Fusion: Our Friend the Nucleus

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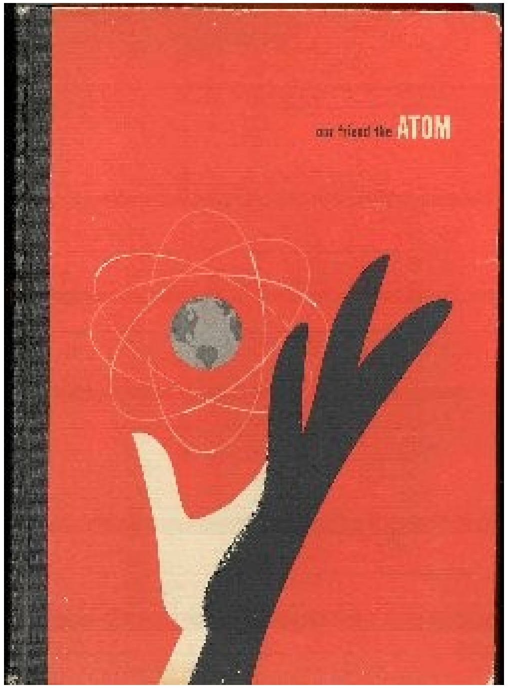
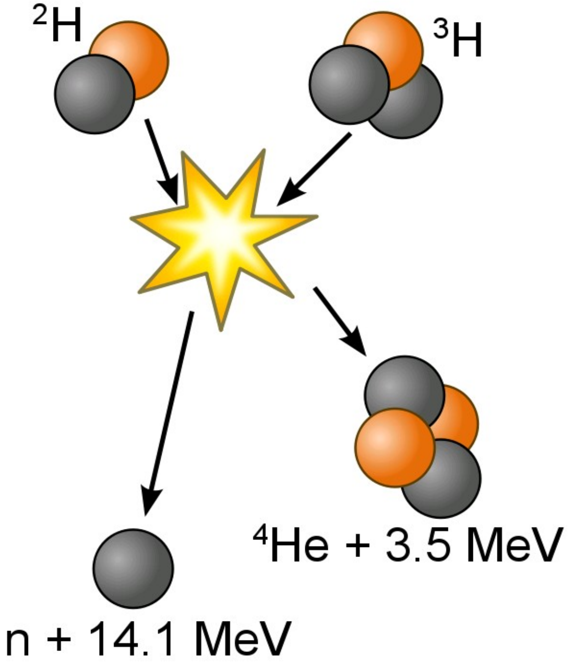


Our Friend the Atom: Disney film (1957)

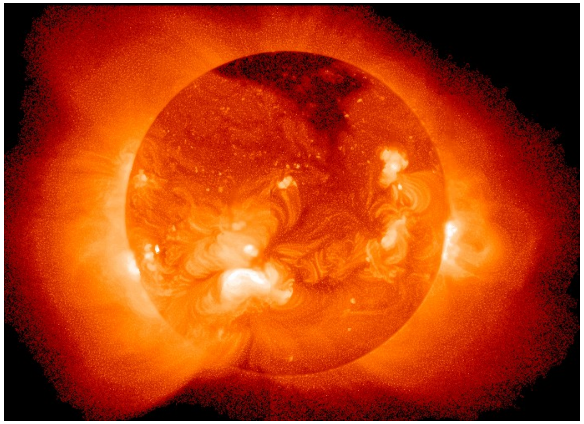


Deuterium-tritium fusion

Internet resources:

Wikipedia (of course)
fire.pppl.gov
fusedweb.llnl.gov
www.pppl.gov
lasers.llnl.gov
www.iter.org
hyperphysics.phy-astr.gsu.edu/hbase/HFrame.html

Nuclear Menu

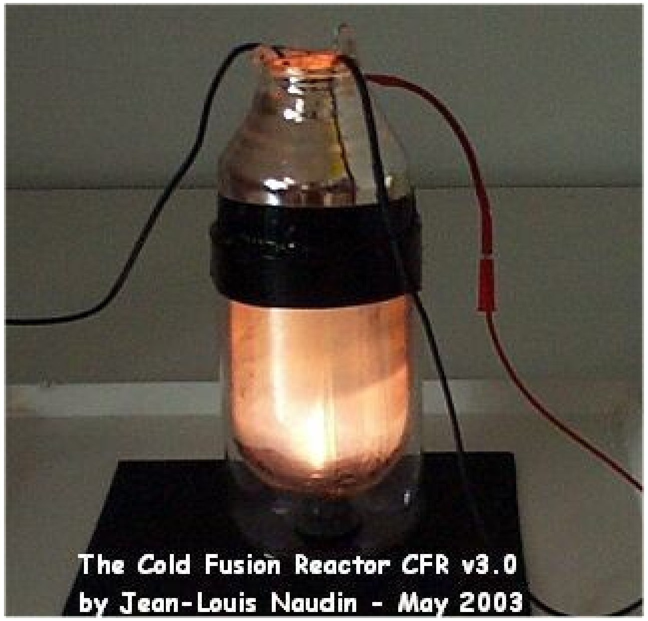


The Sun – very slow fusion

Fission power – it works today

National Ignition Facility (LLNL) inertial fusion

Tsar Bomba (Soviet nuclear test)
– very fast fusion!



The Cold Fusion Reactor CFR v3.0
by Jean-Louis Naudin - May 2003

Cold fusion?

Tokamak – magnetic fusion

Class Outline

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1. Energy, and how nuclear reactions (fission and fusion) “produce” it
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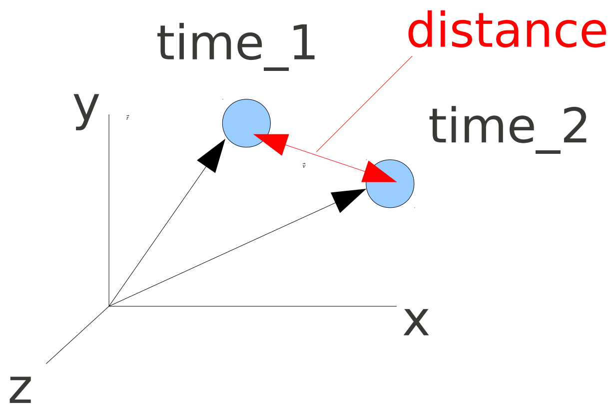
Physics 101: matter, fields, mass, force

The universe consists of **substances**, which come in two kinds:

Matter: made of particle with mass. Includes everything made of atoms.

Fields: generally have no mass, and "carry" the forces exerted by matter. Includes gravity, electric and magnetic fields.



Two key rates of change

$$\text{Velocity (or speed)} = \frac{\text{Change in position}}{\text{Change in time}} = \frac{\text{distance}}{\text{time\_2 - time\_1}}$$

$$\text{Acceleration} = \frac{\text{Change in velocity}}{\text{Change in time}}$$

What is mass?

Force = mass * acceleration

thus saith Newton!

Forces (other than gravity) don't depend on mass. For instance, if you run a car engine at a given rate, the force it exerts on a car does not depend on the car's mass. How fast the car accelerates does depend on its mass.

Physics 101: What is energy?

Universe consists of **substances** = **matter** + **fields**. **Energy** is a *property* of substances.

Matter: Take one piece of matter with mass m. It possesses two kinds of energy:

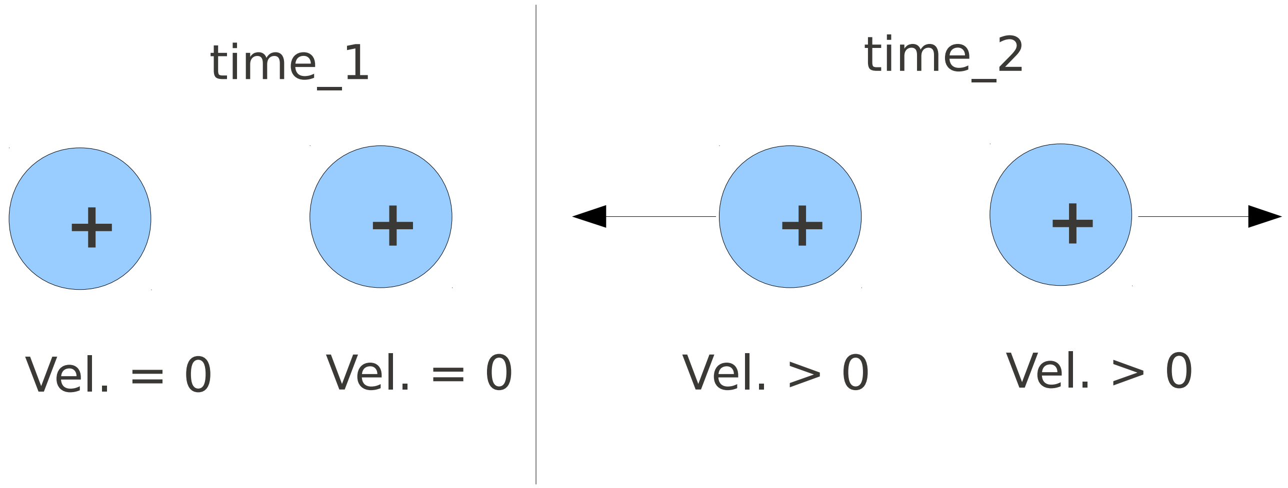
Matter energy = mass energy (rest energy) + kinetic energy (energy of motion)

E_matter = E_mass + E_kin
E_mass = m * c^2 Thus saith Einstein! More later. c = speed of light
E_kin = ½ * m * v^2 v = particle speed

Fields: have no mass but possess energy, called field energy.

Energy is conserved: the *total* amount of it doesn't change over time.
It is conserved **locally**: total energy in a region of space (no matter how small) only changes due to energy entering or leaving it. It's like a flowing fluid.

Matter energy is NOT conserved: consider electric repulsion of two nuclei:



Mass and E_mass the same.

Speed and E_kin went up.

So E_matter went up.

But energy is conserved – what gives?

More on energy: potential (field) energy, power

Two nuclei example: where did the increase in matter energy come from?
The electric field!

The electric repulsion force between the two nuclei is due to the electric field they generate. It depends on the positions of the nuclei, and thus changes as they move. The electric field can store energy and exchange it with the nuclei.

The energy stored in fields is called potential energy: E_pot.

Potential is usually introduced in high school as a problem-solving mathematical trick. But it is physically real – it's the field energy!

$$\boxed{E_{total} = E_{matter} + E_{pot}}$$ this is really always conserved

Some forms of energy (loosely speaking): heat, mechanical, electrical, chemical, nuclear, sound.

Units of energy (all measure the same thing): Joule (official metric unit), erg, British thermal unit (BTU), (kilo-)calorie, Kelvin, electron-Volt, kiloton of TNT.

Power: $$\frac{\text{Change in energy}}{\text{Change in time}}$$

Metric unit: 1 Watt = 1 Joule / second.
Think of a 100 Watt light bulb.

Richard Feynman [1965 physics Nobel prize] on Energy

Imagine a mother who leaves her child alone in a room with 28 indestructible blocks. The child plays with the blocks all day, and when the mother comes back she finds 28 blocks - the blocks are conserved! One day she finds only 27 blocks. However, she finds one hidden in a toy box. So she says, 'I am going to open the box.' 'No', he says, 'you cannot open the box.' Being clever she says, “I know that when the box is empty it weighs 16 ounces, and each block weighs 3 ounces, so I'll weigh the box'.

The blocks are like energy, with some differences. First suppose you never directly saw any blocks. The mother always counts 'blocks in the box', 'blocks in the [sink] water', and so on. With energy there is this difference, that there are no “raw” blocks, as far as we can tell.

For energy, we have a set of rules to calculate the amount of each different kind of energy. When we add them all together, it always gives the same total. But as far as we know there are no real units, no “raw” blocks. It is abstract, purely mathematical.

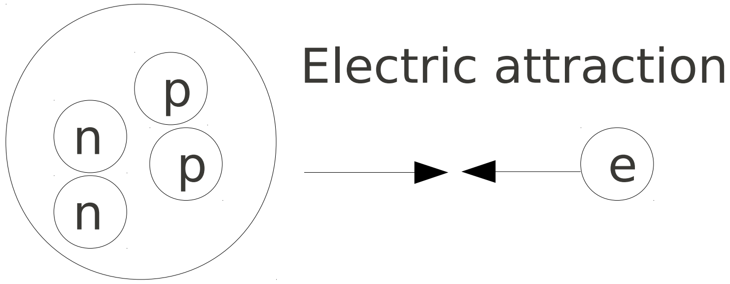
Physicists sometimes feel so superior, so here's something to catch them on. They should be utterly ashamed of the way they take energy and measure it in a host of different ways, with different names. It is absurd that energy can be measured in calories, ergs, electron volts, foot pounds, BTUs, horsepower hours, kilowatt hours – all measuring exactly the same thing. The proof that physicists are human is the idiocy of all the different units they use to measure energy.

Paraphrased from *The Character of Physical Law*, section 3.

The four basic forces, as seen in an atom

Electromagnetic force: like charges repel, opposites attract

p = proton = positive charge
e = electron = negative charge
(minus that of proton)
n = neutron = electrically neutral



Helium nucleus (+ charge)

Weak nuclear force: Decay of neutron, nuclei

“beta” decay:

$n \rightarrow p + e^- + \text{neutrino}$

A free neutron is unstable!
Half-life of 10.2 minutes.

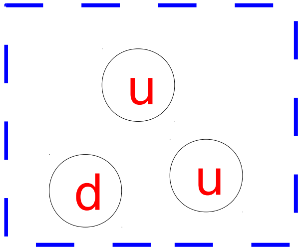
Gravity: mutual attraction of all matter and energy

Unimportant on atomic scales
Important in planets, stars, the universe.

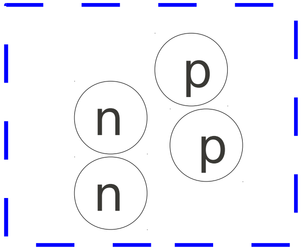
Strong nuclear force: produced by **quarks**

Binds quarks into protons and neutrons

- Binds protons and neutron into nuclei:
- Overcomes electric repulsion of protons



Proton = 3 quarks
(2 up, 1 down)



Helium nucleus

The nucleus: co-dependent, almost dysfunctional family

Nucleus: made of protons and neutrons, much smaller than the atom.

Protons in the nucleus repel electrically, so why does the nucleus hold together?
The strong nuclear force!

Free neutrons are unstable, but stabilized inside a nucleus.

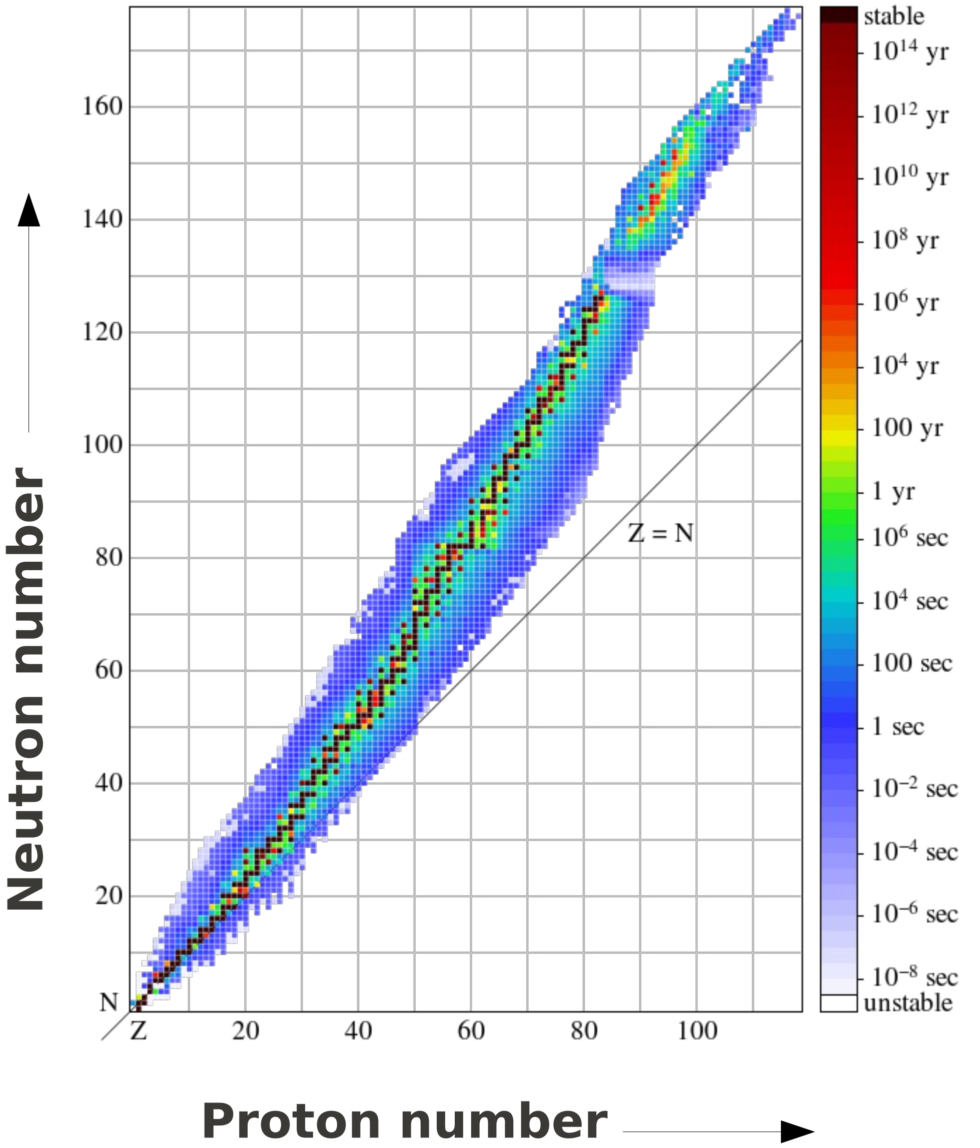
The nucleus is a bizarre, co-dependent, nearly dysfunctional family:

* Protons would fly apart without neutrons.

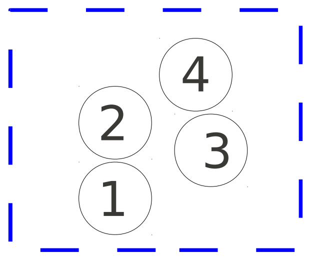
* Neutrons would decay without protons nearby.

Only certain combinations of protons and neutrons form stable nuclei.

Nuclear half-life:
Black squares are stable



E = mc^2 Explained: Binding Energy



Consider a system composed of several parts.
System is at rest: E_sys_kin=0
and isolated: no forces, E_sys_pot = 0

E_sys_total = E_sys_mass = m_sys * c^2

“Open the box” and consider the parts:
They are moving: E_p_kin not 0
and not isolated: they exert forces on each other: E_p_pot not 0

E_p_total = E_p_mass +
E_p_kin + E_p_pot

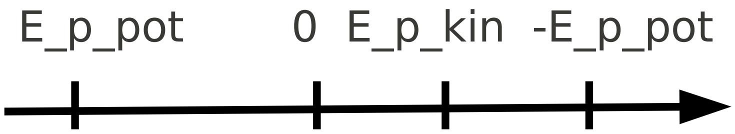
System has same energy whether viewed as a single system or composed of parts:

E_sys_total = E_p_total → m_sys * c^2 = sum(m_p)*c^2 + E_p_kin + E_p_pot

<u>Bound</u> system – forces between parts are strong enough to keep them from flying apart due to their kinetic energy.

Binding energy: E_bind = -E_p_pot – E_p_kin > 0

m_sys = sum(m_parts) – E_bind / c^2



The system's mass (tells how much a given force accelerates it) is **less than** the total mass of its parts.

Binding Energy Examples

m_sys   = sum(m_parts) – m_bind

m_bind = E_bind / c^2

Physicists will freely switch between talking about binding energy and binding mass via the factor c^2. People are not always careful to spell this out.

All systems have binding energy: atoms, molecules, the solar system, galaxies, usually much less than their mass energy ($m*c^2$).

Hydrogen atom = one electron + one proton: m_bind = $4.65*10^{-8}$ amu
Due to electric force.
amu = atomic mass unit (proton mass = 1.01 amu).

Deuteron (deuterium nucleus) = one neutron and one proton:
m_bind = $2.39*10^{-3}$ amu
MUCH larger! Due to strong nuclear force.

The higher the binding energy of a system, the more energy it takes to break it apart. We say that a system with high binding energy is “tightly bound.”

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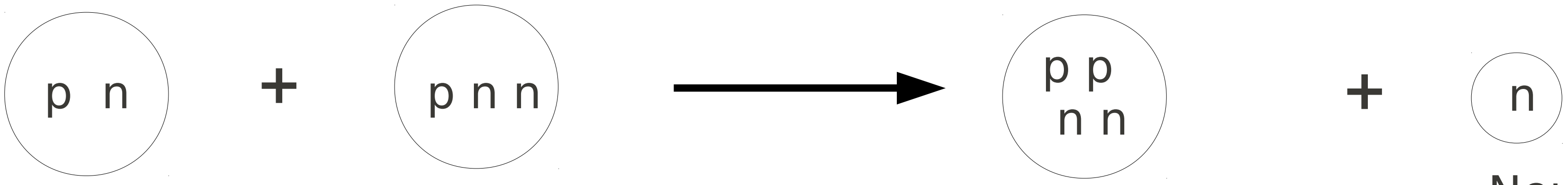
DT fusion: a VIP (very important process)



Deuteron (D)
Bind. En. 2.23

Triton (T)
Bind. En. 8.48

Helium-4
Bind. En. 28.3
alpha particle (α)

Neutron
No Bind. En.
(that we care about)

Deuteron = deuterium nucleus; stable;
naturally occuring - 1/6500 of terrestial hydrogen
“heavy water” = D_20 instead of H_20

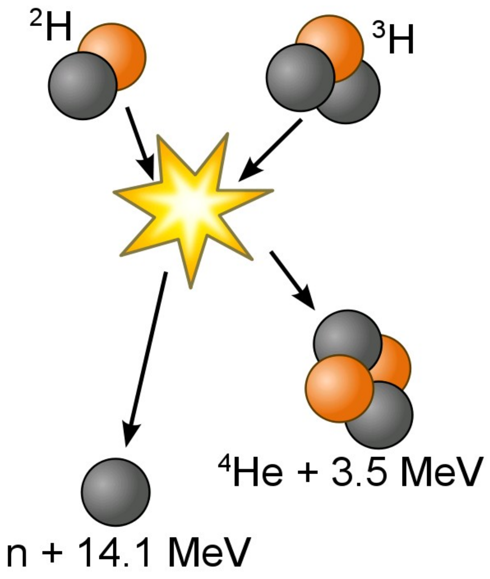
Triton = tritium nucleus;
Unstable - half-life of 12.3 years: T → He3 [=2p + 1n] + electron + neutrino
trace amounts on Earth;
Can be produced from lithium: Li6 [=3p + 3n] + n → α + T

Helium-4 nucleus = also called an alpha particle (α); stable; very tightly bound.

Binding energies in MeV = million electron-Volts.

Chemical reactions involve ~ 1 eV per electron exchanged:
it takes 13.6 eV to ionize hydrogen.

Energy released in DT fusion



● proton ● neutron

D, T, α all composite systems with binding energies.

All we've done is re-arrange 2 p's and 3 n's.

Particles start and end far away (isolated, not exerting forces → no E_pot)
but in motion (→ yes E_kin).
Conservation of initial and final energy:

[E_kin_D + m_D*c^2] + [E_kin_T + m_T*c^2] = [E_kin_a + m_a*c^2] + [E_kin_n + m_n*c^2]

m_D = m_n + m_p – m_bind_D likewise for T, α

initial
final

Kinetic energy released = E_kin_a + E_kin_n – E_kin_D – E_kin_T
= E_bind_a – E_bind_D – E_bind_T
= 28.3 – 2.23 – 9.48 [MeV]
= 17.6 MeV

How much energy released in DT fusion? A lot!

One DT fusion reaction released 17.6 MeV of kinetic energy.

Energy released (by burning chemically, or fission, or fusion) 1 kilogram of:

Fuel	Energy [relative to TNT]
TNT (explosive)	1.0
Coal+air (burning)	7.9
Uranium 235 (fission)	500,000.
DT (fusion)	81,000,000.

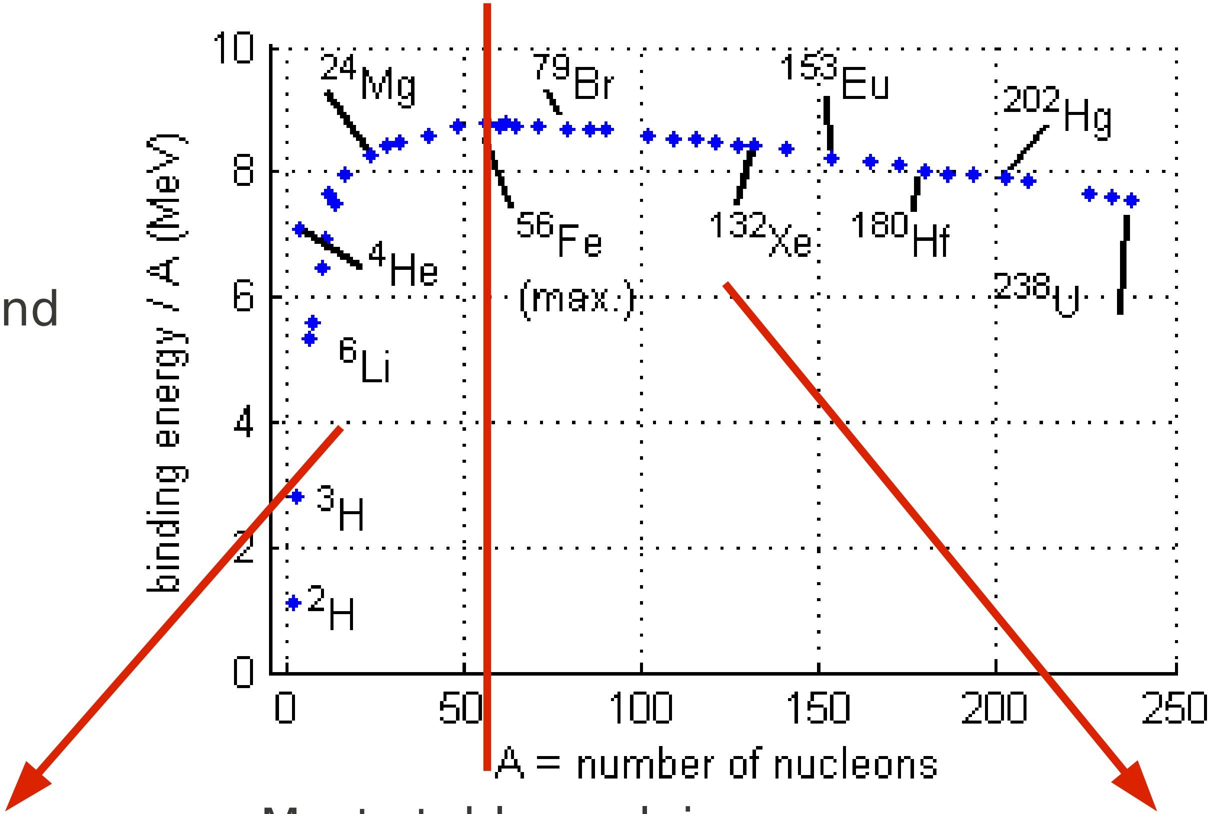
1 kg of DT releases as much energy as 81 million kg, or 81 kilotons, of TNT!

Per mass, nuclear reactions are **millions of times**
as energetic as chemical reactions!

Nuclear reactions release energy when final binding energy lower than initial

MOST IMPORTANT SLIDE!!!

Binding energy per nucleon (neutrons and protons)



Fusion produces energy: Light elements fuse to heavier ones

Most stable nuclei: Nickel, iron

Fission produces energy: heavy element splits into lighter ones

Released energy appears as kinetic energy of reaction products: can be converted to heat when products slow down in matter.

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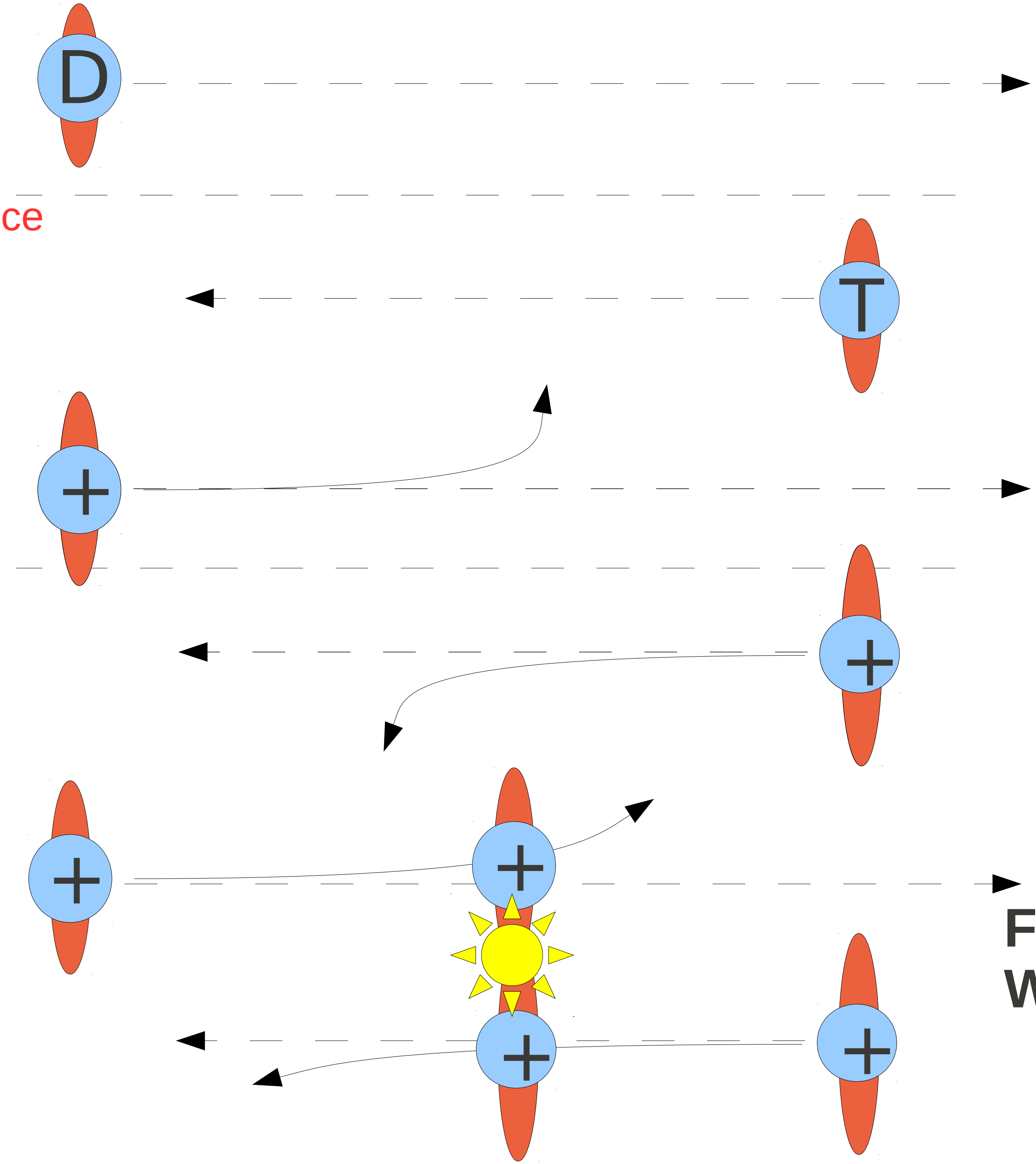
Getting nuclei to fuse: distance, electric repulsion



Bull's eye target:
Range of strong force
to cause fusion

Too far
away:
FAIL

Positive charge:
Electric repulsion

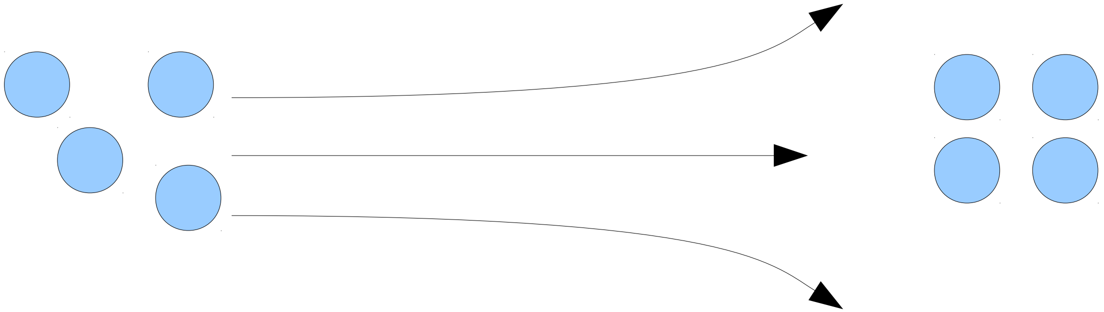
Too much
repulsion:
FAIL

Fast enough:
WIN

Two approahes to fusion: beam and thermonuclear

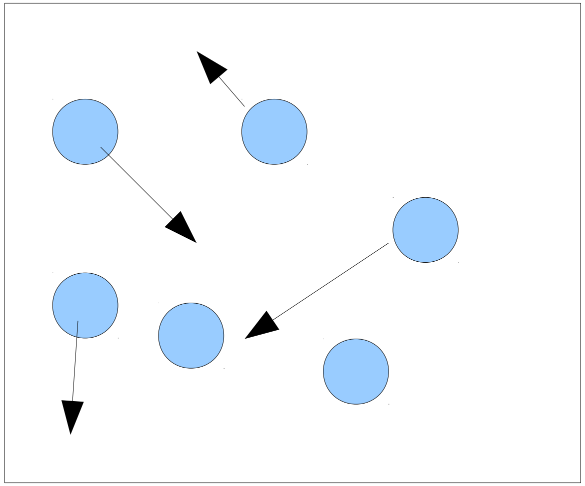
Nuclei must start off close enough, and move fast enough (to overcome nuclear repulsion), in order to fuse.

- **Beam fusion:** acclerating a beam of nuclei into a target (stationary or another beam). Generally not effective way to produce energy. Useful for studying the basic physics of fusion, or making sources of, e.g., neutrons.



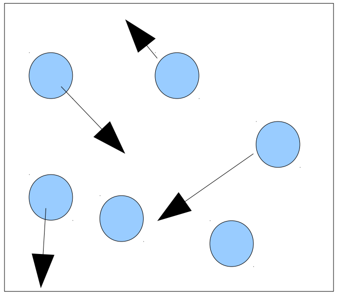
Electric repulsion makes it hard to keep beam and target together, and to keep beam moving in one direction.

Thermonuclear fusion: temperature measures the *average* kinetic energy of particles - some have more, some less. There will always be some very fast particles that can fuse. The trick is to have enough fusion before the system cools or expands.



How hot are we talking, and what kind of box?

Temperature needed for thermonuclear fusion

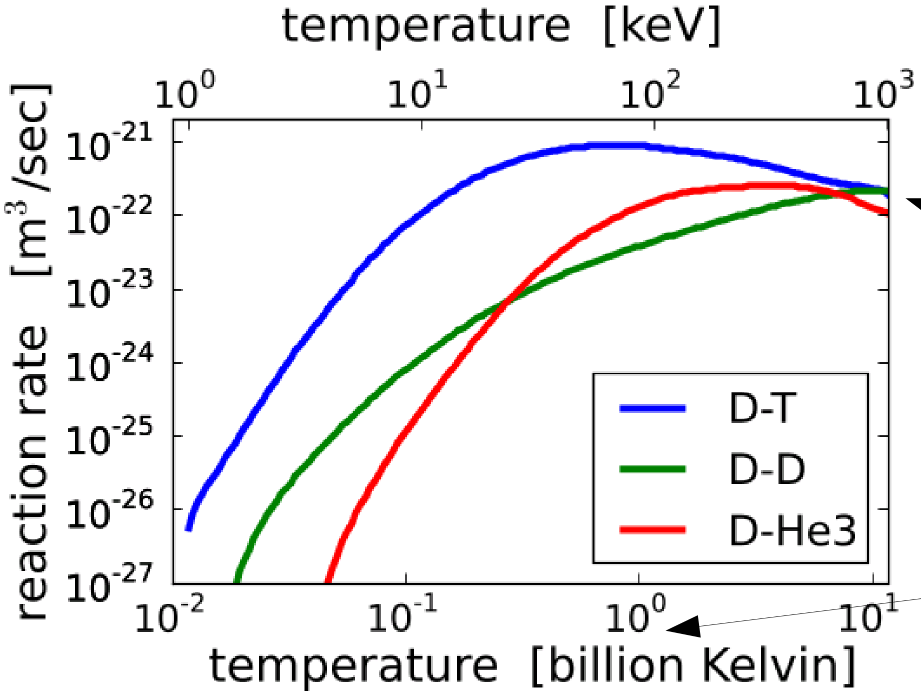


Fusion reactions per second = volume * density^2 * reaction rate

- DT reaction happens at the lowest temperature (easier to get going).

- Atoms start ionizing at temperatures around 10,000 Kelvin, so fusion fuel will be a fully-ionized plasma.

- Rate falls at very high temperatures – sweet spot.

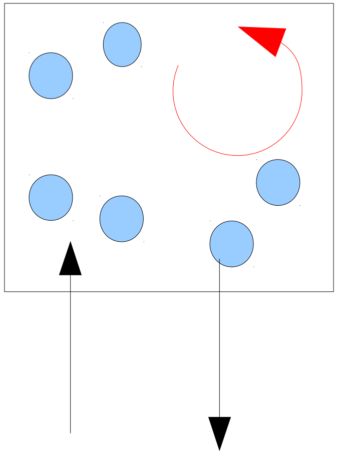


Yes that's billion with a B. Temperatres in the 100 million's are enough.
“A billion here, a billion there, soon you're talking real money.” -attributed to Sen. Everett Dirksen

- Strong force is so short range that huge temperatures needed. Moving so fast that neutral atoms would quickly ionize each other (knock off electrons).

- There are no neutral atoms, but a soup of free electrons and ions. Called a **plasma**, the “fourth state of matter” (after solids, liquids, and gases).

Ignition (self-sustained fusion): the holy grail



Fusion
self-heating

External
heating

cooling

Fusion plasma at high temperature:
Wants to **expand** and **cool**

Need to confine it

Need to heat it

Power balance: heating = cooling

External (provided by us)
Fusion (self heating)

Conduction to “box”
Radiation, etc

Fusion heating rate per volume = density^2 * reaction rate * reaction energy

$$\text{Energy loss rate per volume (if no fusion)} = \frac{\text{Thermal energy = density * temperature}}{\text{t\_en = energy confinement time}}$$

Ignition: heating = cooling with no external heating

Fusion heating rate > thermal energy / t_en

$$\text{density * t\_en} > \frac{\text{temperature}}{\text{rxn rate * rxn energy}} = \text{function just of temperature}$$

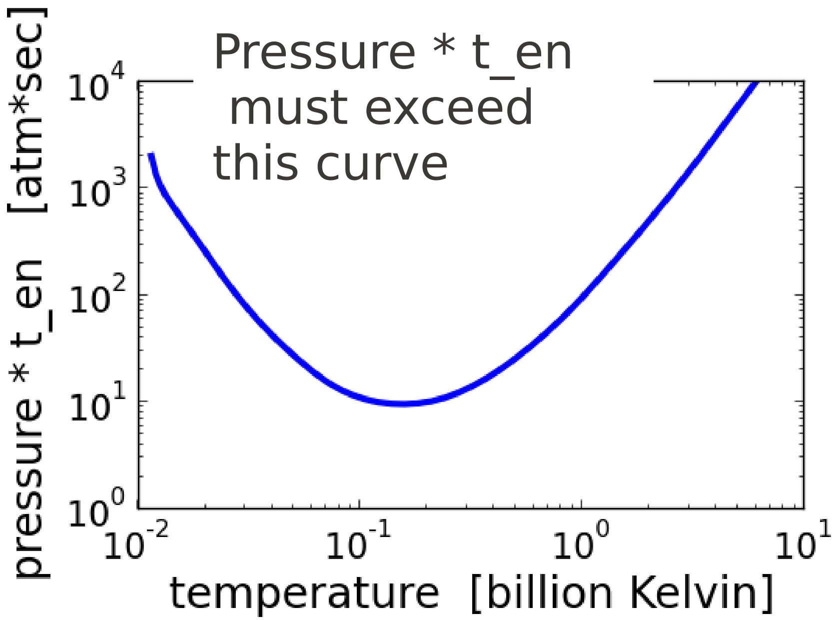
Three keys: density, temperature, confinement time

Ignition condition:
Pressure * t_en > function of temperature

t_en = energy confinement time

Pressure = density * temperature

“triple product:”
Density * temperature * confinement time



Pressure * t_en must exceed this curve

For a plasma to support substantial fusion, it must be:

- Hot: fusion reaction is appreciable only at 100 millions of Kelvins.
- Dense: fusion reactions scale as density squared: two nuclei must find each other.
- Confined: if particles or energy escape too quickly, plasma will cool, expand, stop fusing.

	Magnetic fusion	Inertial fusion	air	Solid gold
Density [g/cm3]				
Temperature [K]				
Pressure [atm]				
Confinement time [sec]				

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How the Sun does it: gravity + billions of years

- Proton-proton fusion (p-p chain): 4 protons fused into helium. First step:

p + p → deuteron [proton + neutron] + positron (“positive electron”) + neutrino

- p-p chain involves an inverse beta decay (w/ 2nd proton to conserve energy):

proton → neutron + positron + neutrino inverse beta decay

- Beta decay is the main reason a free neutron is unstable:

neutron → proton + electron + anti-neutrino beta decay

- The p-p chain rate is **10^{-25}** (minus 25, yes that's 25 zeros) times slower than D-T fusion at comparable temperatures. It is enormously slower because the inverse beta decay is caused by the weak nuclear force, while D-T fusion involves the strong nuclear force. This is a totally different physical process, with a totally different time scale. Humans who live for 10^{25} centuries have totally different biology from us.......

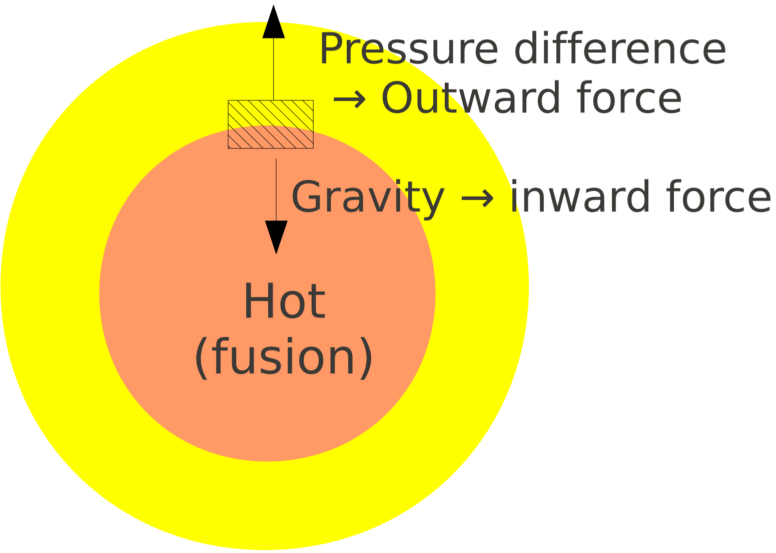
- It takes about a billion years for a typical proton in the Sun's core to undergo the p-p chain. Thus the Sun has been fusing for 5 billion years without consuming all its fuel.

Stellar forces, and production of chemical elements

- Stellar forces: inward gravity balances outward pressure from fusion heating in core.

- Other fusion processes produce nuclei as heavy as nickel or iron. Producing heavier elements by fusion consumes, rather than releases, energy, and is very rare in normal stellar conditions.

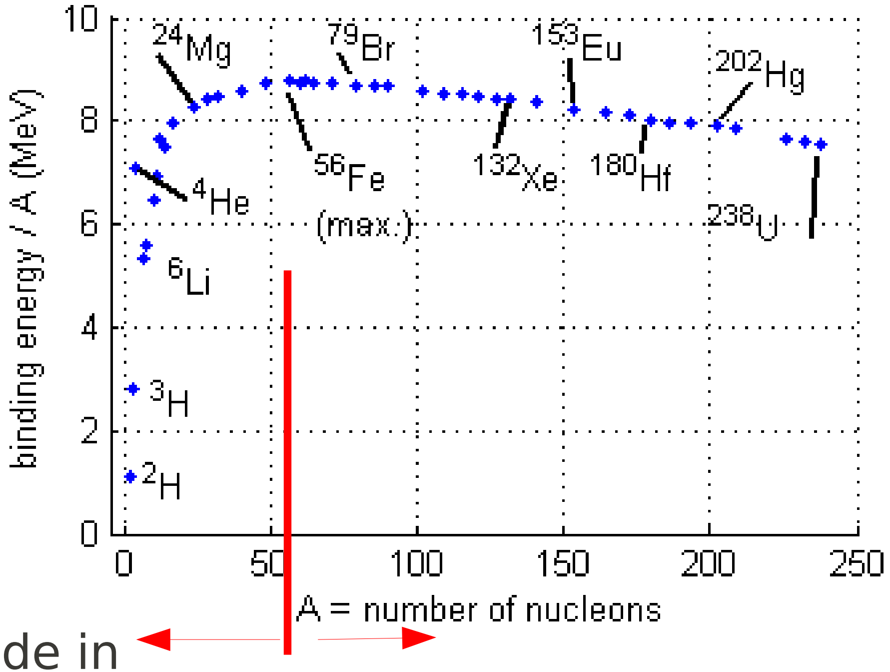
- The heavier elements are produced during violent events like supernovae.



Pressure difference
→ Outward force

Gravity → inward force

Hot
(fusion)



Made in
normal stars

Made in violent events
(supernovae)

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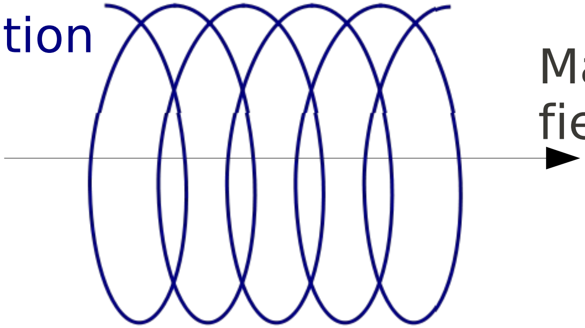
Doing it on Earth: Magnetic confinement

Charged particles (like electrons and nuclei) can move freely along a magnetic field, but move in circles around it.



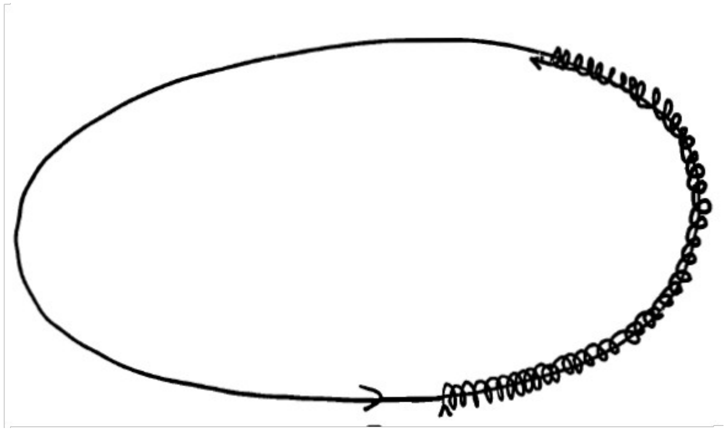
Particle motion

Magnetic field

Radius of orbit = “gyro-radius”
~ 1/(magnetic field)

Big field → small orbits

Closing the magnetic field on itself confines the particle orbit in all three dimensions:



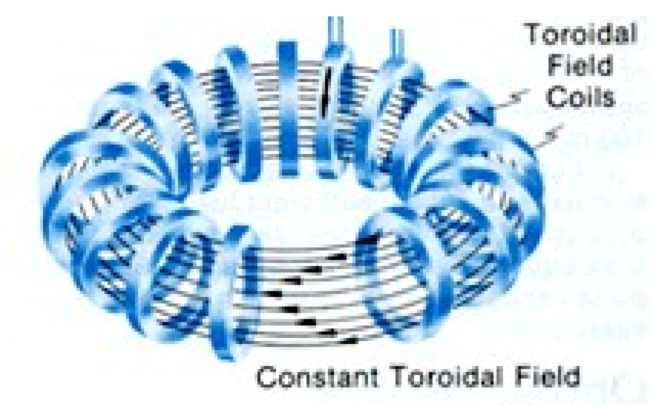
There is still particle and heat transport across the magnetic field, although it is much slower than without the field.

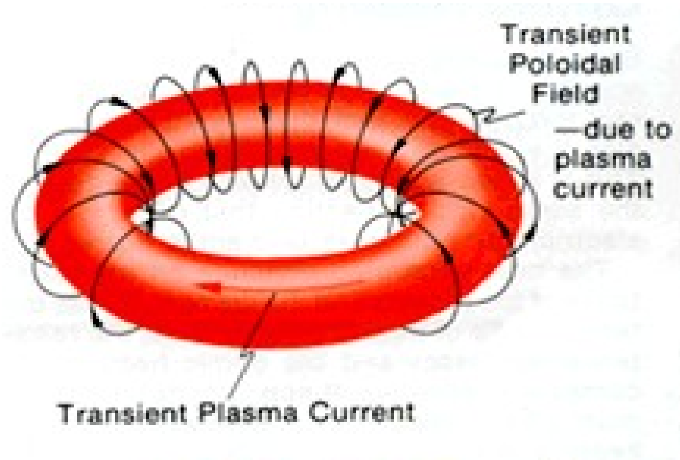
A variety of field geometries have been explored.

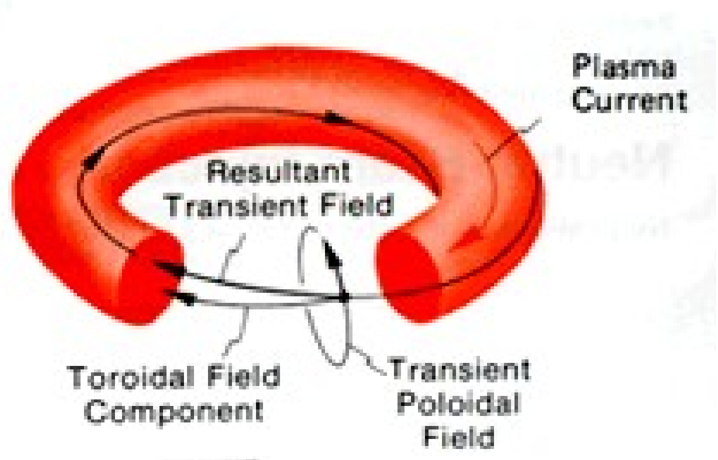
The most promising so far is called the tokamak, originated by the Soviets in the 1950s.

Magnetic confinement: the tokamak

- Magnets (current-carrying coils) provide a toroidal (“the long way”) magnetic field.
- The plasma carries a toroidal current: provides a poloidal (“the short way”) field.
- This field is necessary for a tokamak plasma to be confined.
- However, it can drive instabilities that can degrade confinement.







For a power reactor, a magnetic confinement system should operate in steady state, where the heat lost is (at least mostly) balanced by heating due to fusion reactions. This is called a burning plasma.

Requires machine to be very large compared to the radius of particle gyro-orbits.

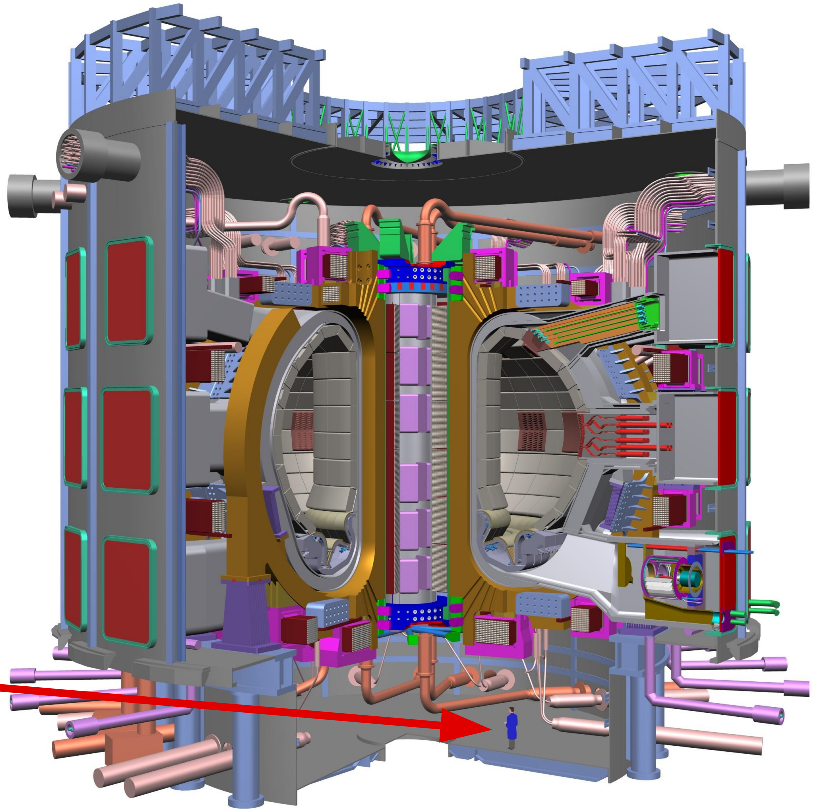
Magnetic confinement: ITER

ITER = International Experimental Thermonuclear Reactor

A tokamak experiment, which is expected to achieve a burning plasma, if not ignition, is being built in France.

Developed by an international consortium: The EU, Japan, USA, Russia, China, India, South Korea.

Expected to be operational ~ 2018, DT shots in 2026, cost $10 billion to construct*.



For scale, there is a man

* BBC News, 17 June 2009:
http://news.bbc.co.uk/2/hi/science/nature/8103557.stm

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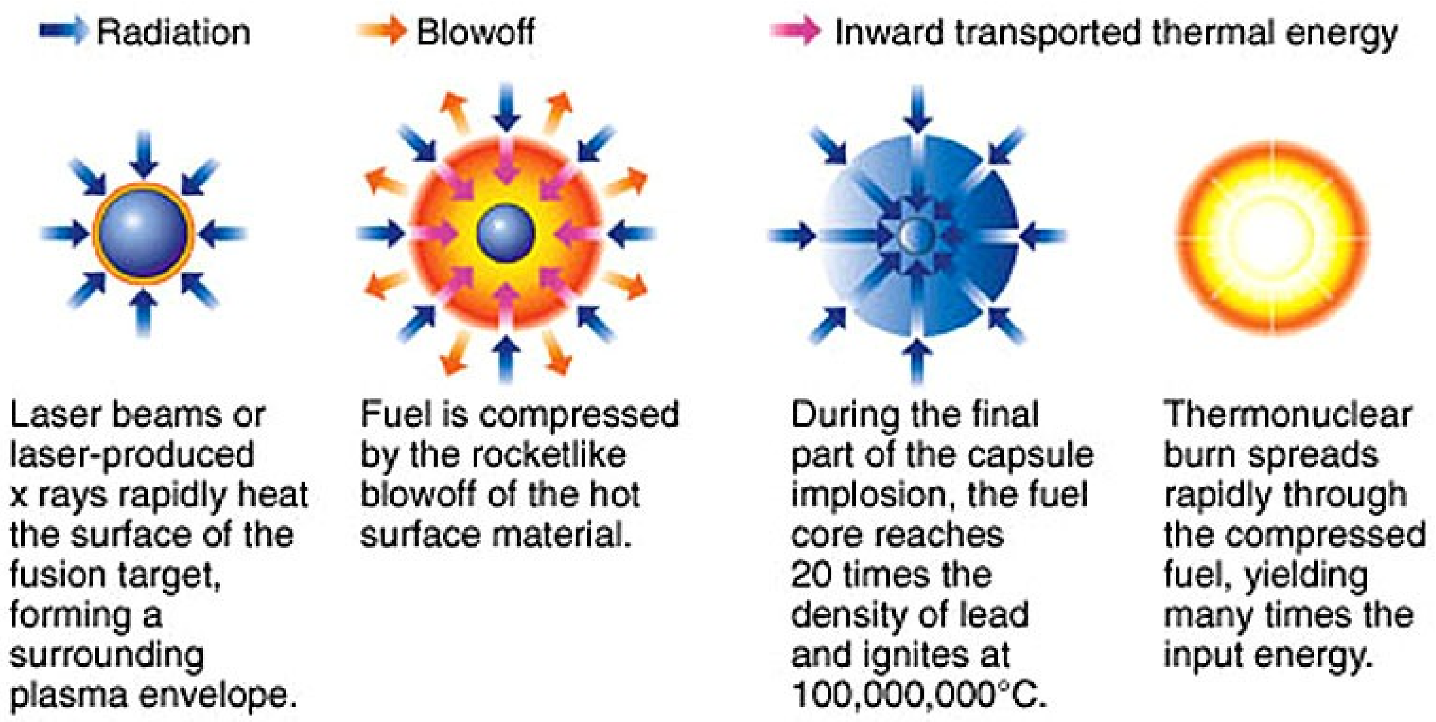
Doing it on Earth: Inertial confinement



Laser beams or laser-produced x rays rapidly heat the surface of the fusion target, forming a surrounding plasma envelope.

Fuel is compressed by the rocketlike blowoff of the hot surface material.

During the final part of the capsule implosion, the fuel core reaches 20 times the density of lead and ignites at 100,000,000°C.

Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the input energy.

- Use light to boil off matter from a spherical pellet of fusion fuel. This ablation process causes the blowoff to expand, and the pellet to implode inward. Like a spherical rocket.

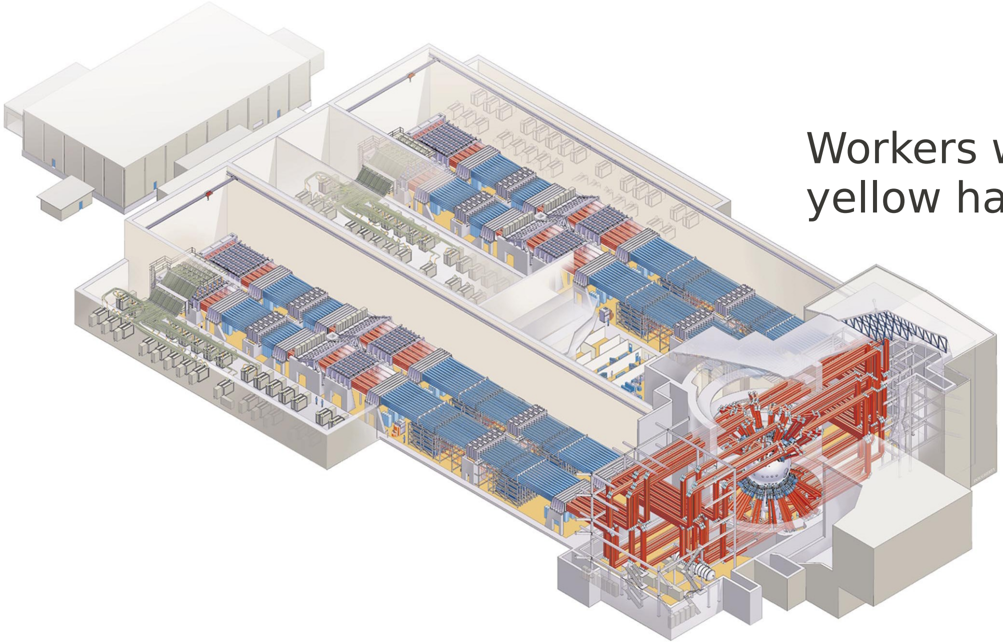
- The compressed fuel will hopefully reach high enough densities (hundreds of times that of liquids) and temperatures for fusion to start.

- What's confining the fuel? Nothing! The compressed fuel disassembles very rapidly, but not instantly, since it has mass (inertia).

- If done right, fusion will occur before fuels dissassembles.

Inertial confinement: National Ignition Facility (NIF)

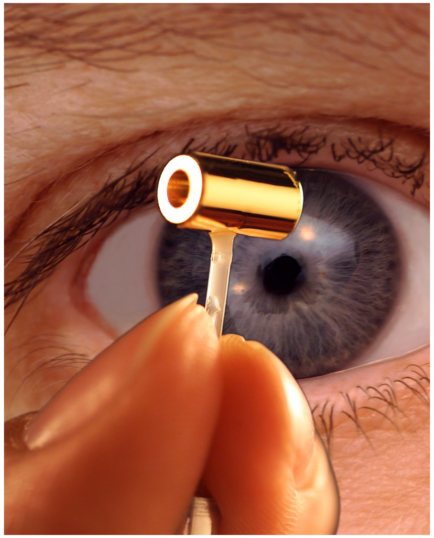
NIF building is about 300 yards long (3 football fields), most of which is laser compor



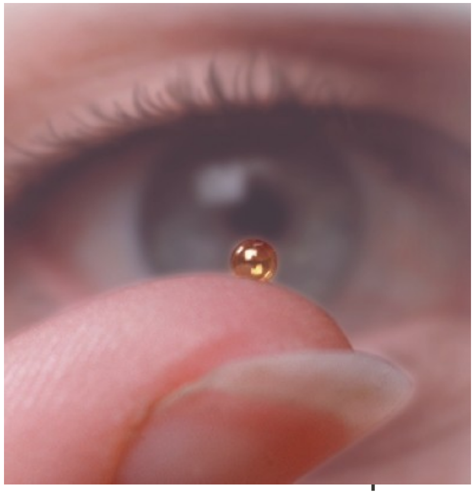
Workers w/
yellow hardhats

1.5 megajoules (360 Calories) of laser energy delivered, in 20 nanoseconds, to:

A hollow gold cylinder
(hohlraum), which gets
hot and radiates x-rays



The x-rays drive the
ablative implosion
of a fuel capsule
inside the hohlraum



More on the National Ignition Facility (NIF)

- Biggest (most energetic, largest building, most expensive) laser in the world.

- Biggest experiment at LLNL.

- Construction started ~1995; cost ~ $4 billion, about twice as original budget; cost overruns developed in the late 1990s, causing political problems.

- NIF is the culmination of earlier, smaller laser systems at LLNL and elsewhere.

- NIF is being funded for stewardship of the US nuclear stockpile, although energy and basic science (e.g. astrophysics) have always been secondary goals.

- Unlike magnetic fusion, ICF has a military “customer.” That's magnetic fusion's real problem!

- Also unlike magnetic confinement, ICF is inherently pulsed and not steady state: once all the fuel in a capsule is burnt up, that's it, you need another capsule and another laser pulse.

- For energy production, the NIF lasers are tremendously inefficient and way too low a repetition rate.

- Replacement “drivers” are possible: diode-pumped lasers, beams of heavy ions, wire-array “Z pinches.”

Uses of fusion: boiling water to make electricity

- “Fission (or fusion) is just another way to boil water.”

- The energetic fusion products will be slowed down in a blanket surrounding the fusion source. This heat will then be exchanged with a water boiler, which will drive a steam turbine.

- Electricity generation by fossil fuels, fission, or fusion all rely on steam turbines and boiling water.

- All fusion approaches that look promising are “big:” can't really be tested, and not productively used, on a small scale.

- You can't power a calculator off fusion, you have to start with a power plant. This has impeded fusion development, funding, and investment. But no one's thought of a “Mr. Fusion” a la Back to the Future.

Fusion Development: Nuclei for Peace?

Oft-heard quips: “Fusion has been 30 years away for the last 60 years.”
“Fusion is the future of energy, and always will be.”

Money, not time, is the correct variable to plot fusion progress against. Fusion is ~ $100 billion problem.

Given that money, no constraints, we could make a reactor in 10 years.
- Still couldn't be done overnight: serious scientific challenges remain.

Per year, in trillions of dollars:
World GDP: 55 Energy market: 3 Energy R&D: 0.012 US pet food*: 0.014

Magnetic fusion: limited by lack of funding – definite plan for experiment to test reactor physics (ITER), but won't be online til ~2020.

Inertial fusion: NIF is working toward ignition in the next few (not 60) years, but to make a power plant several miracles needed:
 Much more efficient laser (or replacement)
 Fabricate fuel pellets for < $0.25, and make ~ 1 million per day
 Ignite 10 pellets *a second* to get about a 1000 megawatts electric.

*Source: World Bank

More Fusion Development

Besides developing a fusion system, a lot of research is needed on materials for a working reactor. The output of a fusion system, especially the energetic neutrons, is much more intense and damaging than in a fission reactor.

The IFMIF (International Fusion Material Integration Facility) had been proposed to address the matierals issues. Comparable in budget to NIF or ITER. No one has been willing to fund it yet.

Fusion's attractive features:
  Inexhaustible (millions of years) of fuel on Earth
  No atmospheric pollution

But fusion is not a silver bullet:
  It will not be free – like nuclear fission, it will have large capital costs
  The cost of electricity will probably be a few times that of coal today

Fusion shares some problems with fission, but in much reduced form:

Radioactive waste: fusion neutrons will cause the reactor materials to become radioactive, but the half-lives will be 10-100 years, not the 10,000 of some fission waste

Nuclear proliferation: you can't build a bomb out of a fusion reactors (there is no uranium or plutonium), but fusion neutrons can be used to breed plutonium from uranium.

Best (or worst) of both worlds: fission-fusion hydrid:
Use fusion neutrons to breed fission fuel, burn fission waste into benign material

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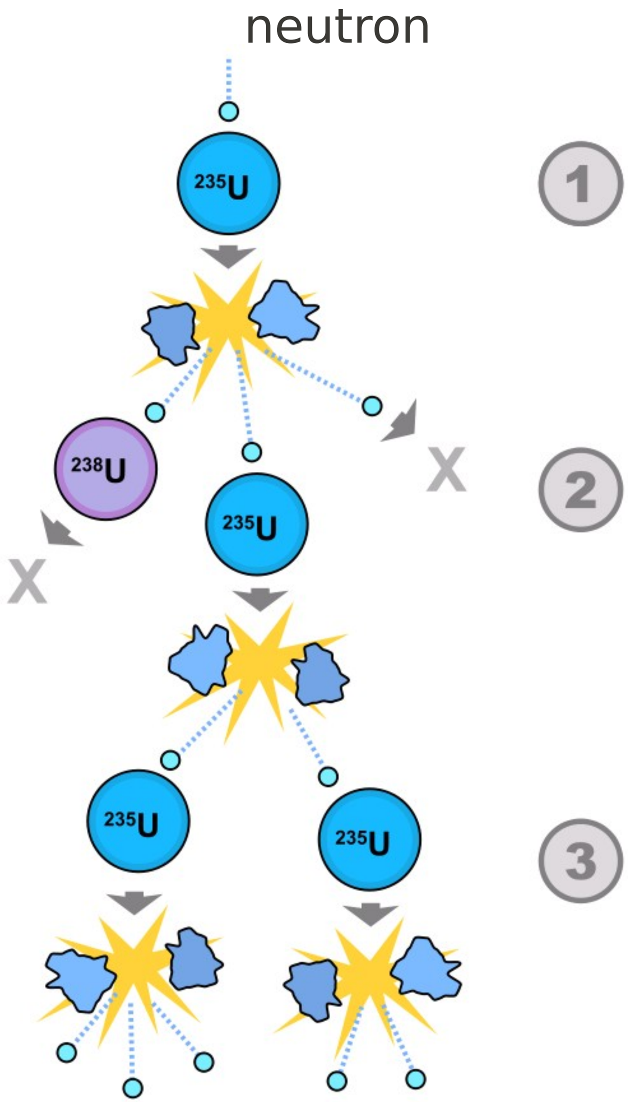
Nuclear fission: the bigger they are the harder they fall



Fission: splitting of a nucleus into smaller fragments.

A nucleus is **fissile** if a “slow” neutron can cause it to fission, and this fissioning produces neutrons which can lead to subsequent fissions.

This allows for a **chain reaction**.

Very few isotopes are fissile. Uranium (U)-235 and Plutonium (Pu)-239 are two such.

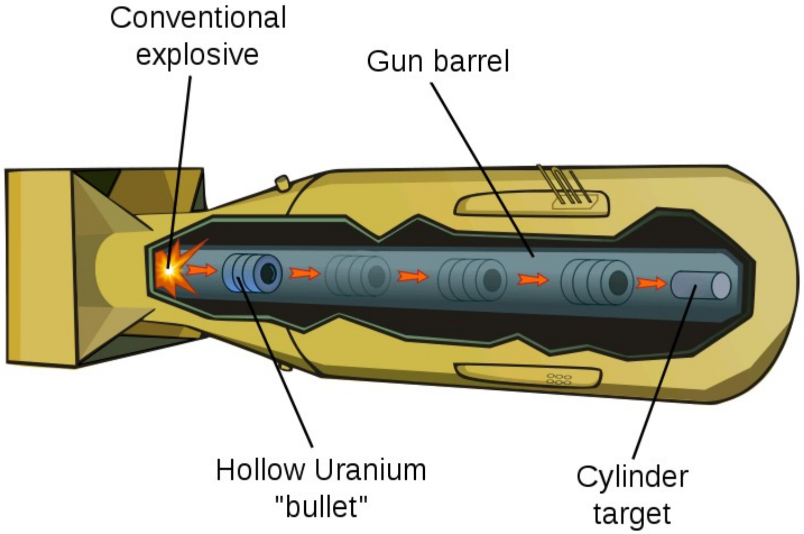
Natural Uranium is 99.28% 238 isotope, 0.7% 235.

U-238 is not fissile, although it does decay radioactively, half-life of 4.5 billion years. When his by a neutron it becomes Pu-239, which is fissile.

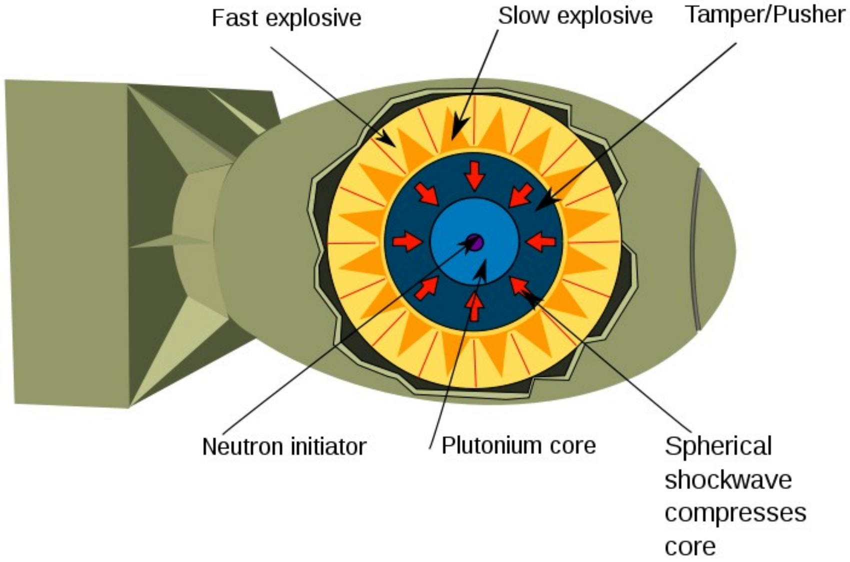
Depleted Uranium is more purely U-238 than naturally occurring, i.e., the leftover from enrichment.

Nuclear Explosives (or, how I learned to stop worrying and love the bomb)

Gun assembly: Hiroshima
Little Boy, U-235, ~15 kT (kiloton) yield



Implosion assembly: Nagasaki
Fat Man, Pu-239, ~20 kT yield



Hydrogen bombs (thermonuclears):

Two stages (Teller-Ulam design): radiation from fission stage implodes a second fusion stage.

First US test: Ivy Mike, 1952, cryogenic D-T.
Not a usable weapon: huge device to keep DT cold. Yield ~10 MT (million tons).

First USSR test of “layer cake” design (not two-stage): 1953, Lithium-deuteride. Tritium bred in-place, small enough to be a weapon, but much smaller yield ~400 kT.

Putting it together: 1954 Castle Bravo US test: 15 MT yield, Li-D fuel and two-stage. Pacific islanders and Japanese fishing boat crew exposed to fallout, some died. Yield was 2.5 times expected, since Lithium-7 + neutron fusion not accounted for. Thanks, Los Alamos!

Before we get carried away...

Our tragedy today is a general and universal physical fear so long sustained by now that we can even bear it. There are no longer problems of the spirit. There is only the question: When will I be blown up? Because of this, the young man or woman writing today has forgotten the problems of the human heart in conflict with itself which alone can make good writing because only that is worth writing about, worth the agony and the sweat.

- William Faulkner, banquet speech, Nobel prize in literature, 1949

I see the danger not in the number or quality of the weapons or in the intentions of those who hold them but in the very existence of weapons of this nature, regardless of whose hands they are in. I believe that unless we consent to recognize that the nuclear weapons we hold in our hands are as much a danger to us as those that repose in the hands of our supposed adversaries there will be no escape from the confusions and dilemmas to which such weapons have brought us, and must bring us increasingly as time goes on. For this reason, I see no solution to the problem other than the complete elimination of these and all other weapons of mass destruction from the national arsenals; and the sooner we move toward that solution, and the greater courage we show in doing so, the safe we will be.

- George F. Kennan, architect of US Cold-War containment policy, *New Yorker*, Nov. 2 1981

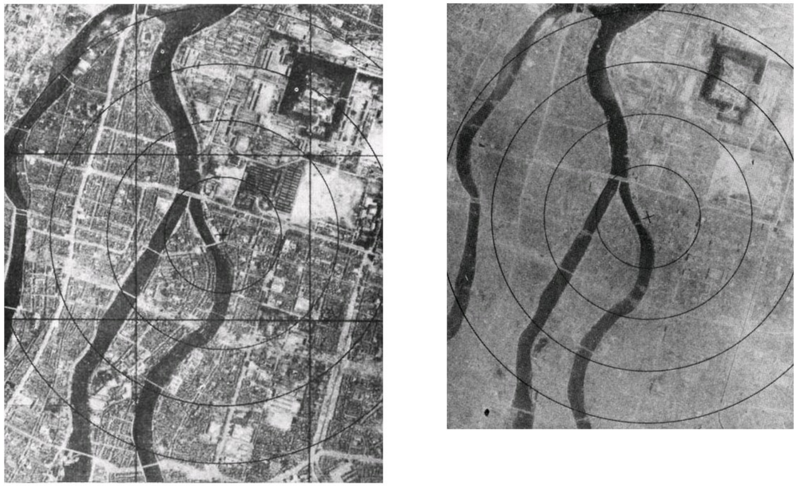
Even if we get rid of nuclear bombs, we'll always know how they work.

- David J. Strozzi, winner of nothing

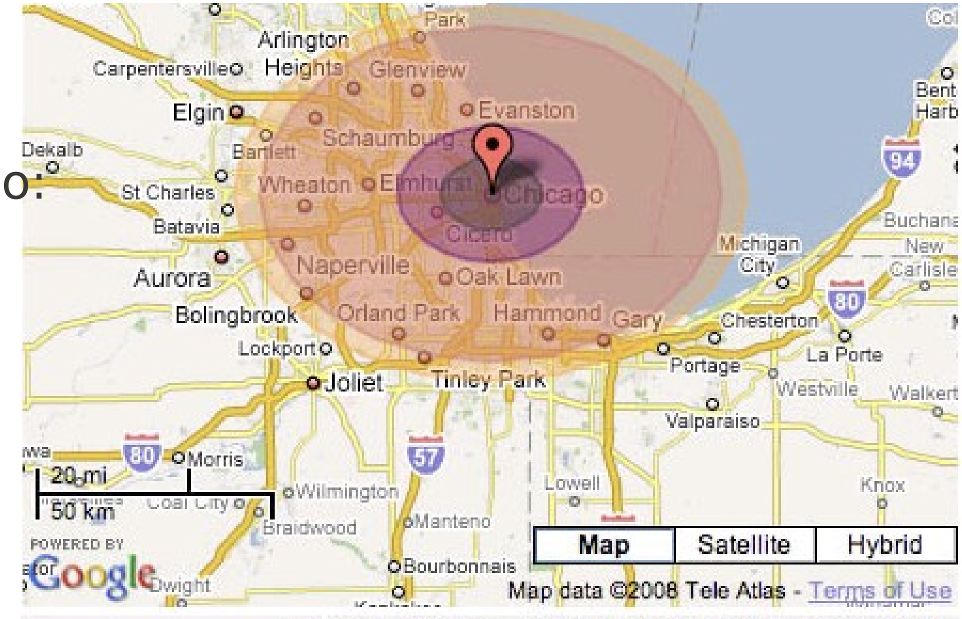
Before we get carried away...

Nagasaki after

Hiroshima before and after



If Tsar Bomba were dropped on Chicago:



Summary: what fusion is and where we stand

- Nucler fusion, and fission, release kinetic energy by increasing the nuclear binding energy of the final products compared to the initial “fuel” nuclei.

- Nuclear reactions release millions of times as much energy per fuel mass as chemical reactions – thus an atomic bomb with 10 kg of plutonium can produce as much energy as 10 kilotons (10 million kg) of TNT explosives.

- Fusion requires enormous temperatures (~100 million degrees), high enough fuel density, and long enough confinement time.

- Magnetic fusion: use magnetic fields to roll up particle orbits. ITER machine being build in France, should be done around 2018.

- Inertial fusion: National Ignition Facility (NIF), at Lawrence Livermore National Lab, is starting experiments now.

- Long-term proposition: fusion is going to take time and more importantly money to develop. It is too far off for private companies to invest in, so we need public research funding.

- Write your Congresspeople!