Nuclear Physics & Its Applications

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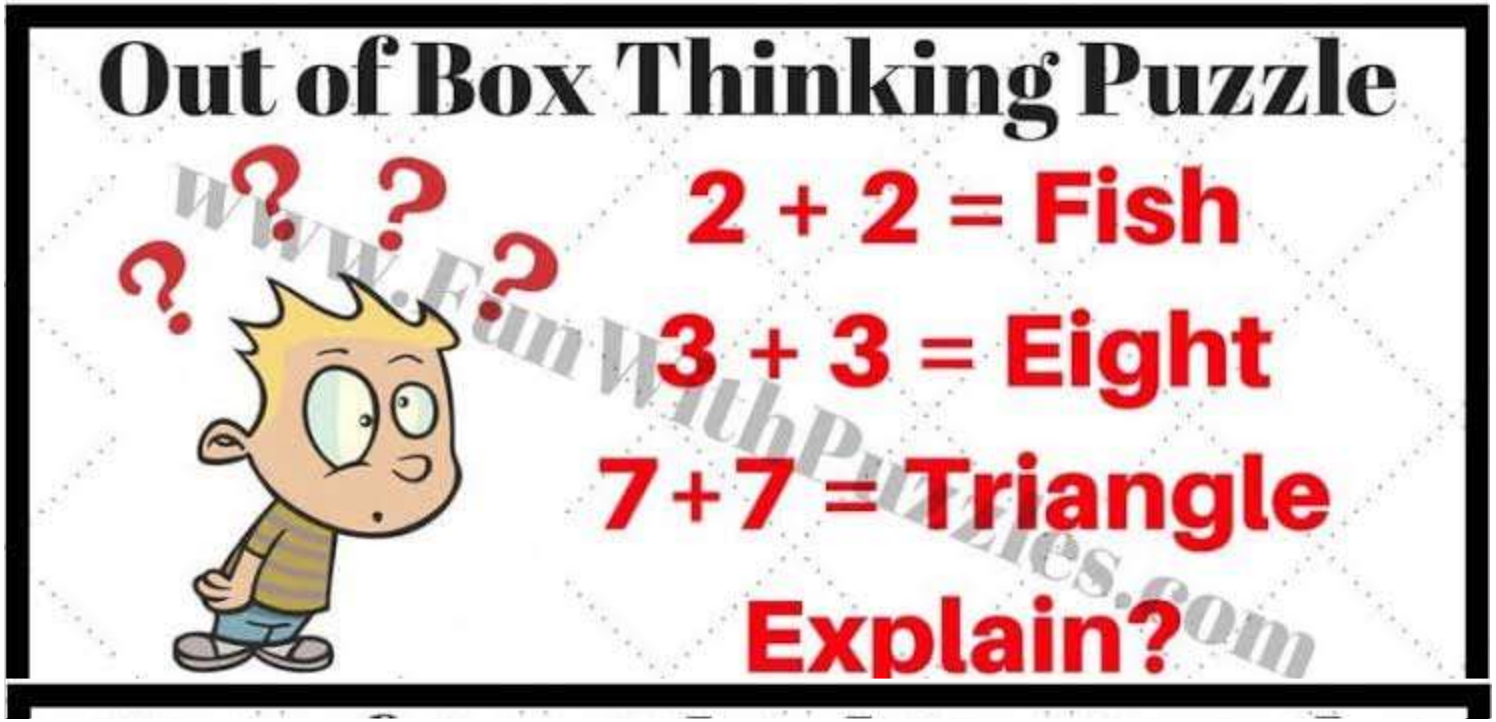
Scope

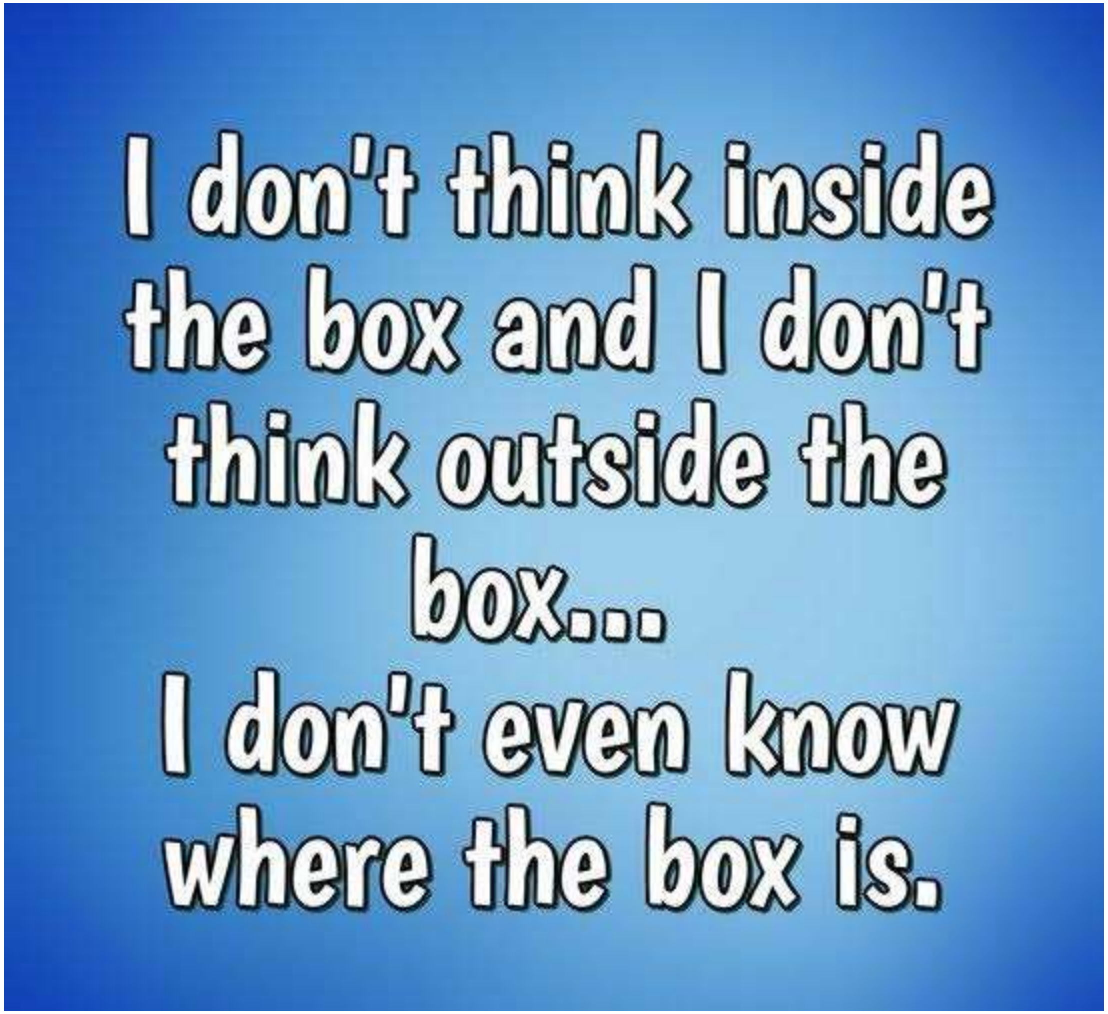
NUCLEAR PHYSICS

- Introduction
- Properties of nucleus
- Binding energy
- radioactivity
- Nuclear Stabiity

APPLICTIONS

- Radio Carbon dating
- Food & Agriculture
- Energy Production
- Medicine
- Radiation Hazards


Out of Box Thinking Puzzle
2 + 2 = Fish
3 + 3 = Eight
7+7 = Triangle
Explain?
www.FunWithPuzzles.com


I don't think inside
the box and I don't
think outside the
box...
I don't even know
where the box is.

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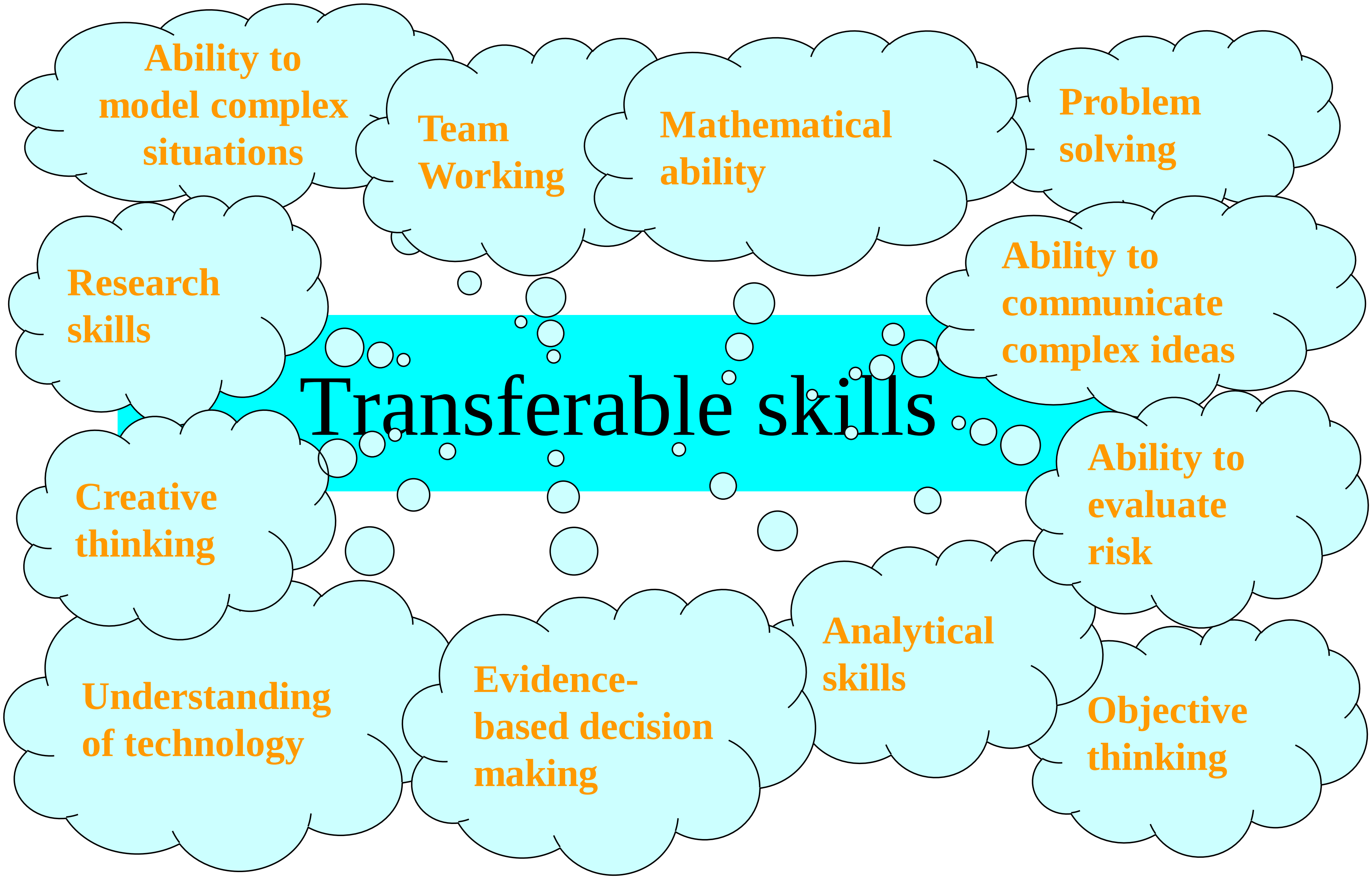
Careers from physics: Skills that studying physics develops



Nuclear Physics

Aim to answer

What are the Elementary Constituents of Matter?

How it can be useful to mankind and upliftment of society?

Atoms

- √ ***Elements*** are made of tiny particles called ***atoms***
- √ Atoms of same element are ***identical***.
- √ Atoms of ***different*** element are different.
- √ Atoms of one element can **combine** with atoms of other elements to form compound systems.
- Atoms cannot be divided into smaller particles - thought to be ***"indivisible"***

John Dalton

Nucleus

- ***Thomson*** (1897) discovers the electron, hence

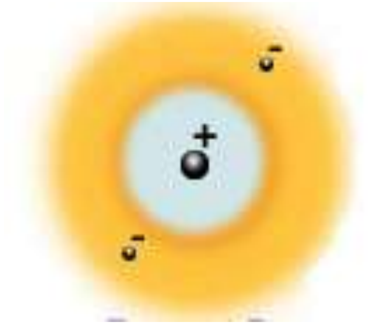
  atom = positive charge + electrons

- ***Rutherford*** (1910) fires radioactive particles at gold atoms: most of the particles go straight through, but occasionally some bounce back

  → **atoms have a hard core**

- ***New Picture:*** atom is dense ***nucleus*** surrounded by cloud of *electrons*

Ernest Rutherford



Types of Nuclei

Number of protons (atomic number) – Z.

Total number nucleons (nucleon number) – A.

$^{A}_{Z}X^{N}$

Number of neutros (N) = A-Z.

Different nuclei with the same number of protons – isotopes.

e.g. $^{16}_{8}O$ or $^{17}_{8}O$

Different nuclei with the same number of neutrons – isotones.

^{36}S, ^{37}Cl both contains 20 neutrons.

Different nuclei with the same number of nucleons – isobars.

^{40}Cl, ^{40}Ar, ^{40}K, and ^{40}Ca

Nuclei with $N_1 = Z_2$ and $N_2 = Z_1$ – mirror nuclei

C and ^{14}O: $J^{\pi} = (1/2)^{+}$

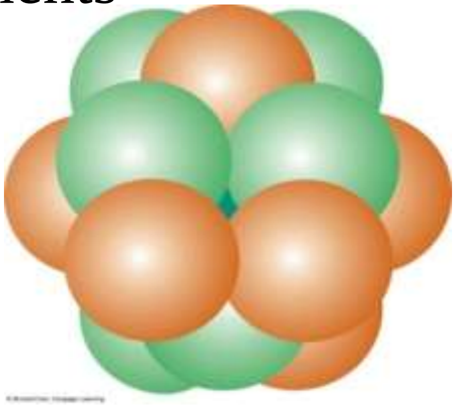
Properties of Nucleus

SIZE

- The radius of most nuclei is given by $\boldsymbol{R = R_0 A^{1/3}}$

  where R_0 is determined by Scattering experiments

  $\boldsymbol{R_0 = 1.2 \times 10^{-15}}$ **m (1.2 fm)**



- Common iron nuclei have mass number 56.

  The radius of an iron nucleus

$$R = R_0 A^{1/3} = (1.2 \times 10^{-15}\ \text{m})(56)^{1/3} = 4.6\ \text{fm}$$

Charge and Mass

Particle	Charge	Mass (kg)	Mass (u)	Mass (MeV/c^2)
Proton	$+e$	$1.672\,6 \times 10^{-27}$	1.007276	938.28
Neutron	0	1.675×10^{-27}	1.008665	939.57
Electron	$-e$	9.109×10^{-31}	5.486×10^{-4}	0.511

- Unified mass unit, u, defined using Carbon 12
- Mass of 1 atom of $^{12}C \equiv 12$ u

Density

- All nuclei have approximately the same density.

- The density of an iron nucleus

$$V = \frac{4}{3}\pi R^3 = \frac{4}{3}\pi(4.6\times10^{-15})^3 = 4.1\times10^{-43}m^3$$

$$\rho = \frac{m}{V} = \frac{9.3\times10^{-26}}{4.1\times10^{-43}} = 2.3\times10^{17}kg/m^3$$

- Nucleus is 10^{13} times the density of iron

let the volume of nucleus be =V, the mass of the nucleus be M, and the mass of nucleon = m

$V = \frac{4}{3}\pi r^3$

density $=\rho = \frac{M}{V}$,

$$M = \frac{4}{3}\pi r^3 \rho$$

As we know $r = r_0 A^{1/3}$

$$r^3 = r_0^3 A$$

$M = \frac{4}{3}\pi r_0^3 A\rho$-----------(i)

As we know mass of nucleon =mA----------(ii)

equating eqs (i) and (ii) we get

$m = \frac{4}{3}\pi r_0^3 \rho$

$\rho = \frac{3m}{4\pi r_0^3}$

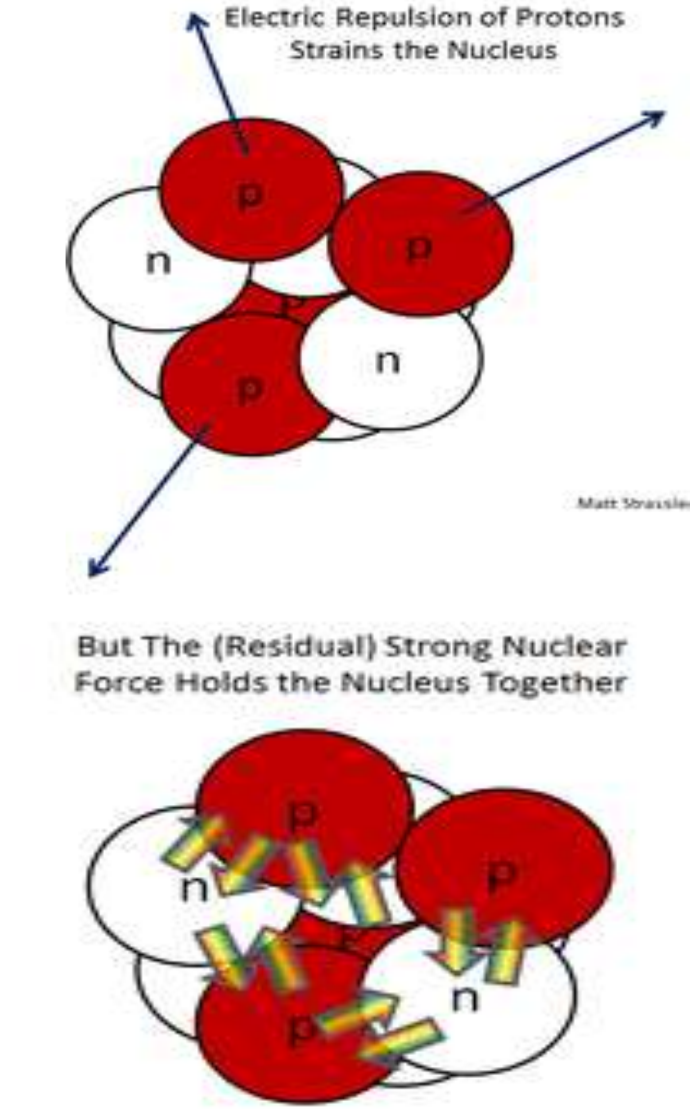
Hence nuclear density is independent to mass number (A).

Magnetic Moment

- Every nucleon has its **own** spin
- Magnitude of the total **angular momentum J** is quantized as:
- $$J = \sqrt{j(j+1)}\,\hbar$$
- When *A* is even, *j* is an integer, but when *A* is odd, *j* is a half-integer.
- Nuclear angular moment is a **magnetic moment**
- Analogous to Bohr magneton, the quantity of **nuclear magneton** is $$\mu_n = \frac{e\hbar}{2m_p}$$
- Magnetic moment for the **proton** is $$\left|\mu_{sz}\right|_{proton} = 2.7928\mu_n$$
- Surprisingly, for a **neutron** it is non-zero $\left|\mu_{sz}\right|_{neutron} = 1.9130\mu_n$

Nuclear Force

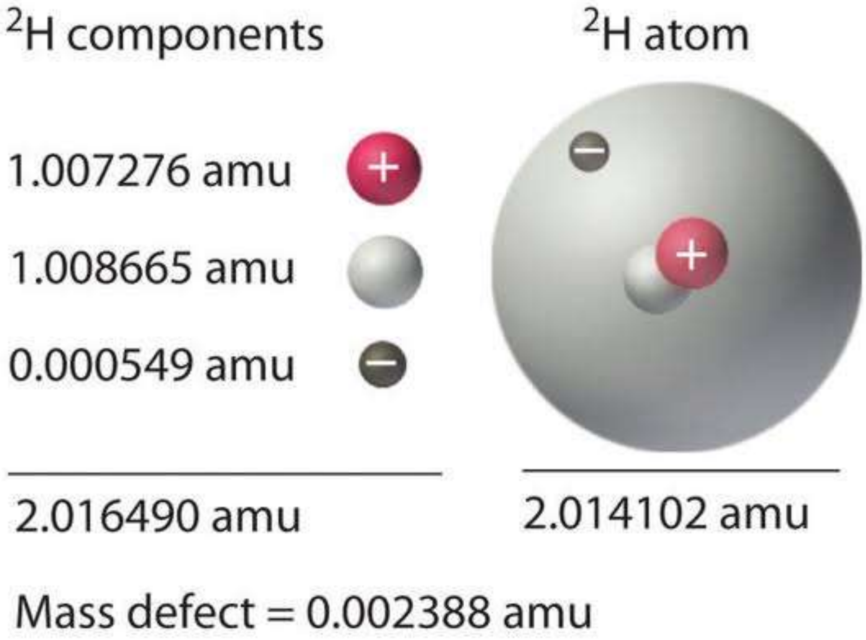
- **Charge Independent**
- **Short range**
- The lack of long-range interaction is called ***saturation***
- The electromagnetic force and gravity **do not** show such saturation.
- It favors binding of ***pairs*** of protons or neutrons with opposite spins and with ***pairs of pairs***



Mass Defect

- Total mass of nucleus is **less than** combined mass of individual nucleons

- Difference is called as **mass defect**
- Mass of an **iron nucleus** $m = (56\text{ u})(1.66\times10^{-27}\text{ kg}) = 9.3\times10^{-26}\text{ kg}$

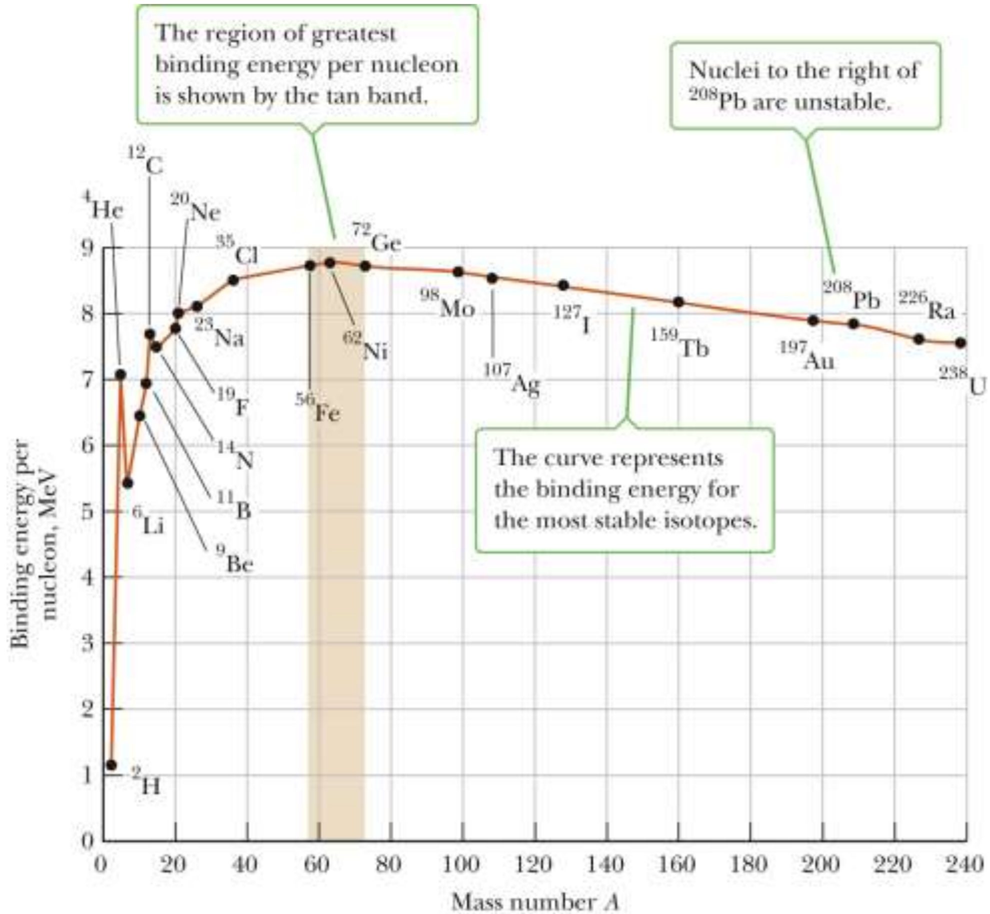


Binding Energy

- **Energy required** to separate nucleus into its constituents

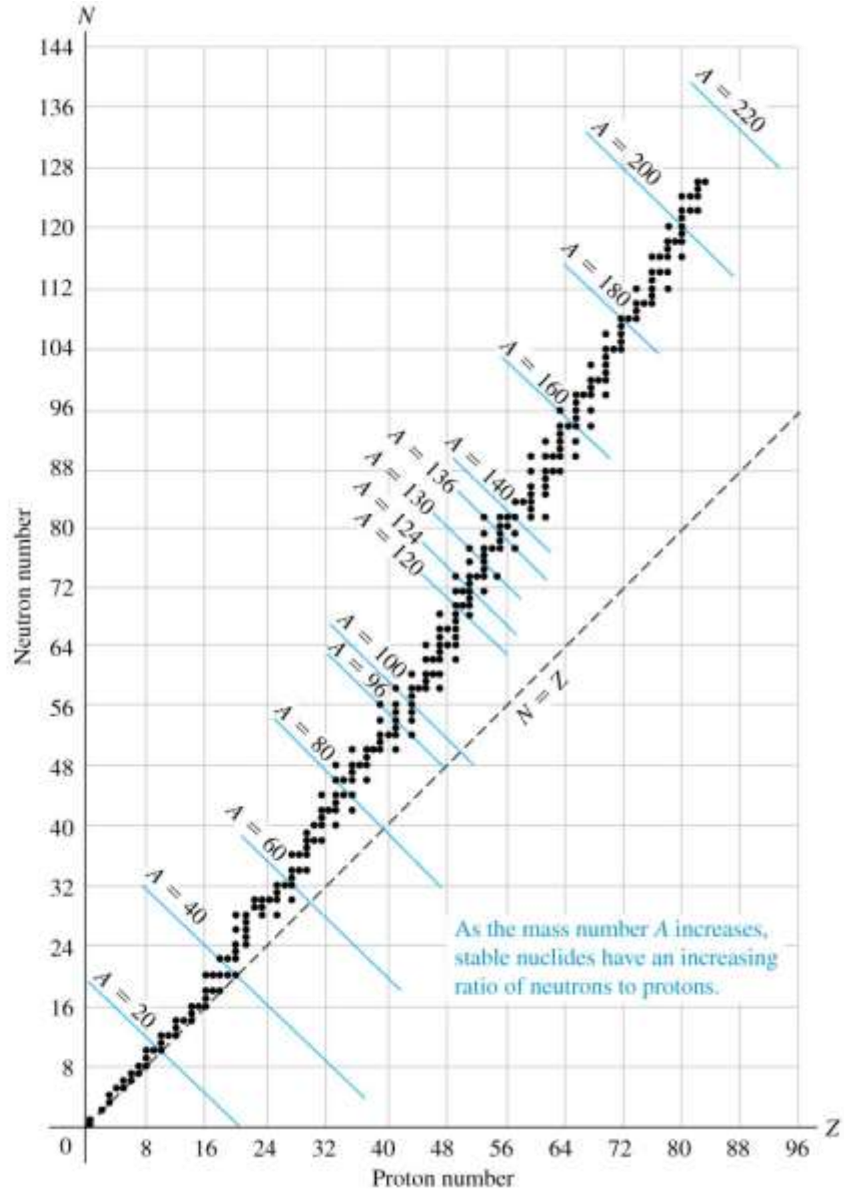
$$\Delta m = \left(\sum m_i\right) - m_A$$

Binding Energy vs. Mass Number



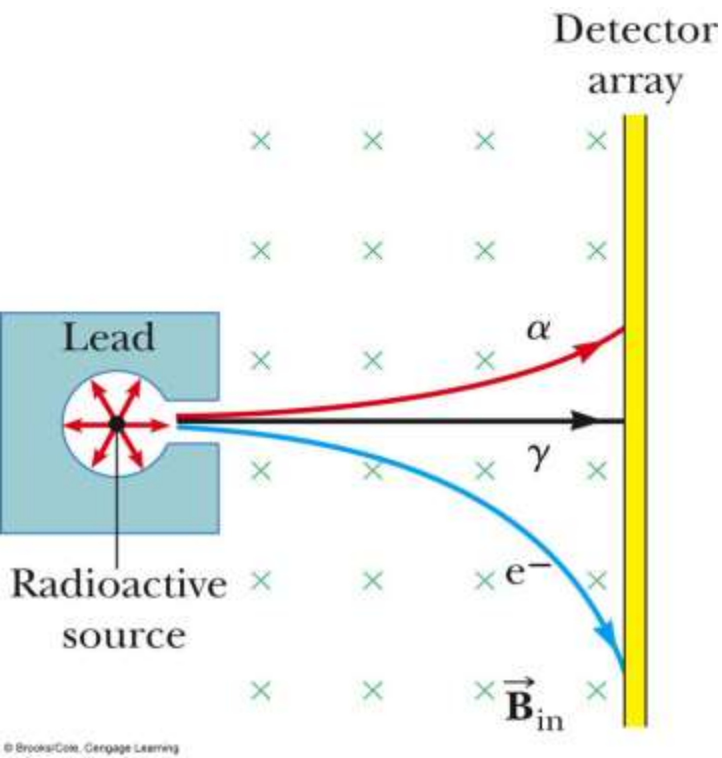
Segrè chart

- Segrè chart showing ***N* versus *Z*** for stable nuclides.
- ***Radioactivity*** is the decay of unstable nuclides
- There are no stable nuclides with *A* = 5 or 8. The $^{8}_{4}Be$ nuclide decays immediately into two He nuclei.
- The highest ***A* is 209**. There are so-called **islands of stability** above this.



Radioactivity

- Unstable nuclei decay to more stable nuclei



- Alpha decay

$$^{226}_{88}\mathrm{Ra} \rightarrow {}^{222}_{86}\mathrm{Rn} + {}^{4}_{2}\mathrm{He}$$

$$^{A}_{Z}\mathrm{X} \rightarrow {}^{A\text{-}4}_{Z\text{-}2}\mathrm{Y} + {}^{4}_{2}a$$

- Beta decay

$$^{14}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} + {}^{0}_{-1}\mathrm{e}$$

$$^{A}_{Z}\mathrm{X} \rightarrow {}^{A}_{Z+1}\mathrm{Y} + {}^{0}_{-1}\beta$$

- Gamma decay: Nucleus left in an excited state after emission of alpha or beta. No change in *A* or *Z*.

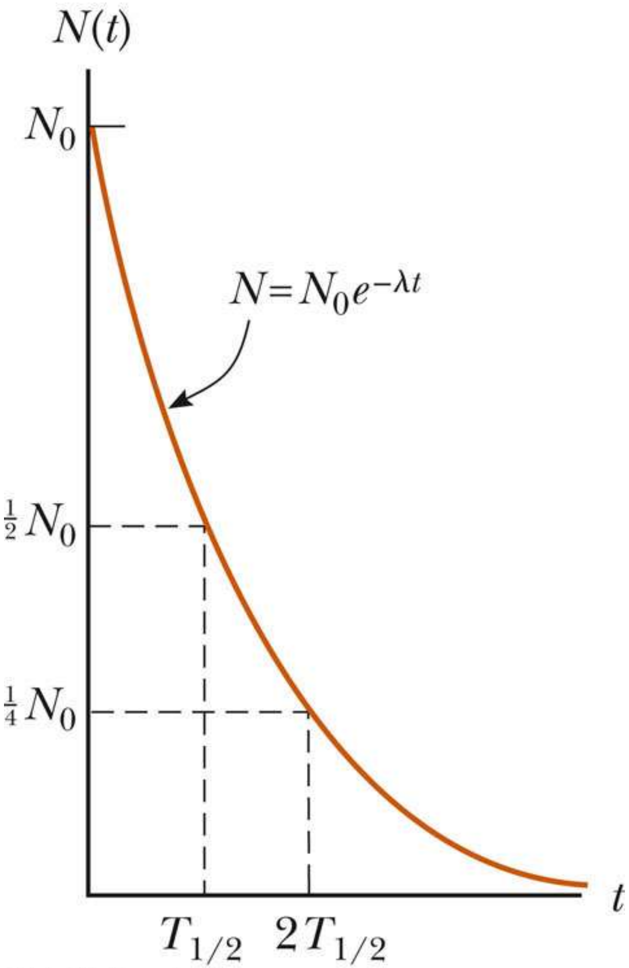
Decay Constant and Half-Life

- Decay rate (activity) is **number of decays per second**
- Unit is **Curie** (Ci) or **Becquerel** (Bq)
- Half-life is time it takes **for half of the sample** to decay

$$1\ \text{Ci} = 3.7\times 10^{10}\ \text{decays/s} \qquad 1\ \text{Bq} = 1\ \text{decay/s}$$

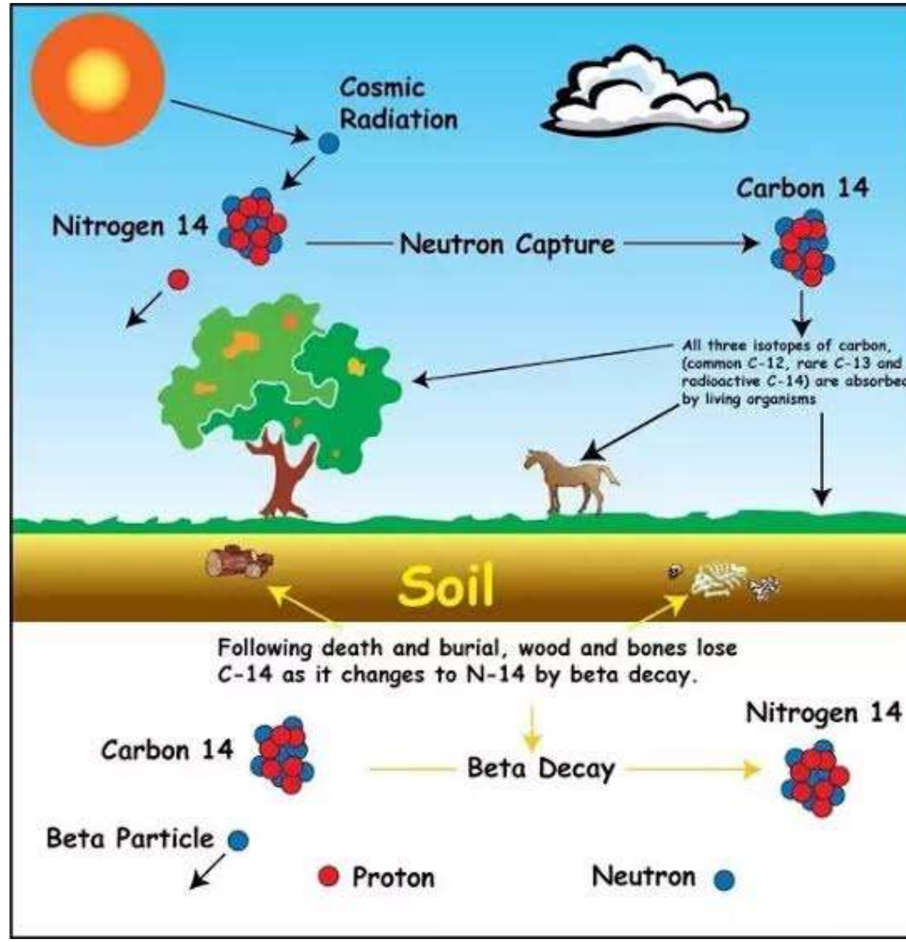
$$R = \left|\frac{\Delta N}{\Delta t}\right| = \lambda N \qquad N = N_0 e^{-\lambda t}$$

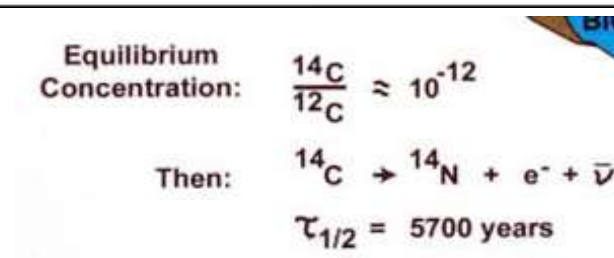
$$T_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda}$$



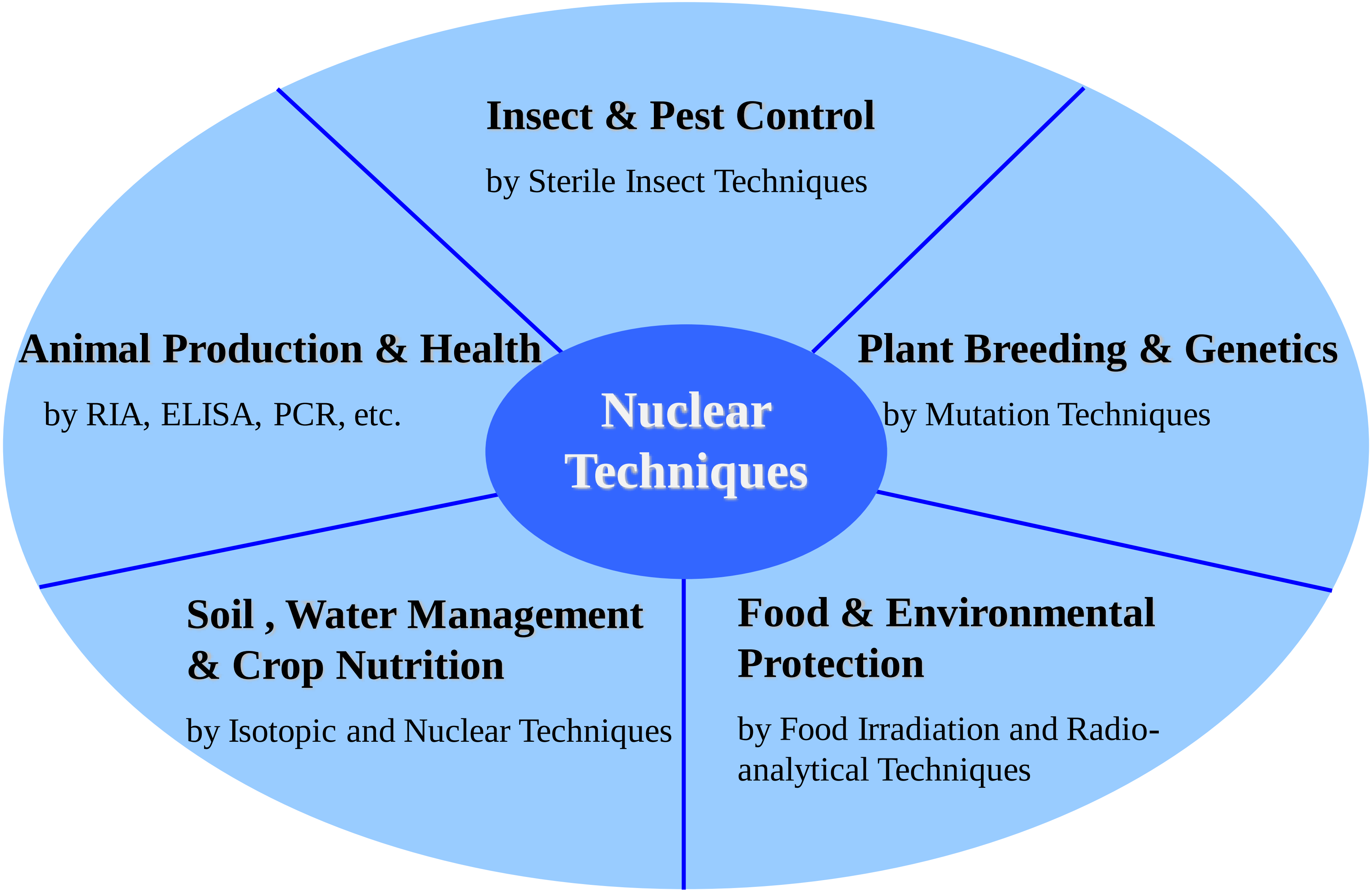
Radioactive Carbon Dating

- Cosmic rays create ^{14}C from ^{14}N
- Ratio of $^{14}C/^{12}C$ remains constant (1.3×10^{-12}) in atmosphere
- Living organisms **have same ratio**
- Dead organisms **do not absorb C** from atmosphere
- $\boldsymbol{T_{1/2}}$ **of ^{14}C = 5730 yr**





Application in Food &Agriculture



Crop improvement by mutation Techniques

- **Spontaneous mutation** rate is $1\times10^{-8} \sim 1\times10^{-5}$
- **Radiation** can cause genetic changes in living organisms and increase mutation rate up to $1\times10^{-5} \sim 1\times10^{-2}$
- Induced mutation is useful for **crop improvement**
- Induced mutants are **not GMOs**, as there is no introduction of foreign hereditary material into induced mutants

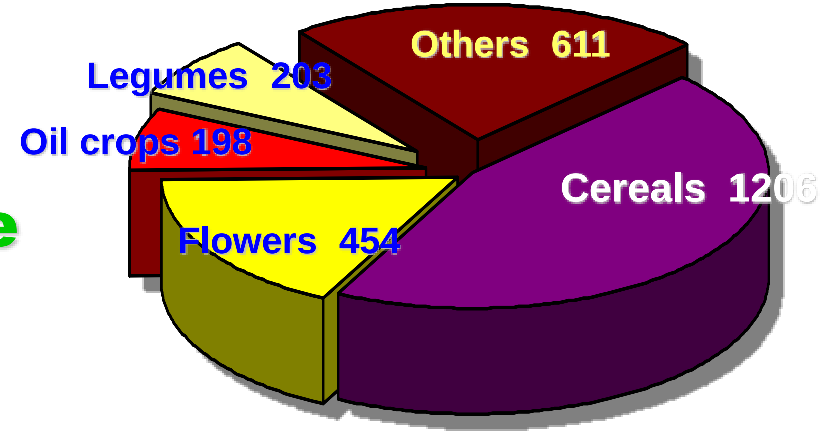
Mutation Techniques

- Improving crop cultivars
- Enhancing biodiversity
- Increasing farmer's income

Total Number : 2672

Plant Species : 170

(2016)



MUTANT VARIETIES

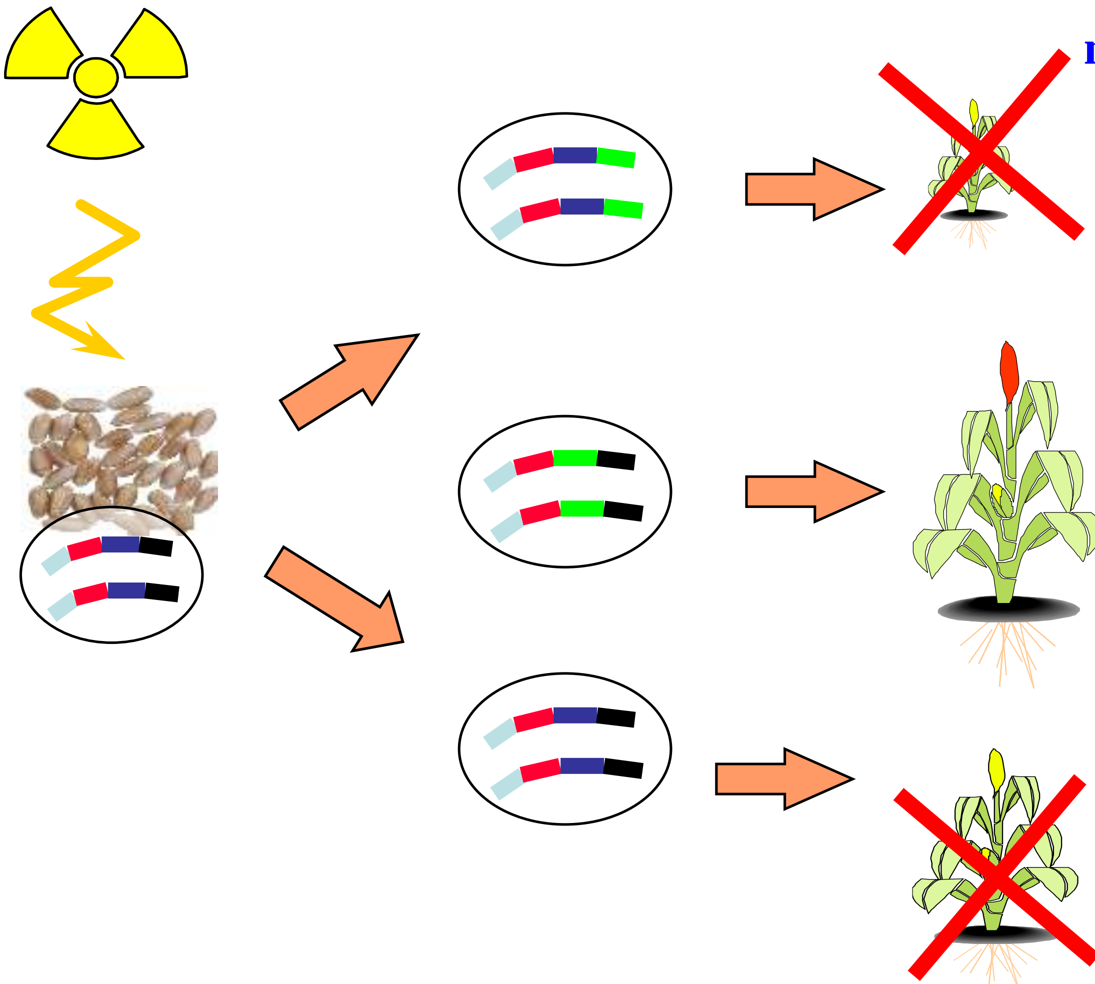






Sources: FAO/IAEA Mutant Varieties Database

Mutation Technique



negative mutation

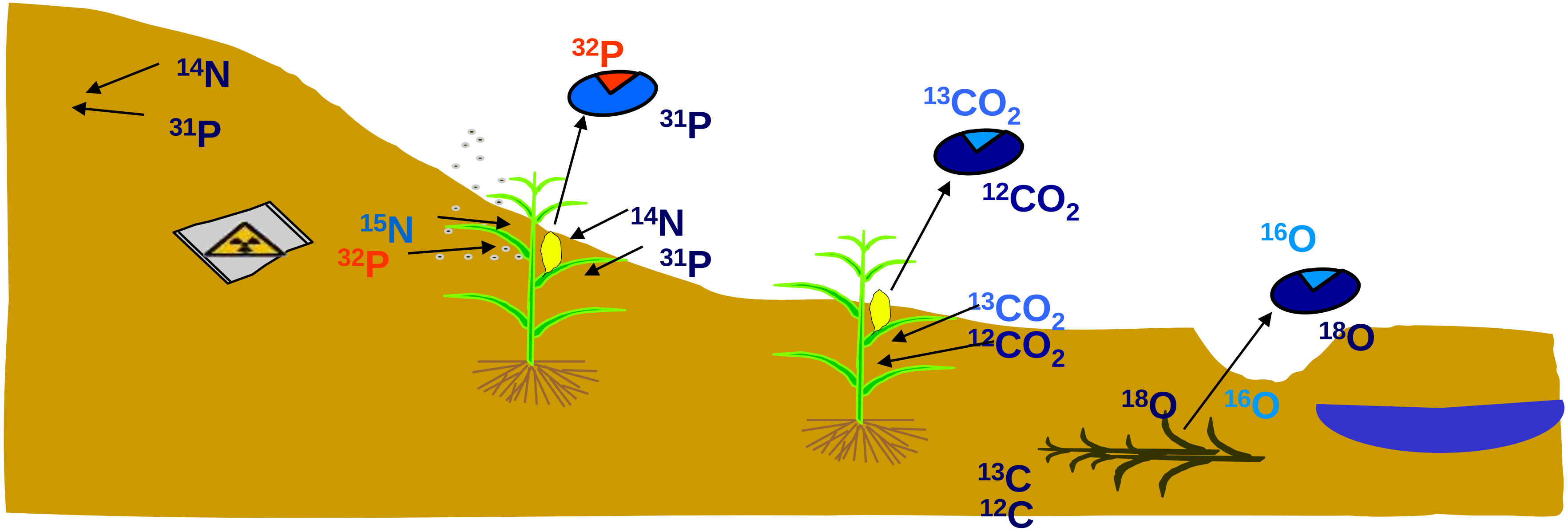
Mutant cultivars

- **Higher yielding**
- **Disease-resistance**
- **Well-adapted**
- **Better nutrition**

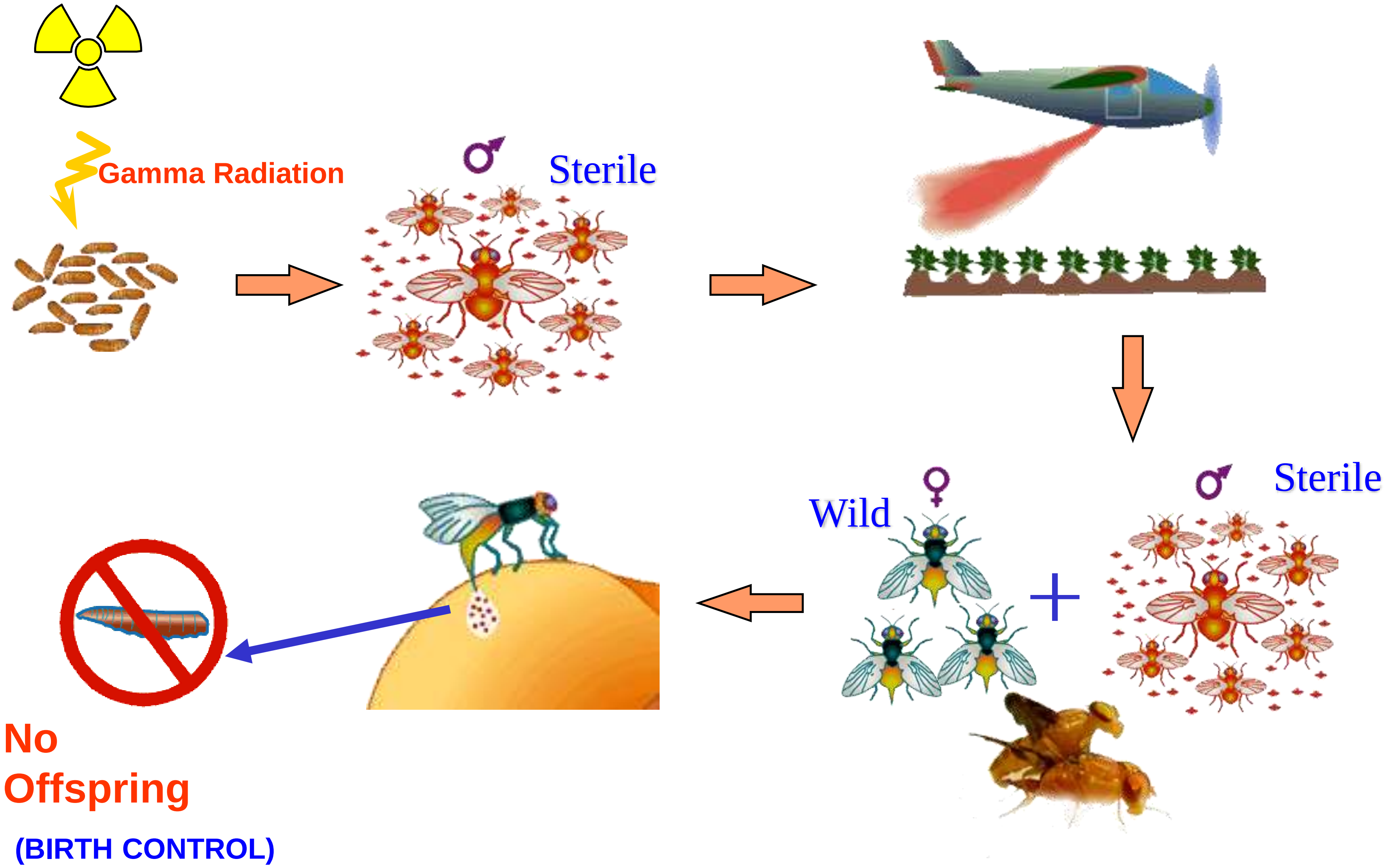
no mutation

Soil-Water-Crop Nutrition Management

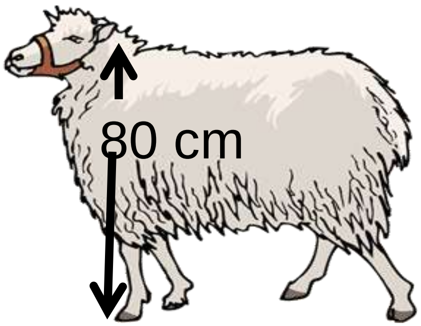
- Isotopes can be used as **tracers in soil** and water management & crop nutrition.
- Isotopes can be either stable or radioactive
  - **stable isotopes:** different masses (^{18}O and ^{16}O).
  - **radioactive isotopes:** radioactive decay (^{32}P).



Insect & Pest Control by SIT

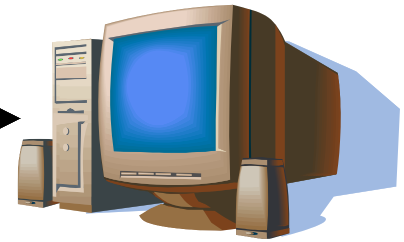


Animal Production & Health

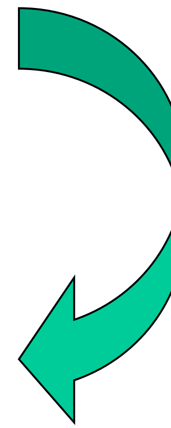


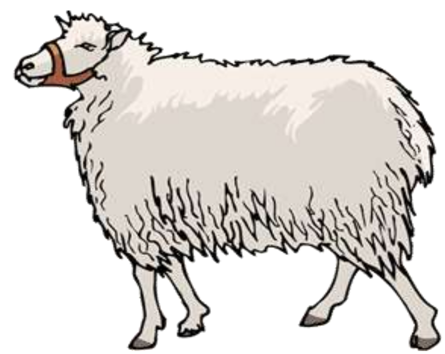
Measure productivity

Sample DNA
(blood, hair, milk)



Identify superior
genes

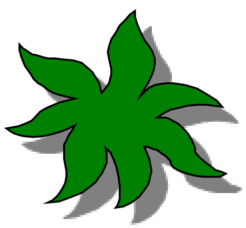




Develop nuclear-related
test for selection and breeding

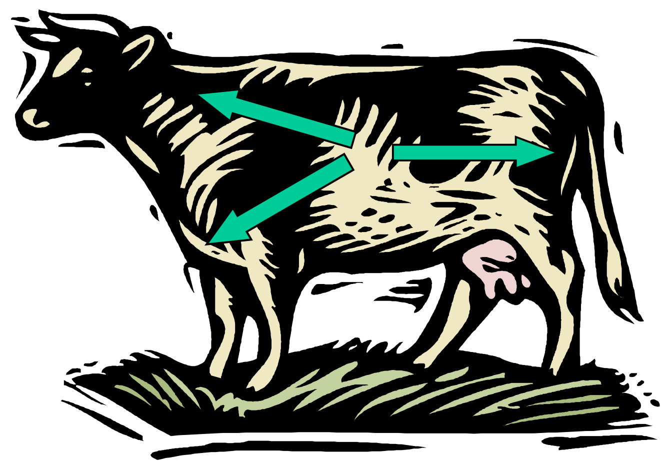
Efficient Utilization of Locally Grown Feeds

Local
plant materials



Label with isotope
e.g. ^{15}N, ^{13}C18

Feed to
livestock

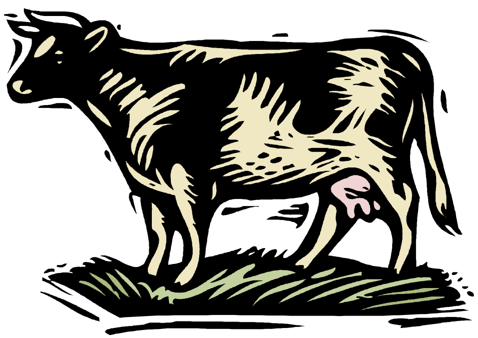


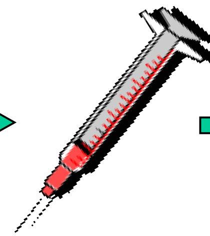
Nutrients dispersed
throughout body

Tissue sampling to
assay isotope
distribution

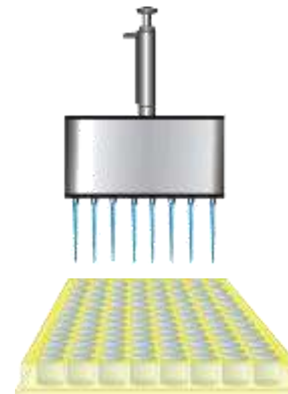
Isotopes in Disease Management

Is this cow vaccinated?





Take blood



Run ELISA

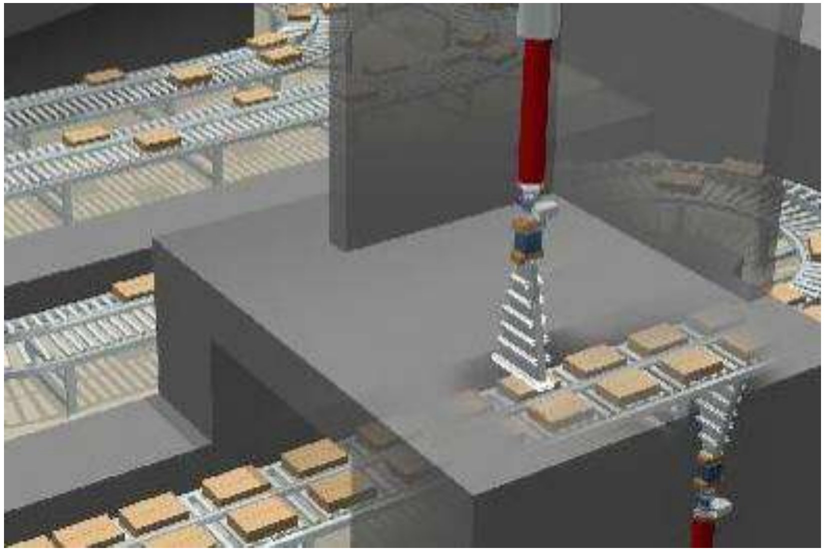
Analyze the result

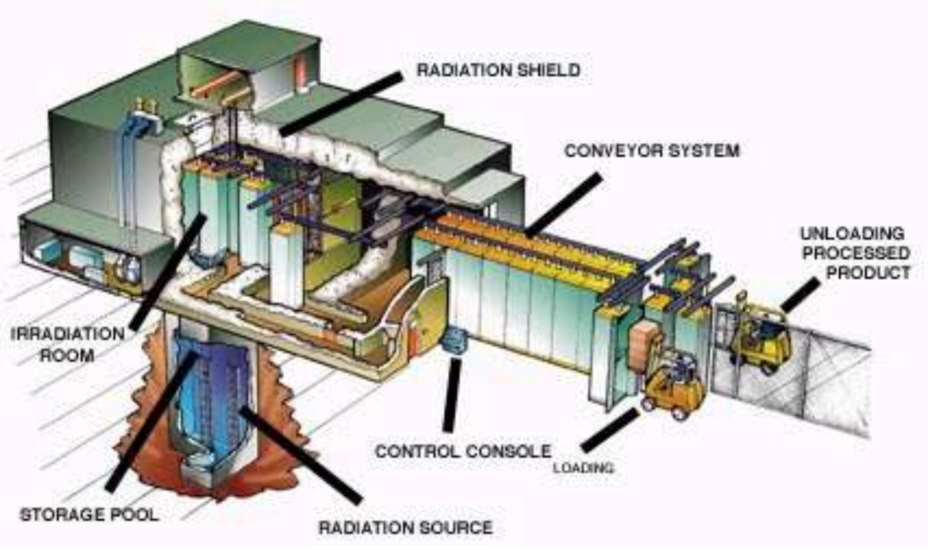
Vaccinate

Protected

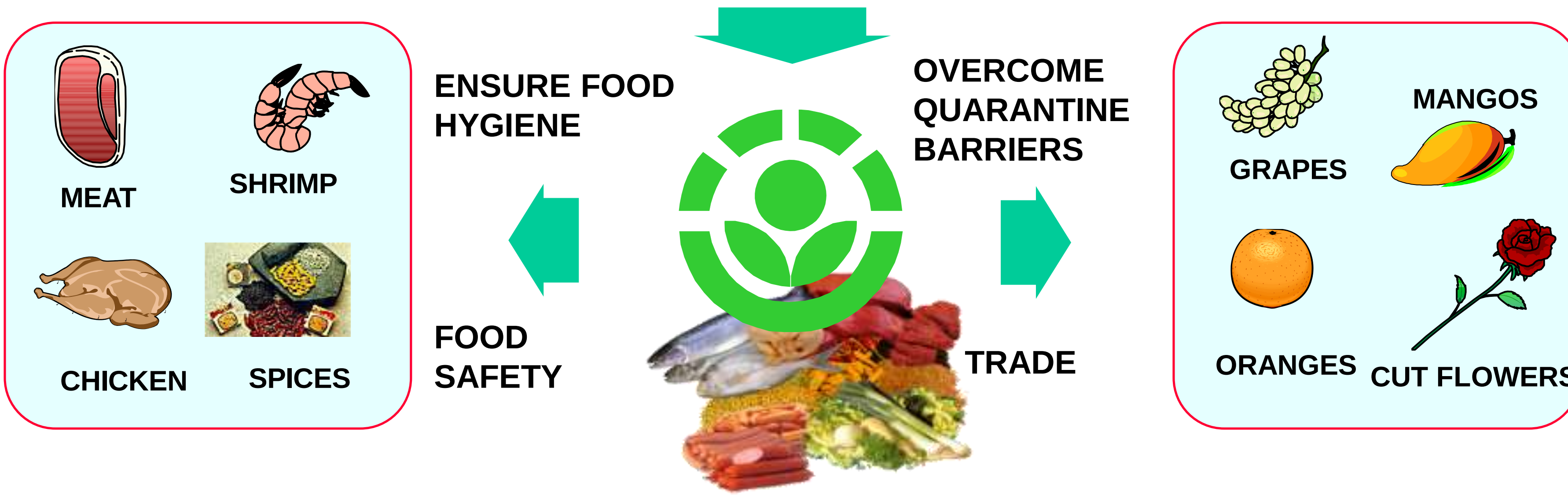
Food Irradiation

- Gamma Rays
- Electron Beams
- X-rays





Codex General Standard for Irradiated Foods



Scope of Food Irradiation

- More than **60 countries** permit the application of irradiation in over 50 different foods
- An estimated **500,000 tons** of food are irradiated **annually**
- **Cobalt-60** irradiation facilities are used to treat foods worldwide
- More and **more countries** accept the use of irradiation as a phytosanitary measure

Energy

- Energy is defined as a capacity to do work.
- Law of Conservation of states that energy can neither be created nor be destroyed.
- Transformed from one form to other.
- Forms of energy: Heat, light, sound, electrical etc.

Need for Electrical Energy

- In the modern era, electrical energy is a part and partial of our daily life.

- Electricity is essential for factories, computers, laboratories, home appliances , hospitals ….

"There is no power as costly as no-power" – Homi Bhabha

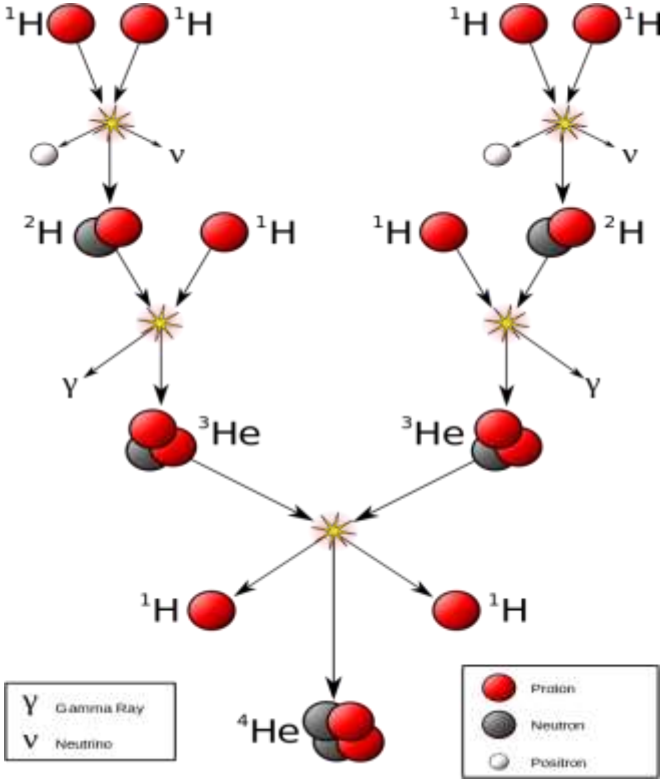
Methods to Produce Electricity

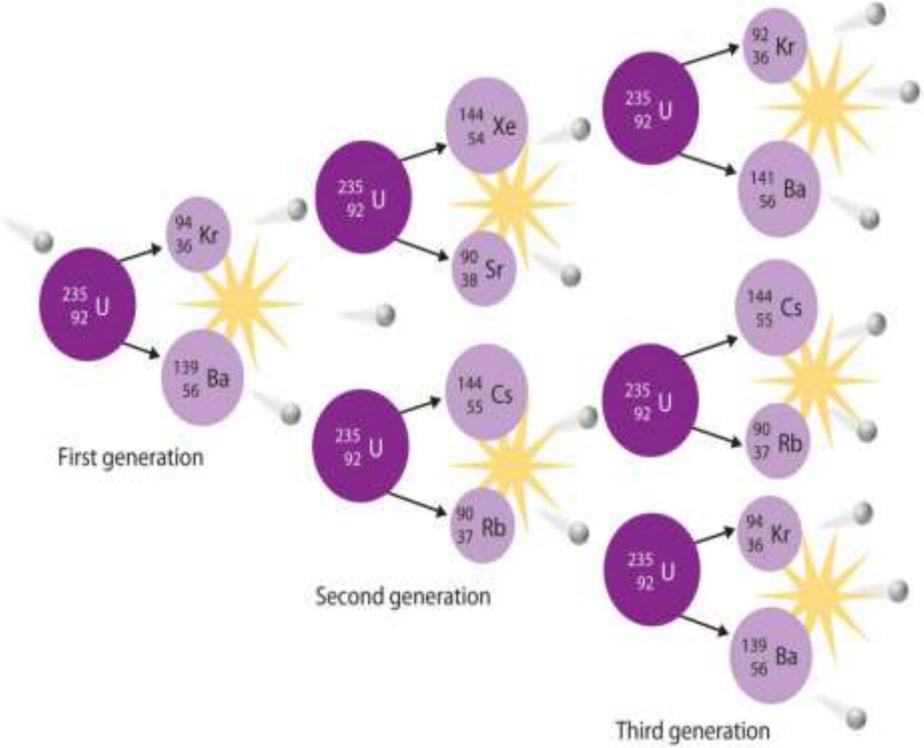
- **Conventional methods**

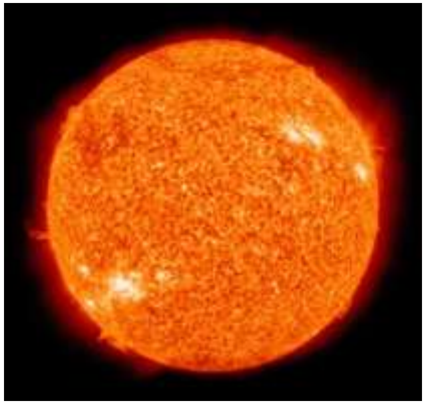
  - Coal
  - Petroleum,
  - Natural gas
  - Hydel Power

- **Non-conventional methods**
  - Solar energy
  - Tidal energy
  - Geo-thermal energy
  - Wind energy
  - Nuclear energy

Fusion and Fission







Why Nuclear Energy?

- Nuclear energy produces electricity from heat through a process called **fission**.

- Nuclear power plants use $_{92}U^{235}$ as **fuel**.

Requirement of natural uranium for a 1000 MW Nuclear Power Plant: ~ 160 t /Year.

Requirement of coal for a 1000 MW Coal fired plant ~ 2.6 million t / Year (i.e. 5 trains of 1400 t /Day)

Fission of 1 gm of U-235 per day generates ~1 MW Power

$E = \Delta m c^2$

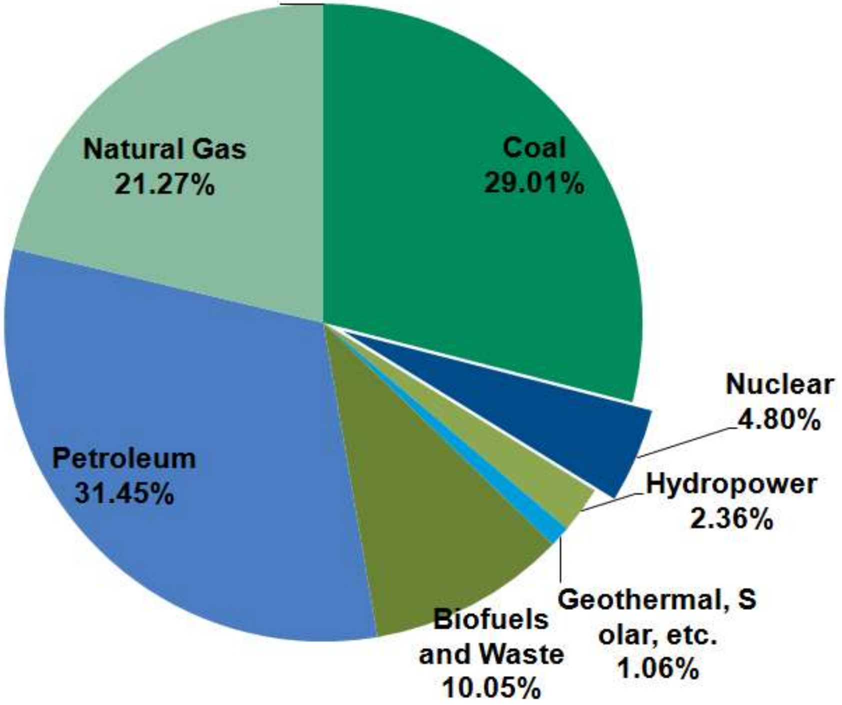
$\Delta m = 0.2194$ gm

$c = 3 \times 10^8$ m/s

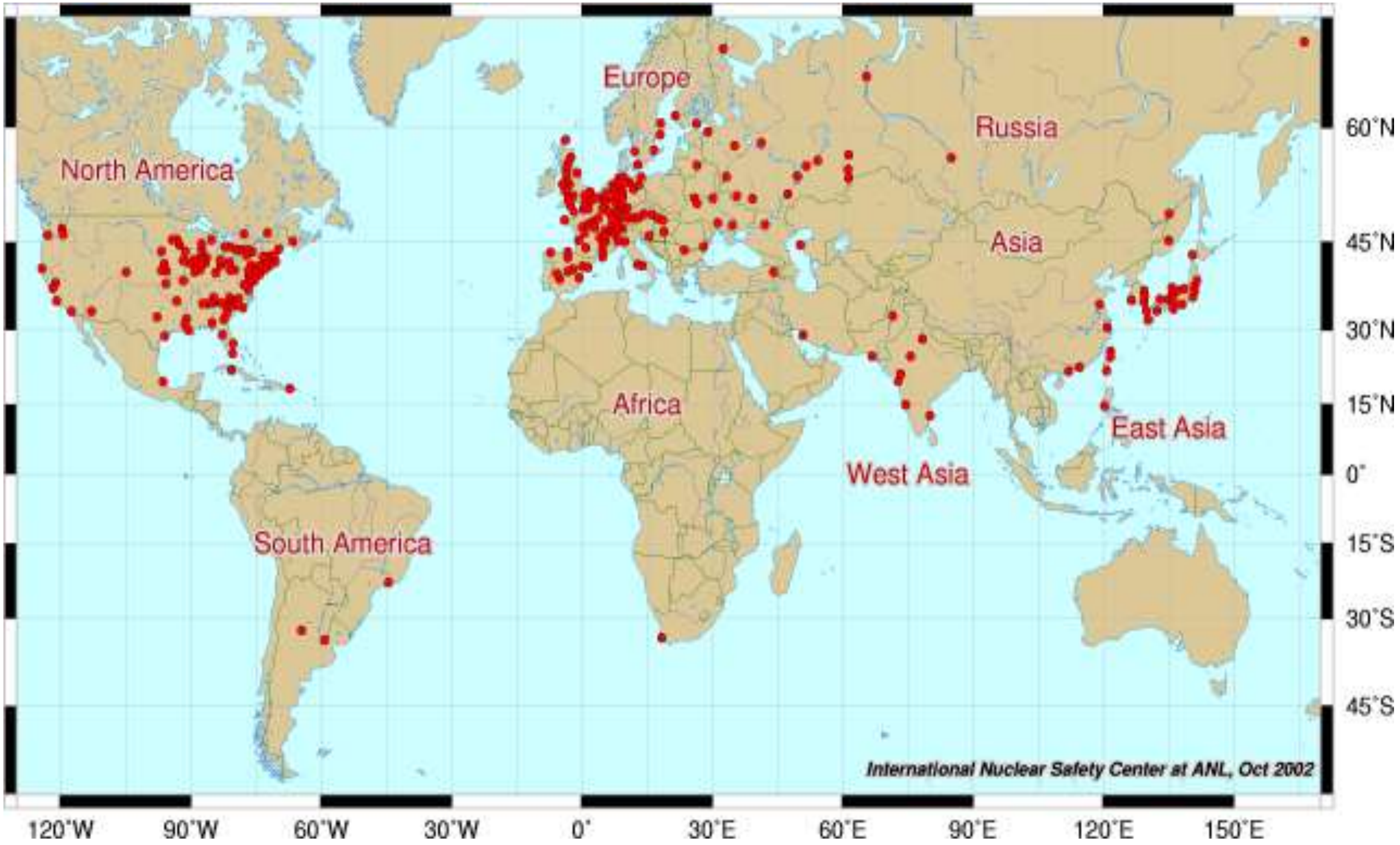
Nuclear Energy – World Status

As of July 2016,

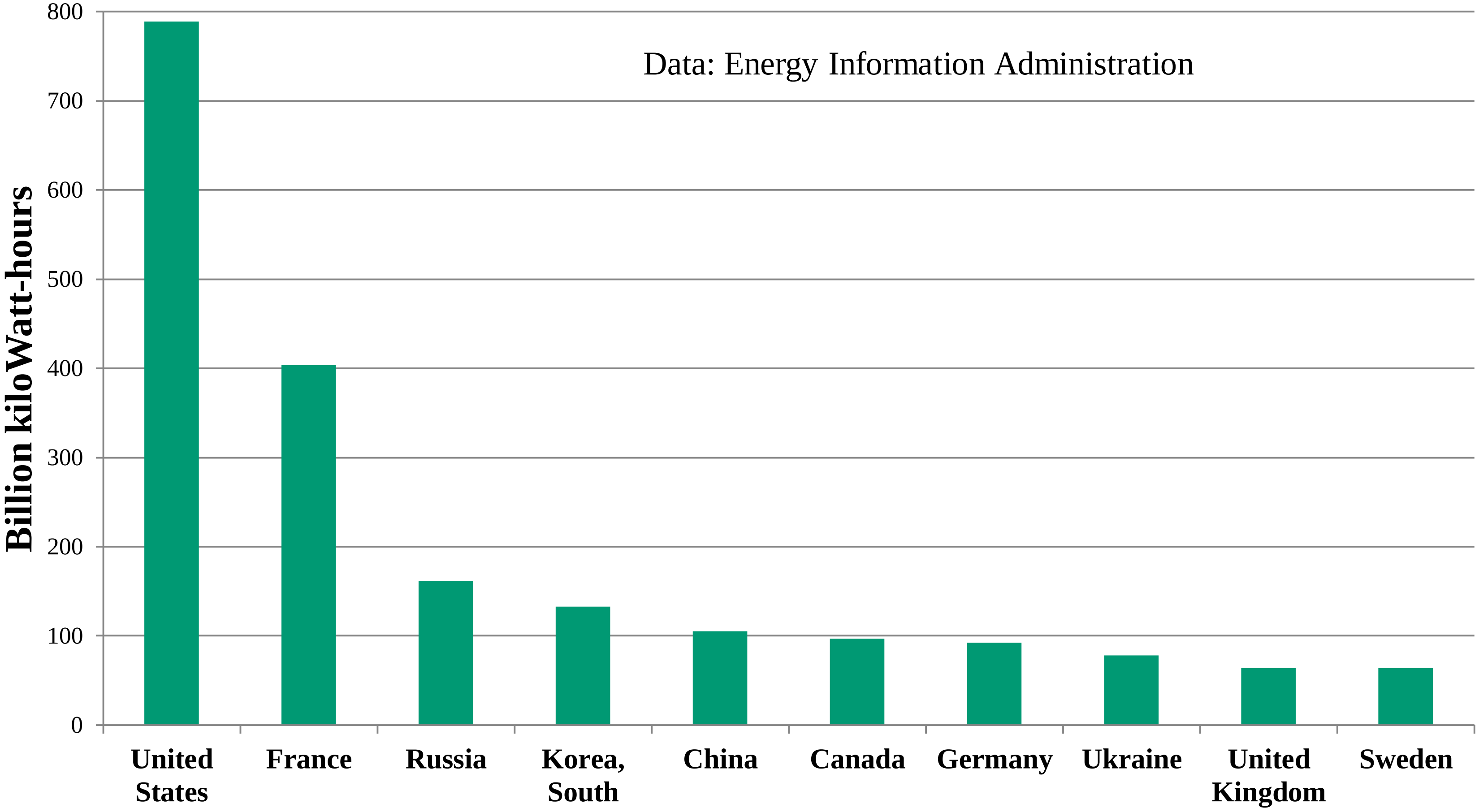
- 30 countries are involved
- Operating 438 nuclear reactors
- 67 plants are under construction
- 5 % energy and provides 10.8% of the world's electricity



World Nuclear Power Plants



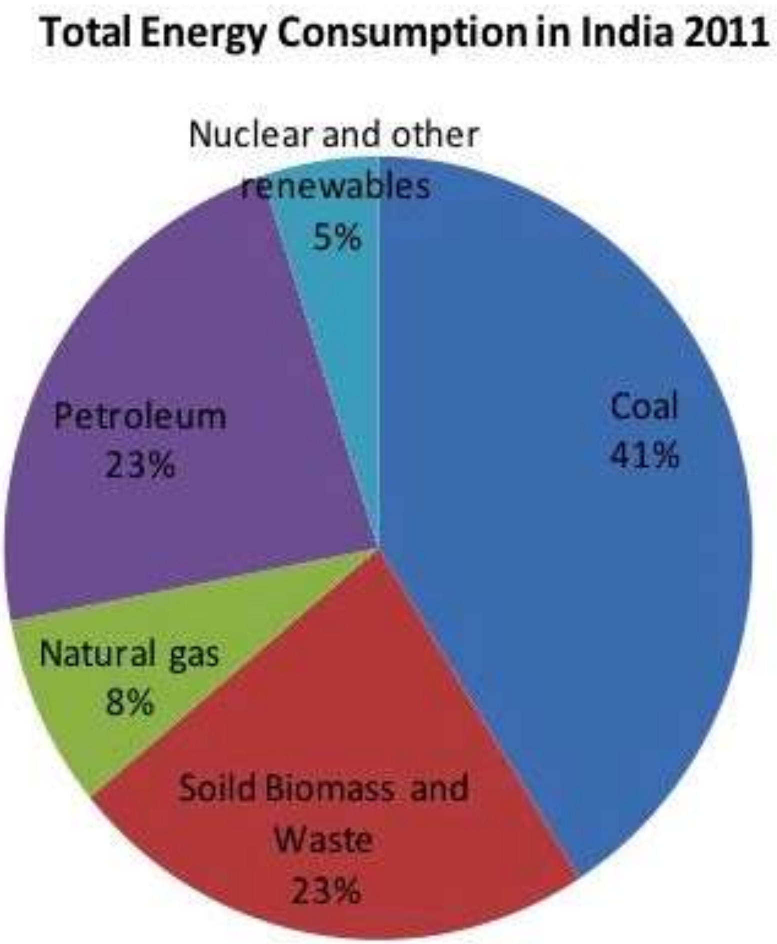
Top 10 Nuclear Generating Countries, 2018



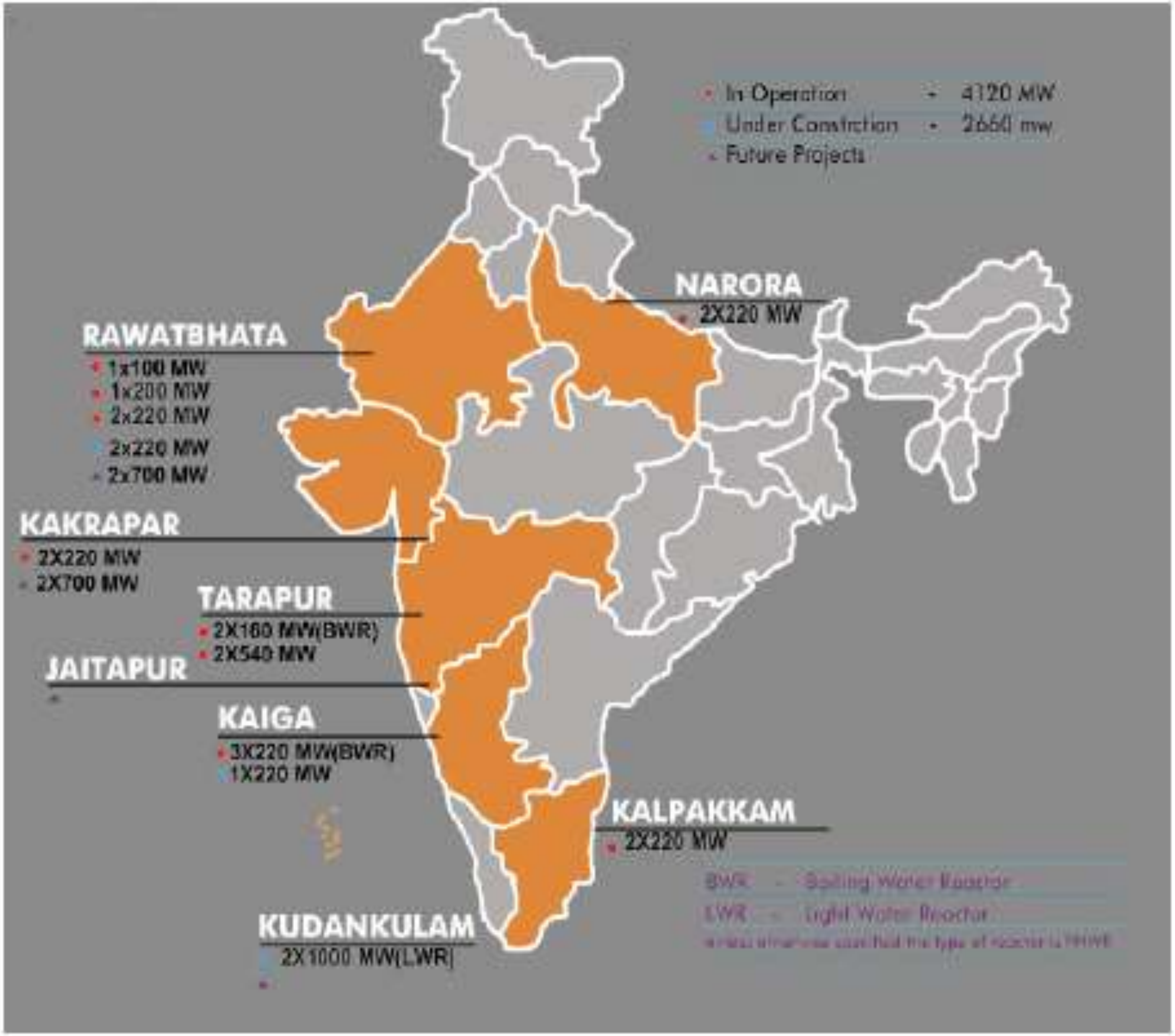
Nuclear Energy – India's Status

As of December 2016,

- 7 sites under operation
  Tarapur, Rawatbhata, Kalpakkam, Narora, Kakrapar Kaiga and kudankulam
- Operating **13** nuclear reactors (4120 MW)
- **3 plants** are under construction (2660 MW)
- **1 future** project
- provides **2%** of the total electricity

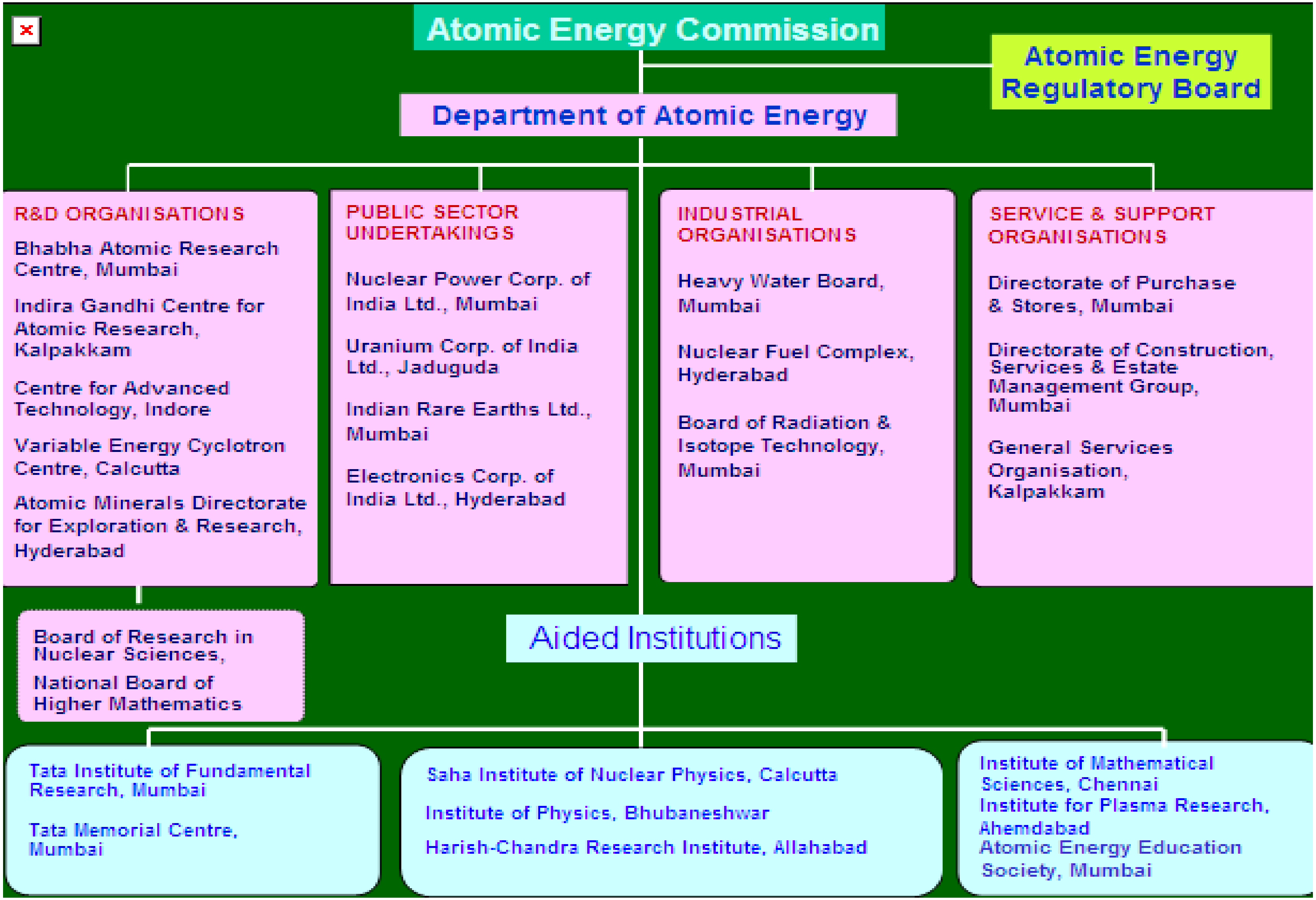


Nuclear Facilities in India



Source : Nuclear Power Corporation of India Ltd.

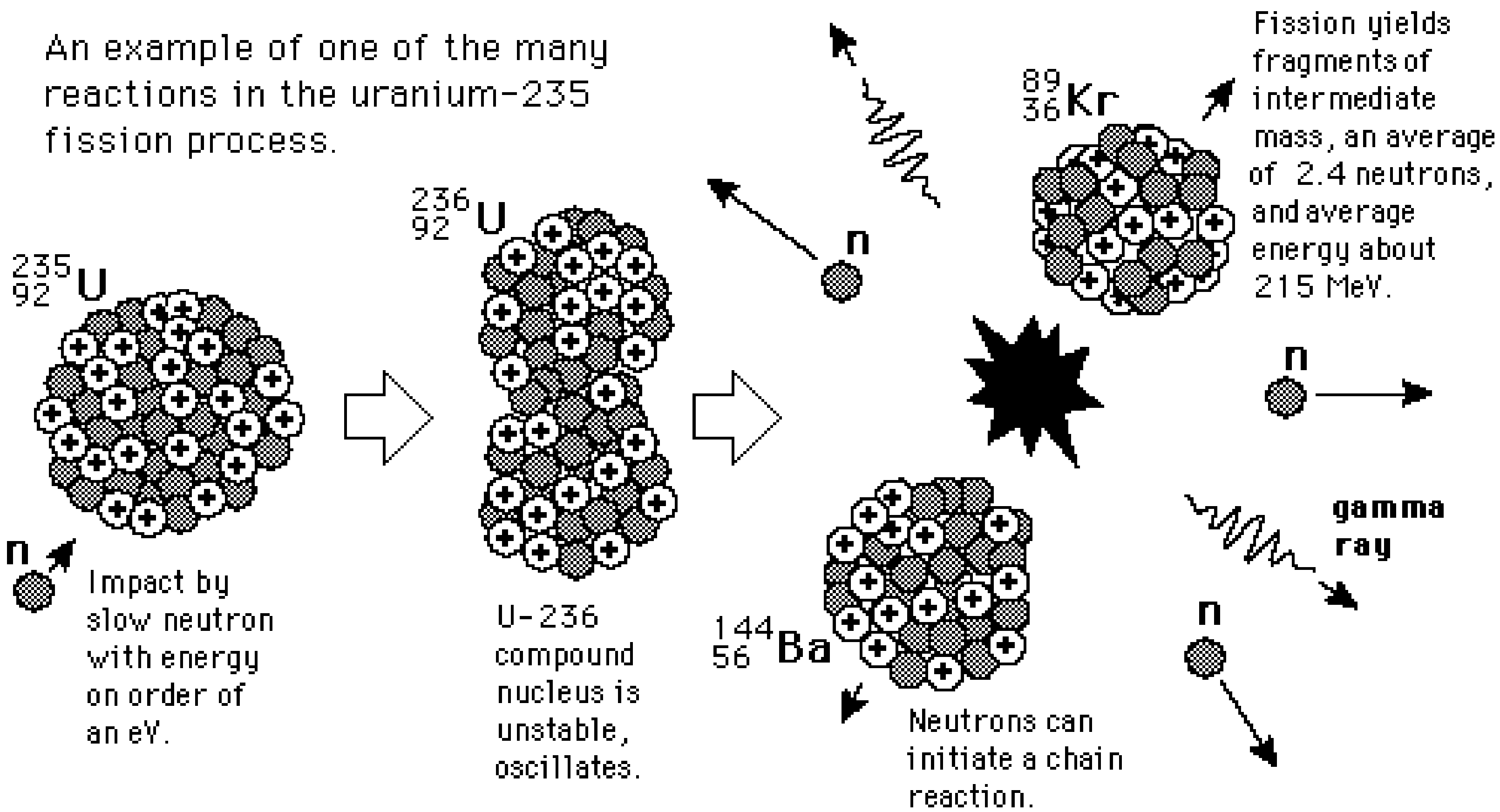
Atomic Energy Commission- India



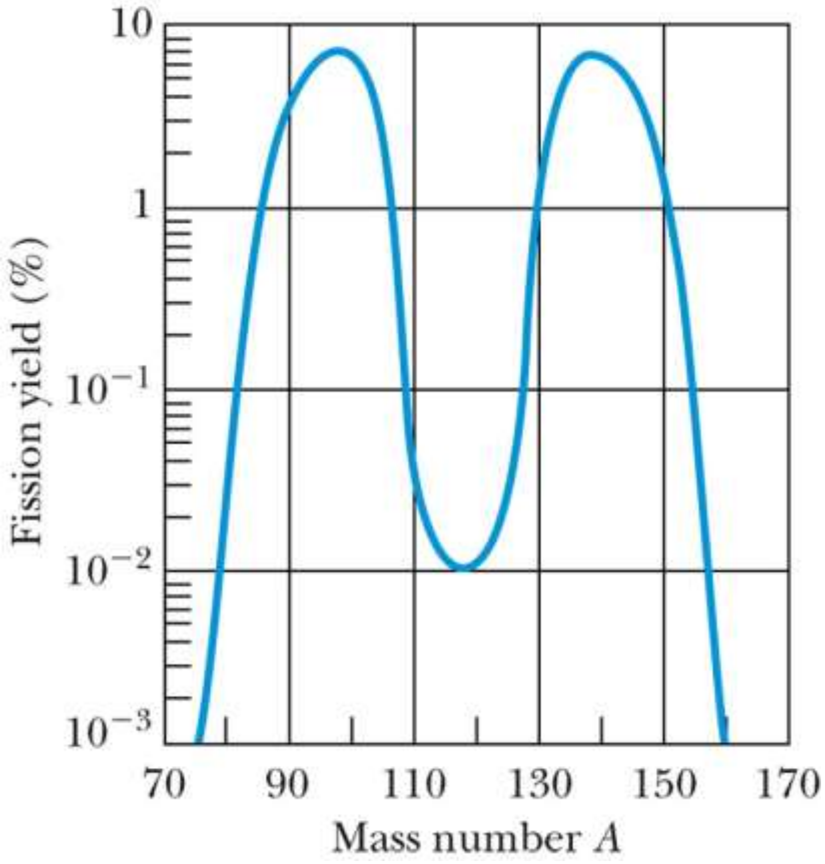
Goals of R&D Activities

- Research, Development, Demonstration and Deployment - **RD3**
- **Pursue excellence** in all areas of nuclear science and technology
- **Indigenous development** of nuclear technology

Nuclear Fission



Nuclear Fission



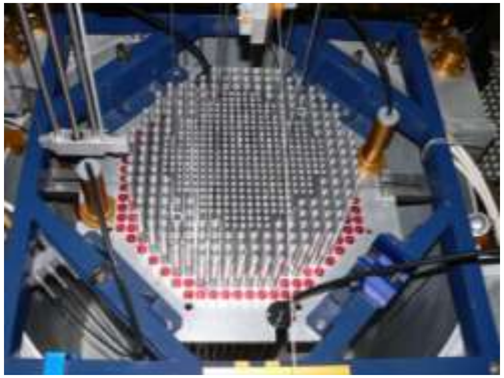
- Spontaneous fission can occur for nuclei with

$$Z^2 / A \geq 49 \; (Z \approx 115,\; A \approx 270)$$

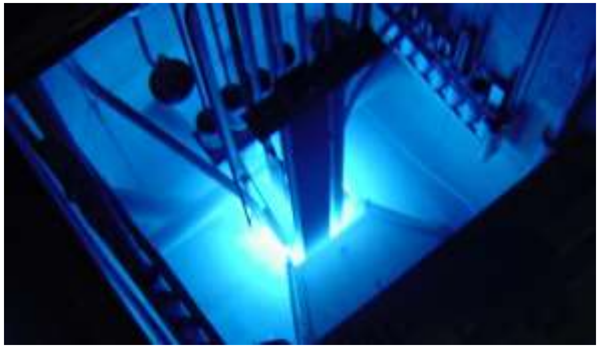
Types of Reactors

- ***Power* reactors** produce commercial electricity
- ***Research* reactors** are operated to produce high neutron fluxes for neutron-scattering experiments
- ***Heat production*** reactors supply heat in some cold countries
- Some reactors are designed to produce ***radioisotopes***
- Several ***training* reactors** are located on college campuses

Nuclear Reactors

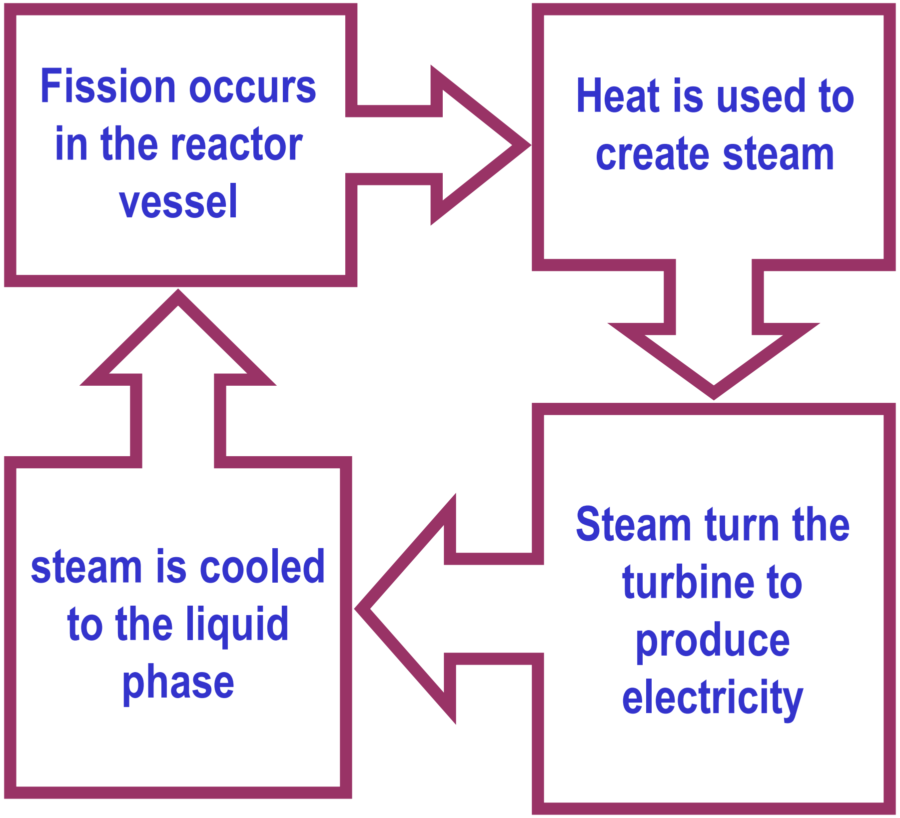


- Nuclear Reactor is built to sustain a controlled **nuclear fission chain reaction**
- Main Components
  - **Reactor vessel**
  - **Tubes of uranium**
  - **Control rods**
  - **Containment structure**

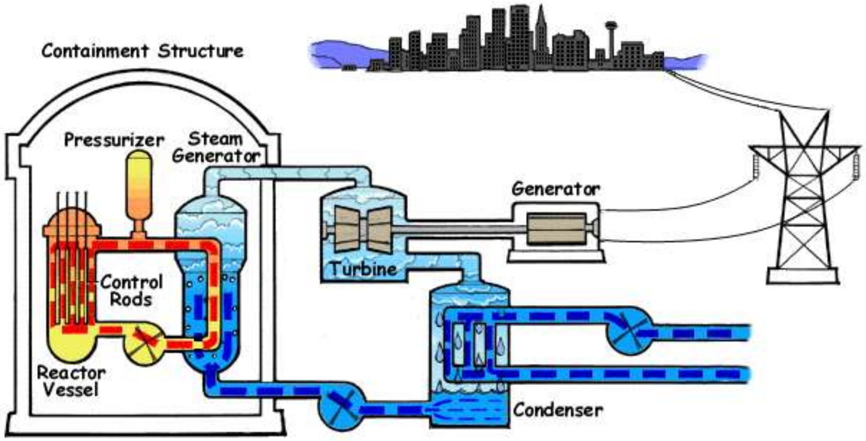


- Containment structure contains the reaction in at least **3 feet of concrete**!

Working of Nuclear Reactor

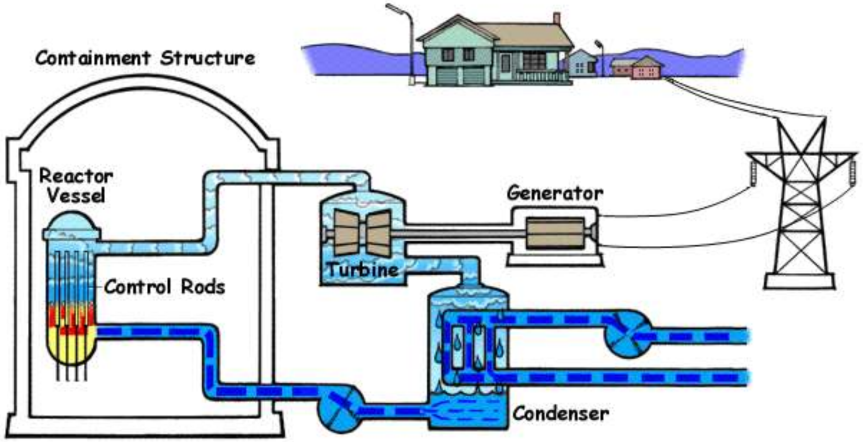


Structure of Nuclear Reactor



Pressurized Water Reactor (PWR)

keeps water under pressure so that it heats up but doesn't boil.



Boiling Water Reactor (BWR)

uses the heat from fission to heat water until it boils.

Breeder Reactors

- A more advanced kind of reactor is the ***breeder* reactor**, which produces **more fissionable fuel** than it consumes.

- The chain reaction is:

$$n + {}^{238}_{92}\mathrm{U} \rightarrow {}^{239}_{92}\mathrm{U}^* \rightarrow \gamma + {}^{239}_{92}\mathrm{U}$$

$$\hookrightarrow \beta^- + {}^{239}_{93}\mathrm{Np} + \bar{\nu}$$

$$\hookrightarrow \beta^- + {}^{239}_{94}\mathrm{Pu} + \bar{\nu}$$

- *Fast breeder reactors* have been built that **convert ^{238}U to ^{239}Pu**. The reactors are designed to use fast neutrons.

- Breeder reactors **hold the promise** of providing an almost unlimited supply of fissionable material.

- One of the downsides of such reactors is that plutonium is **highly toxic**, and there is concern about its use in **unauthorized weapons production**.

Fast Breeder Reactors vs. Pressurized Water Reactors

- **FBR**
  - Fuel is **enriched to 15-20%**
  - Moderator: **none**
  - Heat transfer by liquid metal or metal alloys
    - Typically sodium
  - Reactor **under low pressure**
  - **~1.2 fissile atoms** produced per fission
- **PWR**
  - Fuel is **enriched to 3-5%**
  - Moderator: **water**
  - Heat transfer by water
  - Reactor under **high pressure**
  - Fissile material **is only consumed**

Table 13.1 Energy Content of Fuels

Material	Amount	Energy (J)
Coal	1 kg	3×10^7
Oil	1 barrel (0.16 m^3)	6×10^9
Natural gas	1 ft^3 (0.028 m^3)	10^6
Wood	1 kg	10^7
Gasoline	1 gallon (0.0038 m^3)	10^{10}
Uranium (fission)	1 kg	10^{14}
Uranium (fusion)	1 kg	2×10^{14}

Table 13.2 Daily Fuel Requirements for 1000-MWe Power Plant

Material	Amount	
Coal	8×10^6 kg	(1 trainload/day)
Oil	40,000 barrels (6400 m^3)	(1 tanker/week)
Natural gas	2.5×10^6 ft^3 (7.1×10^4 m^3)	
Uranium	3 kg	

Future of Fast Breeders

- Next generation may use noble gases such as helium or argon instead of sodium
- Increase in the breeding ratio
  - Believed that a ratio of 1:3 will be possible
- Smaller reactors
  - **Lower maintenance and repair costs**
- Higher reactor temperatures
  - Can be used for thermochemical **hydrogen production**

Fusion

- If two light nuclei fuse together, they also form a nucleus with a larger binding energy per nucleon and energy is released. This reaction is called **nuclear fusion**.

- The most energy is released if two isotopes of hydrogen fuse together in the reaction.

$$^{2}\mathrm{H} + {}^{3}\mathrm{H} \rightarrow n + {}^{4}\mathrm{He} \qquad Q = 17.6\ \mathrm{MeV}$$

No Fusion reactor is in working condition at present

Comparison with Conventional Methods

Solidified high level waste produced by generating electricity, for an average Indian family, for 25 years from nuclear power

Waste generated from a 1000 MW Coal fired power plant

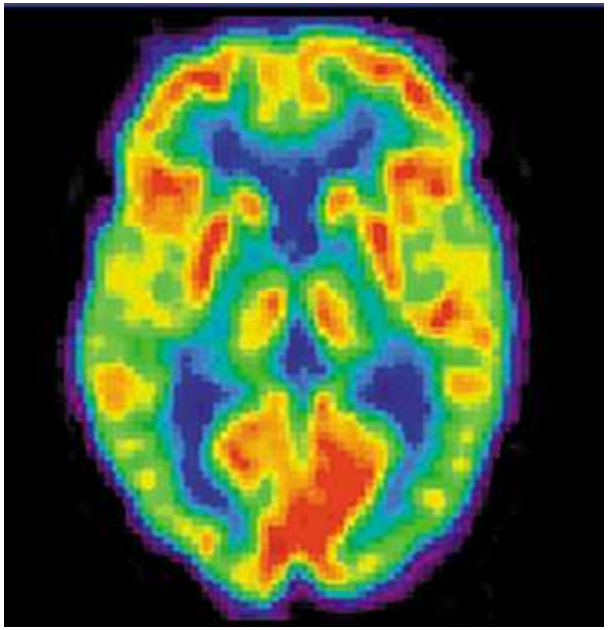
- Carbon dioxide : 2.6 million t /Year
- Sulphur dioxide : 900 t /Year
- NOx : 4500 t /Year
- Ash : 3,20,000 t/Year

(with 400 t/Year of toxic heavy metals)

Waste generated from a 1000 MW NPP

- High Level : 35 t /Year
- Intermediate Level : 310 t /Year
- Low Level : 460 t/year

Medical Applications



- Radioactive form of **iodine** can be used to monitor the **thyroid**

- Radioactive **thallium salt** can be used to follow the **blood stream**

- Radioactive **gallium** can be used for **cancer imaging**

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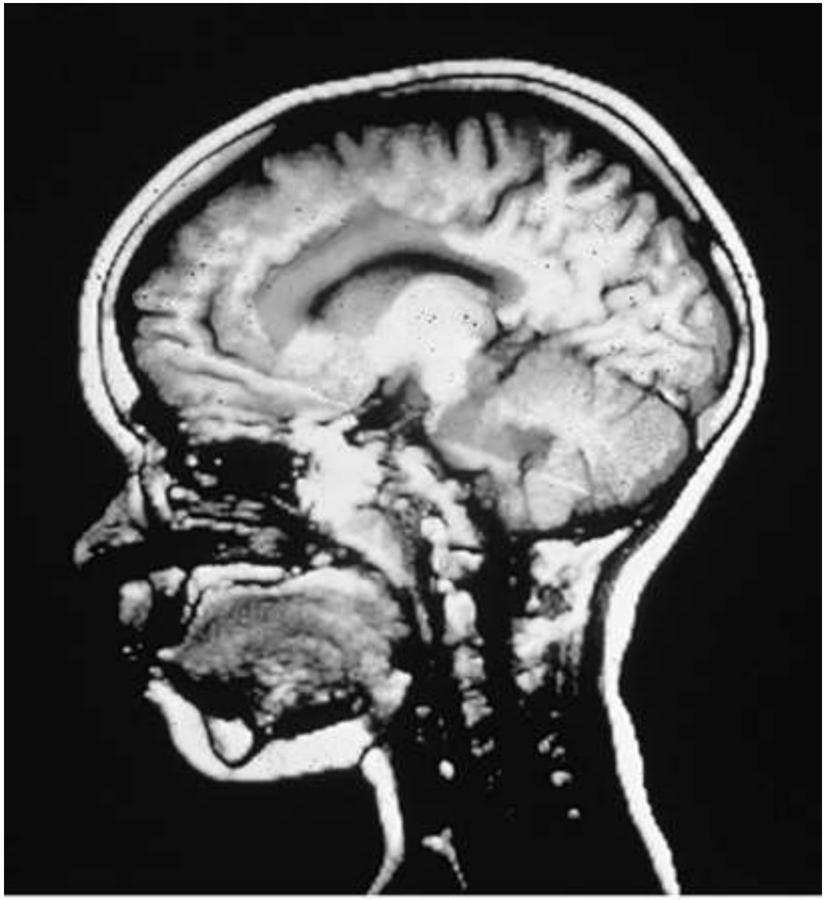
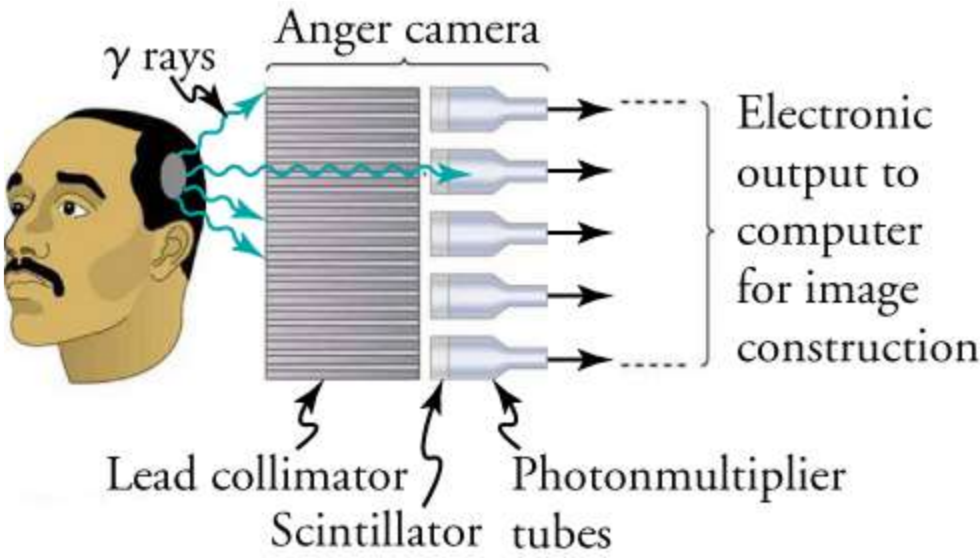
Tomography

- Over **1100 radioisotopes** are available for clinical use
- Radioisotopes are used in **tomography**, a technique for displaying images of practically any part of the body
- **single-photon emission** computed tomography
- **Positron emission** tomography
- **Magnetic Resonance Imaging** (MRI)



Anger camera or gamma camera



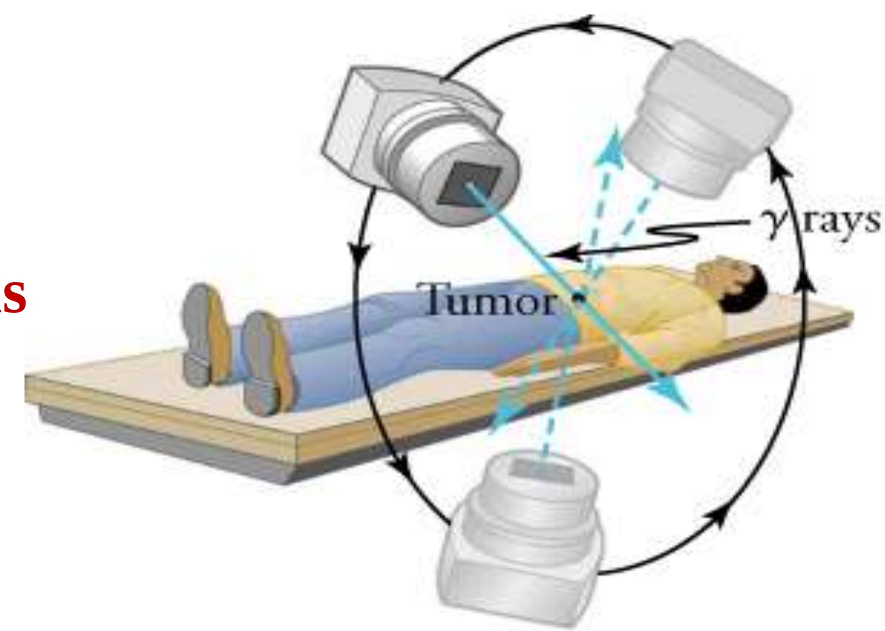
Dosage

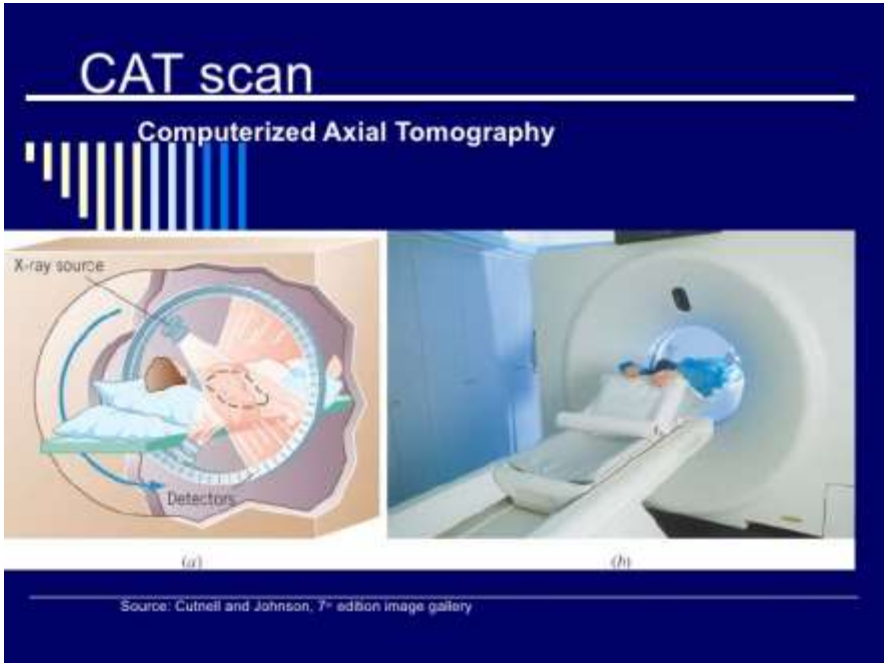
1 rad = 0.01 J/kg

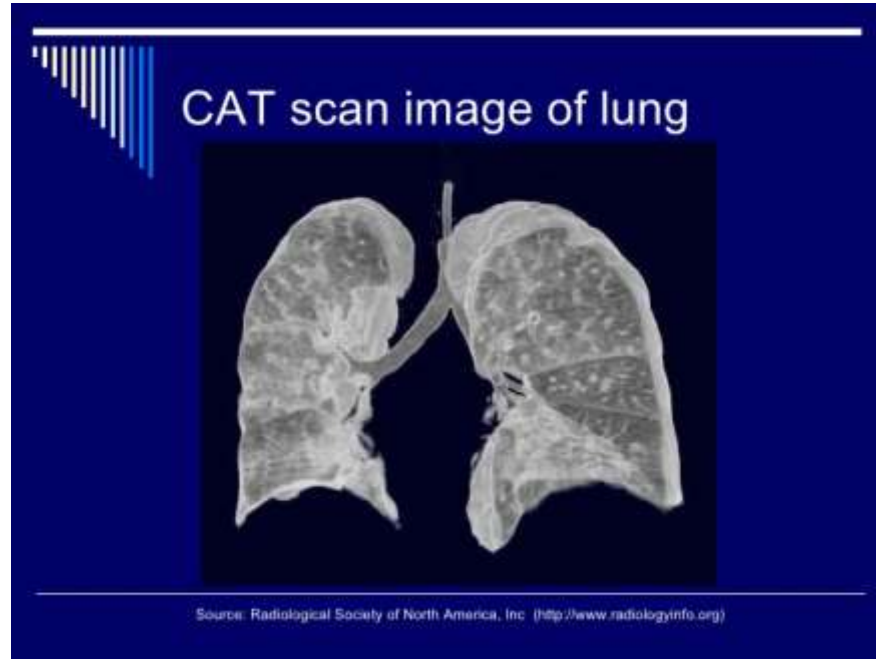
Radiotherapy

- is effective against cancer cells

- more sensitive to radiation.




CAT scan
Computerized Axial Tomography
X-ray source
Detectors
(a)
(b)
Source: Cutnell and Johnson, 7th edition image gallery


CAT scan image of lung
Source: Radiological Society of North America, Inc (http://www.radiologyinfo.org)

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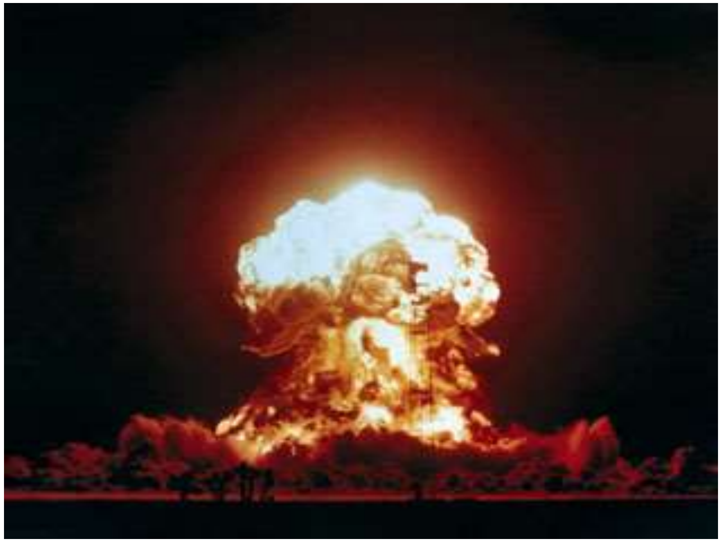
Types of Waste

- **Low Level Waste -90%** of total volume
  - Not dangerous
- **Intermediate Level Waste -7%** of total volume
  - Transuranic elements
- **High Level Waste – 3%** of total volume
  - Highly radioactive

Fear of Radiation

- Usually undetectable by **human senses**
- Serious consequences
  - **cancers (time-delayed)**
  - **contamination long-lasting**
- Unaware of **background radiation**
- **Media scares** - especially after Chernobyl
- **Secrecy** - industrial, military & political interests



Waste Management

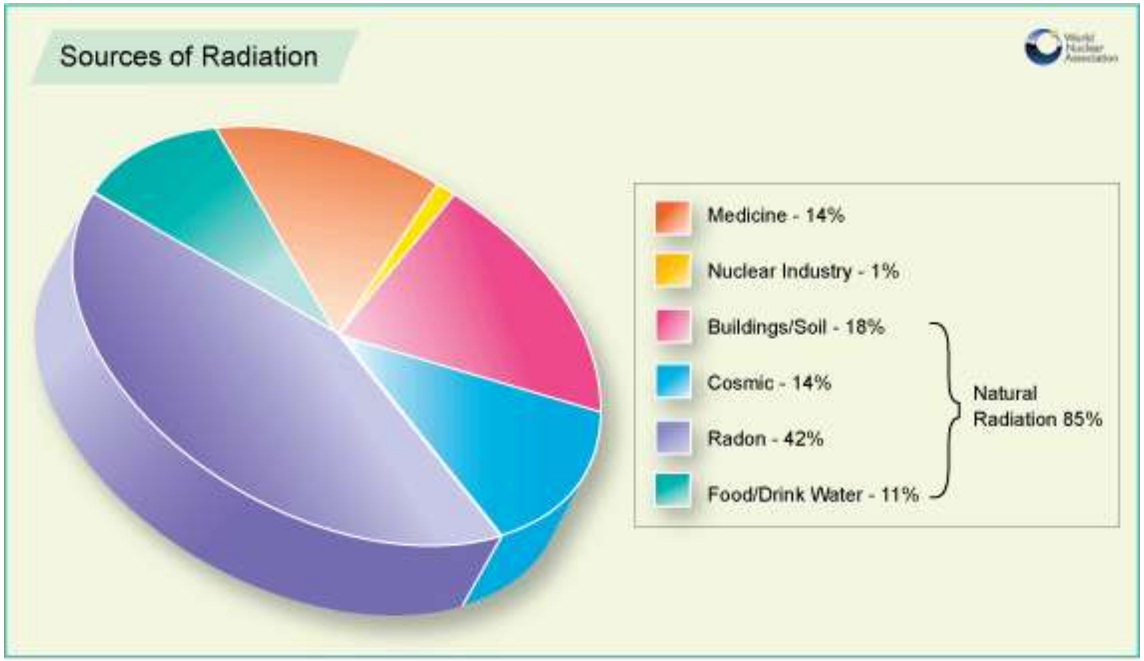
- Waste management include
  - **Deep Geologoical Storage**
  - **Transmutation**
  - **Reuse**
  - **Launching it into space**

Not This

But

Radiation Hazards

Naturally occurring radiations accounts for about 80% of our exposure



Mobile Radiations

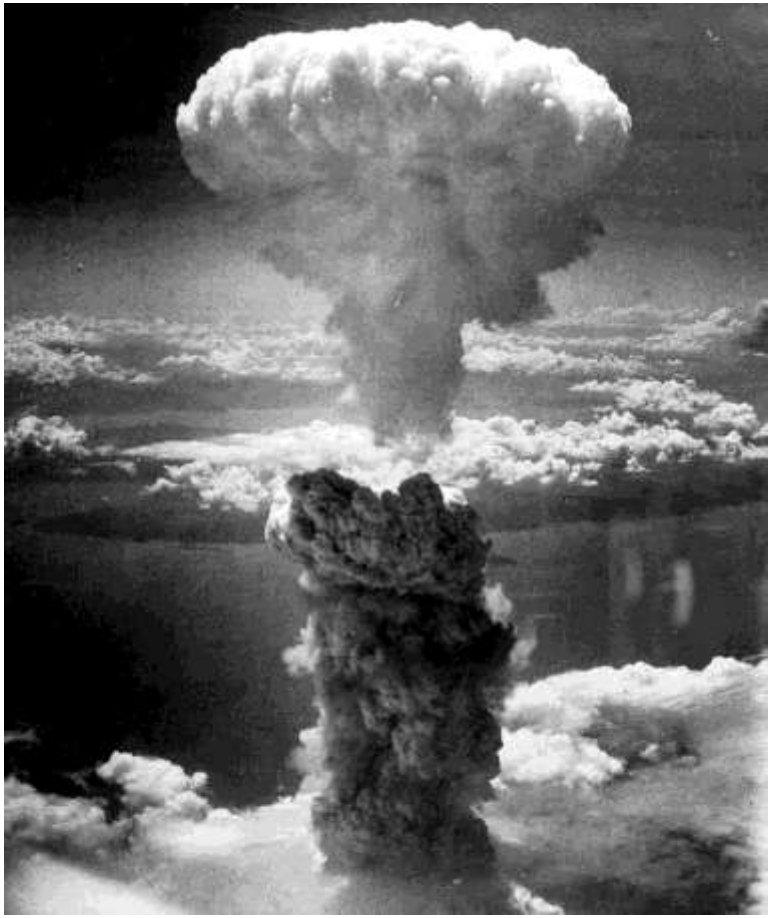
Nuclear Weapons

- Fission bomb

  (~ 20,000 tons of TNT)

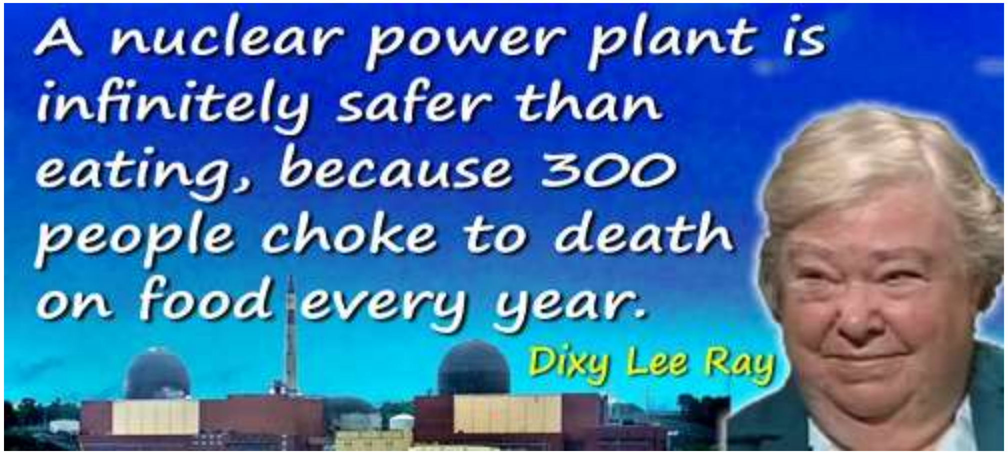
- Thermonuclear bomb

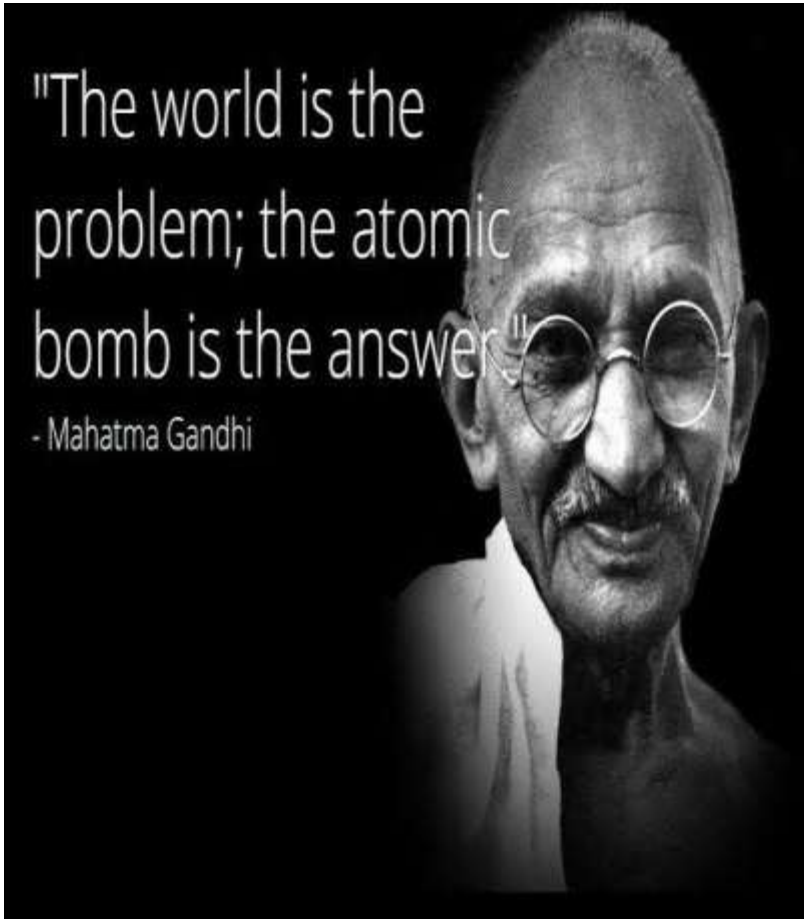
  (~1,00,00,000 tons of TNT).

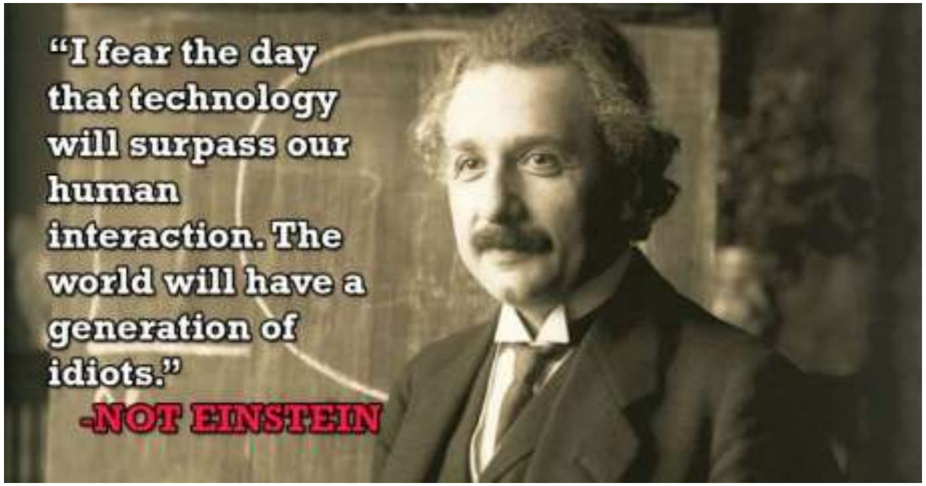


The mushroom cloud of the atomic bombing of the Japanese city of Nagasaki on August 9, 1945 rose some 11 miles (18 km) above the bomb's hypocenter

Country	Warheads (Active/Total)	Date of first test
United States	2,104 / 4,804	16 July 1945
Russia	1,600 / 4,480	29 August 1949
United Kingdom	160 / 225	3 October 1952
France	290 / 300	13 February 1960
China	n.a. / 250	16 October 1964
India	n.a. / 110	18 May 1974
Pakistan	n.a. / 120	28 May 1998
North Korea	n.a. / <10	9 October 2006
Israel	Suspected	Suspected 22 September 1979


A nuclear power plant is infinitely safer than eating, because 300 people choke to death on food every year.
Dixy Lee Ray


"The world is the problem; the atomic bomb is the answer."
- Mahatma Gandhi


"I fear the day that technology will surpass our human interaction. The world will have a generation of idiots."
-NOT EINSTEIN

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Thank You