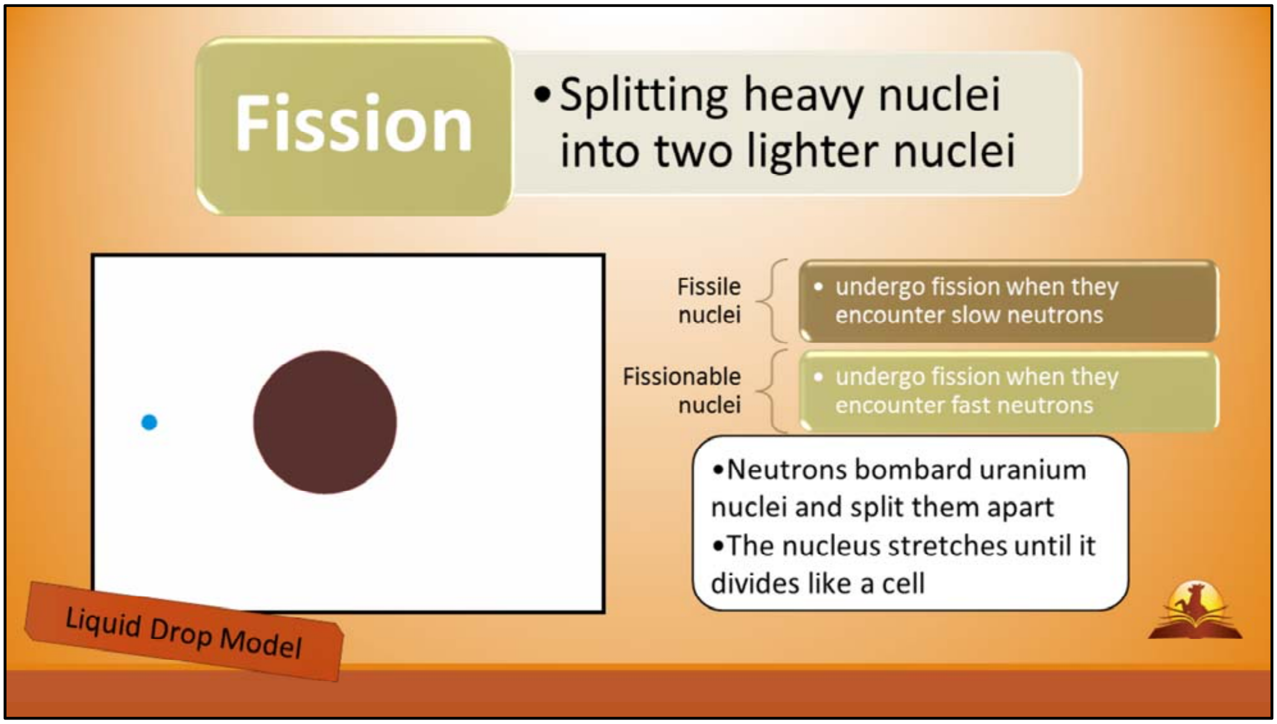
Credit: “Benzoic acid reaction” By Krishnavedala (Own work) [Public domain], via Wikimedia Commons, https://commons.wikimedia.org/wiki/File%3ABenzoic_acid-chemical-reaction-1.svg
Credit: “Voltmeter” By No machine-readable author provided. Journey234 assumed (based on copyright claims). [CC0], via Wikimedia Commons, https://commons.wikimedia.org/wiki/File%3AHelios_Voltmeter.jpg
Credit: “Particle Accelerator” By David Monniaux (Own work) [GFDL (http://www.gnu.org/copyleft/fdl.html) or CC-BY-SA-3.0 (http://creativecommons.org/licenses/by-sa/3.0/)], via Wikimedia Commons, https://commons.wikimedia.org/wiki/File%3AParticle_accelerator_DSC09089.JPG
Credit: “Chemical reaction in flask” By Mfomich (Own work) [CC BY-SA 3.0 (http://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons, https://commons.wikimedia.org/wiki/File%3AFinkelstein_Reaction_in_Flask.jpg



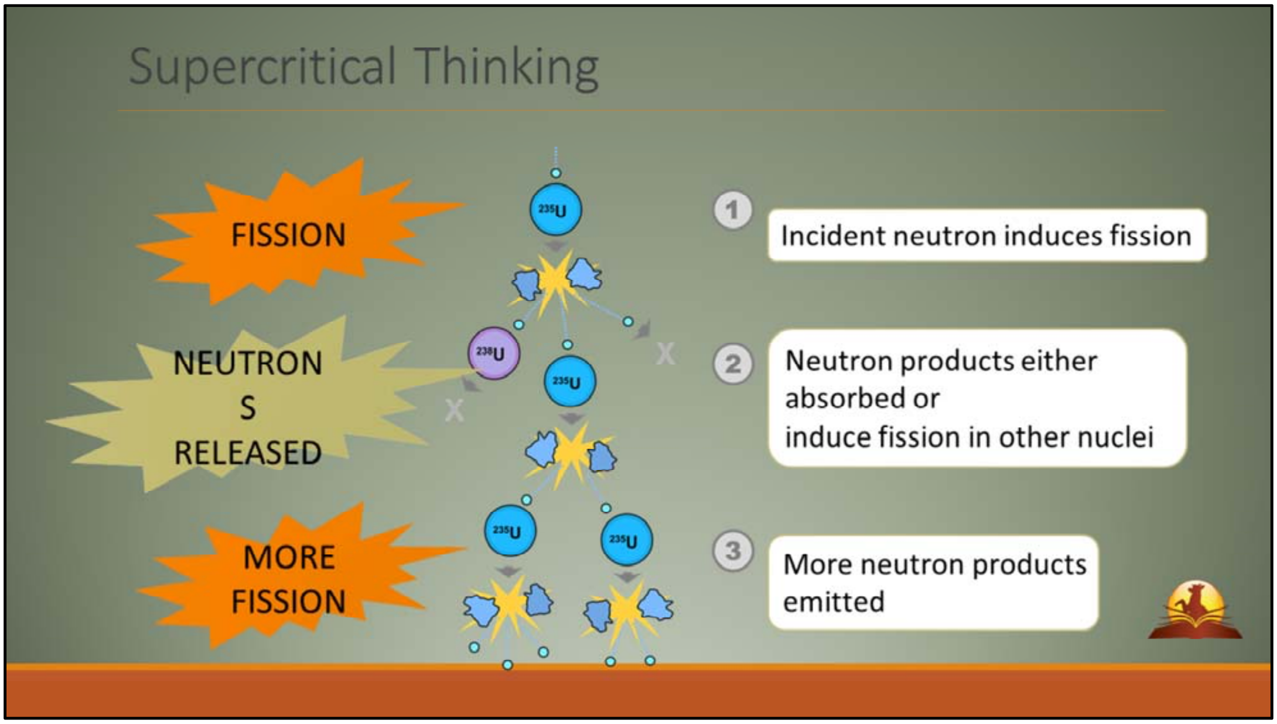
- Q-value represents the energy released by a reaction event.
- To calculate q-value, find the mass of the reactants and subtract the mass of the products.
    - m = mass of incoming nucleus
    - M = mass of stationary target nucleus



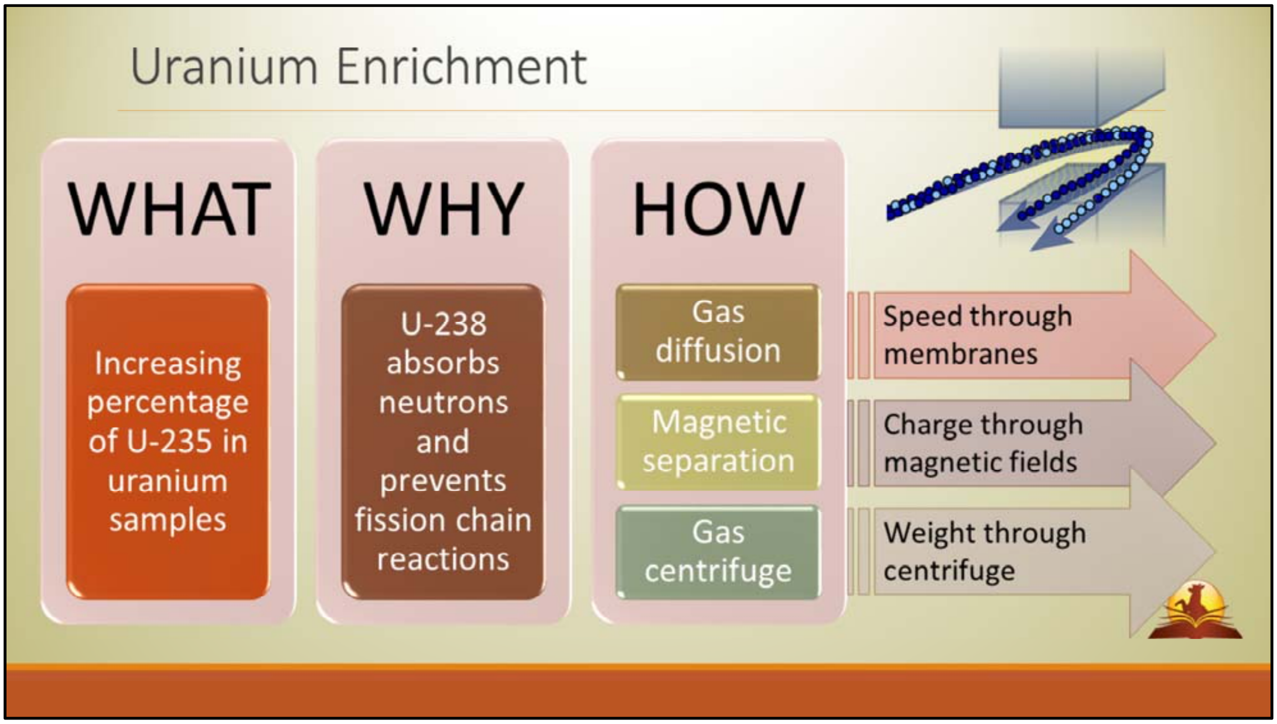
- **Threshold energy:** The minimum amount of kinetic energy an endothermic reaction needs in order to occur.
- +Q represents an exothermic reaction, or a release of energy. Fire is an example of an exothermic reaction.
- -Q represents an endothermic reaction, or an absorption of energy. Ice is an example of an endothermic reaction.



- **Fission** occurs when heavy nuclei split into lighter nuclei.
    - The resulting lighter nuclei are called **fission products.**
- Nuclei that undergo fission when they collide with slow neutrons are **fissile**.
- Nuclei that undergo fission when they collide with fast neutrons are **fissionable.**
- Nuclear reactions (including, but not restricted to, fission reactions) can be induced by bombarding nuclei with **alpha particles, protons, and neutrons.**
- **Otto Hanh** and **Fritz Strassman** observed uranium nuclei splitting into two when bombarded with neutrons (1938)**.**
    - **Lise Meitner** and **Otto Robert Frisch** explained this obvservation using the **liquid drop model*.***
        - They showed that nuclei can oscillate and stretch until they split apart, as shown.
- The fission process takes its name from the similar **fission of biological cells.**

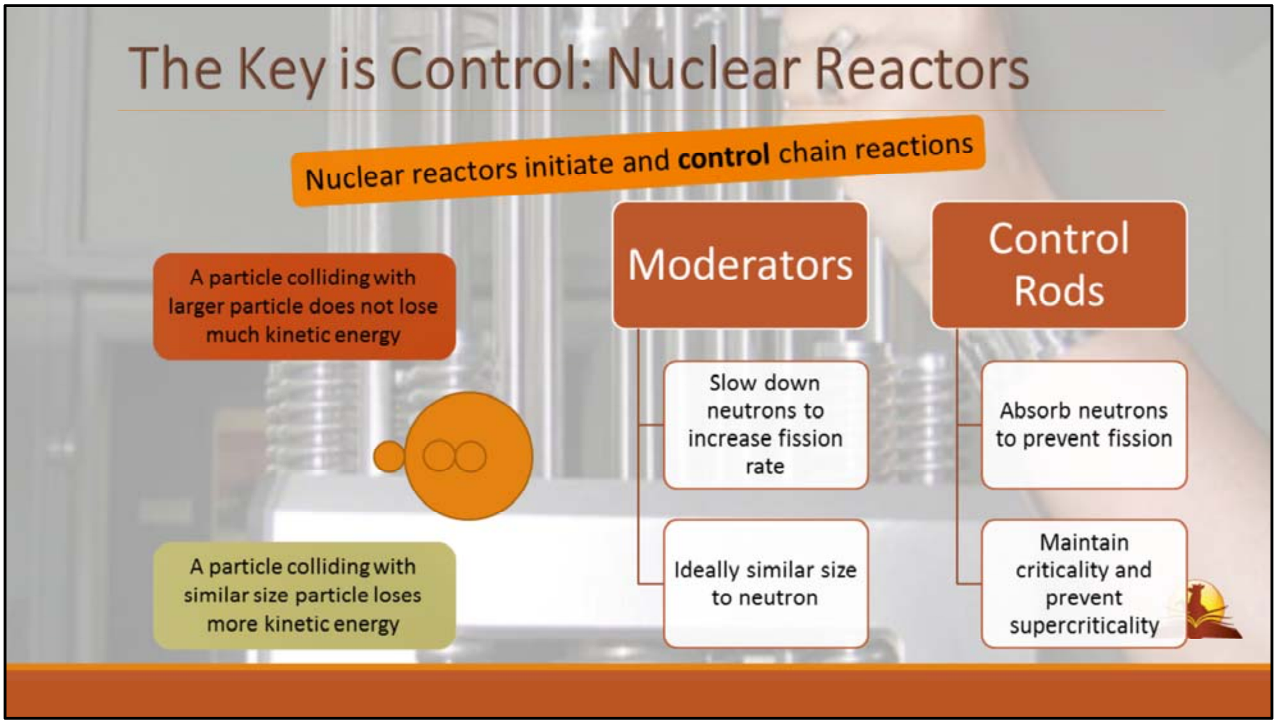


- **Subcritical** reactions are unsustainable because they will eventually die out as the number of fission events decrease.
- **Critical** reactions are sustainable and desired, because fission events are constant.
- **Supercritical** reactions are also unsustainable, because they can proceed out of control as fission events increase.
- The Effective Multiplication Factor (K) calculates the average number of neutrons that will trigger further fission events.
    - Subcritical (K<1)
    - Critical (K=1)
    - Supercritical (K>1)



- U-238 absorbs neutrons and **prevents chain reactions.**
  - Since U-235 has such low natural abundance, the percentage needs to be increased through enrichment in order for chain reactions to occur.
  - Natural uranium consists of 0.7% U-235 and 99.3% U-238.
- **Gas diffusion**
  - Gaseous UF_6 with lighter U-235 travels faster than U-238. Passing through thousands of semipermeable membranes separates the two by speed.
- **Magnetic separation**
  - U-235 and U-238 curve slightly differently in magnetic fields, which allows them to separate.
- **Gas centrifuge**
  - UF_6 with heavier U-238 separates outward when spun in a centrifuge.

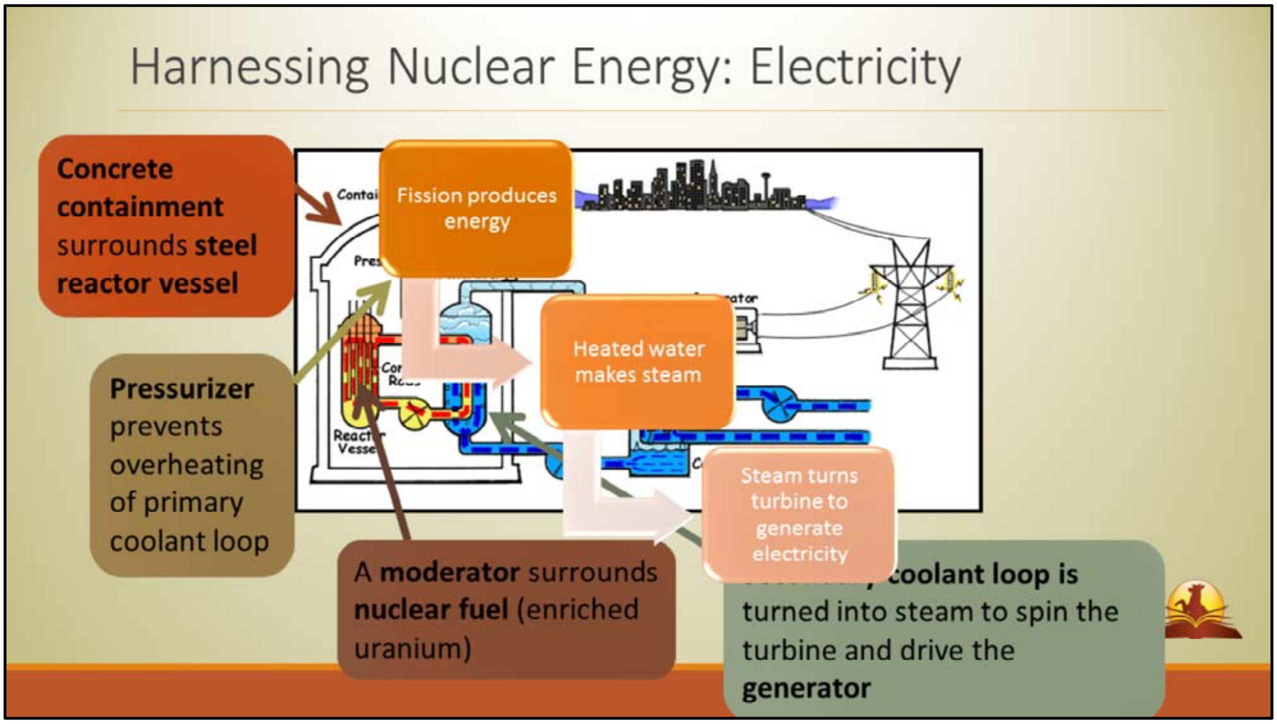
Credit: “Magnetic separation”
https://commons.wikimedia.org/wiki/File:Electromagnetic_separation.svg#filehistory



- In order for us to harness the incredible energy released from fission, we need to control its reaction rate using nuclear reactors.
  - Controlling fission rate requires a balance between increasing power from moderators and slowing power from control rods.
    - **Moderators** surround the nuclear fuel and slow down neutrons.
      - U-235 can undergo fission better with slow neutrons.
      - Like playing marbles, more kinetic energy is lost (and thus the particles move more slowly) when two similarly sized particles collide.
      - Heavy water works as a moderator because deuterium is a similar size to neutrons but doesn't absorb them.
      - Scientists also use graphite, although it is 12 times more massive, because 100 collisions is enough to sufficiently slow neutrons.
    - **Control rods** are inserted to slow fission rate and maintain criticality.
      - The control rods absorb neutrons to prevent them from causing more fission.
      - When a reactor first starts, control rods are not present. Scientists maintain supercriticality until they reach the desired power output, and then they insert the rods.

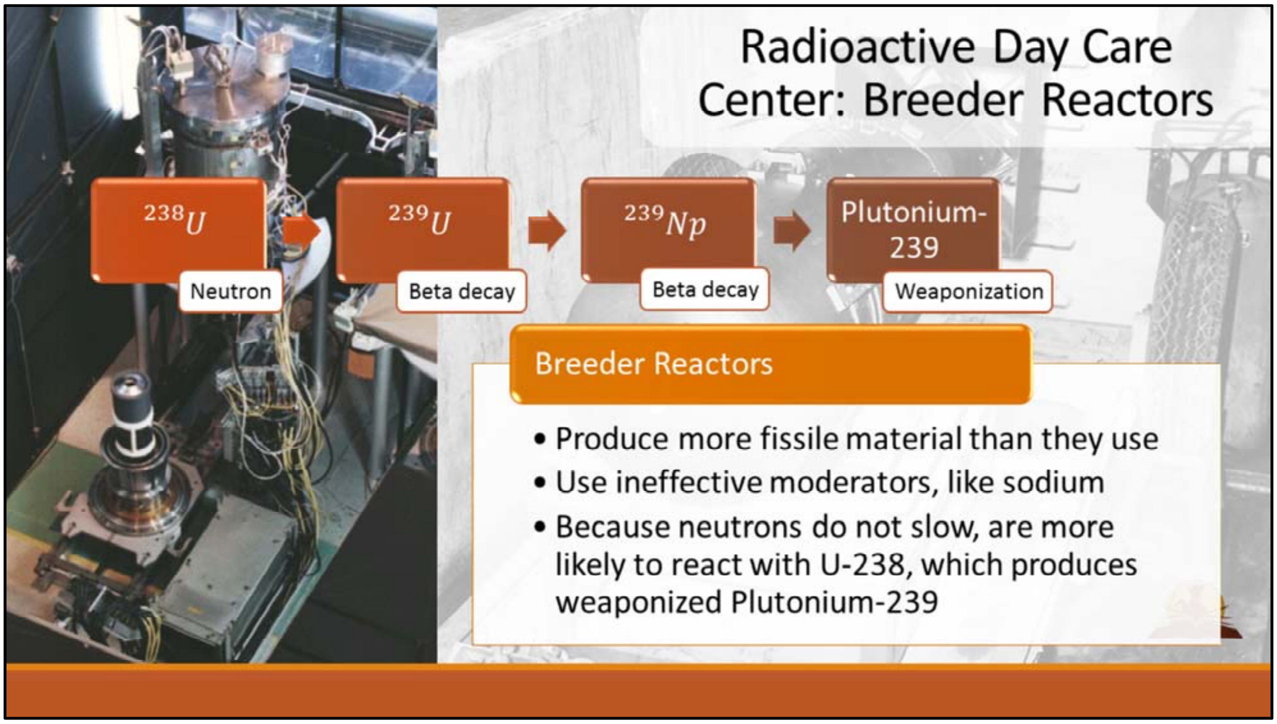
- The rods are made of boron.

Credit: “Control Rods” By Nic Ransby (http://en.wikipedia.org/wiki/Image:Controlrods.jpg) [Public domain], via Wikimedia Commons, https://commons.wikimedia.org/wiki/File%3APWR_control_rod_assemby.jpg



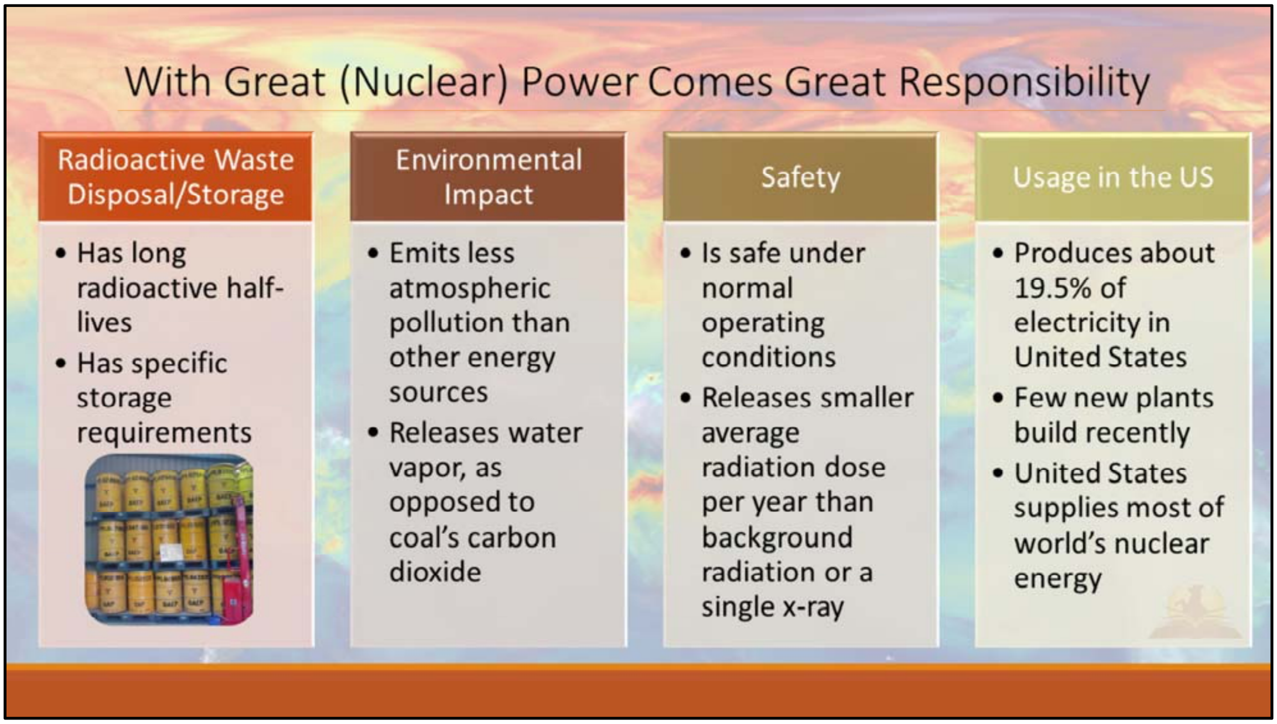
- Nuclear power plants usually generate electricity in three basic steps:
  - 1) Fission reactions produce energy.
  - 2) That energy produces steam from water.
  - 3) That steam team spins a turbine and drives a generator.
- The **nuclear fuel** is usually enriched to 2-4% U-235.
  - It is surrounded by a **moderator** to increase the fission rate.
  - The different types of moderators include:
    - Heavy water moderator
      - These moderators are costly, but they slow the neutron so well that enriched fuel is unnecessary.
    - Light water moderator
      - This type of moderator is a boiling water reactor.
      - The pressurized water reactor incorporates two loops of coolant so that radioactive material does not leak.
- A **concrete containment structure** surrounds the **steel reactor vessel.**
  - The **pressurizer** in pressurized water reactors prevents the primary coolant loop from overheating.
- The **secondary coolant loop** turns into steam from the heat that the **primary coolant loop** provides to generate electricity.

Credit: “Pressurized Water Reactor” By U.S.NRC. [Public domain], via Wikimedia Commons, https://commons.wikimedia.org/wiki/File%3APressurizedWaterReactor.gif



- When U-238 absorbs neutrons, it becomes U-239.
  - U-239 undergoes beta decay to be Neptunium-239, and undergoes another decay to become Plutonium-239.
  - Plutonium-239 and its breeder reactors were utilized for **weaponization.**
- **Breeder reactors** are designed to produce more fissile material than they use up.
  - The reactors use an **ineffective moderator** (like sodium).
    - Neutrons do not slow, and are more likely to react with U-238 instead of U-235.
    - In this case, fission does not occur and instead the neutrons produce Plutonium-239.
  - Breeder reactors were originally constructed for the production of weaponized plutonium, but have largely been abandoned since the 1980s.

Credit: “Little Boy” See page for author [Public domain], via Wikimedia Commons, https://commons.wikimedia.org/wiki/File%3AAtombombe_Little_Boy_2.jpg
Credit: “Breeder Reactor” By Argonne National Laboratory [Public domain], via Wikimedia Commons, https://commons.wikimedia.org/wiki/File%3AEBRCathodeProcessor.jpg

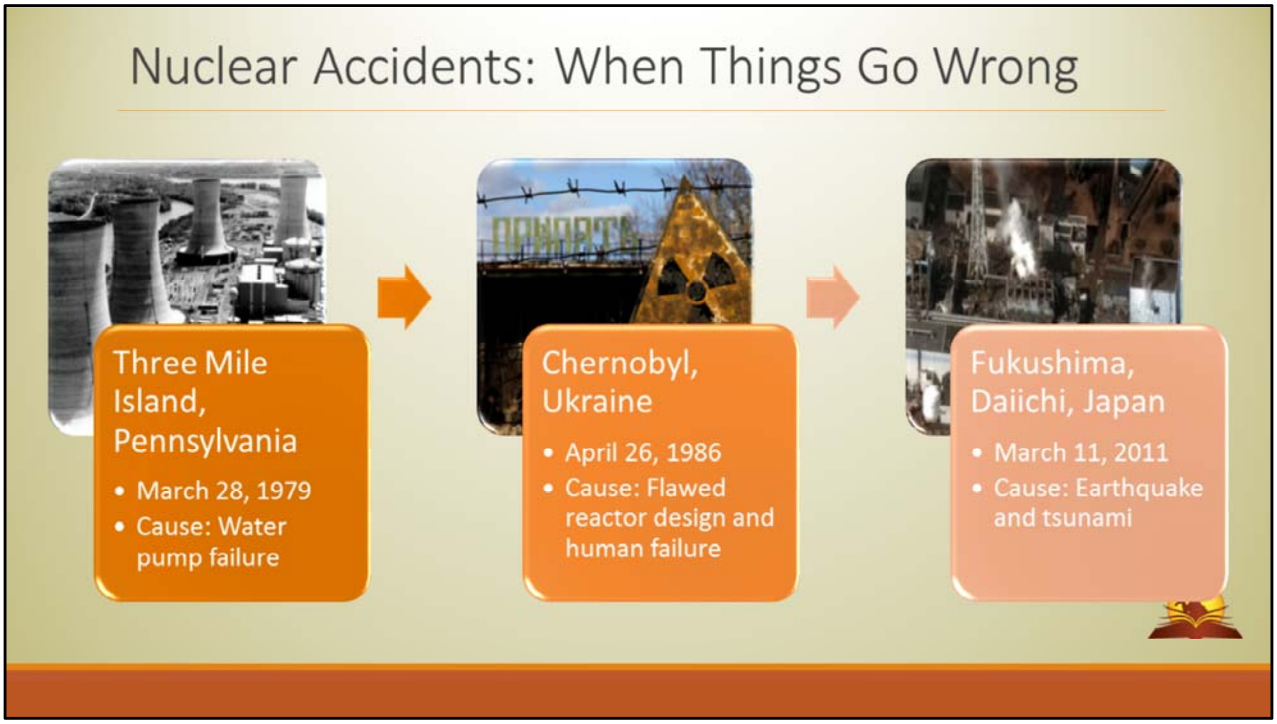


- **Radioactive Waste Disposal/Storage**
    - Radioactive waste, like uranium and plutonium-239, have very long half-lives—24,000 years for plutonium-239.
    - Waste must be stored and isolated for as long as they pose a risk to health, which often exceeds humans' life spans.
    - Older nuclear power plants have to be decommissioned and dismantled entirely after about 30 years, because they accumulate radiation or experience structural damage due to radiation.
- **Environmental Impact**
    - Nuclear power emits less harmful greenhouse gases than many other energy generation methods, such as coal, which releases greenhouse gases like carbon dioxide and exposes workers to radon.
    - Nuclear power only emits water vapor, which is not harmful.
- **Safety**
    - Nuclear power generation is generally safe under normal operation conditions, with many precautions.
    - The average radiation dose for a person living within 50 miles of a plant is less than the average annual exposure to background radiation, or the radiation exposure from a single x-ray.
    - Generation IV reactors are currently in development (and aim to be complete by

2030), which will lower waste and increase safety and reliability.

- **Usage in the US**
    - Nuclear power provides about 19.5% of electricity in USA.
    - Construction on many nuclear plants have halted since the accident at Three Mile Island in 1979.
    - The USA remains the largest supplier of nuclear energy in the world, claiming one third of the world's nuclear electricity supply.

Credit: "Radioactive Waste Barrels" By ShinRyu Forgers (Own work) [CC BY-SA 4.0 (http://creativecommons.org/licenses/by-sa/4.0)], via Wikimedia Commons, https://commons.wikimedia.org/wiki/File%3ATINT_Radioactive_wastes'_Barrel.jpg
Credit: "Global Warming Simulation" By NASA/GSFC [Public domain], via Wikimedia Commons, https://commons.wikimedia.org/wiki/File%3AM15-162b-EarthAtmosphere-CarbonDioxide-FutureRoleInGlobalWarming-Simulation-20151109.jpg



Three Mile Island, PA (March 28, 1979)

- A water pump shutoff stopped the circulation of the secondary coolant loop.
  - The secondary coolant loop boiled off, while the primary coolant loop overheated.
  - Water flooded the containment structure.
- Three Mile Island was the worst nuclear accident in U.S. history and led to negative public opinion on nuclear power in USA for many years.

Chernobyl, Ukraine (April 26, 1986)

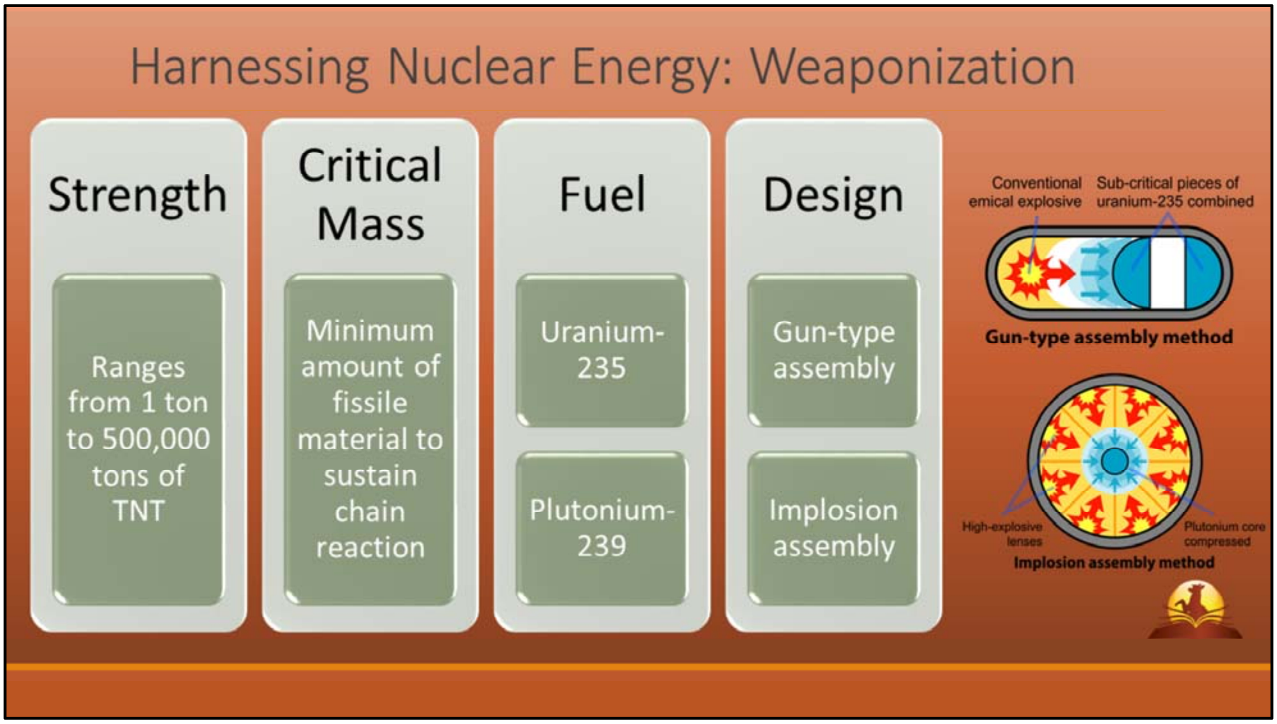
- This accident occurred due to a flawed reactor design as well as human error.
  - A power surge led the reactor to rupture and explode.
  - 31 people died as a direct result of the accident.
  - Hundreds of thousands of people living in the area had to be relocated.
- Chernobyl was the worst nuclear accident in history.

Fukushima Daiichi, Japan (March 11, 2011)

- This accident occurred due to an earthquake and ensuing tsunami.
  - The primary and secondary coolant pumps lost power.

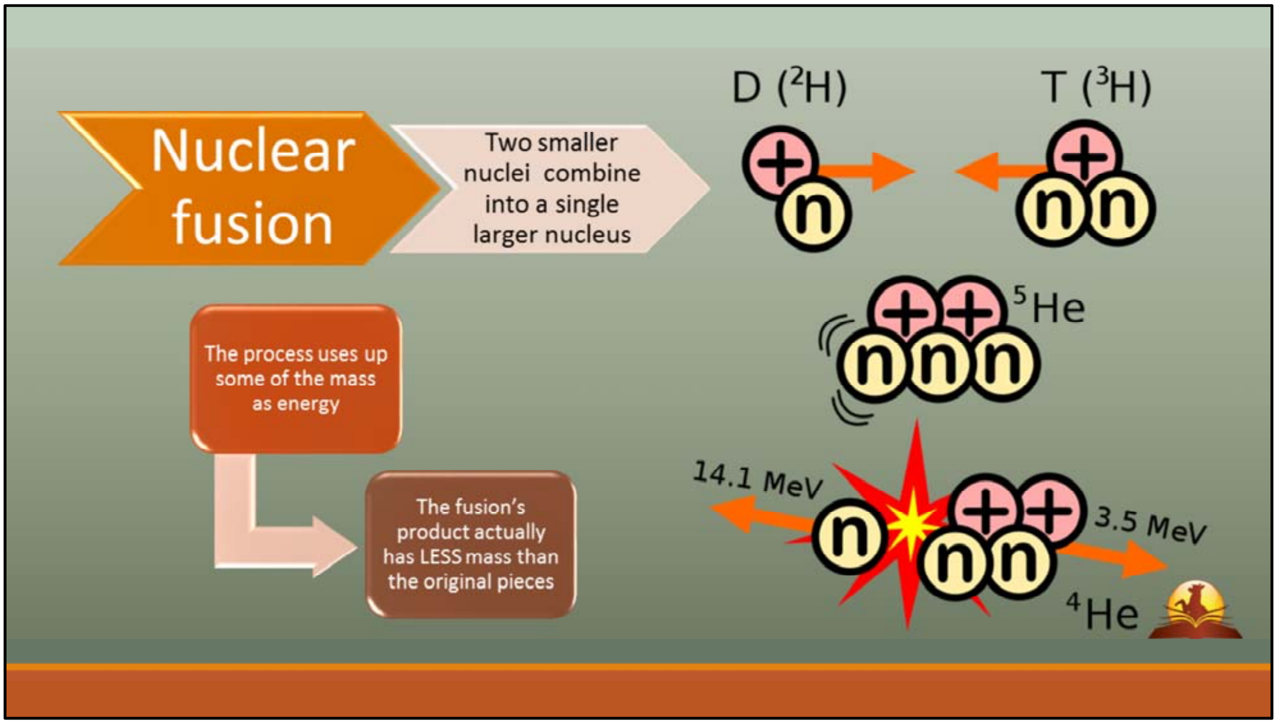
- The reactors then overheated and a meltdown occurred.
    - No negative health effects were reported following the evacuations.
- As a result, Japan shut down all 54 of its power plants for assessment.

Credit: “Three Mile Island” See page for author [Public domain], via Wikimedia Commons, https://commons.wikimedia.org/wiki/File%3A3MileIsland.jpg
Credit: “Chernobyl” https://commons.wikimedia.org/wiki/File:VOA_Markosian_-_Chernobyl02.jpg
Credit: “Fukishima Daiichi” By Digital Globe [CC BY-SA 3.0 (http://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons, https://commons.wikimedia.org/wiki/File%3AFukushima_I_by_Digital_Globe_B.jpg



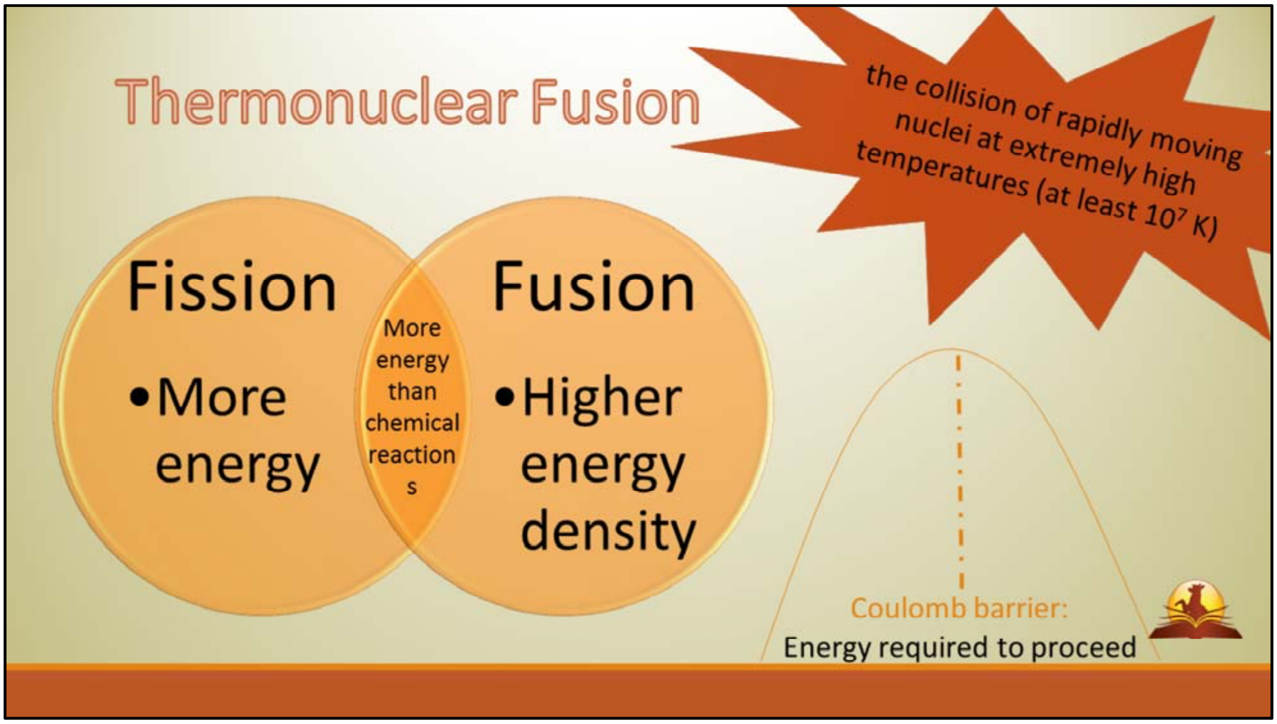
- Nuclear weapons have a strength ranging from 1 ton to 500,000 tons of TNT.
  - They release this amount of energy by operating **above criticality** to release as much energy as possible.
  - This function is the opposite of a nuclear reactor.
- **Critical mass** is the minimum amount of fissile material needed to sustain a nuclear chain reaction*.*
  - Neutrons travel through material until they collide with another uranium nucleus.
  - If the mass is too small, neutrons may "leak" through the surface before causing another fission event, and the chain reaction is broken.
  - The critical mass of uranium-235 is about the size of a large cantaloupe.
- Nuclear weapons use **uranium-235** and **plutonium-239** as fuel*.*
  - The first atom bombs produced in WWII used plutonium-239.
- Nuclear weapons must be kept below criticality until the time of detonation*.*
  - The fuel is **split up** the fuel so that it remains **below critical mass**
  - The fuel is then brought together by one of two methods:
    - **Gun type assembly,** in which two subcritical pieces are fired into each other by explosives.
    - **Implosion assembly***,* in which subcritical mass is compressed inwards by explosives to increase density and achieve critical mass.

Credit: “The explosion of the hydrogen bomb Ivy Mike” By U.S. Department of Energy (http://images-of-elements.com/fermium.php) [Public domain], via Wikimedia Commons, https://commons.wikimedia.org/wiki/File%3AThe_explosion_of_the_hydrogen_bomb_Ivy_Mike.jpg
Credit: “Dynamite” See page for author [Public domain], via Wikimedia Commons, https://commons.wikimedia.org/wiki/File%3APSM_V56_D0465_Hollow_dynamite_cartridge_elevation_view.png
Credit: “Cantaloupe”
https://commons.wikimedia.org/wiki/File:Cucumis_melo_2_(Piotr_Kuczynski).jpg
Credit: “Nuclear Weapon Design” By Fastfission (Own work) [Public domain], via Wikimedia Commons,
https://commons.wikimedia.org/wiki/File%3AFission_bomb_assembly_methods.svg

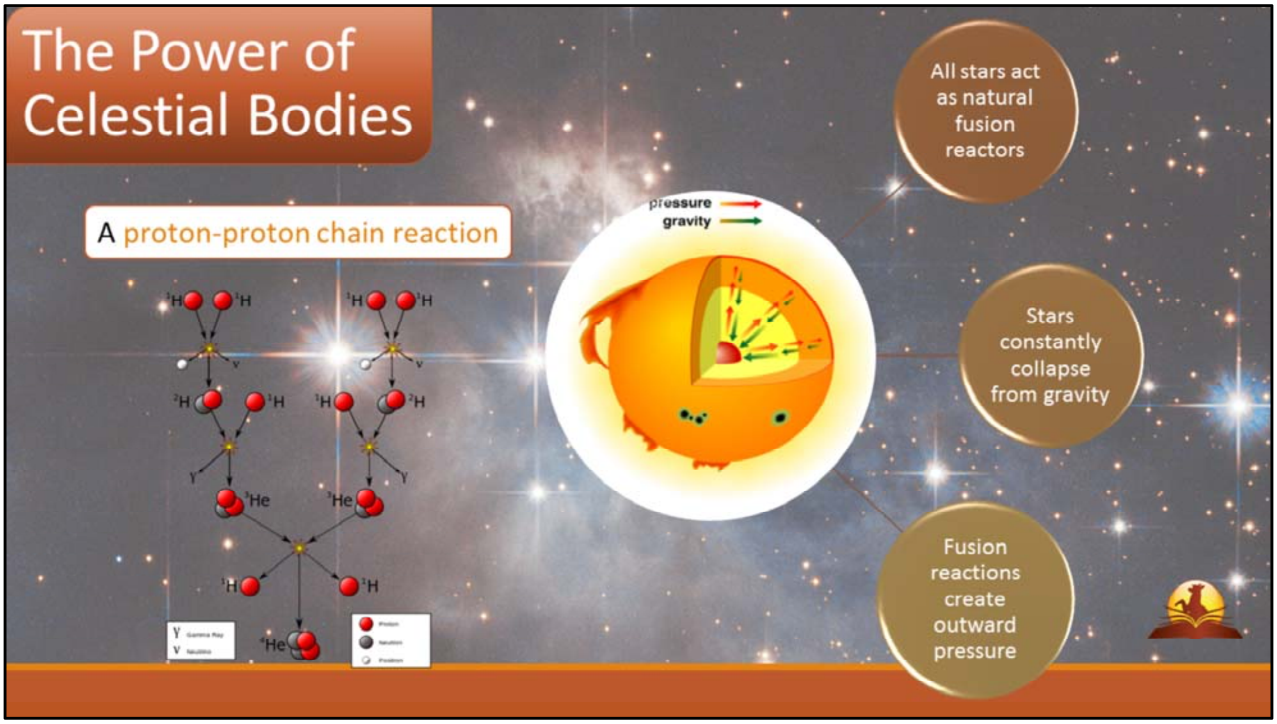


- **Nuclear fusion** is the process of two smaller nuclei combining to form a larger nucleus.
  - The product of nuclear fusion is actually less massive than the original parts, because some of the mass ends up as energy in the output.
  - Einstein's equation ($E = mc^2$) applies here.

Credit: "Nuclear fusion", By I, Panoptik, CC BY 2.5, https://commons.wikimedia.org/w/index.php?curid=2510231

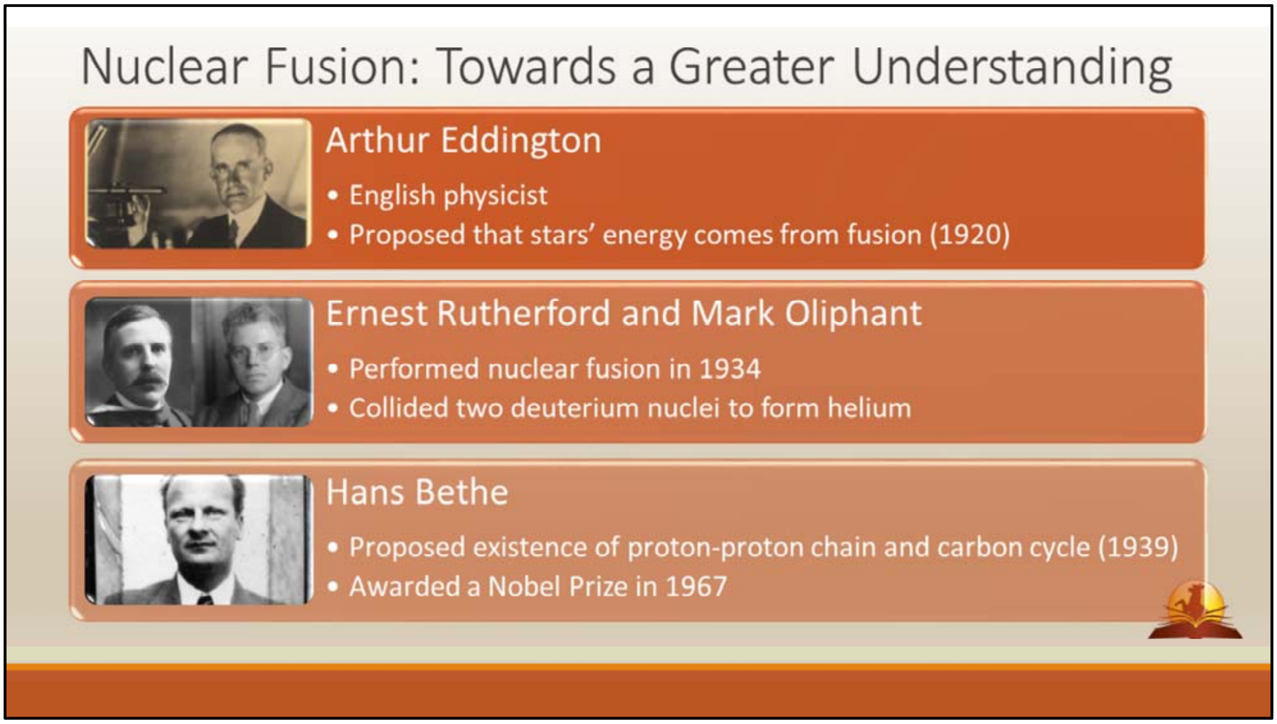


- All nuclei are positively charged and tend to repel each other.
  - Thus, nuclei only fuse when they collide at extremely high speeds. Large kinetic energies are required, and high temperatures of over 10^7 K.
    - The fusion of rapidly moving nuclei at high temperatures refers to **thermonuclear fusion.**
- Thermonuclear fusion is similar to combustion reactions, but on a larger scale.
  - Both types of fusion result in less massive products and an energy output.
- Fusion reactants must overcome a large energy barrier known as the **Coulomb** barrier and can be explained as a result of quantum tunneling.
  - The wave nature of protons results in a nonzero probability of tunneling through Coulomb barrier.
- Fusion reactions have a higher energy density than fission reactions, though they lose in terms of the output per individual reactions.
- Both fusion and fission reactions produce millions of more times of energy than chemical reactions.



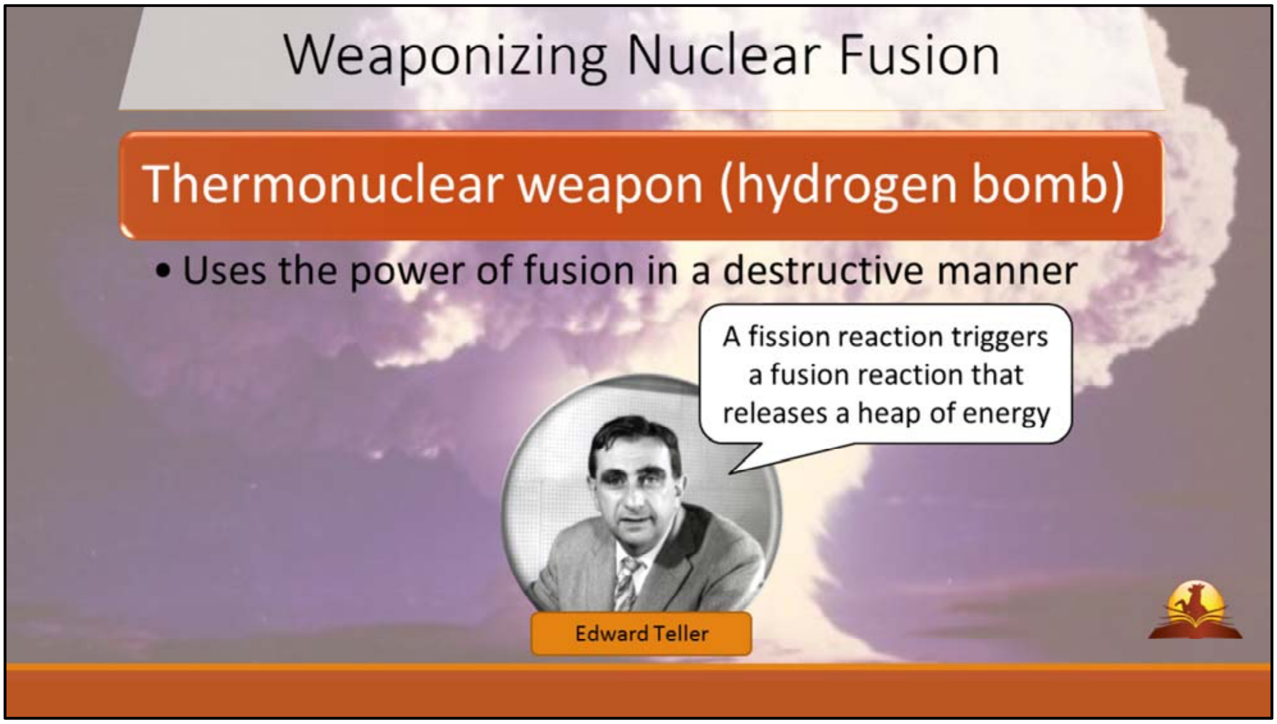
- **Stellar fusion** occurs on stars, operating at temperatures of millions of degrees.
  - Hydrogen fusion powers most stars, though older stars fuse heavier elements.
  - The sun is approximately 74% hydrogen and 25% helium by mass.
  - The mass lost in the conversion of hydrogen into helium is released as radiation energy that reaches the earth as light and "solar wind."
- Stars constantly collapse inward due to the force of gravity.
  - Fusion reactions produce an outward pressure that opposes the collapsing force.
    - As such, a star must maintain energy production (that is, it must be hot and dense enough that fusion occurs) in order to result in the multi-step fusion reaction known as a **proton-proton chain.**
    - The first step in a proton-proton chain is when two protons form a deuterium, which serves as a "bottleneck" that regulates the rest of the chain.
      - Otherwise, the sun would have a smaller lifetime.
- A more complex series of reactions called a carbon (or CNO) cycle acts as the primary source of power of hotter and more massive cycles.

Credit: "Proton-proton chain" by Borb [GFDL (http://www.gnu.org/copyleft/fdl.html) or CC BY-SA 3.0 (http://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons
Credit: "Hydrostatic Equilibrium" at https://ryanoursun.wikispaces.com/file/view/hydro.jpg/62193798/hydro.jpg
Credit: "A Stellar Fingerprint" By ESA/Hubble, CC BY 3.0, https://commons.wikimedia.org/w/index.php?curid=47236344



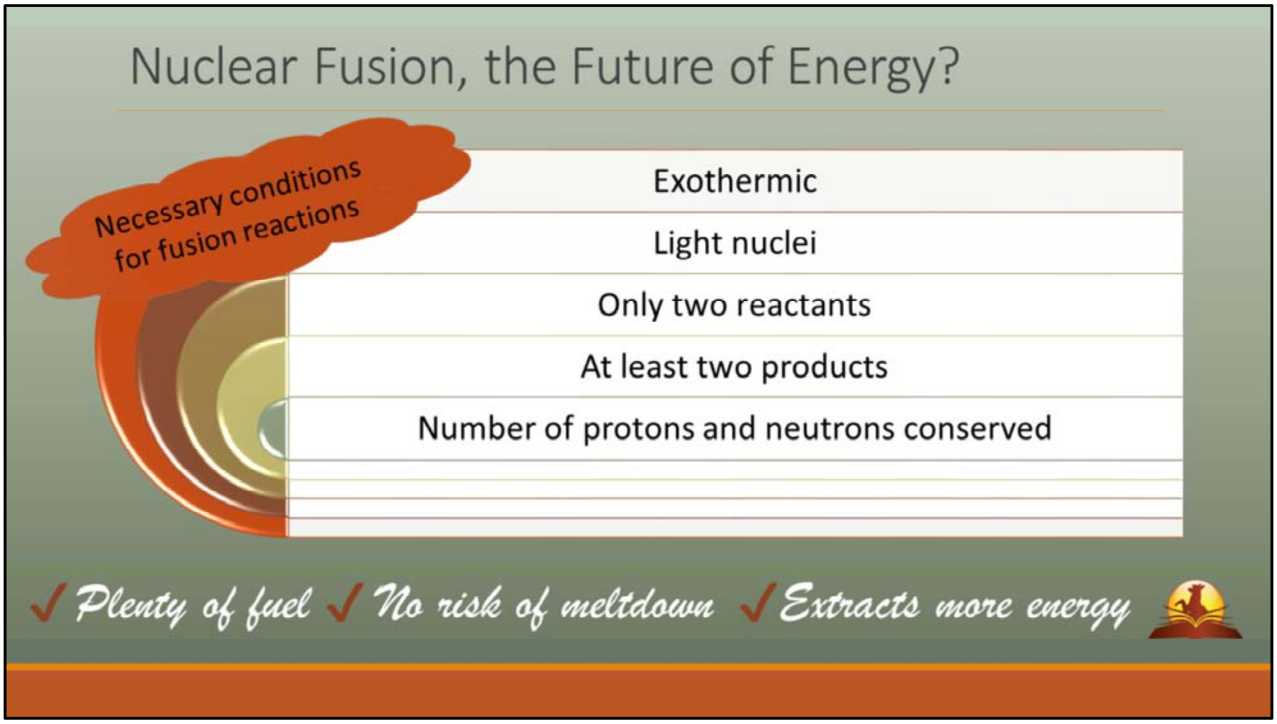
- Stellar Fusion
  - In 1920, English physicist Arthur Eddington first proposed that fusion was the source of energy in stars.
  - In 1934, Ernest Rutherford and Mark Oliphant were able to experimentally demonstrate nuclear fusion and affirmed Eddington's proposal.
  - Hans Bethe proposed the proton-proton chain and carbon cycle in 1939
    - Bethe earned the 1967 Nobel Prize.

Credit: "Arthur Eddington" By Smithsonian Institution from United States - Portrait of Arthur Stanley Eddington (1882-1944), Astronomer, No restrictions, https://commons.wikimedia.org/w/index.php?curid=43686386
Credit: "Ernest Rutherford" By Unknown - http://www.nobelprize.org/nobel_prizes/chemistry/laureates/1908/rutherford.html und Nobel Prize 1908, Public Domain, https://commons.wikimedia.org/w/index.php?curid=18253247
Credit: "Mark Oliphant" By Bassano Ltd [Public domain or Public domain], via Wikimedia Commons
Credit: "Hans Bethe" Public Domain, https://commons.wikimedia.org/w/index.php?curid=315577

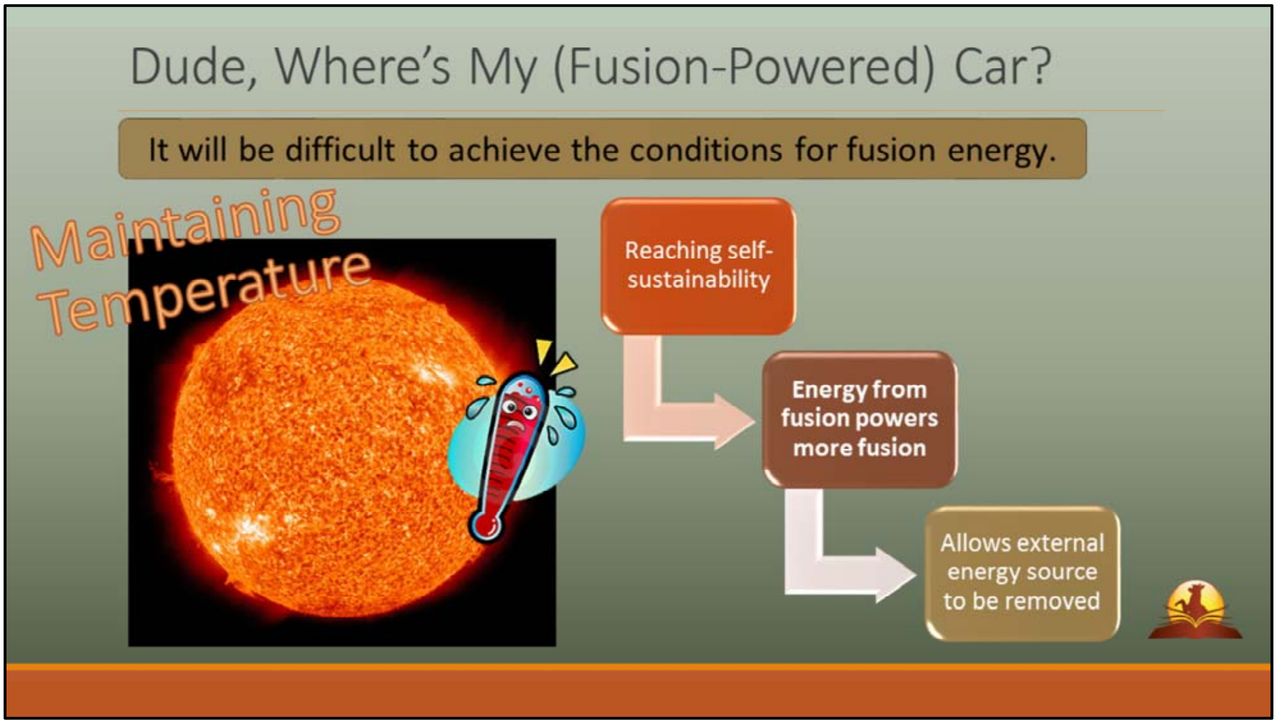


- Nuclear fusion can be used as a weapon in the form of a **thermonuclear weapon**, or **hydrogen bomb.**
    - A fission reaction heats and compresses the fusion reactants, which leads to series of fission charges. The fusion is induced and the energy from initial fusion induces another, which leads to an explosion.
- Edward Teller, the “father of the hydrogen bomb,” worked on the Manhattan Project.
    - Teller discovered the principle behind a hydrogen bomb and developed a final design in 1951.
    - His first bomb was detonated in 1952, which produced a 10.4 megaton blast.

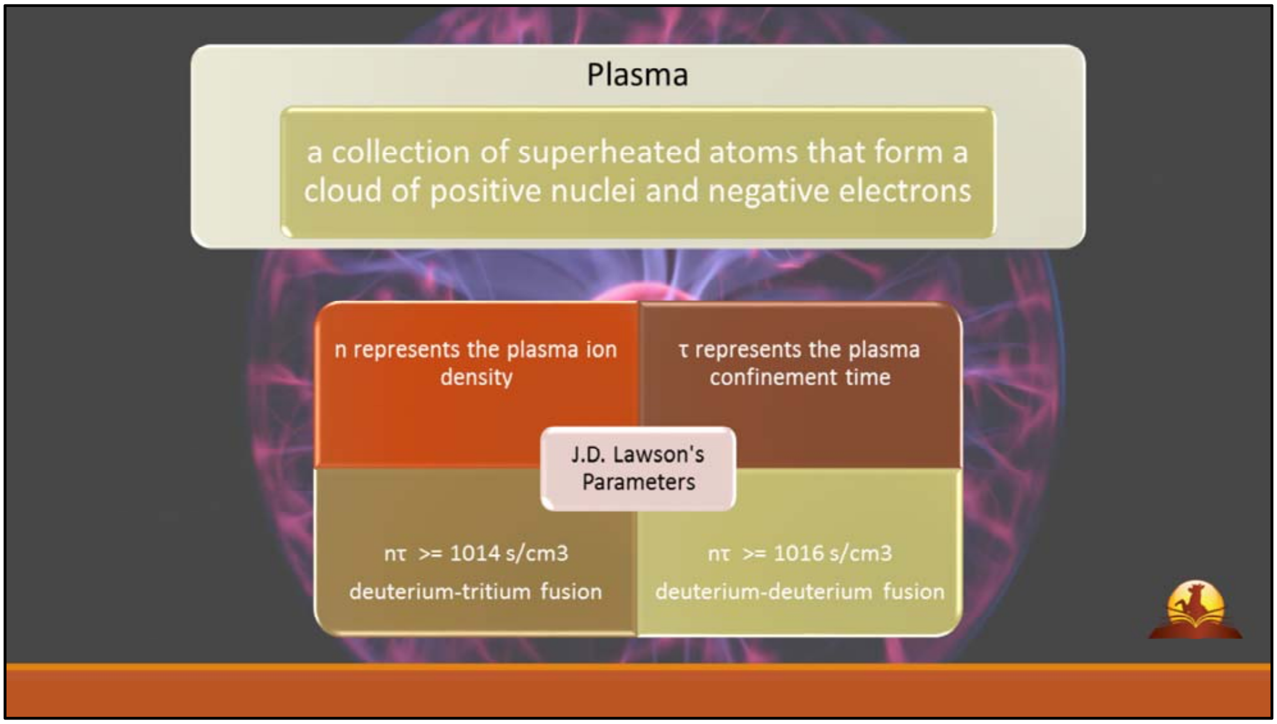
Credit: “Edward Teller” Image credit Lawrence Livermore National Laboratory; https://commons.wikimedia.org/wiki/File:EdwardTeller1958.jpg
Credit: “Hydrogen bomb” By U.S. Department of Energy (http://images-of-elements.com/fermium.php) [Public domain], via Wikimedia Commons



- Energy from controlled fusion has been prospective for over 50 years.
  - In order to create fusion reactions, the following conditions must be satisfied:
    - Must be exothermic
    - Light nuclei are involved to minimize Coulomb repulsion
    - Two reactants, as collision between more than two is improbable
    - Two or more products to conserve momentum
    - Proton and neutron count must be conserved
  - Only a few reactions will work, and the greatest potential reactions involve deuterium and tritium isotopes of hydrogen.
- Fuel for nuclear fusion (hydrogen) is extremely abundant.
  - Deuterium can be harvested from just water.
  - Tritium is less abundant, but it can be created in a process known as “breeding.”
- Fusion reactors offer a number of advantages over fission reactors:
  - More energy can be extracted per unit of fuel in fusion reactions
  - No risk of meltdowns as no “supercritical” state exists
  - No air pollution
  - No radioactive waste



- We have not yet achieved the means to use fusion energy
  - Temperature
    - At least 10 million K necessary for nuclei to be energetic enough
    - Difficult to maintain something like the Sun's temperature on Earth
  - Self-sustainability
    - Like fission reactors, using fusion for energy requires reaching **fusion ignition**, the point at which the reaction is self-sustaining
    - Energy released by fusion continues to power more fusion
    - Allows for external energy source to be removed

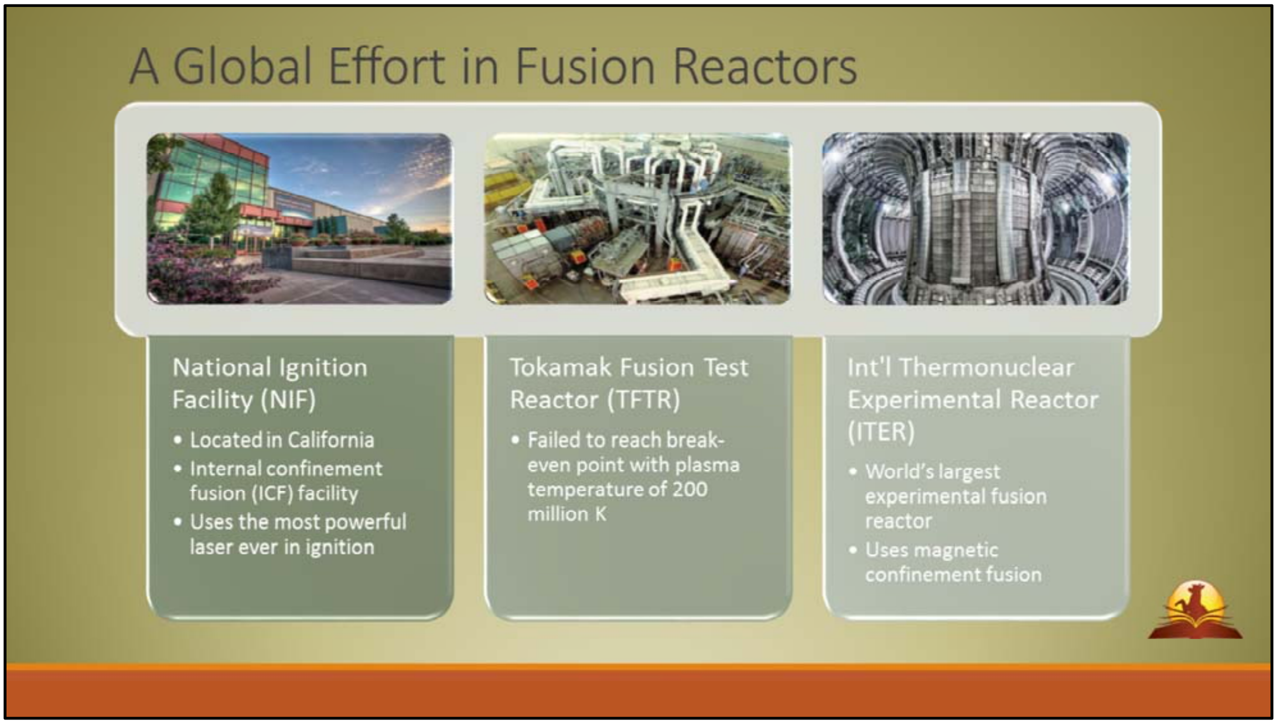


- Fusion requires not only high temperatures, but also high density of nuclei to ensure the continuation of fusion reactions at a sufficient rate.
  - Atoms heated past their ionization result in no electrons bound to the nucleus.
    - The collection of superheated atoms forms a cloud of positive nuclei and negative electrons results in a state of matter known as **plasma,** which is achieved through fusion.
    - J.D. Lawson proposed two parameters for plasmas in 1957:
      - *n* – plasma ion density
      - τ – plasma confinement time
        - Fusion reactor produces net output with these following values:
          - $n\tau$ >= 10^{14} s/cm^3 (deuterium-tritium fusion)
          - $n\tau$ >= 10^{16} s/cm^3 (deuterium-deuterium fusion)
  - The containment of plasmas poses a challenge in fusion reactions.
    - Two techniques can contain plasma: magnetic or inertial confinement.
      - Magnetic confinement relies on the idea that magnetic fields can bend the trajectory of charged particles
        - “Magnetic bottle” is the magnetic field used for this purpose.
        - A tokamak is a device that confines plasmas using two

magnetic fields, developed by Soviets following WWII.

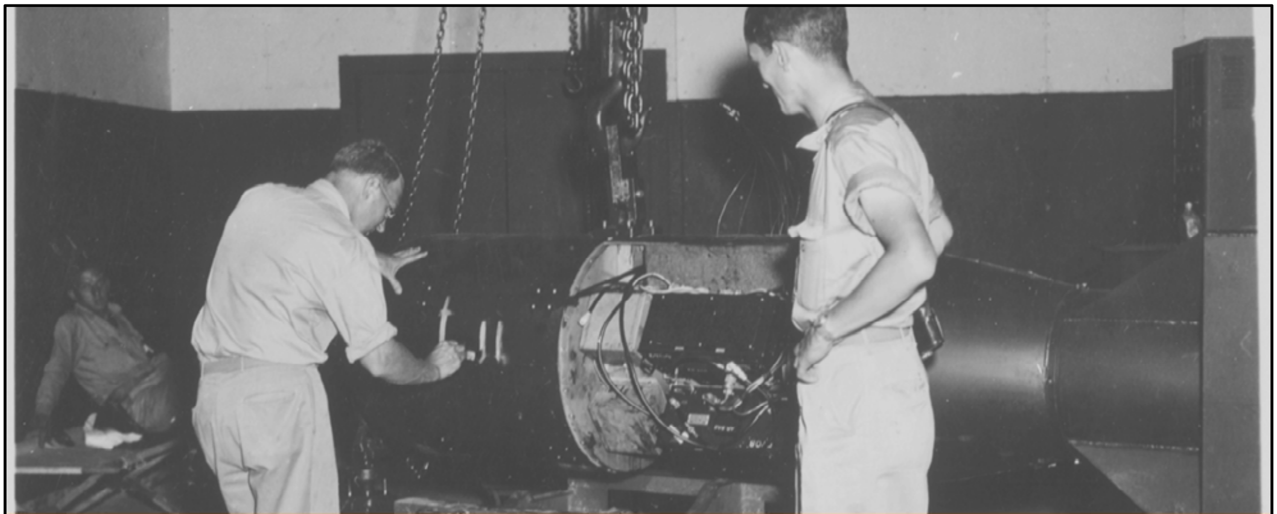
- Inertial confinement occurs in inertial confinement fusion (ICF), and relies on high-intensity lasers to compress the fuel (deuterium and tritium in a pellet).
  - Unlike magnetic confinement, fusion occurs fast enough so that there is no time for nuclei to split apart.
    - When the temperature reaches above 10^8 K, it ignites and fusion is achieved in under 10^{-9} s.

-



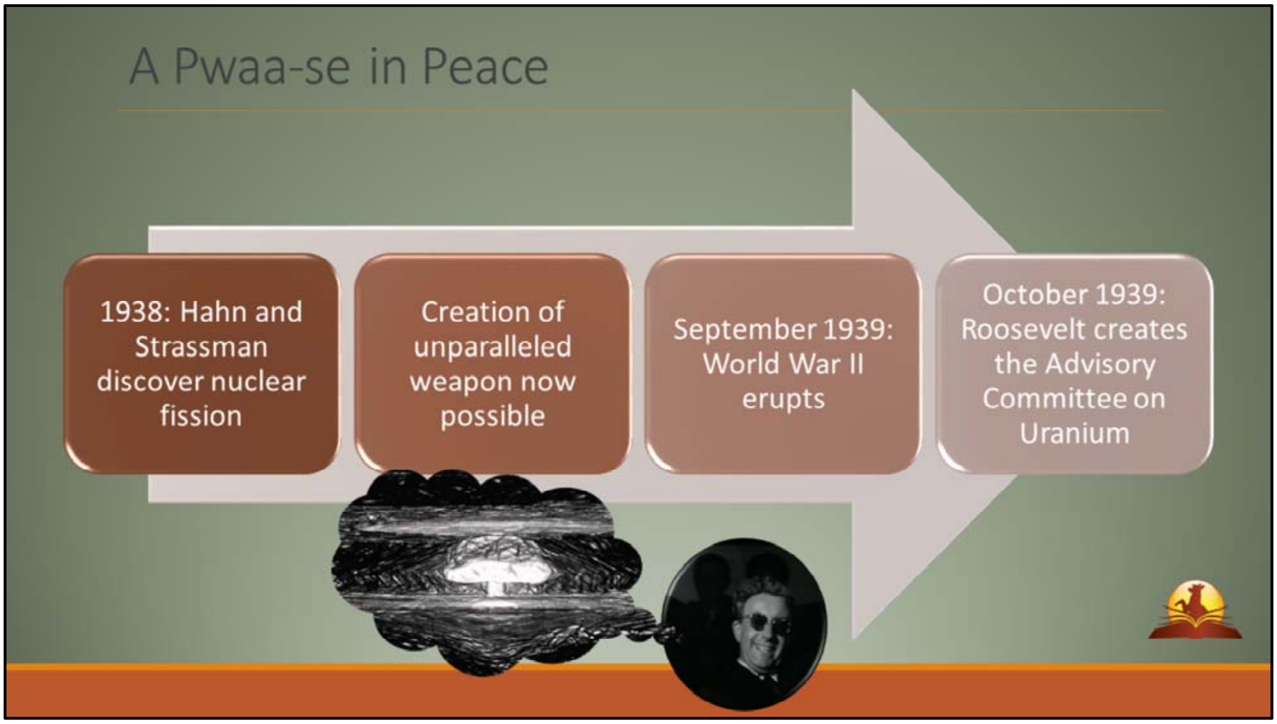
Various facilities for fusion reactors exist:

- National Ignition Facility (NIF)
  - Largest ICF device in the world
  - Located at Lawrence Livermore National Laboratory in California
  - Uses most powerful laser ever to ignite fusion
  - In 2012, conducted a laser pulse with 500 trillion watts of power
- Tokamak Fusion Test Reactor (TFTR)
  - Began operation in 1982 with goal to reach "break-even," a state where the energy output from a reactor equals the energy input to heat plasma
  - Achieved plasma temperature of 200 million K and still failed
  - Shut down in 1997
  - The Joint European Torus (JET) in the UK exists today as another tokamak fusion effort
- International Thermonuclear Experimental Reactor (ITER)
  - Effort by 6 nations (India, Japan, Korea, China, Russia, and USA) + EU
  - Purpose is to demonstrate the feasibility of magnetic confinement fusion
  - Construction in France with a start date of 2027 (preliminary)
  - First deuterium-tritium experiments

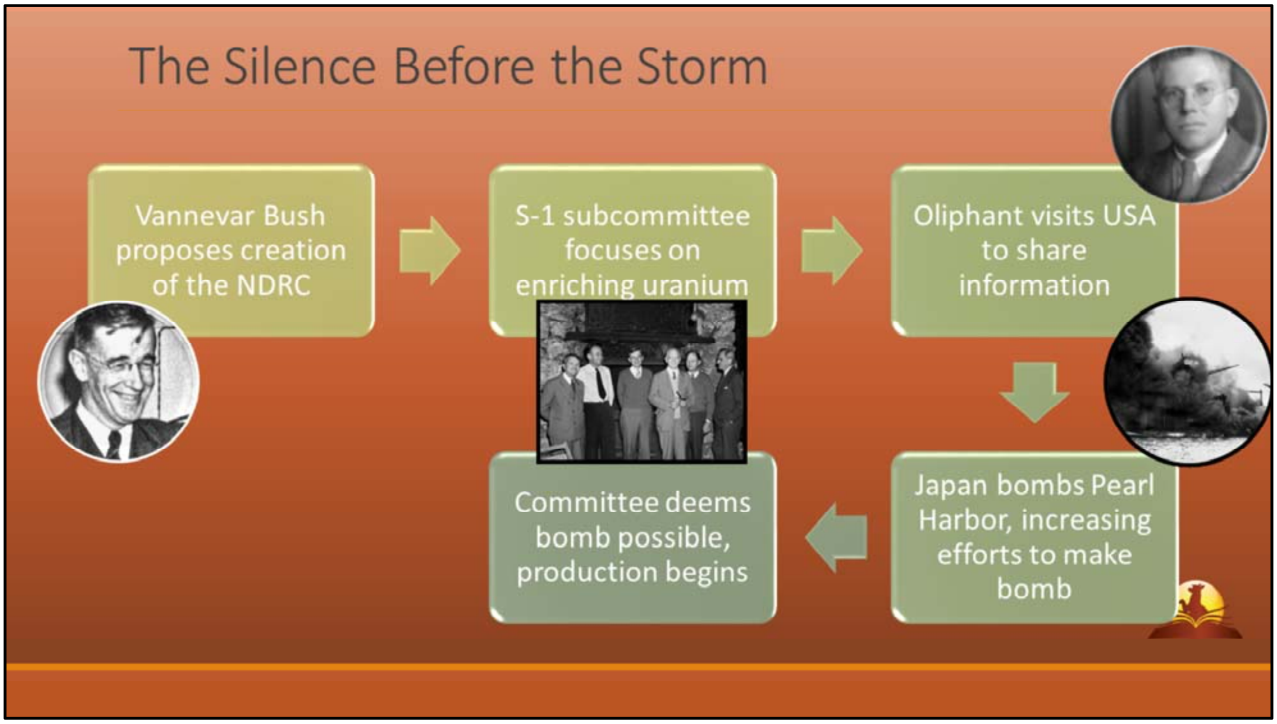


IV: The Manhattan Project and the Atomic Bomb

Credit: By Unknown or not provided - U.S. National Archives and Records Administration, Public Domain, https://commons.wikimedia.org/w/index.php?curid=16659561



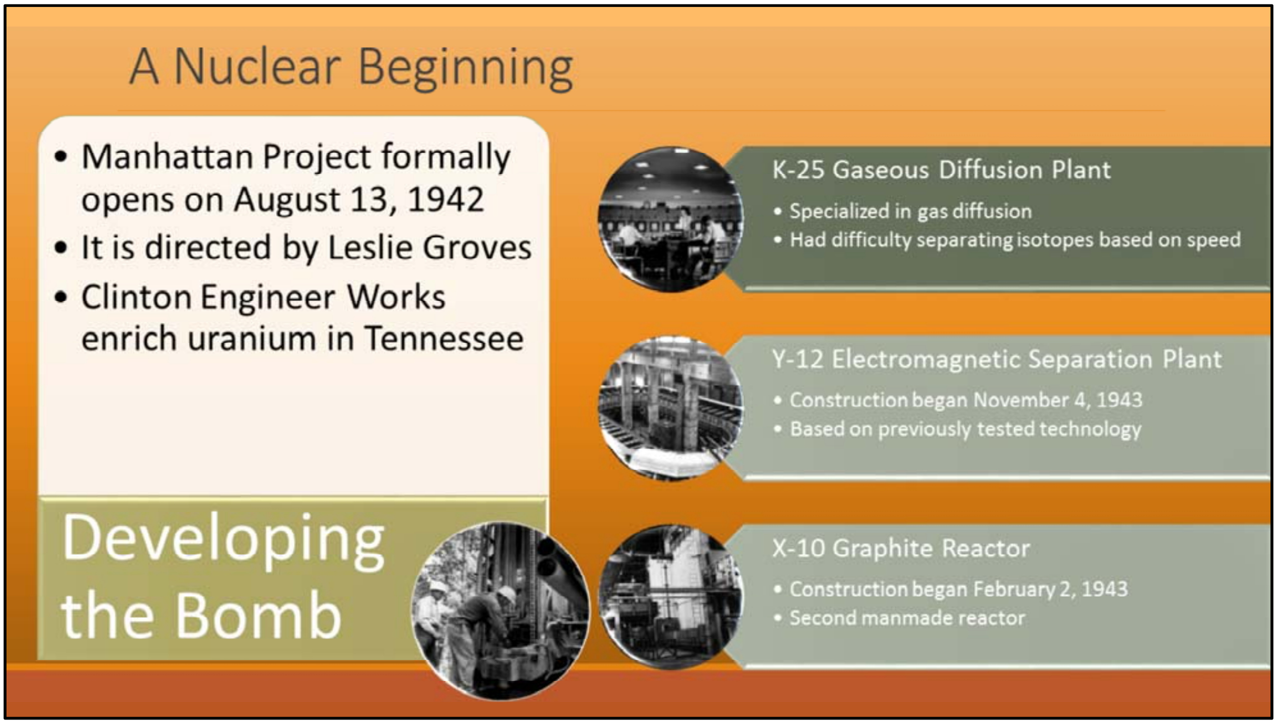
- **Hitler** became chancellor of Germany in **1933**, around the same time that **Mussolini** established the Fascist government in Italy.
    - Hitler and Mussolini formed an alliance.
    - Germany’s invasion of **Poland** in **September 1939** begins **WWII** in Europe.
- **Hahn** and **Strassman** discover **nuclear fission** in **1938,** making the atomic bomb possible.
    - Many scientists involved in research flee Europe due to fear of Hitler making the bomb, including **Enrico Fermi** and **Leo Szilard.**
    - On **August 2,1939,** Szilard sends letter to **FDR** about Germany researching the bomb, cosigned by Albert Einstein.
- Roosevelt created the **Advisory Committee on Uranium** under **Lyman Briggs** after receiving the letter.
    - On November 1, 1939, the committee purchased $6,000 worth of uranium oxide and graphite.
- Credit: “Dr. Strangelove” by Stanley Kubrick, distributed by Columbia Pictures [Public domain], via Wikimedia Commons
- Credit: “Castle Romeo” by United States Department of Energy [Public domain], via Wikimedia Commons



- **Vannevar Bush** was concerned over lack of coordination between scientists and military.
    - He proposed the creation of the **National Defense Research Committee (NDRC)** in **June 1940,** which was passed immediately.
- **National Defense Research Committee**
    - Subcommittee, **S-1**, was designed to improve uranium enrichment techniques.
        - **Ernest O. Lawrence** was a member**.**
- **Lawrence** invented the **cyclotron,** the first particle accelerator.
    - The cyclotron was later converted into the mass spectrometer, which separated U-235 and U-238 isotopes.
- The committee needed to find critical mass for U-238 to explode.
- Britain had a team for this procedure as well, and estimated that 10 kg U-238 would be needed.
    - British representative **Mark Oliphant** visited the USA in August 1941 to share information.
- On **October 9, 1941, Bush** gave **Roosevelt** and VP **Henry Wallace** a summary of his findings.
    - **Roosevelt** instructed **Bush** to continue the research, as long as the bomb was feasible.
    - After the bombing of **Pearl Harbor,** America officially entered the war.
- In **May 1942, Arthur Compton** had **J. Robert Openheimer** perform neutron calculations

for the chain reaction.
  - **Openheimer's** group discovered that a fission bomb was possible.
- At this time, the **S-1** committee could still not come to a consensus regarding the enrichment process.
  - Three separate uranium enrichment plants were built to remedy this issue.
- **Fermi's** first successful chain reaction took place on **December 2, 1942.**
  - **S-1** began finalizing plans for the bomb following this event.
  - Half a million dollars had been allocated by **Roosevelt** for the project's completion by the end of 1942.

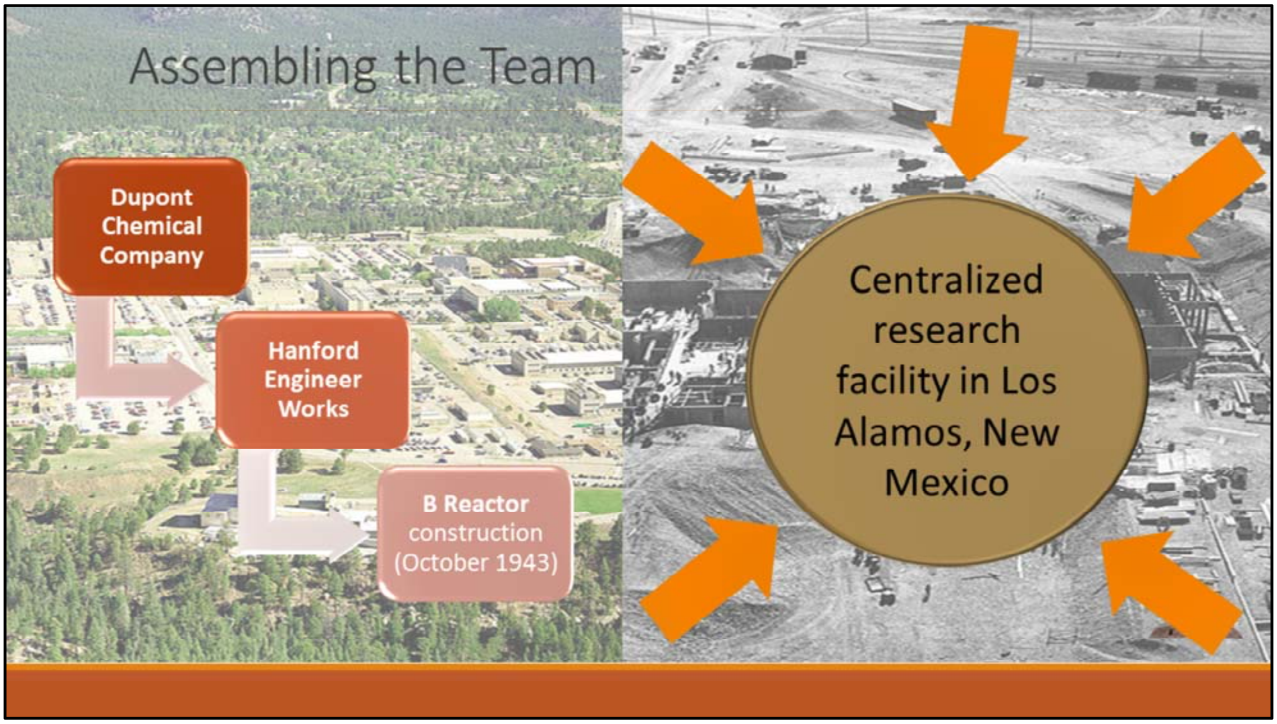
Credit: "Vannevar Bush" By ENERGY.GOV (HD.1A.018) [Public domain], via Wikimedia Commons
Credit: "S1-Committee"
Credit: "Sir Mark Oliphant" By Bassano Ltd [Public domain or Public domain], via Wikimedia Commons
Credit: "USSArizona PearlHarbor" by See page for author [Public domain], via Wikimedia Commons



- The **Army Corps of Engineers** controlled plant construction and bomb assembly.
- On **August 13, 1942** the office in charge of construction begins in **Manhattan**
  - **Leslie Groves** enters as the director of the project in **September,** ultimately known as the **Manhattan Project.**
- **Groves** appointed **Oppenheimer** as leader of **Project Y**, the weapons development lab, on **July 20, 1943.**
- **Oak Ridge**
  - Rural Tennessee, primary nuclear facility
  - 60,000 acres of land
  - Began **January 1943**
  - Originally called **Clinton Engineer Works**
  - City of **Oak Ridge** later founded to house the workers there
  - Had different facilities for enrichment, including the **X-10 Graphite Reactor (started February 2, 1943)**, **Y-12 electromagnetic separation plant (started November 4, 1943)**, and **K-25 gaseous diffusion plant**
    - **Centrifuge separation method** rejected
  - **Y-12**
    - Based on tested technology
    - Less efficient
  - **K-25**

- Specialized in gas diffusion
- Experimental but promising
- Had difficulty separating isotopes based on small speed difference

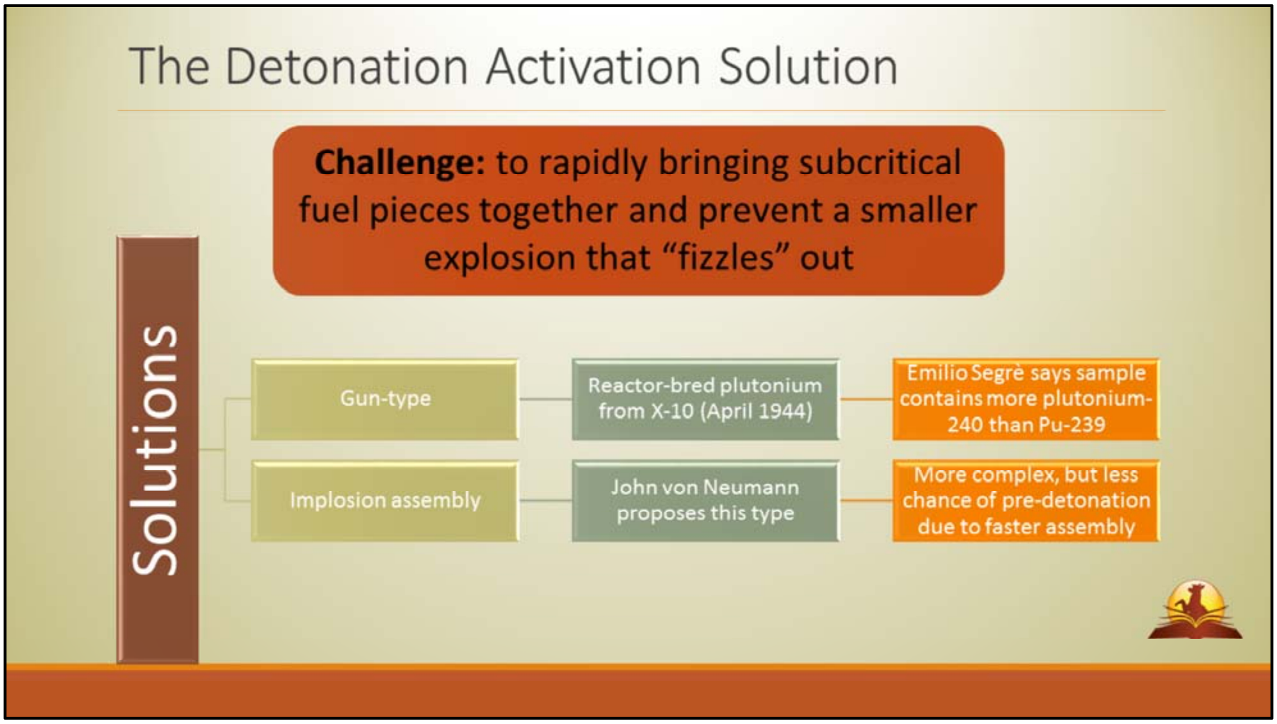
Credit: “**Oak Ridge** picture” by ENERGY.GOV (HD.16A.026) [Public domain], via Wikimedia Commons
Credit: “K-25 control room” by Ed Westcott (K-25 virtual tour) [Public domain], via Wikimedia Commons
Credit: “Oak Ridge Y-12 Alpha Track” by Ed Westcott (James Edward Westcott), in official capacity as photographer employed by the US government. [Public domain], via Wikimedia Commons
Credit: “X-10 at Oak Ridge” By ENERGY.GOV (HD.30.652) [Public domain], via Wikimedia Commons



- **Enrico Fermi**'s pilot tests suggested the need for a full-scale reactor.
  - Groves contracted industry players to support the development.
  - **The Dupont Chemical Company** was in charge of a full scale plutonium generation plant for the **Manhattan Project.**
  - **Dupont** created the **Hanford Engineer Works** along the **Columbia River.**
    - Construction of the **B Reactor** began **October 1943,** and reached criticality in **September 1944.**
- In **1942**, researchers were scattered, making it difficult to communicate.
  - **Oppenheimer** suggested creating a single facility to gather them all together.
  - The lab at Los Alamos, New Mexico, known as Site Y, is created in 1943.
    - Los Alamos was designed to gather scientists and let them collaborate.

Credits: “building at Hanford Engineer Works” by ENERGY.GOV (HD.4A.129) [Public domain], via Wikimedia Commons

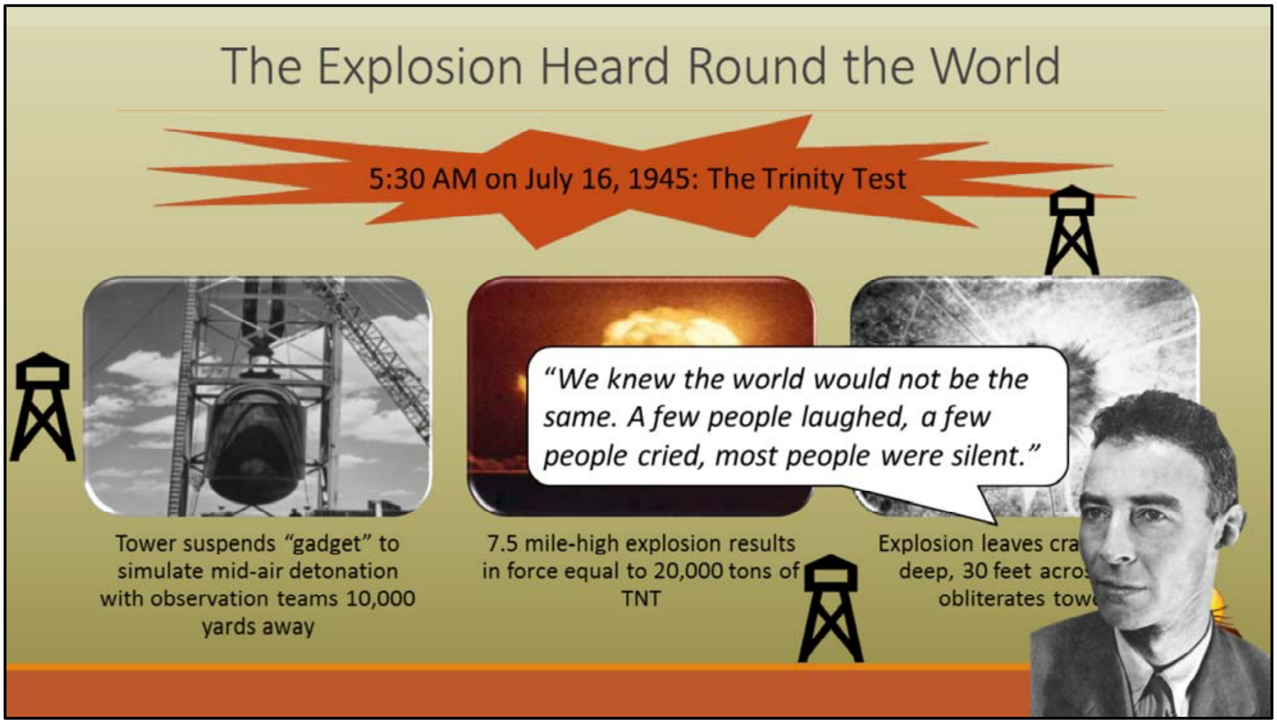
Credits: “Los Alamos aerial view” by Los Alamos National Laboratory [Public domain or Public domain], via Wikimedia Commons



- The subcritical pieces of fuel needed to be brought together rapidly.
    - If it was too slow, there would be a **smaller explosion** that would blow the material apart before all it underwent fission.
    - This process was called **pre-detonation,** and lowered the expected yield of energy.
- Initially, the researchers focused on a **gun-type** plutonium fission device (nicknamed **"Thin Man"** because of its elongated shape).
    - In April 1944, the first shipment of plutonium arrives from the Clinton X-10 reactor.
        - **Emilio Segre** determines it contains more **Pu-240** than would be produced by the cyclotron.
        - Pu-240 has a tendency to **initiate the chain reaction too soon** causing **pre-detonation.**
        - This realization made the gun-type style too impractical for their purposes.
- In July 1944, Oppenheimer directed Los Alamos to **focus on implosion assembly.**
    - **John von Neumann** proposed this type of assembly based on earlier work by **Seth Neddermeyer.**
    - This assembly was more complex, but brought fuel together more quickly, meaning there was **less chance of pre-detonation.**

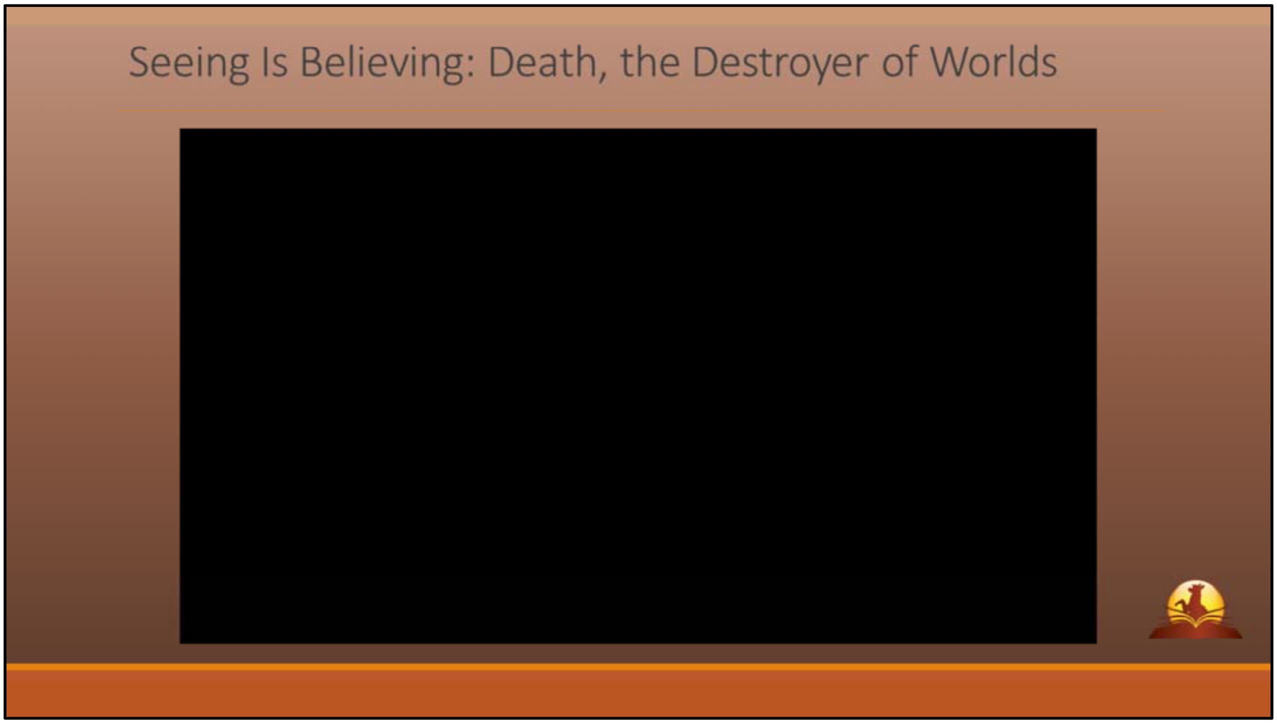
- This change in focus slowed the project timeline.

- On August 7, 1944, **Groves** announced that an implosion device would be ready by spring 1945.
    - The uranium gun device was ready by August 1945, as the Pu gun-device was still too impractical with Pu-240.

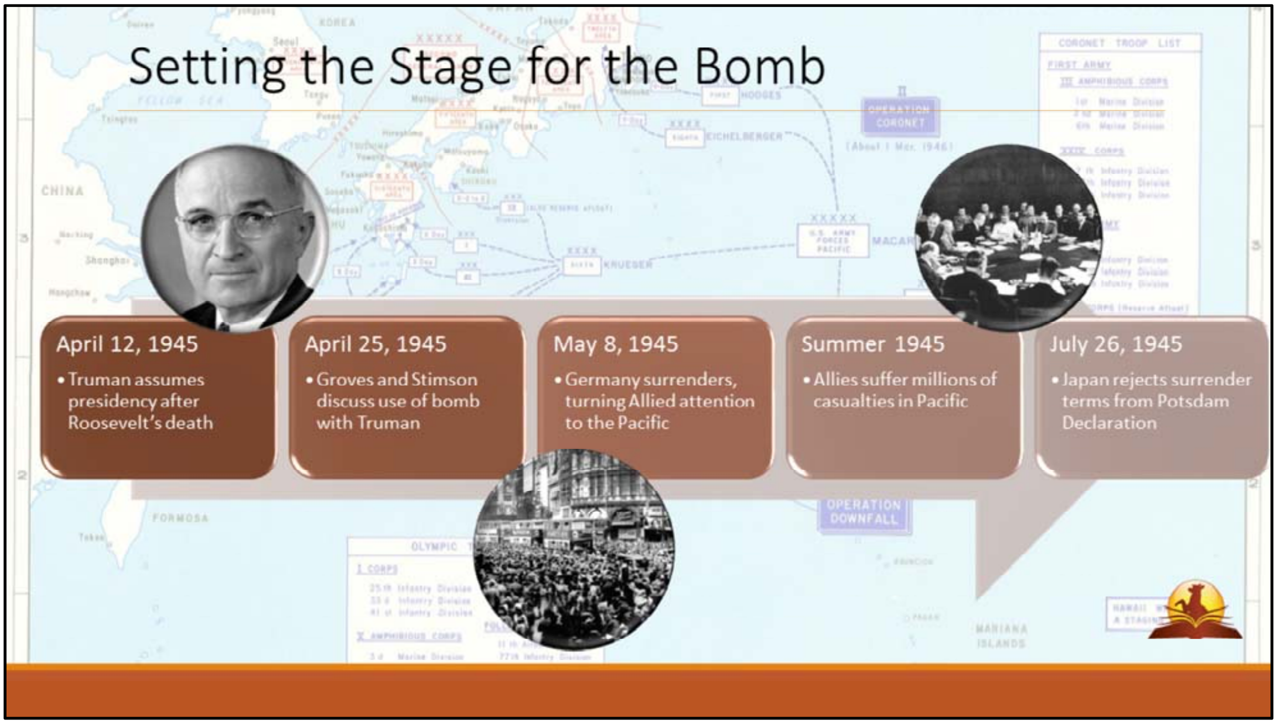


- The Trinity test would be conducted in the desert outside **Alamogordo, New Mexico.**
  - Oppenheimer used the codename "Trinity" after John Donne's poetry.
  - The bomb was nicknamed **"the gadget"** and supplied with plutonium from the **Hanford B reactor.**

Credit: "Trinity Test- Installation of Jumbo prior to the test" See page for author [Public domain], via Wikimedia Commons, https://commons.wikimedia.org/wiki/File%3ATrinity_Test_-_Installation_of_Jumbo_prior_to_the_test.jpg
Credit: "Trinity test (LANL)" By Federal government of the United States (http://www.cddc.vt.edu/host/atomic/testpix/) [Public domain or Public domain], via Wikimedia Commons, https://commons.wikimedia.org/wiki/File%3ATrinity_test_(LANL).jpg
Credit: "Trinity crater" By Federal government of the United States [Public domain], via Wikimedia Commons, https://commons.wikimedia.org/wiki/File%3ATrinity_crater.jpg



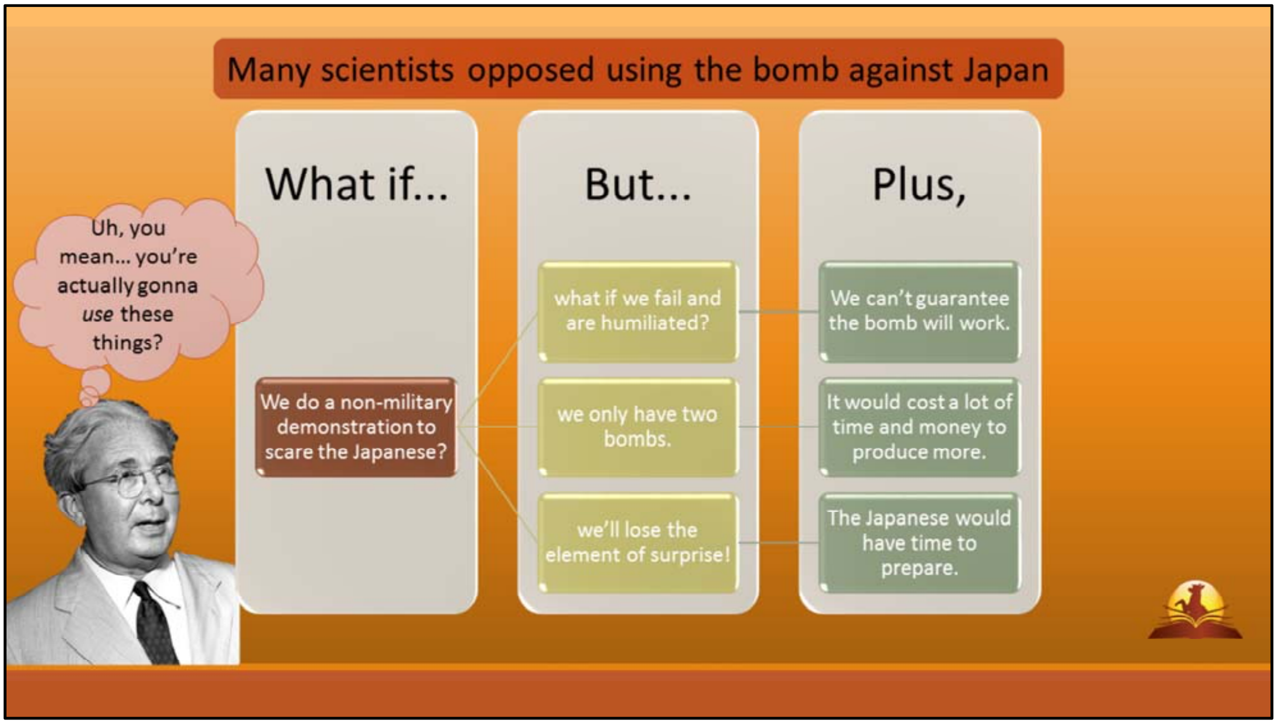
- After witnessing the incredible power of the explosion at the Trinity Test, Robert Oppenheimer would later say, “Now I am become Death, the destroyer of Worlds” from the *Bhagavad Gita*.
- Credit: https://www.youtube.com/watch?v=0w6LsP3UBeM



- April 12, 1945 – Harry S. Truman becomes president after Roosevelt dies.
    - A vice president of less than three months, Truman learns about the Manhattan Project.
- April 25, 1945 – General Groves and Secretary of War Stimson meet with Truman to discuss the possible use of the bomb in the war.
- May 7, 1945 – Germany surrenders and Allied attention turns to the Pacific front.
- Spring 1945 – Allies prepare for an invasion of Japan that seems inevitable.
    - Unwillingness to surrender and a favorable defensive geography lead to projected casualty rates in the millions for both sides.
    - Americans schedule the invasion to occur on November 1, 1945.
- July 26, 1945 – Japan rejects the Potsdam Declaration surrender terms.

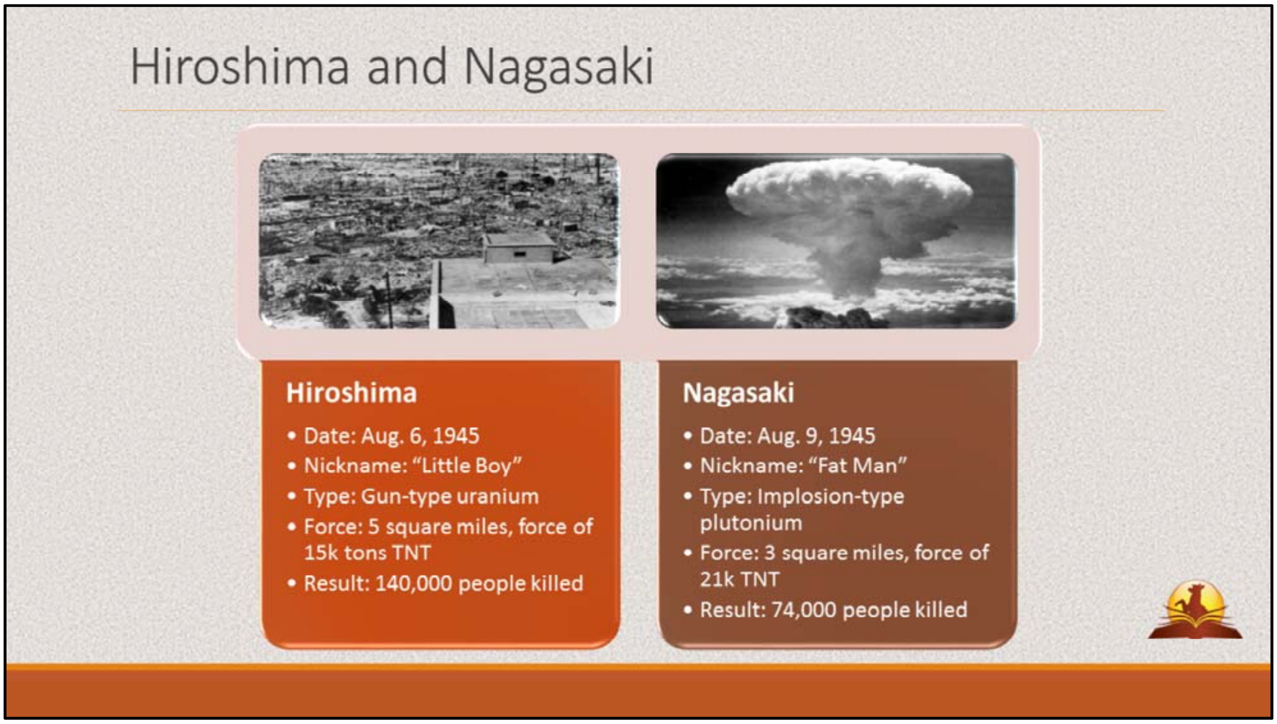
Credit: "Harry S. Truman" By Frank Gatteri, United States Army Signal Corps [Public domain], via Wikimedia Commons, https://commons.wikimedia.org/wiki/File%3AHarry_S._Truman.jpg
Credit: "VE Day Piccadily 1945" Mrjspence at English Wikipedia [CC BY-SA 3.0 (http://creativecommons.org/licenses/by-sa/3.0) or GFDL (http://www.gnu.org/copyleft/fdl.html)], via Wikimedia Commons, https://commons.wikimedia.org/wiki/File%3AVE_DAY_Piccadily_1945.jpg
Credit: "Operation Downfall – Map" Public Domain,

https://commons.wikimedia.org/w/index.php?curid=190543



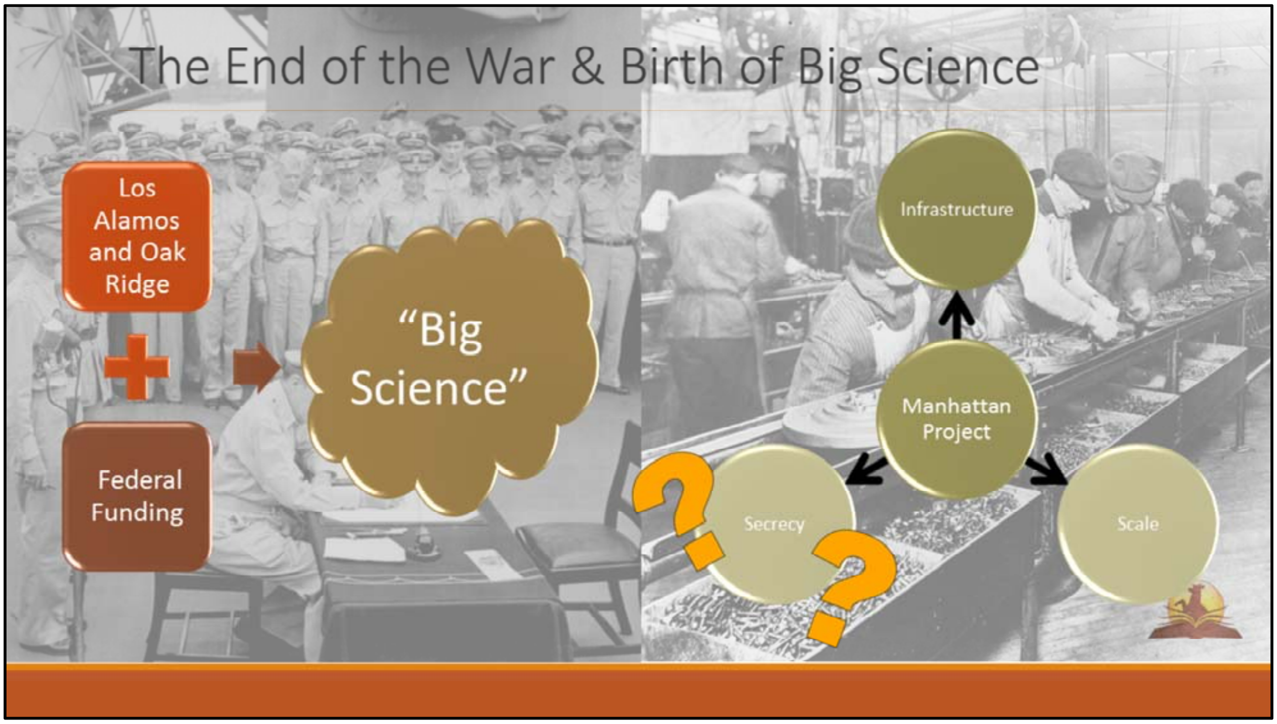
- More scientists began to grow **uncomfortable** with military use of the bomb.
  - In July 1945, **Leo Szilard** and 70 Manhattan Project scientists circulate a **petition** against its use on Japanese civilians.
  - Incoming **Secretary of State James Byrnes prevents** the petition from reaching the President.
- **Ernest Lawrence** proposes a non-military demonstration of the bomb to scare Japanese into surrender**.**
  - Reasons against this approach included**:**
    - **Potential failure/humiliation**
      - The bomb was still new, and it wasn't guaranteed that it would even work.
    - **USA only two bombs**
      - It would cost a lot of time and money to make more.
    - **Lose element of surprise**
      - The Japanese could be given time to prepare, potentially moving American POWs to potential bomb targets.
  - In the end, the **Scientific Advisory Panel** rejected the possibility of a demonstration.
- Potential targets for the bomb included***:***
  - Hiroshima – major port and military headquarters

- Kokura and Yokohama – centers of manufacturing
- Kyoto – later scrapped because of historical significance
- Nagasaki – critical seaport and industrial center



- **Hiroshima**
  - 90% of medical personnel were killed/injured in the initial blast, making the casualty rate even higher.
- **Nagasaki**
  - Although it was a bigger strength bomb, there was less damage because local geography contained the blast to a smaller area.

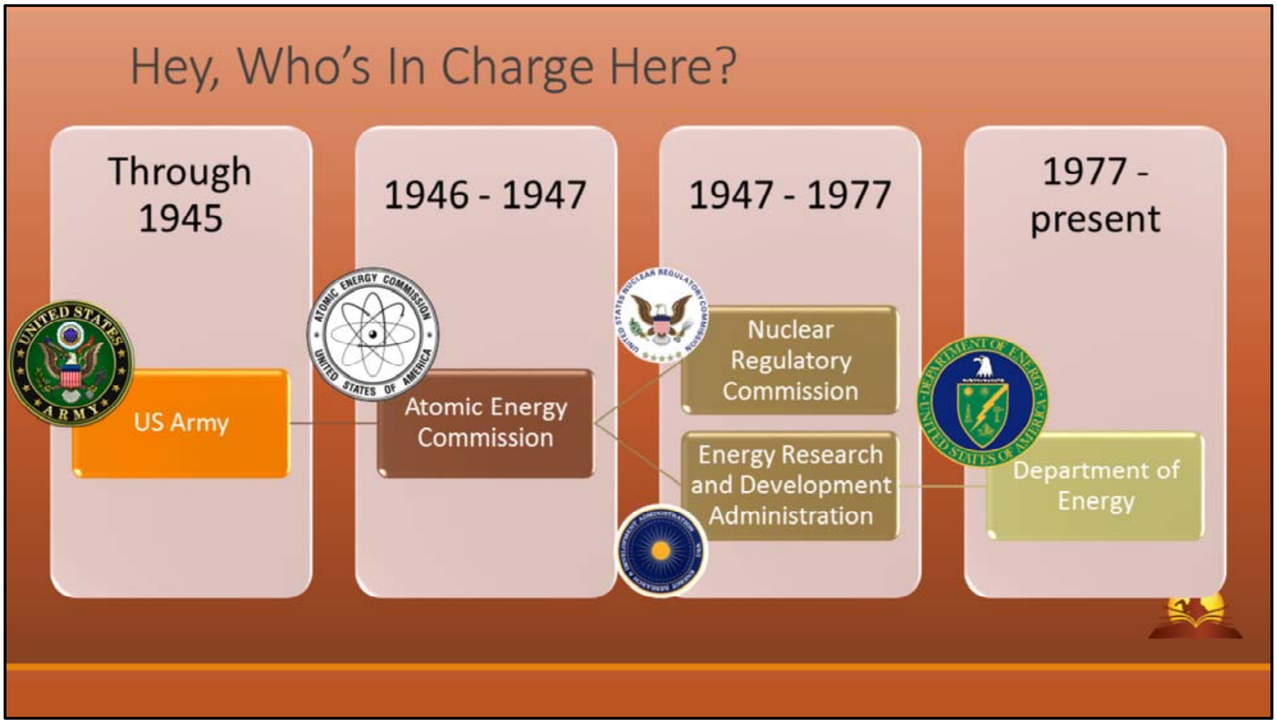
Credit: "AtomicEffects – Hiroshima" By US government, Post-Work: User:W.wolny [Public domain], via Wikimedia Commons, https://commons.wikimedia.org/wiki/File%3AAtomicEffects-Hiroshima.jpg
Credit: "Nagasakibomb" By Charles Levy from one of the B-29 Superfortresses used in the attack. [Public domain], via Wikimedia Commons, https://commons.wikimedia.org/wiki/File%3ANagasakibomb.jpg



- The **Manhattan Project** helped bring about the end of WWII and the birth of **"Big Science"** today.
    - It was a large-scale undertaking that quickly transformed knowledge about nuclear reactions to application.
    - Its impact lasted beyond just the development of the bomb.
- **Infrastructure**
    - The **Los Alamos** and **Oak Ridge** laboratories continued to be used for research, supported by federal funding.
    - "Big Science," termed by Alvin Weinberg of Oak Ridge National Laboratory, described the new kind of scientific research taking place.
- **Scale**
    - By the end of the Manhattan Project, it involved over **130,000 people** with a **$2 billion** budget.
    - This scale was comparable in size to the American automotive industry at the time.
- **Secrecy**
    - The project was kept a secret so well that many involved didn't know its final objective until the bombing of Hiroshima and Nagasaki.
- **End of WWII**
    - Japan **surrendered** on **August 15**, with the official surrender signed aboard the

USS *Missouri* on **September 2.**

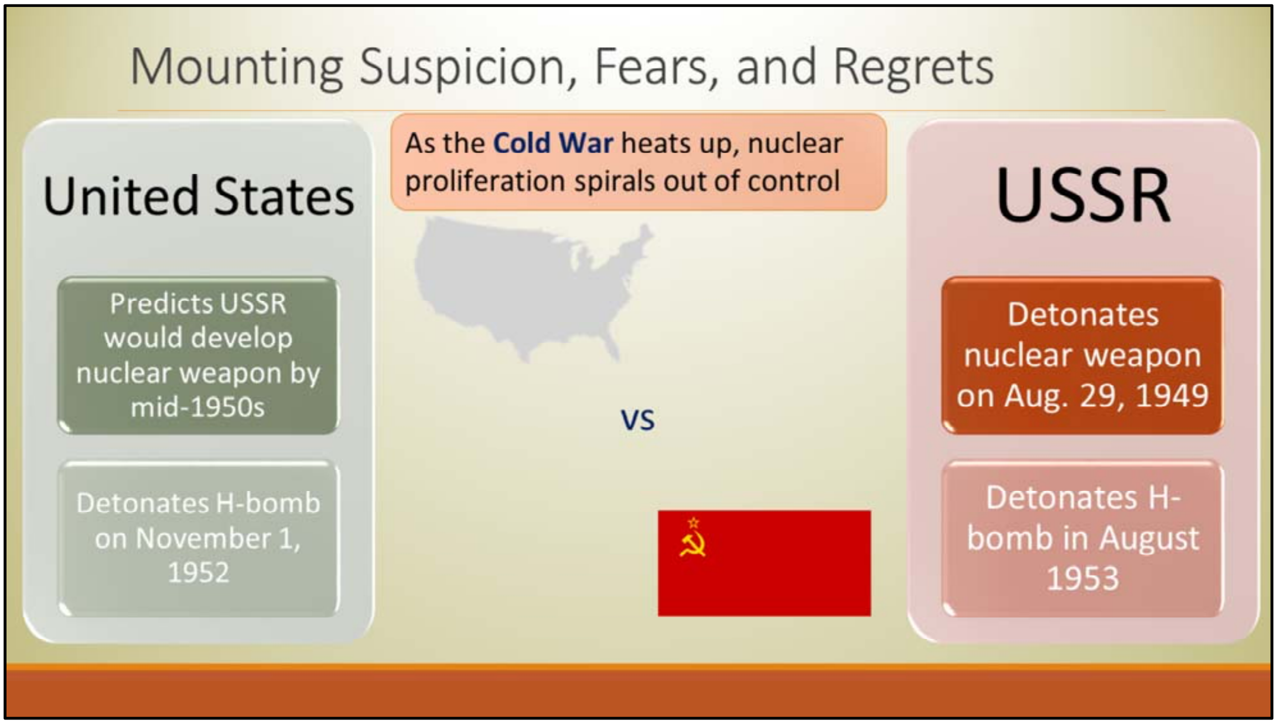
Credit: “Japanese surrender aboard USS Missouri” By United States Navy [Public domain], via Wikimedia Commons, https://commons.wikimedia.org/wiki/File%3AWw2-198.jpg
Credit: “Ford assembly line – 1913” See page for author [Public domain], via Wikimedia Commons, https://commons.wikimedia.org/wiki/File%3AFord_assembly_line_-_1913.jpg



- After WWII, there was debate over who should control the atomic energy program during peace.
    - **May-Johnson Bill** (October 1945)
        - Continued military authority over nuclear program
    - **McMahon Bill** (December 1945)
        - Transferred authority to civilians through the Atomic Energy Commission
        - Passed Congress as the **Atomic Energy Act of 1946**
- The **Atomic Energy Commission** gained control over the atomic program on January 1, 1947.
    - Included a five member civilian board
    - Aided by general advisory committee and military liaisons
    - Established the National Laboratory system to continue nuclear testing and expansion of U.S. nuclear arsenal
- 1947, the AEC is **abolished.**
    - Duties reassigned to the **Nuclear Regulatory Commission** and the **Energy Research and Development Administration**
- **Jimmy Carter** establishes the **US Department of Energy** in 1977, which continues to oversee the U.S. nuclear program today.

Credit: "Atomic Energy Commission" By Idaho National Laboratory (Atomic Energy

Commission) [CC BY 2.0 (http://creativecommons.org/licenses/by/2.0)], via Wikimedia Commons, https://commons.wikimedia.org/wiki/File%3AAtomic_Energy_Commission.jpg
Credit: “US-NuclearRegulatoryCommission-Seal” By U.S. Government [Public domain], via Wikimedia Commons, https://commons.wikimedia.org/wiki/File%3AUS-NuclearRegulatoryCommission-Seal.png
Credit: “ERDA logo” See page for author [Public domain], via Wikimedia Commons, https://commons.wikimedia.org/wiki/File%3AERDA_logo.jpg
Credit: “Carter cropped” By JimmyCarterPortrait.jpg: Department of Defense. Department of the Navy. Naval Photographic Center derivative work: wadester16 (JimmyCarterPortrait.jpg) [Public domain], via Wikimedia Commons, https://commons.wikimedia.org/wiki/File%3ACarter_cropped.jpg



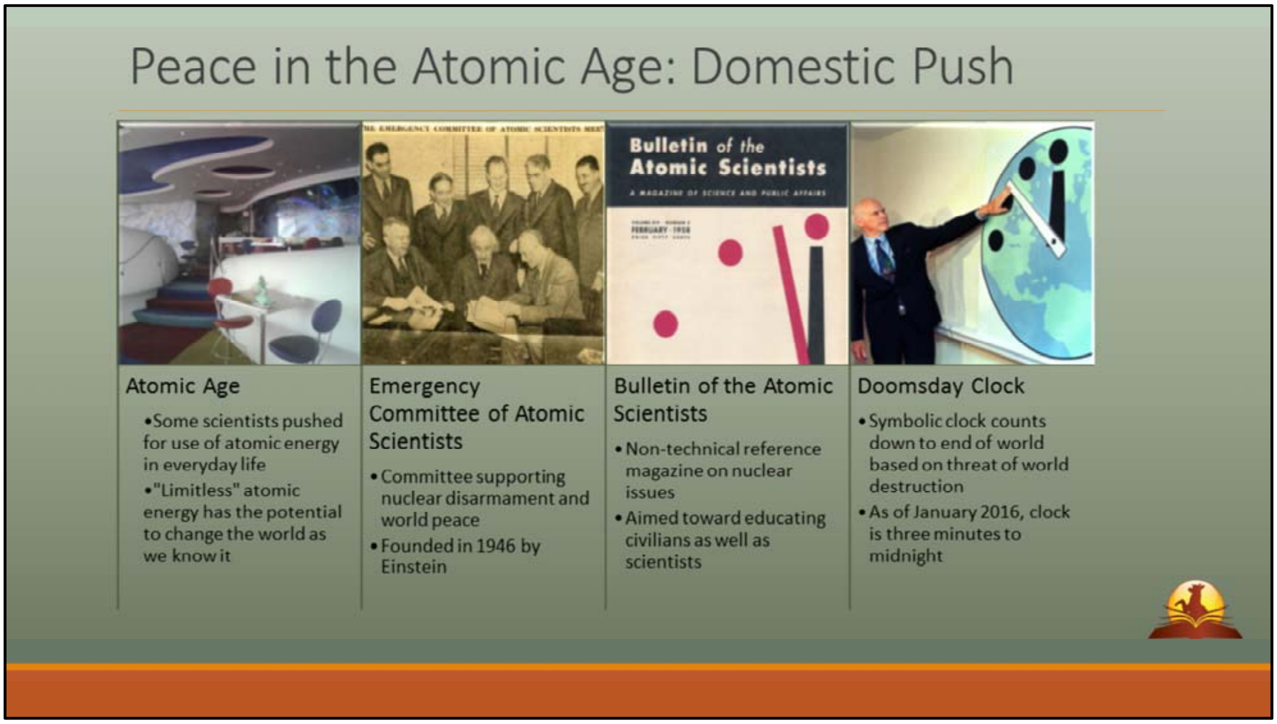
- At the end of WWII, the **USA** and the **Soviet Union** emerge as the two strongest powers*.*
  - **Tensions mount** and the Cold War intensifies.
  - The **nuclear arms race begins** as the two countries attempt to construct more nuclear weapons than the other*.*
  - Mutually Assured Destruction (MAD) becomes a possibility.
- Many scientists who had worked on the Manhattan Project now regretted their involvement.
  - In 1947**, Einstein** tells *Newsweek* "had I known that the Germans would not succeed in developing an atomic bomb, I would have done nothing."
  - **Oppenheimer** told Pres. Truman, "I feel I have blood on my hands."
  - Neither nation is willing to give up their arsenals.
  - Supporters of disarmament are often investigated or blacklisted
    - **Lewis Strauss** targets Oppenheimer and revokes his security clearance.

Credit: "Flag of the Soviet Union" By CCCP (http://pravo.levonevsky.org/) [Public domain], via Wikimedia Commons, https://commons.wikimedia.org/wiki/File%3AFlag_of_the_Soviet_Union.svg
Credit: "Blank US Map, Mainland with no States" Lokal_Profil [CC BY-SA 2.5 (http://creativecommons.org/licenses/by-sa/2.5)], via Wikimedia Commons,

https://commons.wikimedia.org/wiki/File%3ABlank_US_Map%2C_Mainland_with_no_States.svg
Credit: “Flag of the United States” By Dbenbenn, Zscout370, Jacobolus, Indolences, Technion. [Public domain], via Wikimedia Commons,
https://commons.wikimedia.org/wiki/File%3AFlag_of_the_United_States.svg

- With the proliferation of nuclear weapons, the threat of nuclear attack was forefront in public thought.
    - School children were taught to “duck and cover” in educational video.

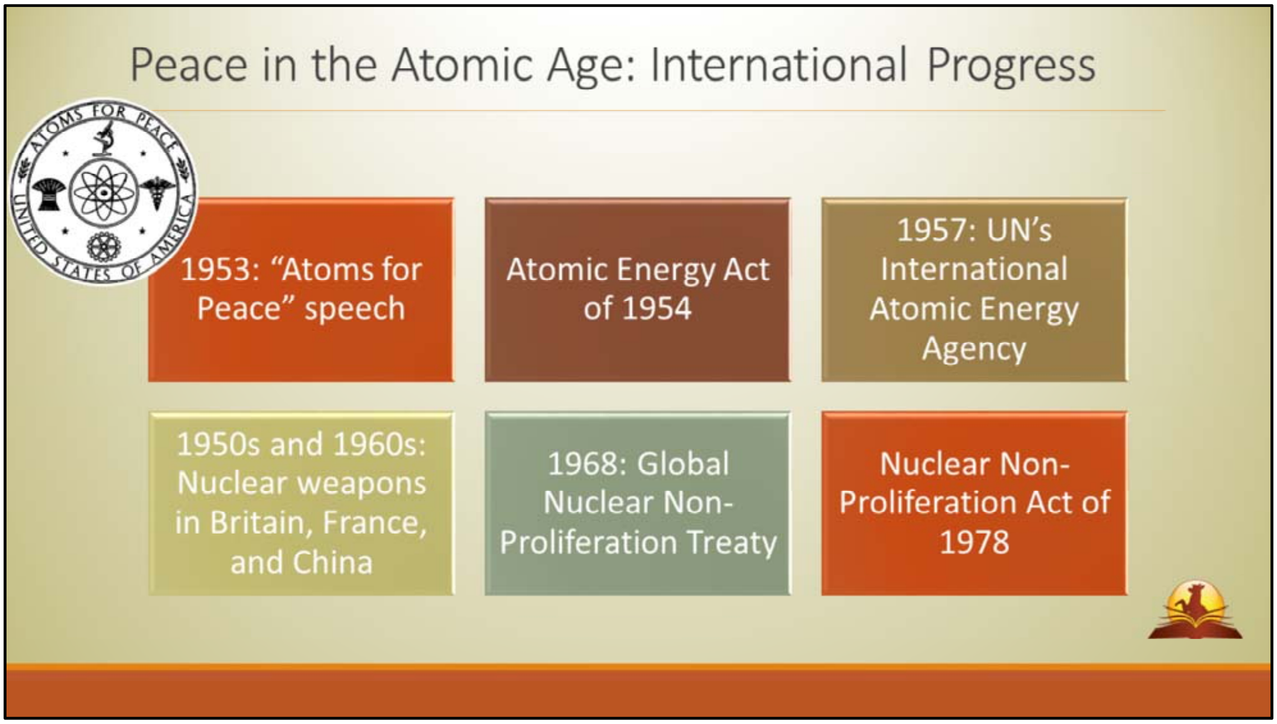
Credit: https://www.youtube.com/watch?v=89od_W8lMtA



- **Atomic Age**
  - William Laurence coined the term “Atomic Age.”
  - Atomic energy was predicted to change everyday life.
  - It offered a “limitless” source of energy that could be used for anything from atomic cars, medicine, to energy generation.
- Various scientists and civilians pushed for the use of atomic energy for **peaceful applications.**
  - Various organizations also attempted to inform the public about the dangers (and uses) of atomic energy.
- **Emergency Committee of Atomic Scientists**
  - Founded in 1946 by Albert Einstein
  - It supported nuclear disarmament and world peace.
  - Conducted speaking tours and published material for the public
- ***Bulletin of the Atomic Scientists***
  - Cofounded by Eugene Rabinowitch (1945), a Manhattan Project scientist
  - Sought to be a **reference magazine** used to inform the public, civilian and scientists alike, about nuclear weapons and global issues
- **Doomsday Clock**
  - Created by the *Bulletin* in 1947
  - The closer the clock is set to midnight, the bigger the threat of global

destruction.

- As of January 2016, the clock is three minutes to midnight.
- At its creation, it was seven minutes to midnight; it has been as close as two minutes and as far as 17 minutes.



- December 8, 1953 – President Eisenhower delivers "Atoms for Peace" address to UN General Assembly
    - Outlines commitment to peaceful applications of nuclear power
- Eisenhower signs Atomic Energy Act of 1954 into law
    - Relaxes 1946 Act to allow for civilian use of nuclear power plants
- July 27, 1957 – UN establishes International Atomic Energy Agency (IAEA)
    - Protects against misuse of nuclear material
- United Kingdom, France, and China develop nuclear weapons besides U.S. and USSR in the '50s and '60s
- July 1, 1968 – US and USSR join 60 other nations in signing Nuclear Non-Proliferation Treaty.
    - Prevents nations that don't have nuclear weapons from obtaining them
- President Carter signs Nuclear Non-Proliferation Act of 1978.
    - Outlines strategies against the spread of nuclear material for weapons
    - Allows foreign access for peaceful use such as power plants

Credit: "Atoms for Peace" By United States Atomic Energy Commission [Public domain], via Wikimedia Commons, https://commons.wikimedia.org/wiki/File%3AAtoms_For_Peace_symbol.png

Author and Editor

Your Name Here	Keely Saar
	
Led by Henri Matisse, the Fauves used intense "arbitrary color" that violated traditional notions of naturalism.	Cubist artists such as Pablo Picasso and Georges Braque attacked natural form by breaking figures up into multiple overlapping perspectives.