Geothermal Energy

Sources of Earth’s Internal Energy

- 70% comes from the decay of radioactive nuclei with long half lives that are embedded within the Earth
- Some energy is from residual heat left over from Earths formation.
- The rest of the energy comes from meteorite impacts.

Different Geothermal Energy Sources

- **Hot Water Reservoirs**: As the name implies these are reservoirs of hot underground water. There is a large amount of them in the US, but they are more suited for space heating than for electricity production.
- **Natural Stem Reservoirs**: In this case a hole dug into the ground can cause steam to come to the surface. This type of resource is rare in the US.
- **Geopressured Reservoirs**: In this type of reserve, brine completely saturated with natural gas in stored under pressure from the weight of overlying rock. This type of resource can be used for both heat and for natural gas.

- **Normal Geothermal Gradient**: At any place on the planet, there is a normal temperature gradient of +30^{0}C per km dug into the earth. Therefore, if one digs 20,000 feet the temperature will be about 190^{0}C above the surface temperature. This difference will be enough to produce electricity. However, no useful and economical technology has been developed to extracted this large source of energy.

- **Hot Dry Rock**: This type of condition exists in 5% of the US. It is similar to Normal Geothermal Gradient, but the gradient is 40^{0}C/km dug underground.

- **Molten Magma**: No technology exists to tap into the heat reserves stored in magma. The best sources for this in the US are in Alaska and Hawaii.

Direct uses of geothermal energy is appropriate for sources below 150^{0}C

- space heating
- air conditioning
- industrial processes
- drying
- Greenhouses
- Aguaculture
- hot water
- resorts and pools
- melting snow

Gretz, Warren

Crop dehydration plant in Nevada.

Gretz, Warren

A fish farm in Colorado

Gretz, Warren

Greenhouse in Colorado

How Direct Uses Work

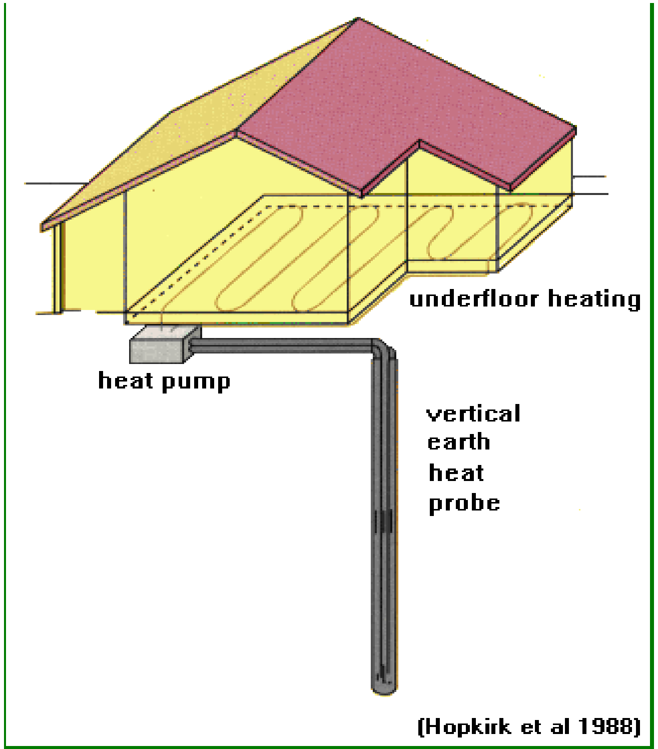
- Direct Sources function by sending water down a well to be heated by the Earth’s warmth.
- Then a heat pump is used to take the heat from the underground water to the substance that heats the house.
- Then after the water it is cooled is injected back into the Earth.

Ground Heat Collectors

This system uses horizontal loops filled with circulating water at a depth of 80 to 160 cm underground.

Borehole Heat Exchange

This type uses one or two underground vertical loops that extend 150 meters below the surface.



(Hopkirk et al 1988)

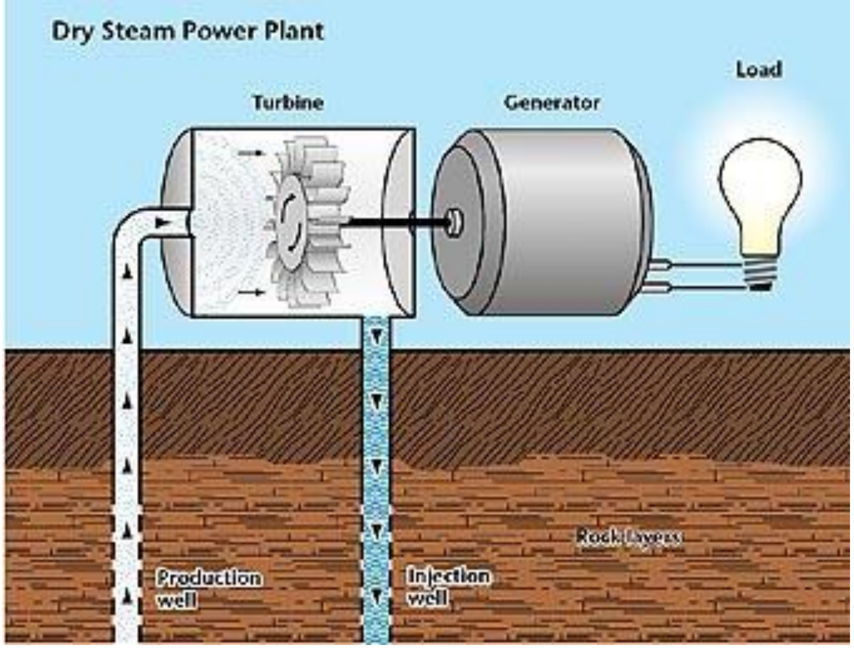
Schema of a U tube system installed in a small diameter well

Generation of Electricity is appropriate for sources >150^{o}C

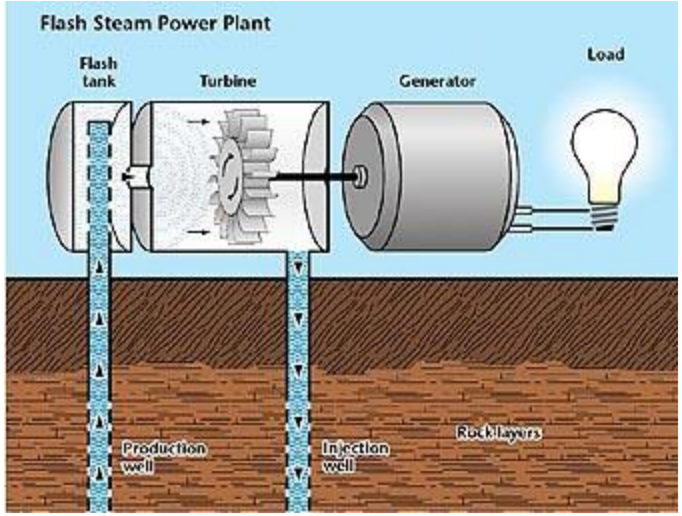
Dry Steam Plants: These were the first type of plants created. They use underground steam to directly turn the turbines.


Pacific Gas & Electric

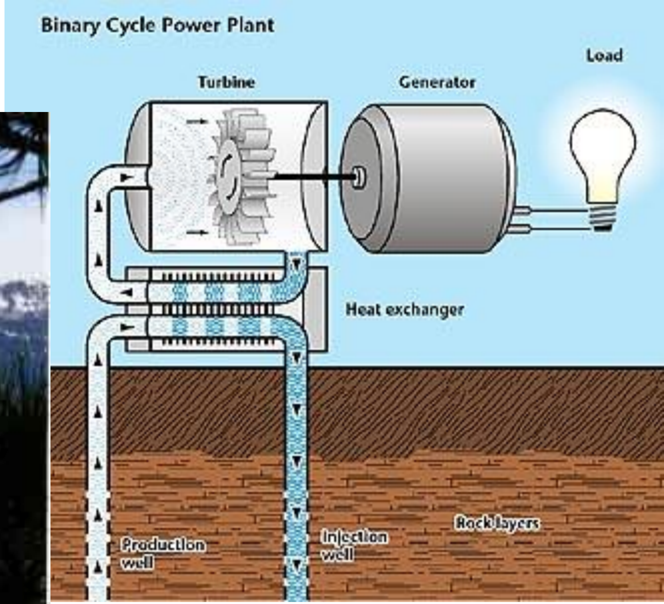
Dry steam power plants at The Geysers in California.

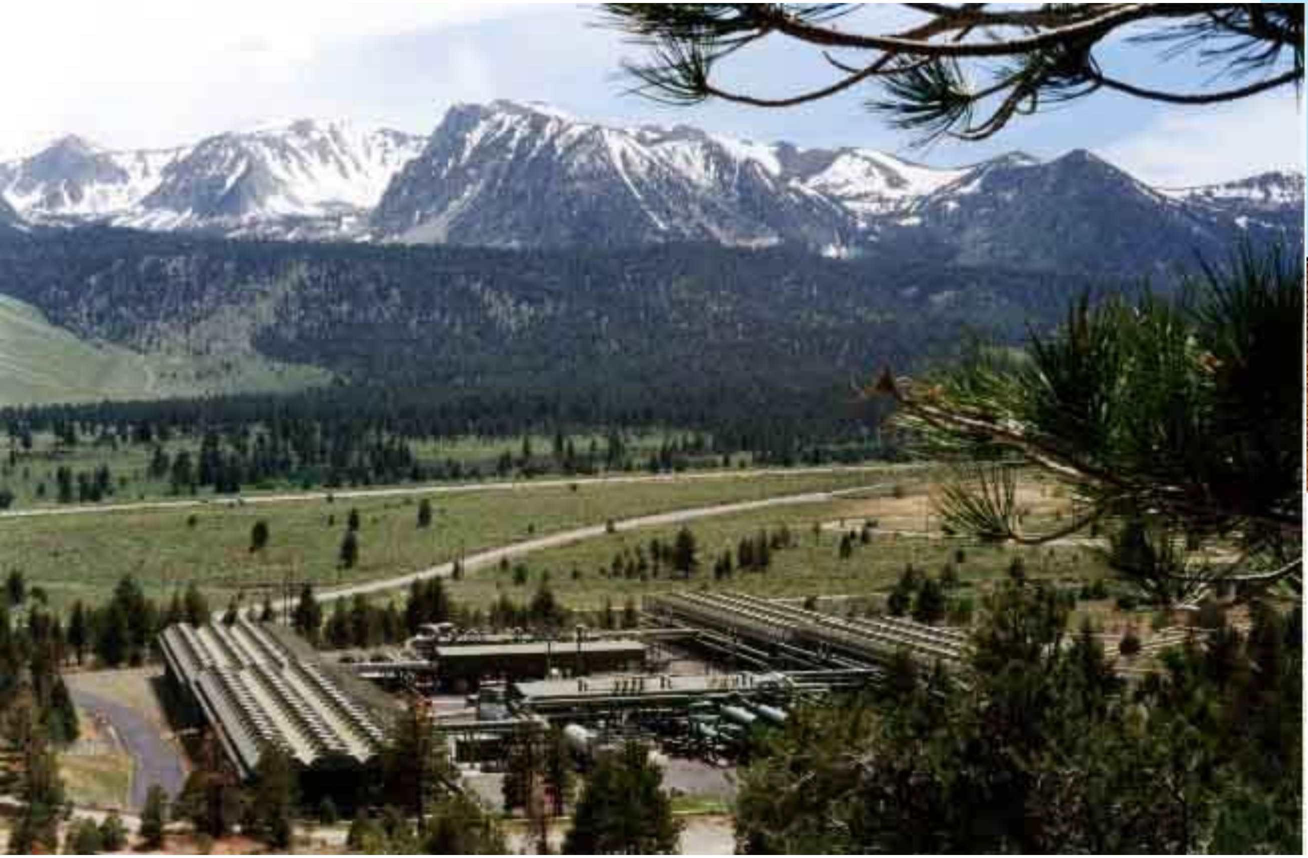


Flash Steam Plants: These are the most common plants. These systems pull deep, high pressured hot water that reaches temperatures of 360^0F or more to the surface. This water is transported to low pressure chambers, and the resulting steam drives the turbines. The remaining water and steam are then injected back into the source from which they were taken.



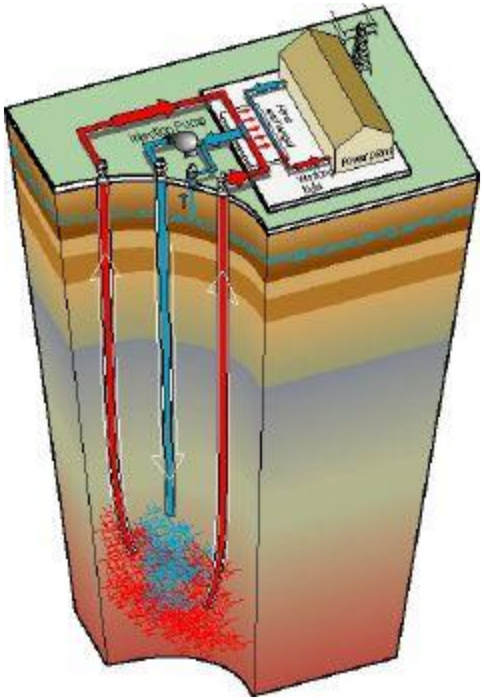
Binary Cycle Plants: This system passes moderately hot geothermal water past a liquid, usually an organic fluid, that has a lower boiling point. The resulting steam from the organic liquid drives the turbines. This process does not produce any emissions and the water temperature needed for the water is lower than that needed in the Flash Steam Plants (250^0F – 360^0F).





Casa Diablo

Hot Dry Rocks: The simplest models have one injection well and two production wells. Pressurized cold water is sent down the injection well where the hot rocks heat the water up. Then pressurized water of temperatures greater than 200^0F is brought to the surface and passed near a liquid with a lower boiling temperature, such as an organic liquid like butane. The ensuing steam turns the turbines. Then, the cool water is again injected to be heated. This system does not produce any emissions. US geothermal industries are making plans to commercialize this new technology.



Geothermal’s Harmful Effects

- Brine can salinate soil if the water is not injected back into the reserve after the heat is extracted.

- Extracting large amounts of water can cause land subsidence, and this can lead to an increase in seismic activity. To prevented this the cooled water must be injected back into the reserve in order to keep the water pressure constant underground.

- Power plants that do not inject the cooled water back into the ground can release H_2S, the “rotten eggs” gas. This gas can cause problems if large quantities escape because inhaling too much is fatal.

- One well “blew its top” 10 years after it was built, and this threw hundreds of tons of rock, mud and steam into the atmosphere.

- There is the fear of noise pollution during the drilling of wells.

Geothermal's Positive Attributes

- Useful minerals, such as zinc and silica, can be extracted from underground water.
- Geothermal energy is "homegrown." This will create jobs, a better global trading position and less reliance on oil producing countries.
- US geothermal companies have signed $6 billion worth of contracts to build plants in foreign countries in the past couple of years.
- In large plants the cost is 4-8 cents per kilowatt hour. This cost is almost competitive with conventional energy sources.

- Geothermal plants can be online 100%-90% of the time. Coal plants can only be online 75% of the time and nuclear plants can only be online 65% of the time.

- Flash and Dry Steam Power Plants emit 1000x to 2000x less carbon dioxide than fossil fuel plants, no nitrogen oxides and little SO_2.

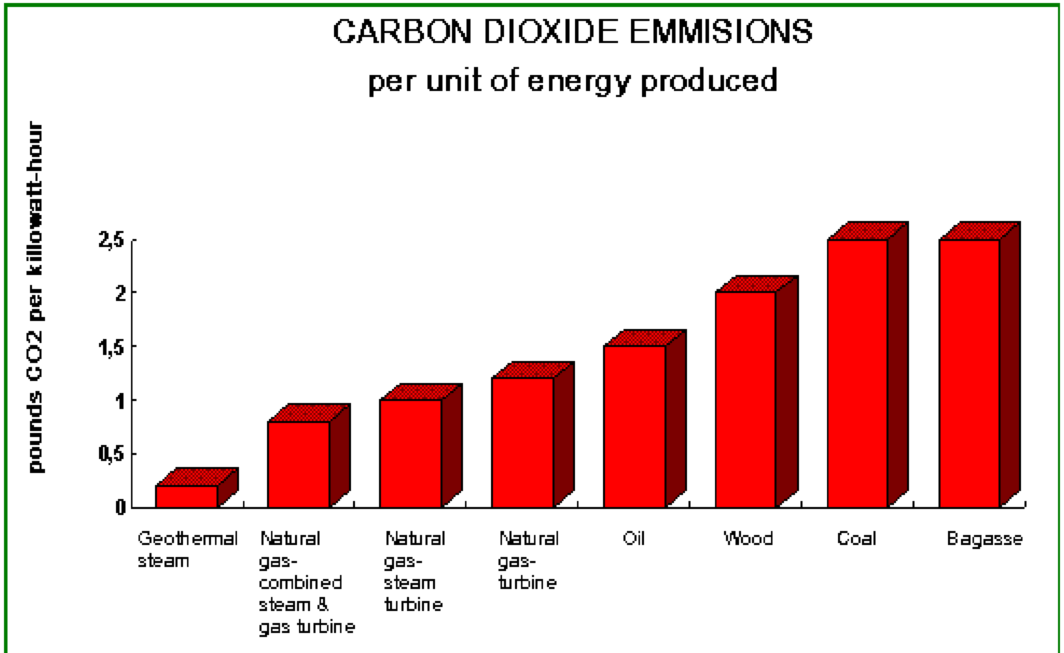
- Geothermal electric plants production in 13.380 g of Carbon dioxide per kWh, whereas the CO_2 emissions are 453 g/kWh for natural gas, 906g g/kWh for oil and 1042 g/kWh for coal.

- Binary and Hot Dry Rock plants have no gaseous emission at all.

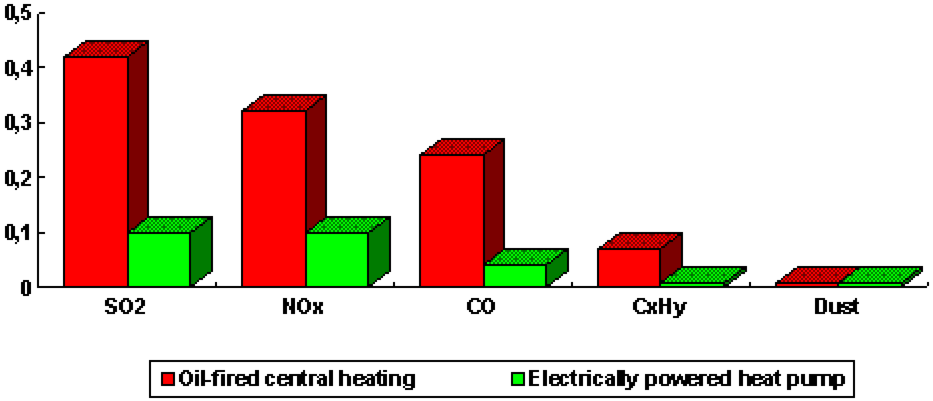
- Geothermal plants do not require a lot of land, $400m^2$ can produce a gigawatt of energy over 30 years.

- Geothermal Heat Pumps:
  - produces 4 times the energy that they consume.
  - initially costs more to install, but its maintenance cost is 1/3 of the cost for a typical conventional heating system and it decreases electric bill. This means that geothermal space heating will save the consumer money.
  - can be installed with the help of special programs that offer low interest rate loans.

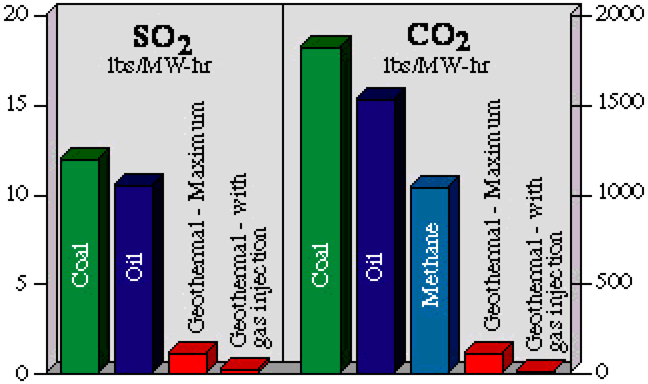
- Electricity generated by geothermal plants saves 83.3 million barrels of fuel each year from being burned world wide. This prevents 40.2 million tons of CO_2 from being emitted into the atmosphere.
- Direct use of geothermal energy prevents 103.6 million barrels of fuel each year from being burned world wide. This stops 49.6 tons of CO_2 from being emitted into the atmosphere.



Comparison of CO_2 emissions between conventional energy systems and geothermal plants to generate electricity



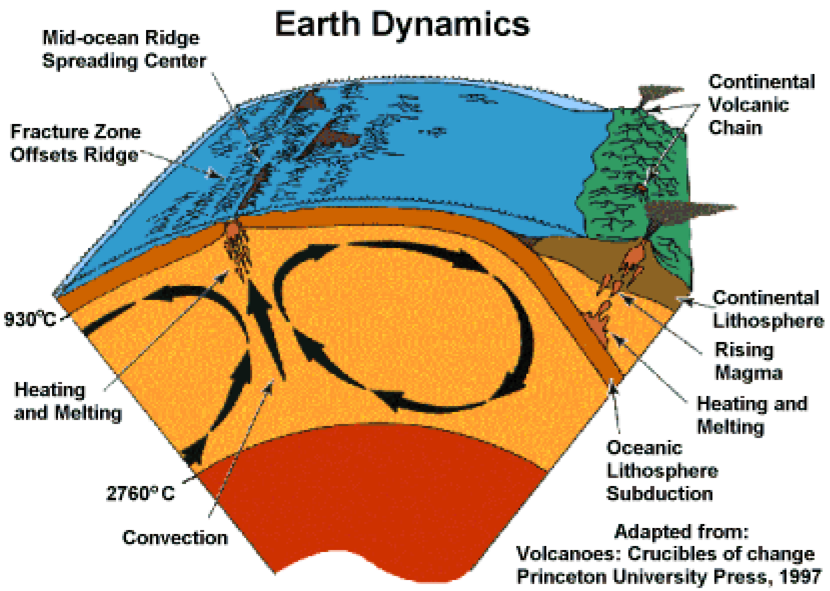
Comparison of harmfull emissions between a conventional oil fired central heating system and water/water based heat pumps.



After Goddard & Goddard, GRC Transactions, 14, 643-649 (1 lb = 0.4536 kg)

Availability of Geothermal Energy

- On average, the Earth emits 1/16 W/m^2. However, this number can be much higher in areas such as regions near volcanoes, hot springs and fumaroles.
- As a rough rule, 1 km^3 of hot rock cooled by 100^{0}C will yield 30 MW of electricity over thirty years.
- It is estimated that the world could produce 600,000 EJ over 5 million years.
- There is believed to be enough heat radiating from the center of the Earth to fulfill human energy demands for the remainder of the biosphere's lifetime.



Adapted from:
Volcanoes: Crucibles of change
Princeton University Press, 1997

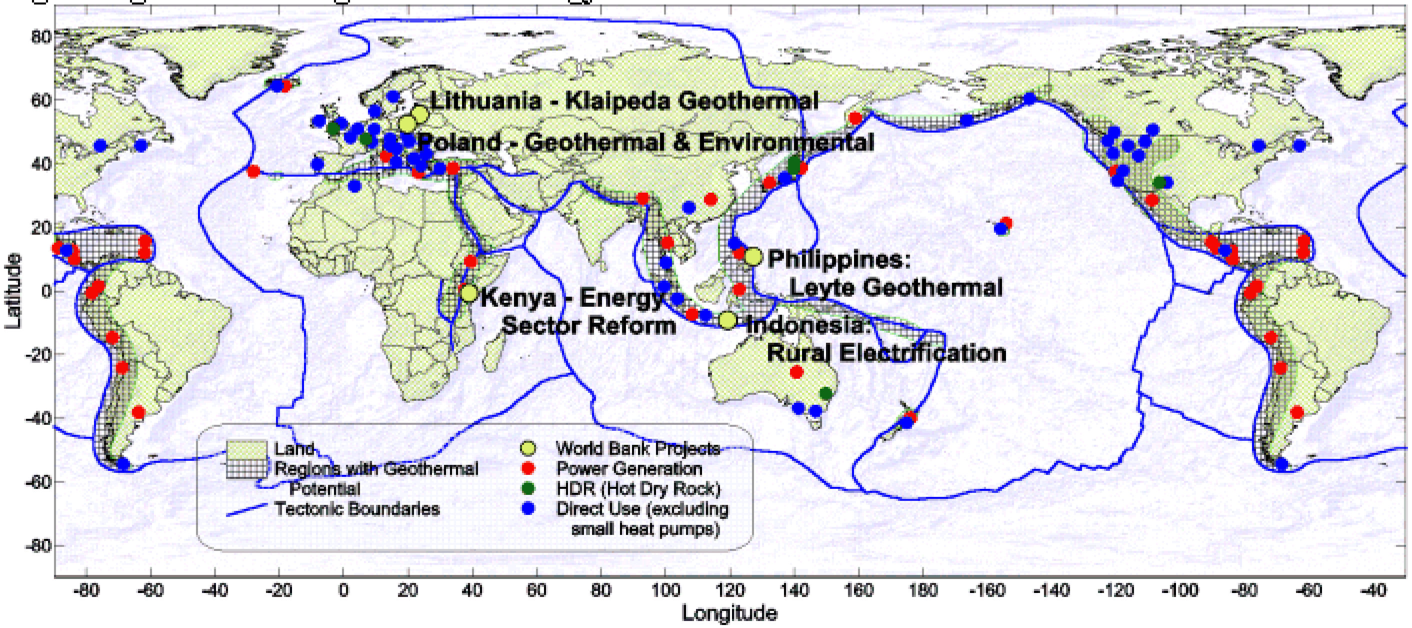
Geothermal production of energy is 3rd highest among renewable energies. It is behind hydro and biomass, but before solar and wind.

Iceland is one of the more countries successful in using geothermal energy:

-86% of their space heating uses geothermal energy.
-16% of their electricity generation uses geothermal energy.

World Wide Geothermal Uses and Potential

Figure a global view of geothermal energy



NATION	**Installed MWe**	**GWh Generated**	**% of National Capacity**
Australia	0.17	0.9	n/a
China	29	100	n/a
Costa Rica	142	592	7.77
El Salvador	161	800	15.39
Ethiopia	9	30	1.93
France	4	n/a	n/a
Guatemala	33	216	3.68
Iceland	170	662	13.36
Indonesia	589	4,575	3.04
Italy	785	4,403	1.03
Japan	547	3,532	0.23
Kenya	45	366	5.29
Mexico	755	5,681	2.11
New Zealand	437	2,268	5.11
Nicaragua	70	583	16.99
Philippines	1,909	9,181	n/a
Portugal	16	n/a	0.21
Russia	23	85	0.01
Thailand	0.3	n/a	n/a
Turkey	20	n/a	n/a
USA	2,228	15,470	0.25
TOTAL	**7,974**	**48,545**	

NATION	**1995 MWe**	**2000 MWe**	**2005 est. MWe**
Argentina	0.7	0	n/a
Australia	0.2	0.2	n/a
China	29	29	n/a
Costa Rica	55	142	161
El Salvador	105	161	200
Ethiopia	0	9	9
France	4	4	20
Guatemala	0	33	33
Iceland	50	170	170
Indonesia	310	589	1987
Italy	632	785	946
Japan	414	547	567
Kenya	45	45	173
Mexico	753	755	1080
New Zealand	286	437	437
Nicaragua	70	70	145
Philippines	1,227	1,909	2,673
Portugal	5	16	45
Russia	11	23	125
Thailand	0.3	0.3	0.3
Turkey	20	20	250
USA	2,817	2,228	2,376
TOTAL	**6,833**	**7,974**	**11,398**

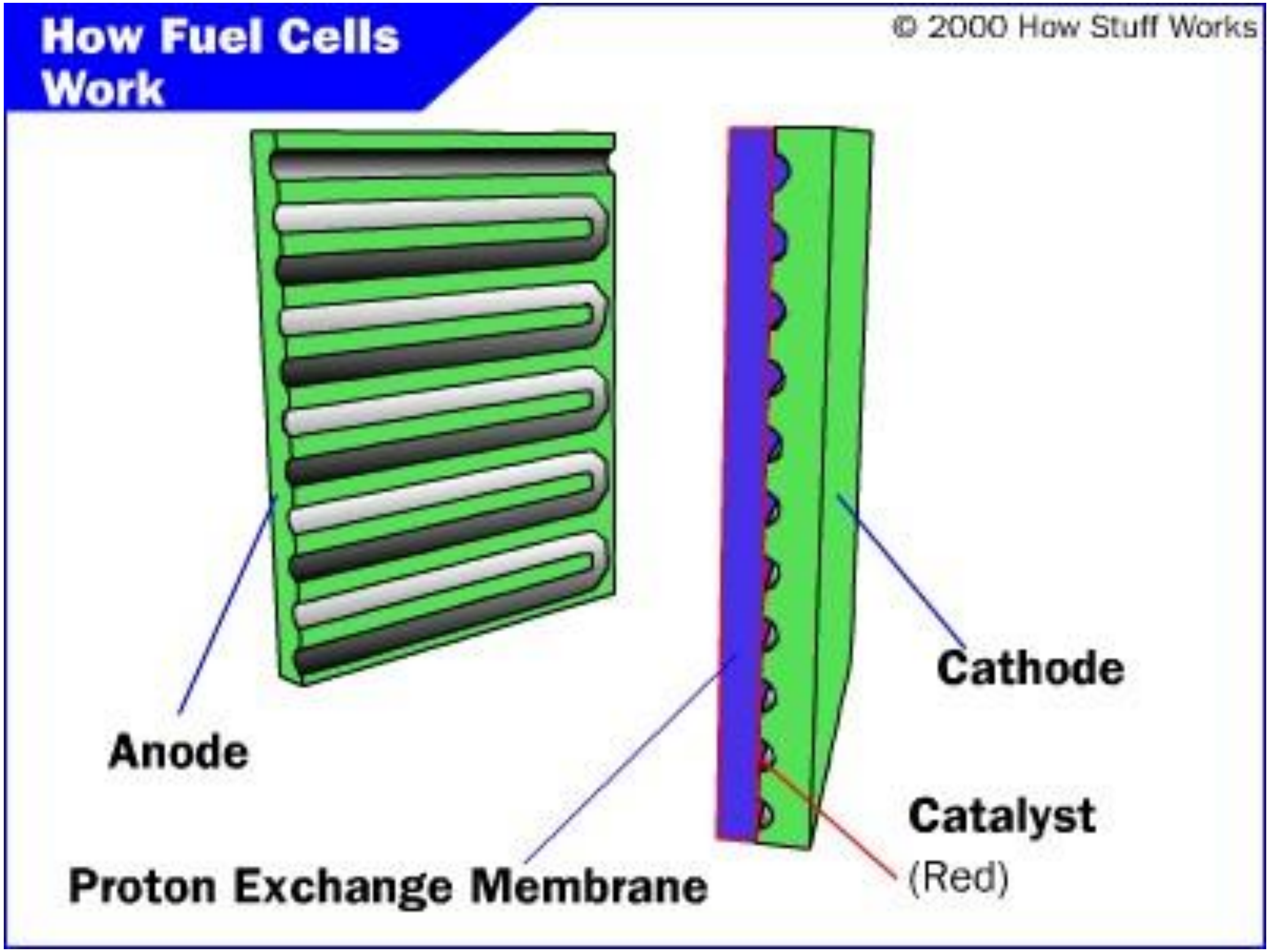
Fuel Cells

The Promise of Fuel Cells

- *"A score of nonutility companies are well advanced toward developing a powerful chemical fuel cell, which could sit in some hidden closet of every home silently ticking off electric power."*
  - Theodore Levitt, "Marketing Myopia," *Harvard Business Review,* 1960

Theodore Levitt, "Marketing Myopia," *Harvard Business Review,* 1960

PEM Fuel Cell



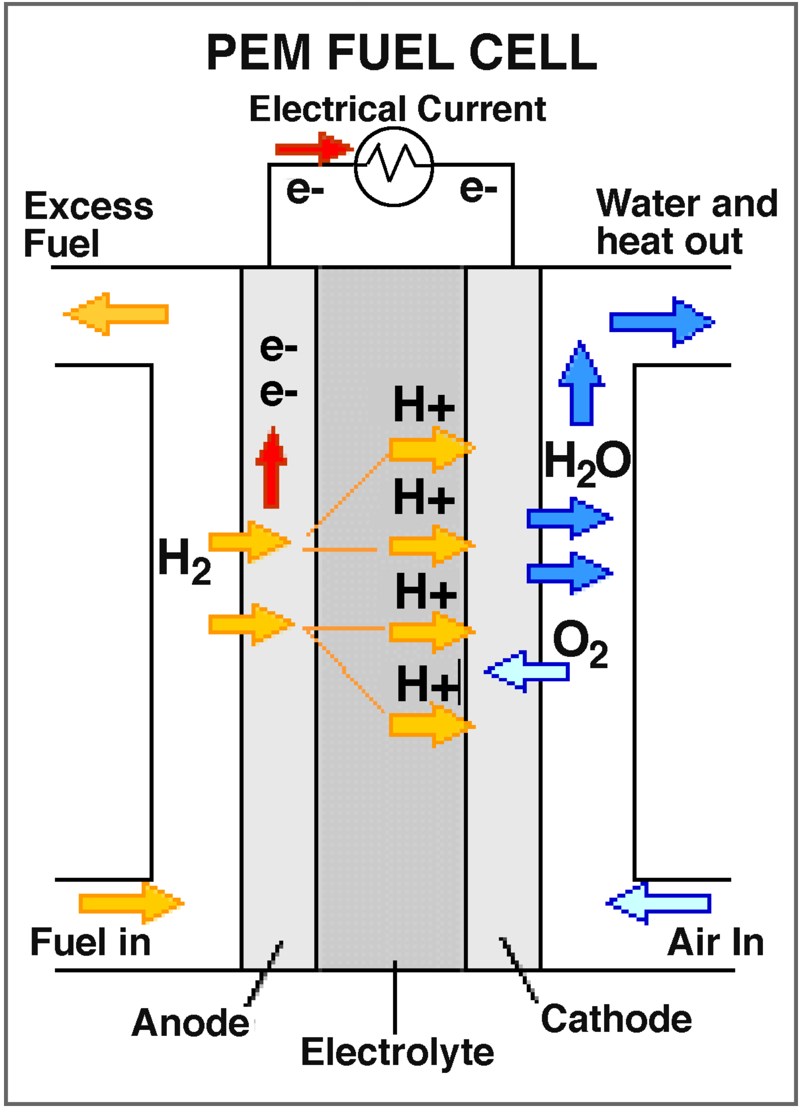
Parts of a Fuel Cell

- Anode
  - Negative post of the fuel cell.
  - Conducts the electrons that are freed from the hydrogen molecules so that they can be used in an external circuit.
  - Etched channels disperse hydrogen gas over the surface of catalyst.
- Cathode
  - Positive post of the fuel cell
  - Etched channels distribute oxygen to the surface of the catalyst.
  - Conducts electrons back from the external circuit to the catalyst
  - Recombine with the hydrogen ions and oxygen to form water.
- Electrolyte
  - Proton exchange membrane.
  - Specially treated material, only conducts positively charged ions.
  - Membrane blocks electrons.
- Catalyst
  - Special material that facilitates reaction of oxygen and hydrogen
  - Usually platinum powder very thinly coated onto carbon paper or cloth.
  - Rough & porous maximizes surface area exposed to hydrogen or oxygen
  - The platinum-coated side of the catalyst faces the PEM.

Fuel Cell Operation

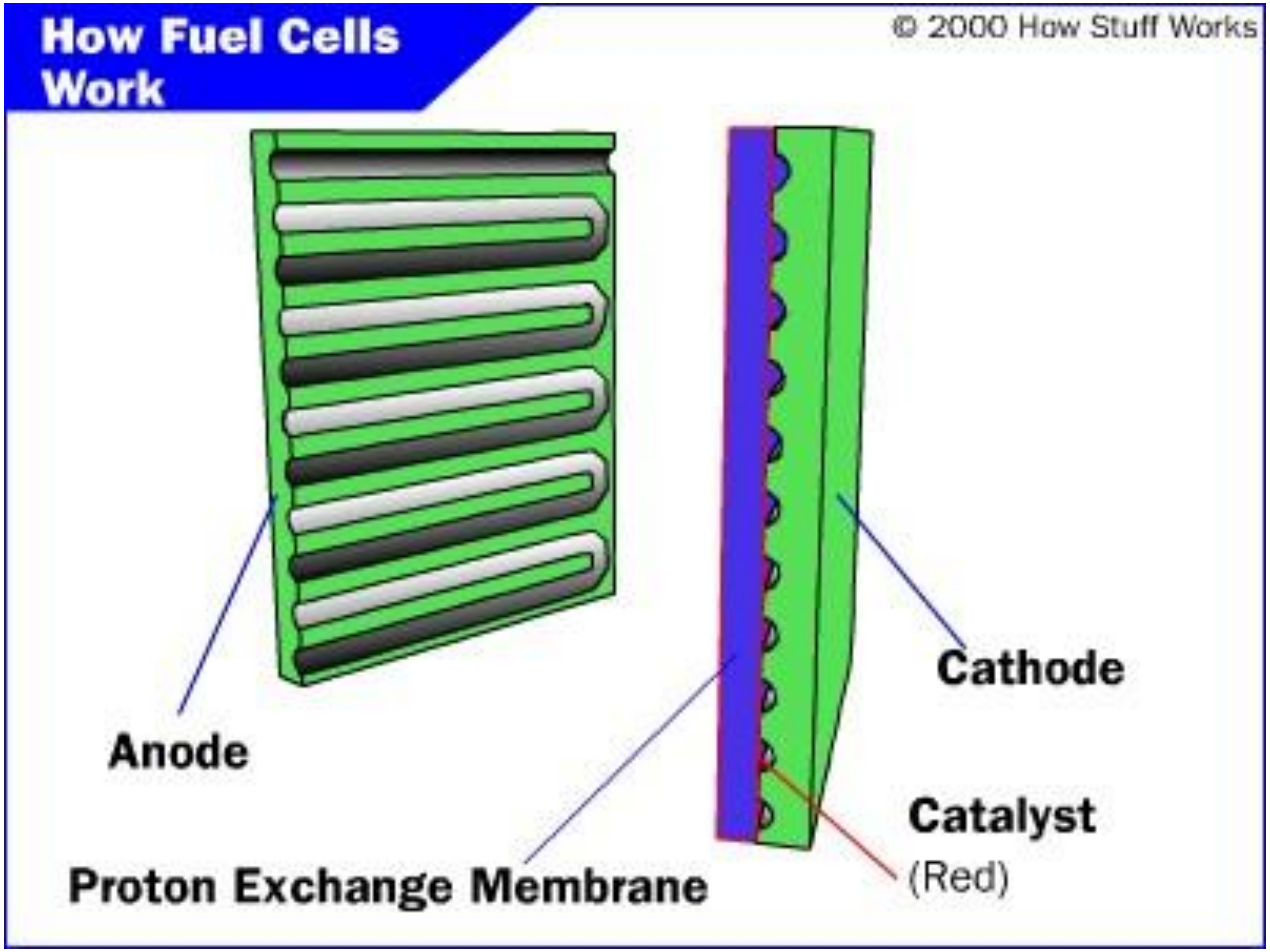
- Pressurized hydrogen gas (H_2) enters cell on anode side.
- Gas is forced through catalyst by pressure.
  - When H_2 molecule comes contacts platinum catalyst, it splits into two H+ ions and two electrons (e-).
- Electrons are conducted through the anode
  - Make their way through the external circuit (doing useful work such as turning a motor) and return to the cathode side of the fuel cell.
- On the cathode side, oxygen gas (O_2) is forced through the catalyst
  - Forms two oxygen atoms, each with a strong negative charge.
  - Negative charge attracts the two H+ ions through the membrane,
  - Combine with an oxygen atom and two electrons from the external circuit to form a water molecule (H_2O).

Proton-Exchange Membrane Cell



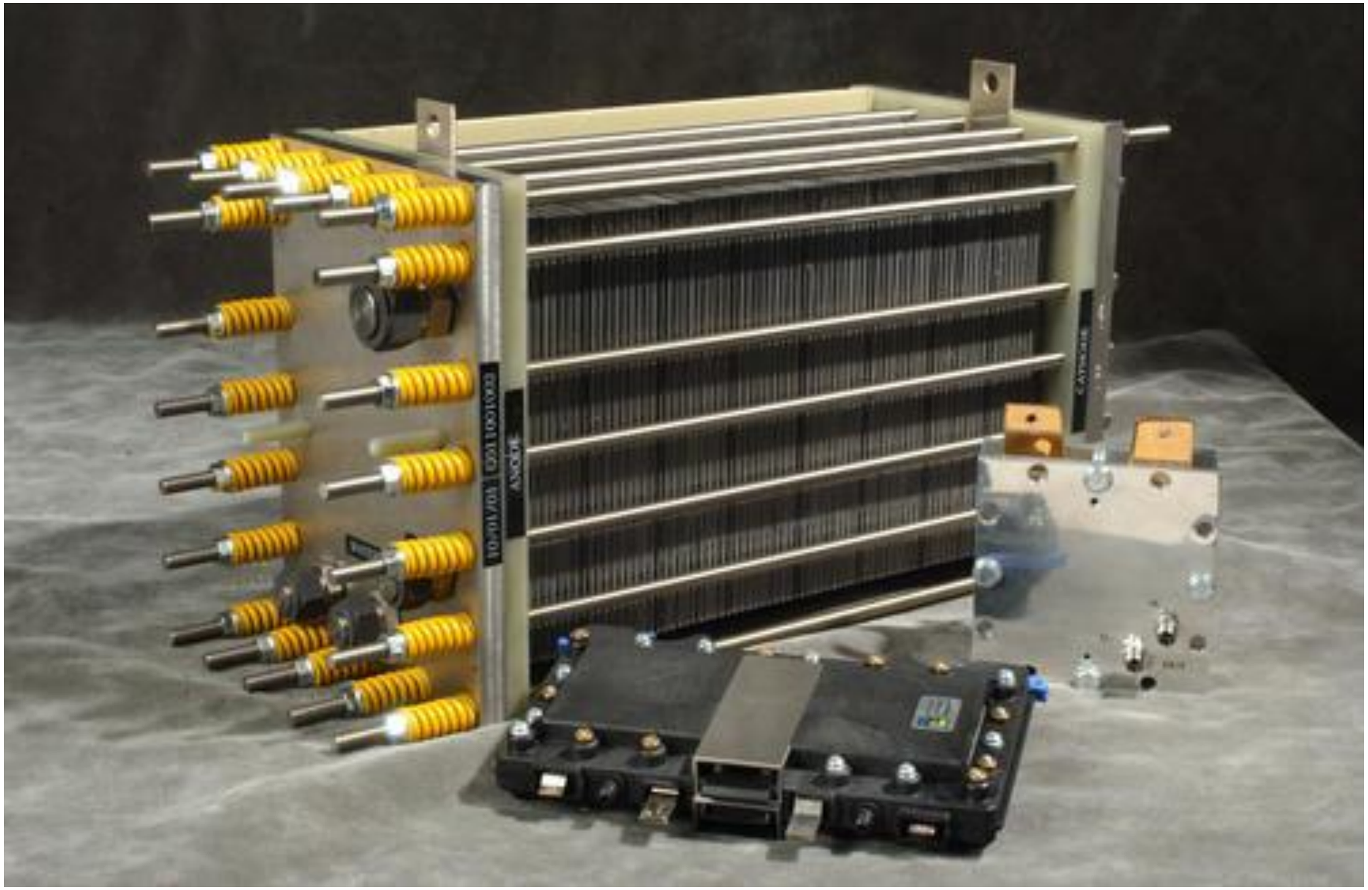
http://www.news.cornell.edu/releases/Nov03/Fuelcell.institute.deb.html

PEM Fuel Cell Animation



Click on Diagram

Fuel Cell Stack



http://www.nrel.gov/hydrogen/photos.html

Hydrogen Fuel Cell Efficiency

- 40% efficiency converting methanol to hydrogen in reformer
- 80% of hydrogen energy content converted to electrical energy
- 80% efficiency for inverter/motor
  - Converts electrical to mechanical energy
- Overall efficiency of 24-32%

Auto Power Efficiency Comparison

Technology	System Efficiency
Fuel Cell	24-32%
Electric Battery	26%
Gasoline Engine	20%

http://www.howstuffworks.com/fuel-cell.htm/printable

Other Types of Fuel Cells

- Alkaline fuel cell (AFC)
  - This is one of the oldest designs. It has been used in the U.S. space program since the 1960s. The AFC is very susceptible to contamination, so it requires pure hydrogen and oxygen. It is also very expensive, so this type of fuel cell is unlikely to be commercialized.
- Phosphoric-acid fuel cell (PAFC)
  - The phosphoric-acid fuel cell has potential for use in small stationary power-generation systems. It operates at a higher temperature than PEM fuel cells, so it has a longer warm-up time. This makes it unsuitable for use in cars.
- Solid oxide fuel cell (SOFC)
  - These fuel cells are best suited for large-scale stationary power generators that could provide electricity for factories or towns. This type of fuel cell operates at very high temperatures (around 1,832 F, 1,000 C). This high temperature makes reliability a problem, but it also has an advantage: The steam produced by the fuel cell can be channeled into turbines to generate more electricity. This improves the overall efficiency of the system.
- Molten carbonate fuel cell (MCFC)
  - These fuel cells are also best suited for large stationary power generators. They operate at 1,112 F (600 C), so they also generate steam that can be used to generate more power. They have a lower operating temperature than the SOFC, which means they don't need such exotic materials. This makes the design a little less expensive.

http://www.howstuffworks.com/fuel-cell.htm/printable

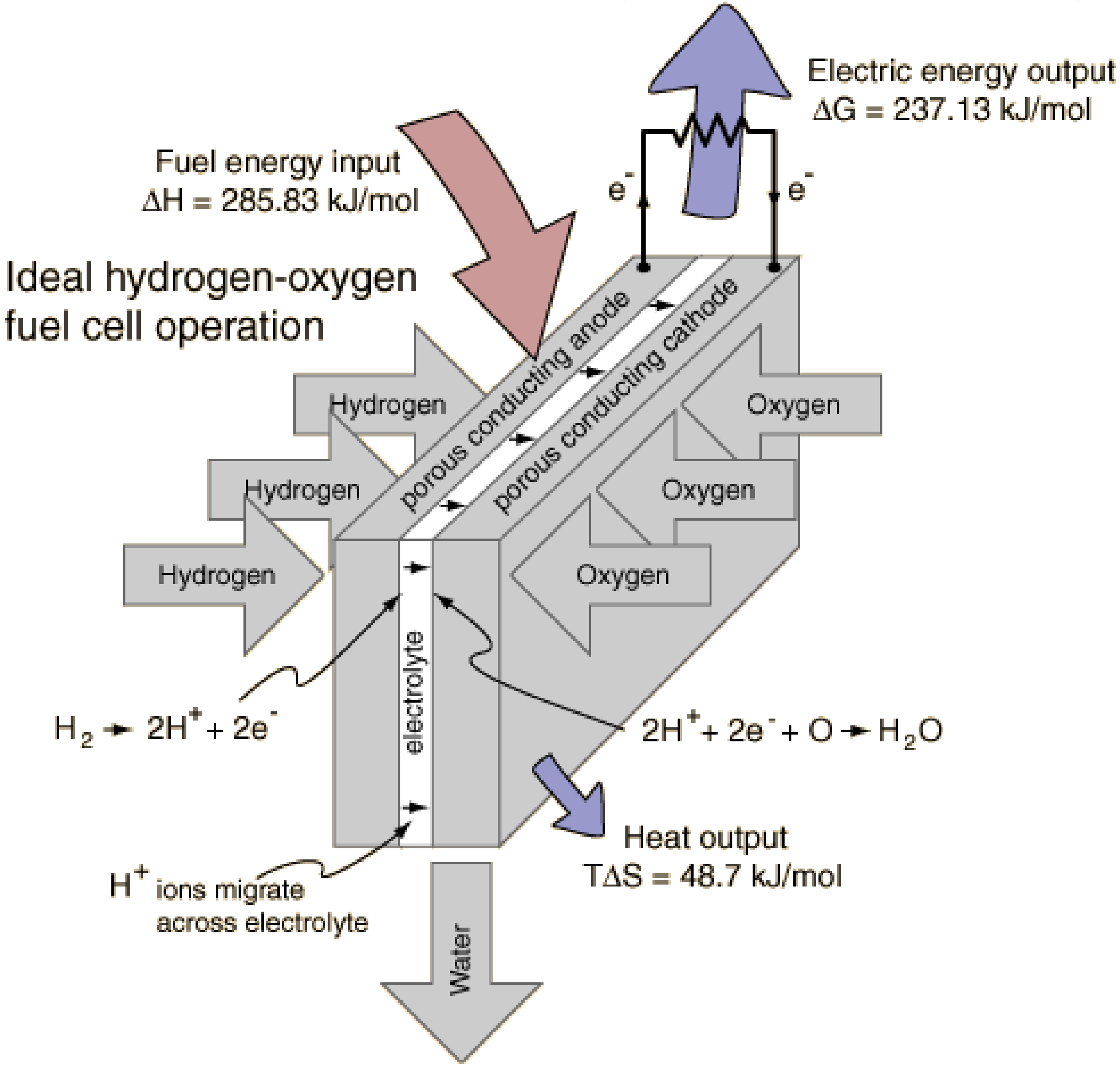
Advantages/Disadvantages of Fuel Cells

- Advantages
  - Water is the only discharge (pure H_2)
- Disadvantages
  - CO_2 discharged with methanol reform
  - Little more efficient than alternatives
  - Technology currently expensive
    - Many design issues still in progress
  - Hydrogen often created using “dirty” energy (*e.g.,* coal)
  - Pure hydrogen is difficult to handle
    - Refilling stations, storage tanks, …

Fuel Cells

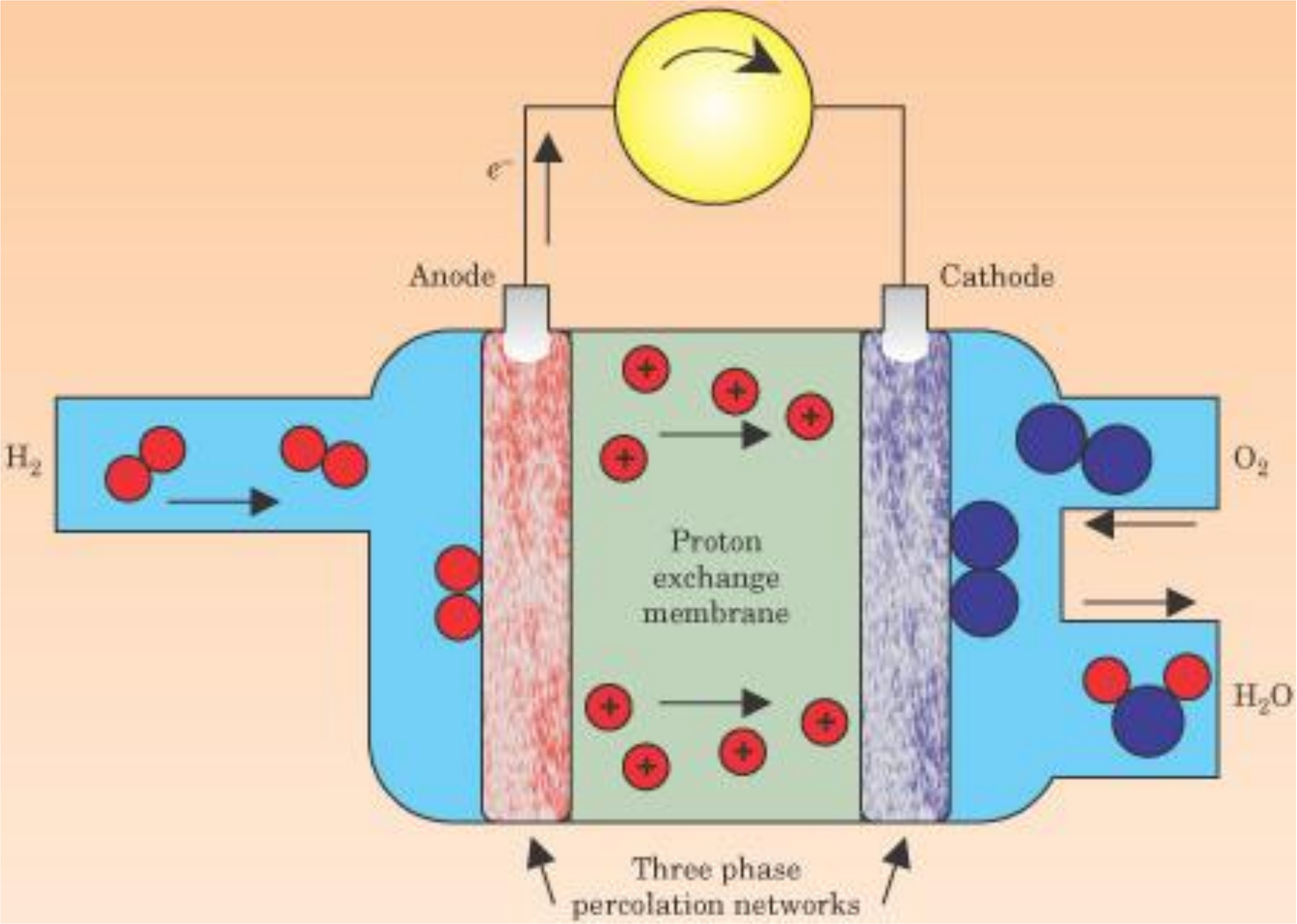
Extra Slides

Fuel Cell Energy Exchange



http://hyperphysics.phy-astr.gsu.edu/hbase/thermo/electrol.html

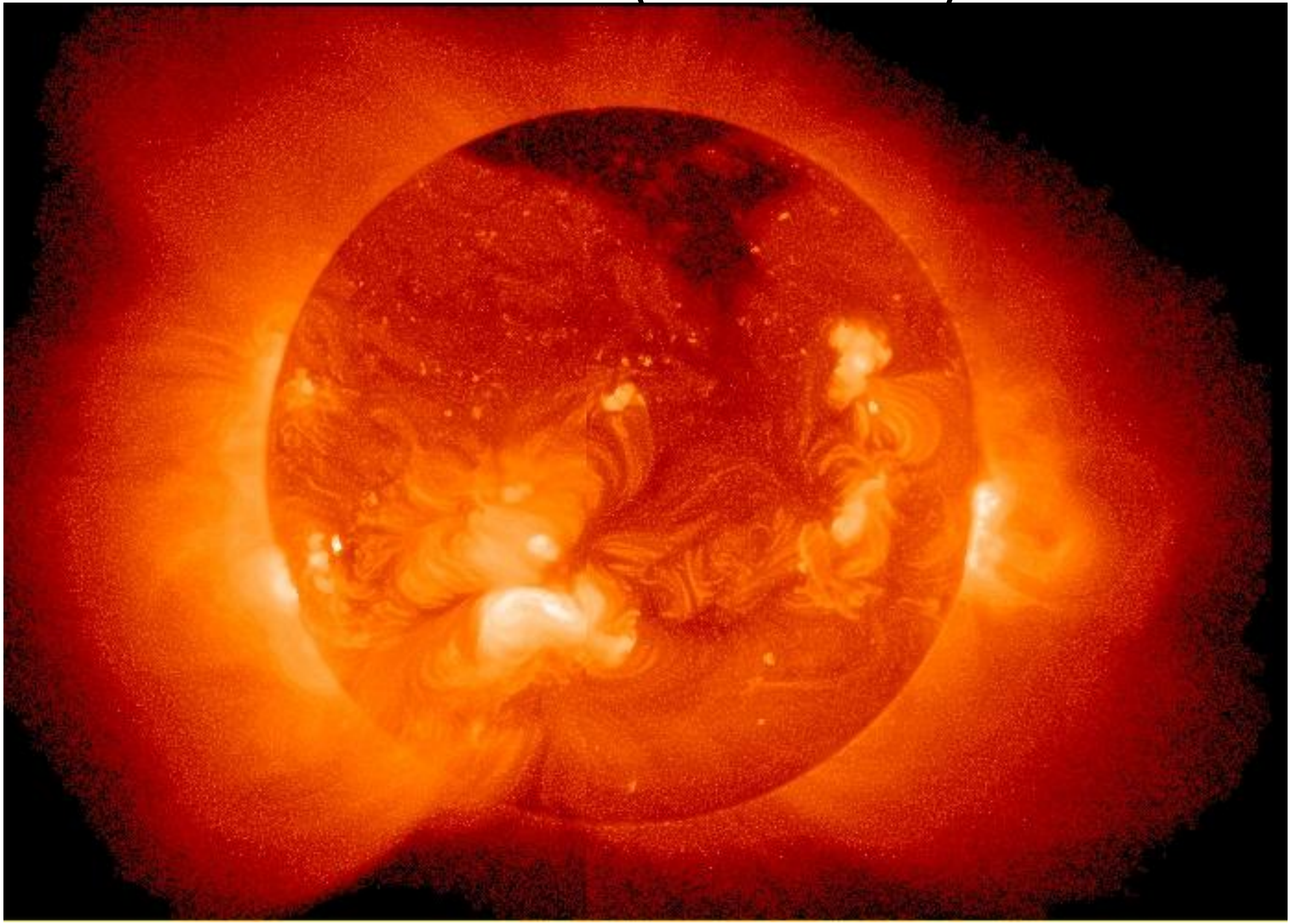
PEM Fuel Cell Schematic



II. MAGNETOHYDRODYNAMICS

(Space Climate School, Lapland, March, 2009)

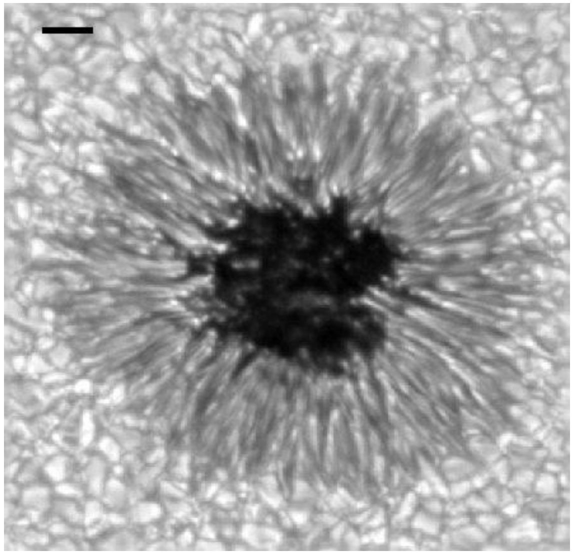
Eric Priest (St Andrews)



CONTENTS

1. INTRODUCTION

Magnetic Field Effects:



-- exerts a **force**

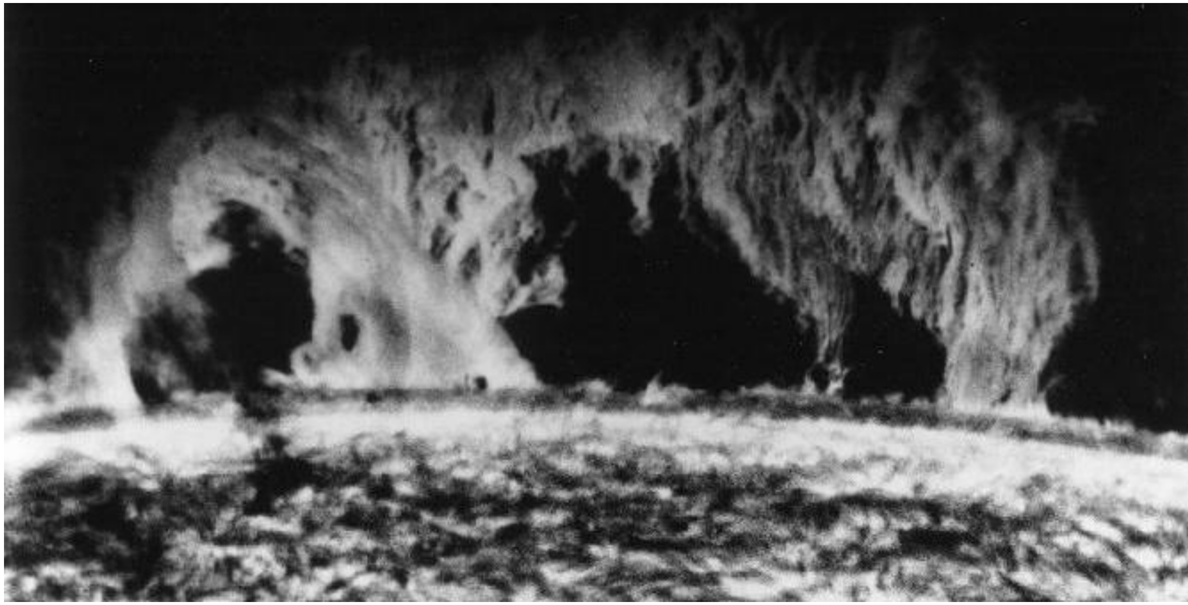
(creates structure)

-- provides **insulation**

-- stores **energy**

(released in

CME or flare)



Magnetohydrodynamics

- MHD - the study of the interaction between a magnetic field and a plasma, treated as a continuous medium

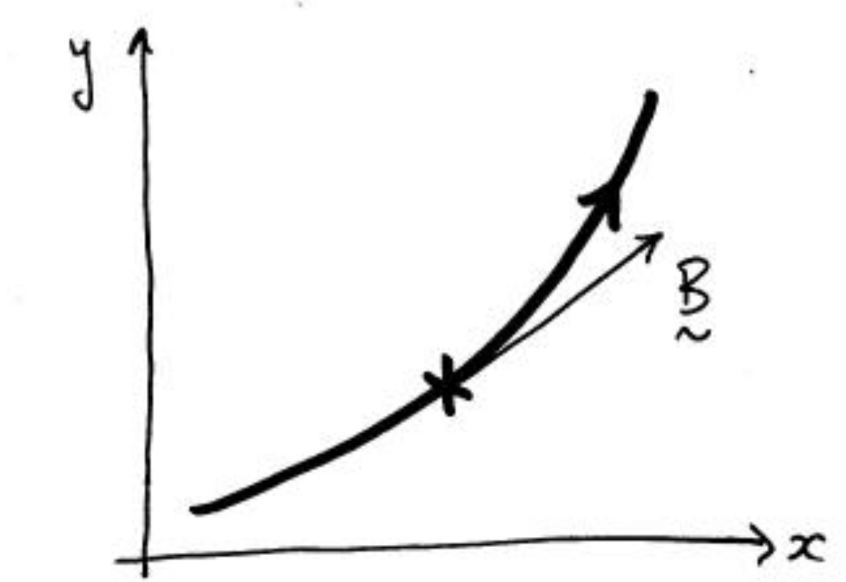
- This assumption of a continuous medium is valid for length-scales

$$L >> 300\left(\frac{T}{10^6 K}\right)^2\left(\frac{n}{10^{17} m^{-3}}\right)^{-1} km$$

  - Chromosphere $(T=10^4, n=10^{20})\ \ L>>3\,cm$
  - Corona $\left(T=10^6, n=10^{16}\right)\ \ L>>30km$

2. FLUX TUBES

Magnetic Field Line -- Curve w. tangent in direction of B.

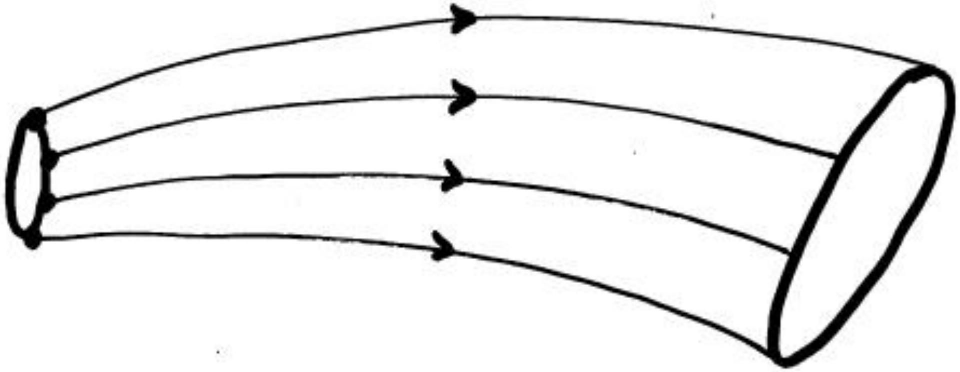


Equation:

In 2D: * _ _ _ _ _ _* or in 3D: $\frac{dx}{B_x} = \frac{dy}{B_y} = \frac{dz}{B_z}$

Magnetic Flux Tube

Surface generated by set of field lines intersecting simple closed curve.

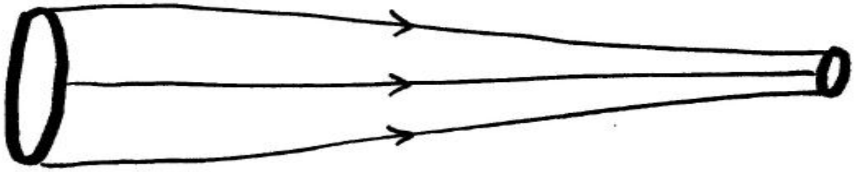


(i) Strength (F) -- magnetic flux crossing a section

i.e., *_ _ _ _ __ _ _ _*

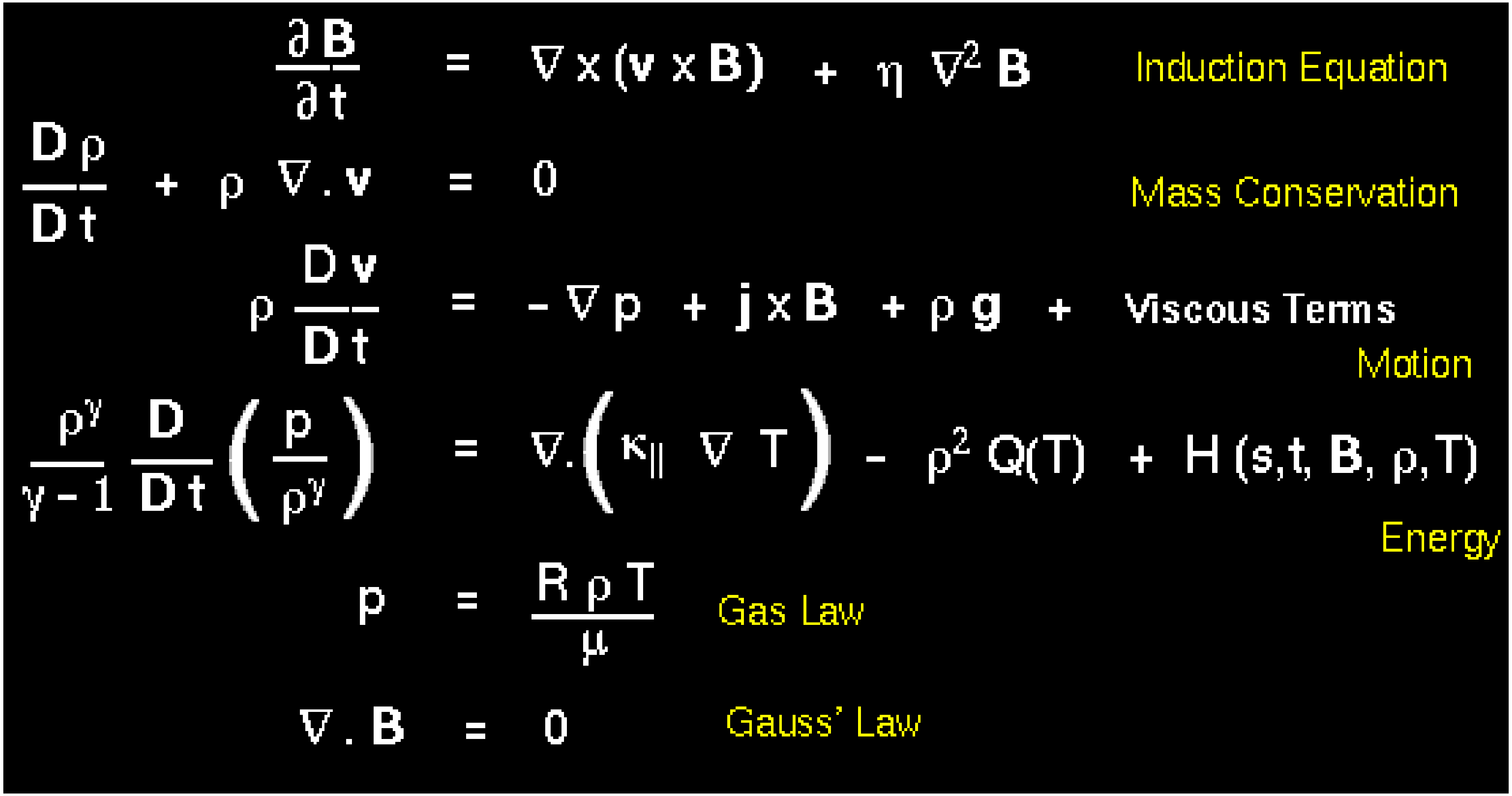
(ii) But $\nabla.\mathbf{B}=0$ **---> F is constant along tube**

(iii) If cross-section is small, *_ _ _ _ _ _ _*



Eqns of Magnetohydrodynamics

Model interaction of **B** and plasma (cont^s medium)



$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

Induction Equation

$$\frac{D\rho}{Dt} + \rho \nabla . \mathbf{v} = 0$$

Mass Conservation

$$\rho \frac{D\mathbf{v}}{Dt} = - \nabla p + \mathbf{j} \times \mathbf{B} + \rho \mathbf{g} + \text{Viscous Terms}$$

Motion

$$\frac{\rho^\gamma}{\gamma - 1} \frac{D}{Dt} \left(\frac{p}{\rho^\gamma} \right) = \nabla . \left(\kappa_{\|} \nabla T \right) - \rho^2 Q(T) + H(s, t, \mathbf{B}, \rho, T)$$

Energy

$$p = \frac{R \rho T}{\mu}$$

Gas Law

$$\nabla . \mathbf{B} = 0$$

Gauss' Law

3. FUNDAMENTAL EQUATIONS of MHD

- **Unification of Eqns of:**

(i) Maxwell

$$\nabla \times \mathbf{B} / \mu = \mathbf{j} + \boxed{\partial \mathbf{D} / \partial t,}$$

$$\nabla . \mathbf{B} = 0,$$

$$\nabla \times \mathbf{E} = -\partial \mathbf{B} / \partial t,$$

$$\nabla . \mathbf{D} = \rho_c,$$

$$\text{where} \quad \mathbf{B} = \mu \mathbf{H}, \quad \mathbf{D} = \varepsilon \mathbf{E}, \quad \boxed{\mathbf{E} = \mathbf{j} / \sigma.}$$

(ii) Fluid Mechanics

$$\textit{Motion} \qquad \rho\frac{d\mathbf{v}}{dt} = -\nabla p,$$

$$\textit{Continuity} \qquad \frac{d\rho}{dt} + \rho\nabla.\mathbf{v} = \mathbf{0},$$

$$\textit{Perfect gas} \qquad p = R\,\rho\,T,$$

$$\textit{Energy eqn.} \qquad \ldots\ldots\ldots\ldots\ldots$$

$$\textit{where} \quad d/dt = \partial/\partial t + \mathbf{v.}\nabla$$

or (D/Dt)

In MHD

- **1. Assume v << c** --> Neglect *_ _ _ *

$$\nabla \times \mathbf{B}/\mu = \mathbf{j} \qquad -(1)$$

- **2. Extra E on plasma moving**

$$\mathbf{E} + \boxed{*\_\ \_\ \_\ \_*} = \mathbf{j}/\sigma \qquad -(2)$$

- **3. Add magnetic force**

$$\rho \frac{d\mathbf{v}}{dt} = -\nabla p + \boxed{*\_\ \_\ \_\ \_*}$$

- **Eliminate E and j: take curl (2), use (1) for j**

4. INDUCTION EQUATION

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} = \nabla \times (\mathbf{v} \times \mathbf{B} - \mathbf{j} / \sigma)$$

$$= \nabla \times (\mathbf{v} \times \mathbf{B}) - \eta \nabla \times (\nabla \times \mathbf{B})$$

$$\boxed{= \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B},}$$

where $^{*}\eta = \frac{1}{\mu\sigma}{}^{*}$ *is magnetic diffusivity*

Induction Equation

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

N.B.:

(i) --> B if v is known

(ii) In MHD, v and B are * **primary variables** *:
induction eqn + eqn of motion --> basic physics

(iii) $\mathbf{j} = \nabla \times \mathbf{B} / \mu \quad \textit{and} \quad \mathbf{E} = -\mathbf{v} \times \mathbf{B} + \mathbf{j} / \sigma$
are **secondary variables**

(iv) **B** changes due to transport + diffusion

Induction Equation

$$\frac{\partial \mathbf{B}}{\partial t} = \underset{\mathbf{A}}{\nabla \times (\mathbf{v} \times \mathbf{B})} + \underset{\mathbf{B}}{\eta \nabla^2 \mathbf{B}}$$

(v) $\boxed{\frac{A}{B} = \frac{L_0 \, v_0}{\eta} = R_m}$ -- * **magnetic Reynolds number** *

eg, $\eta = 1 \ \mathrm{m}^2/s$, $L_0 = 10^5$ m, $v_0 = 10^3$ m/s --> $\mathbf{R_m = 10^8}$

(vi) **A** >> **B** in most of Universe -->

B moves with plasma -- keeps its energy

Except SINGULARITIES -- j & ∇B large

Form at **NULL POINTS**, B = 0 --> reconnection

(a) If $R_m \ll 1$

- The induction equation reduces to

$$\boxed{\frac{\partial \mathbf{B}}{\partial t} = \eta \nabla^2 \mathbf{B}}$$

- B is governed by a diffusion equation

  --> field variations on a scale L_0

  diffuse away on time * $\boxed{t_d = \frac{{L_0}^2}{\eta}}$ *

  with speed $v_d = L_0 / t_d \boxed{= \frac{\eta}{L_0}}$

(b) If $R_m >> 1$

The induction equation reduces to

$$\boxed{\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B})}$$

and Ohm's law -->

$$\boxed{\mathbf{E} + \mathbf{v} \times \mathbf{B} = \mathbf{0}}$$

Magnetic field is "*   frozen to the plasma   *"

5. EQUATION of MOTION

$$\boxed{\rho \frac{d\mathbf{v}}{dt} \quad = \quad -\nabla p \quad + \quad \mathbf{j} \times \mathbf{B} \quad + \quad \rho \mathbf{g}}$$

(1) **(2)** **(3)** **(4)**

- In most of corona, (3) dominates
- Along **B**, (3) = 0, so (2) + (4) important

Magnetic force:

$$\mathbf{j}\times\mathbf{B} = (\nabla\times\mathbf{B})\times\frac{\mathbf{B}}{\mu}$$

$$= (\mathbf{B}.\nabla)\frac{\mathbf{B}}{\mu} - \nabla\left(\frac{B^2}{2\mu}\right)$$

Magnetic field lines have a

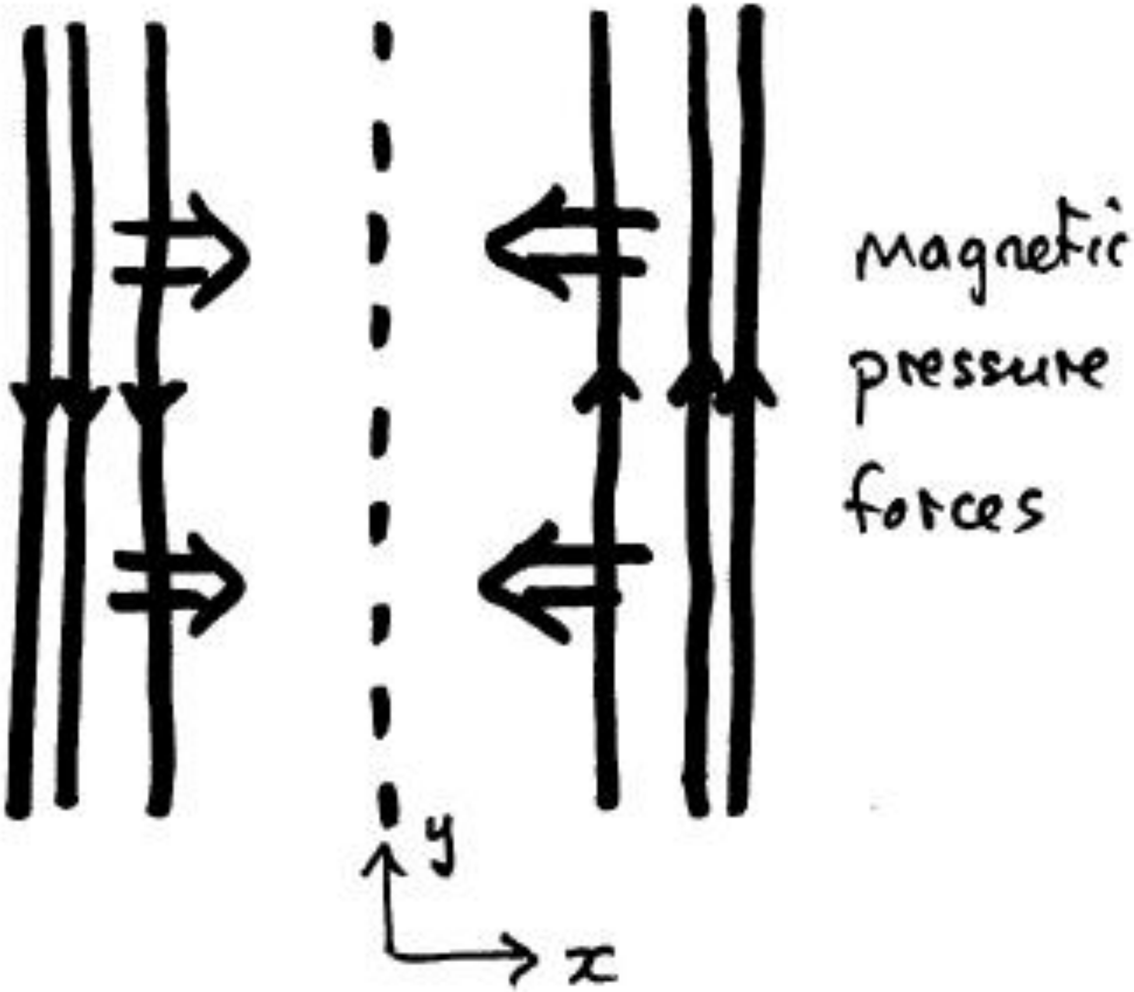
Tension $B^2/\ \mu$ ----> force when lines curved

Pressure $B^2/(2\ \mu)$----> force from high to low B^2

Ex

$$\mathbf{B} = x\,\hat{\mathbf{y}}$$

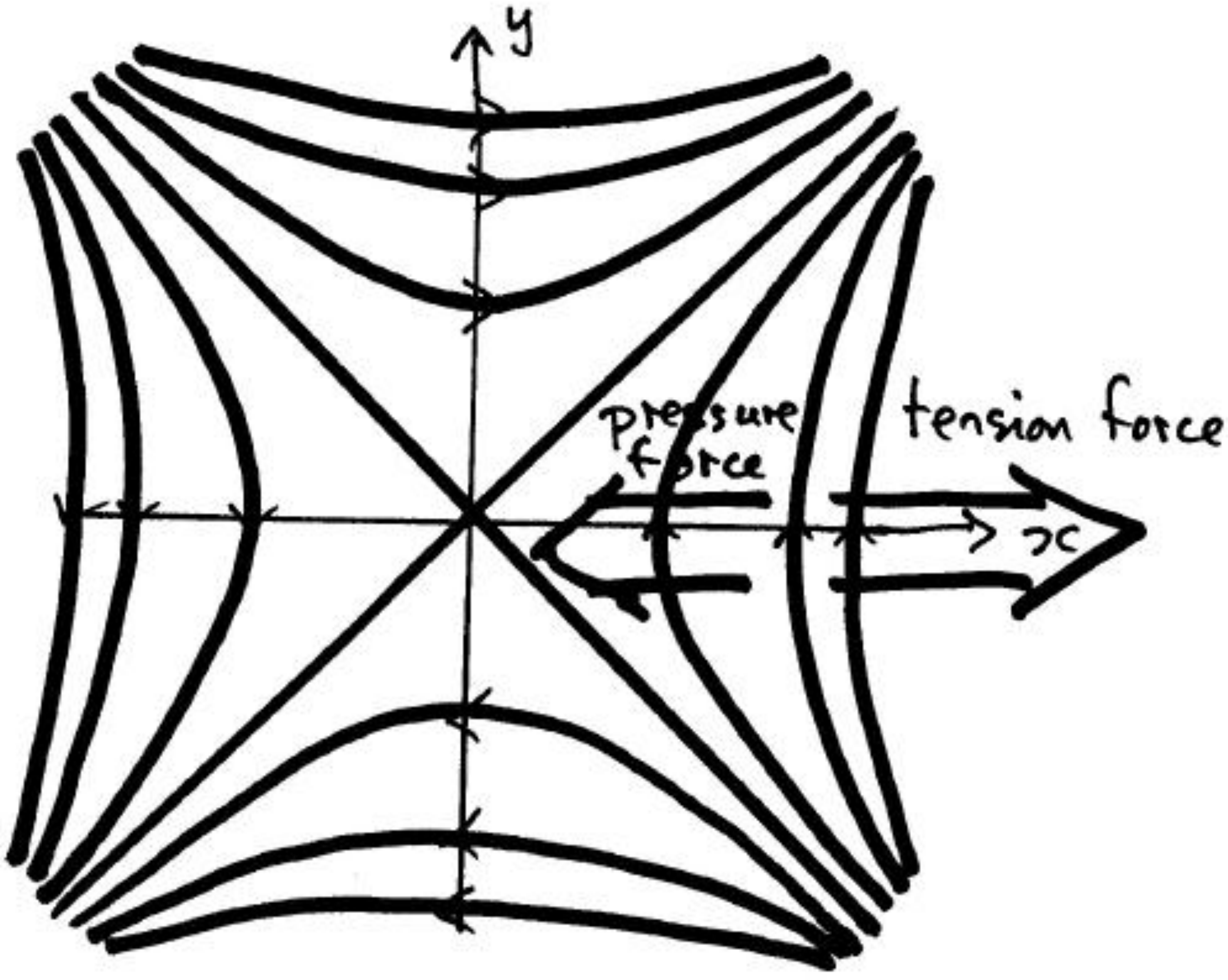
Expect physically:



(check mathematically)

Ex $\mathbf{B} = y\,\hat{\mathbf{x}} + x\,\hat{\mathbf{y}}$

Expect physically:



(check mathematically)

Equation of Motion

$$\boxed{\rho\frac{d\mathbf{v}}{dt} = -\nabla p + \mathbf{j}\times\mathbf{B} + \rho\,\mathbf{g}}$$

(1) **(2)** **(3)** **(4)**

(i) $$\frac{(2)}{(3)} = \beta = \frac{p}{B^2/(2\mu)}$$ * **Plasma beta** *

When $\beta \ll 1$, $\mathbf{j}\times\mathbf{B}$ dominates

(ii) $$(1)\approx(3) \rightarrow v \approx v_{\mathrm{A}} = \frac{B}{\sqrt{\mu\rho}}$$ ***Alfvén speed***

Typical Values on Sun

	Photosphere	Chromosphere	Corona
N (m^{-3})	10^{23}	10^{20}	10^{15}
T (K)	6000	10^4	10^6
B (G)	5 - 10^3	100	10
β	10^6 - 1	10^{-1}	10^{-3}
v_A (km/s)	0.05 - 10	10	10^3

N (m^{-3}) = 10^6 N (cm^{-3}), B (G) = 10^4 B (tesla)

$\beta = 3.5 \times 10^{-21}\, N\, T/B^2$, $v_A = 2 \times 10^9\, B/N^{1/2}$

6. In Solar MHD

$$\rho \frac{d\mathbf{v}}{dt} = -\nabla p + \mathbf{j} \times \mathbf{B} + \rho \mathbf{g}$$

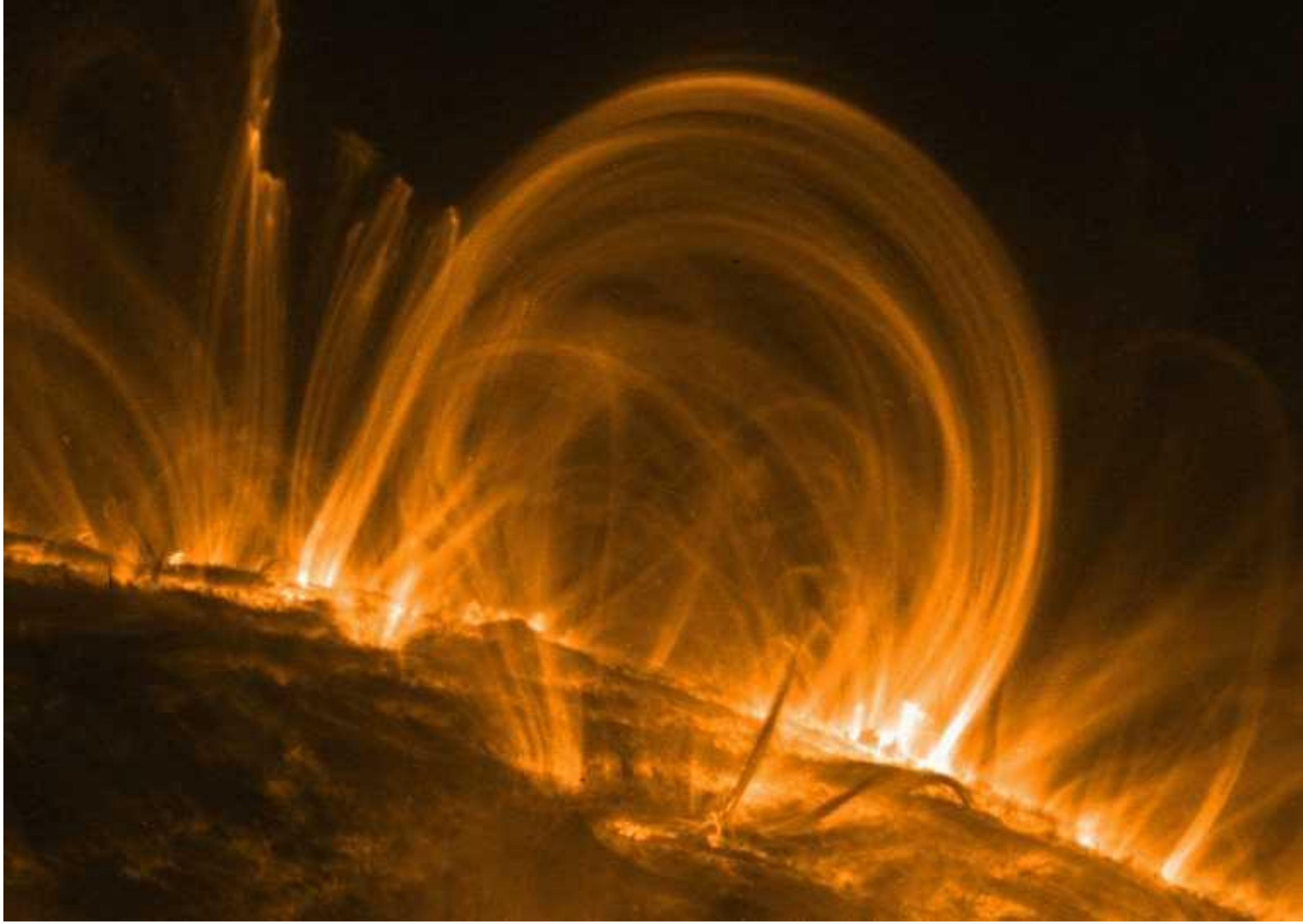
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

We study **Equilibria, Waves, Instabilities,**

Magnetic reconnection

in **dynamos, magnetoconvection, sunspots, prominences,**
coronal loops, solar wind,
coronal mass ejections, solar flares

Example

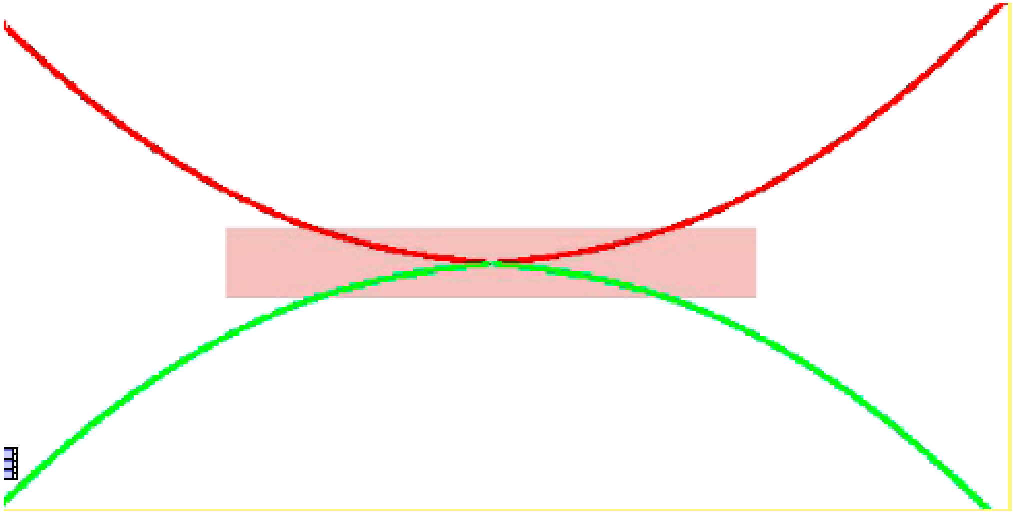


Shapes - caused by magnetic field (force-free)

Fineness - small scale of heating process + small $\kappa_\perp$

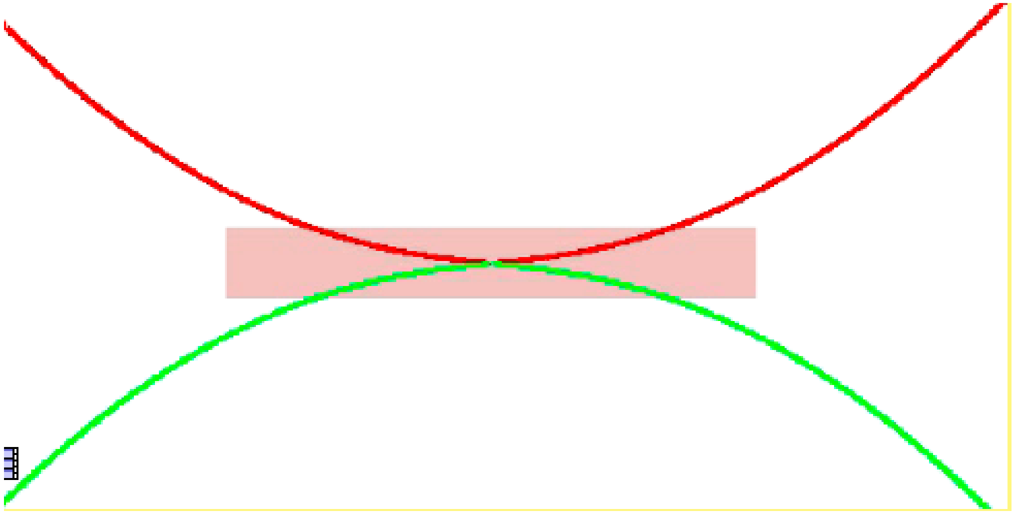
Structure along loops - hydrostatics/hydrodynamics (--H)

7. MAGNETIC RECONNECITON



- Reconnection is a **fundamental process** in a plasma:
  - **Changes the topology**
  - **Converts magnetic energy** to heat/K.E
  - **Accelerates fast particles**
- In Sun ---> **Solar flares, CME's / heats Corona**

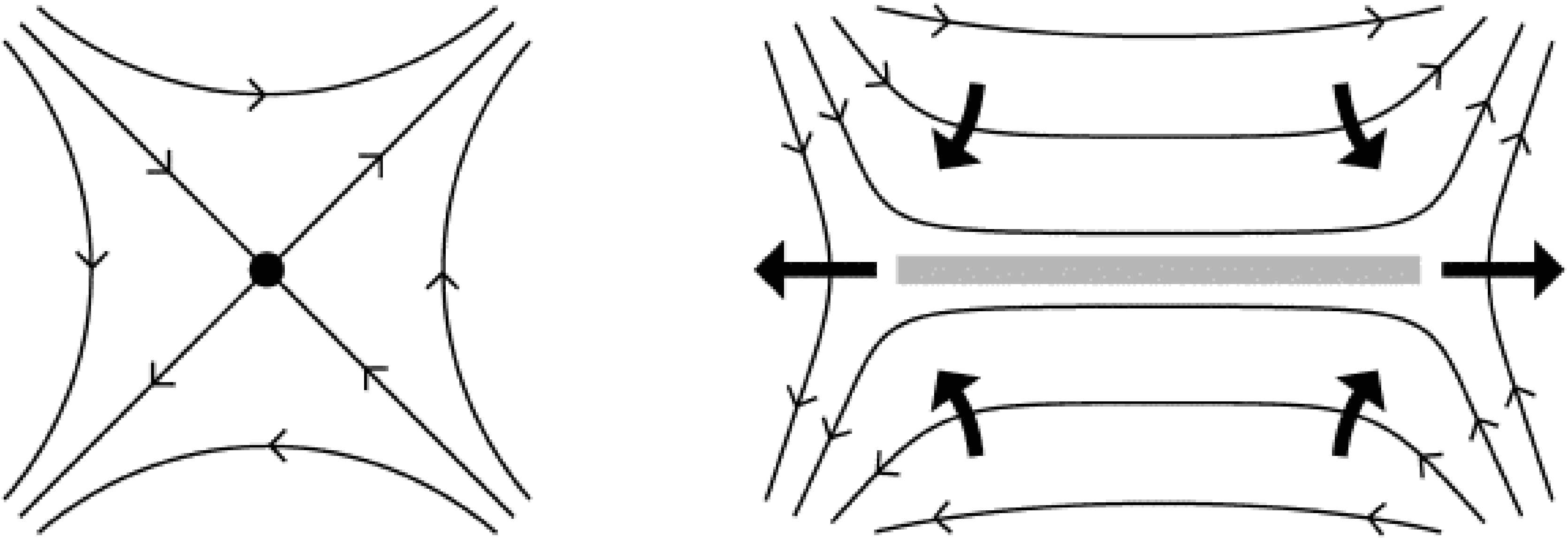
In 2D takes place only at an X-Point



-- **Current very large** --> ohmic heating

-- Strong diffusion allows field-lines to break
/ change connectivity
and diffuse through plasma

Reconnection can occur **when X-point collapses**



Small current sheet width

--> magnetic field diffuses outwards at speed

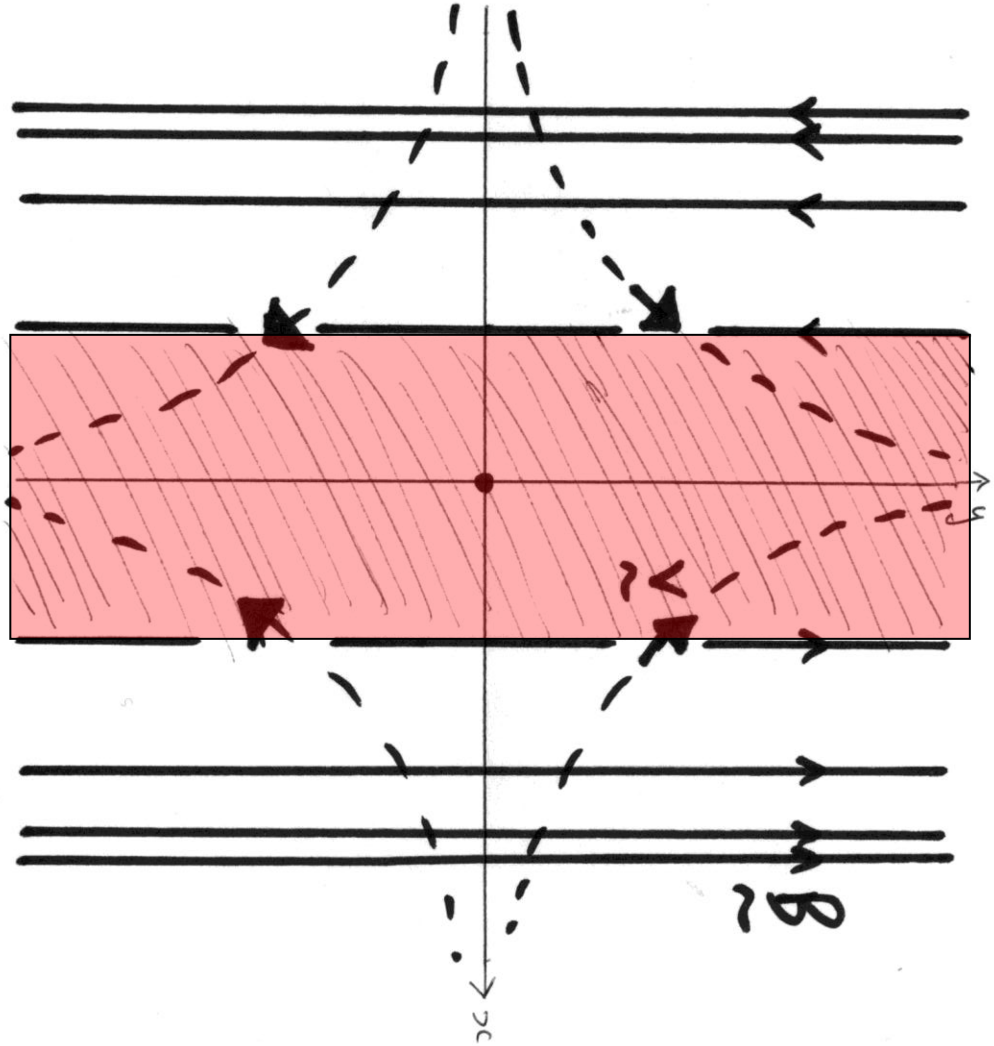
$$v_d = \boxed{\begin{matrix} * & & * \\ \\ \\ - & - & - \end{matrix}}$$

If magnetic field is brought in by a flow

$(v_x = -Ux/a$

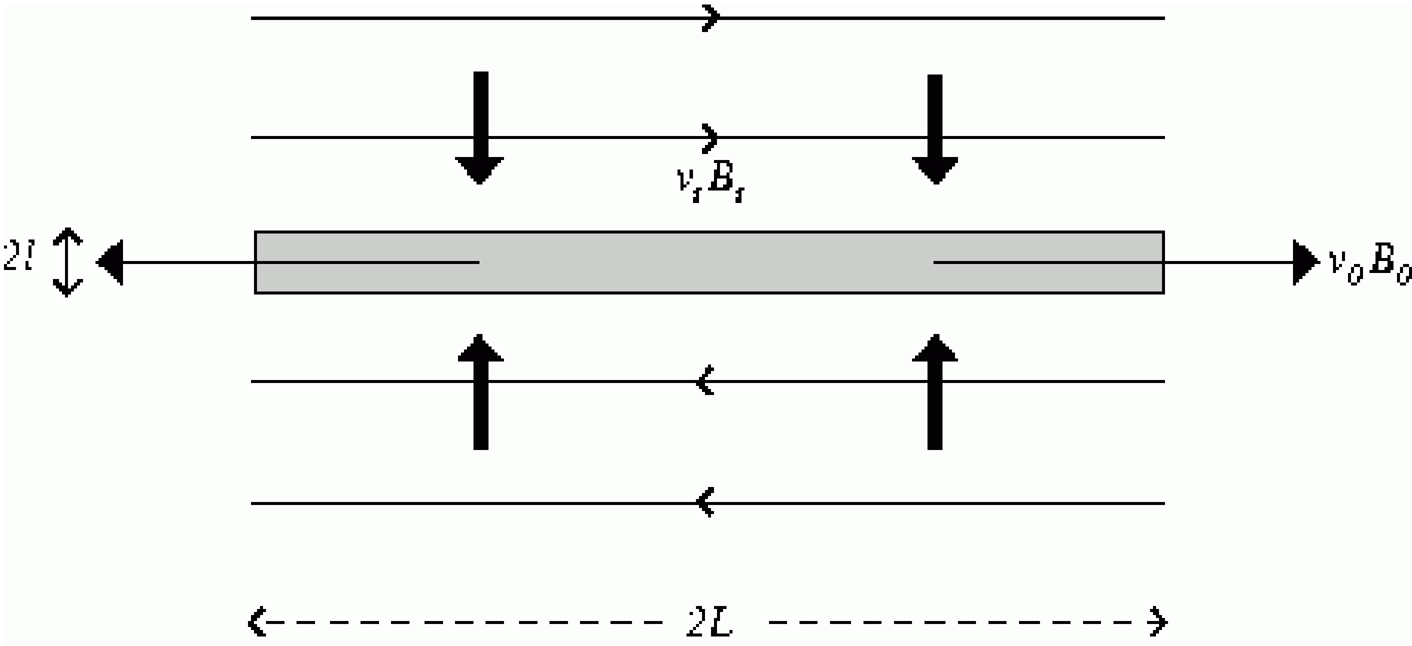
$v_y = Uy/a)$

then a steady balance can be set up



Sweet-Parker (1958)

Simple current sheet - uniform inflow



Mass conservation : $L\, v_i = l\, v_o$

Advection/diffusion: $v_i = \eta / l$

Accelerate along sheet: $v_o = v_{Ai}$

$$\boxed{\text{Reconnection rate } v_i = \frac{v_{Ai}}{R_{mi}^{1/2}}}$$

$$\boxed{R_{mi} = \frac{L\, v_{Ai}}{\eta},}$$

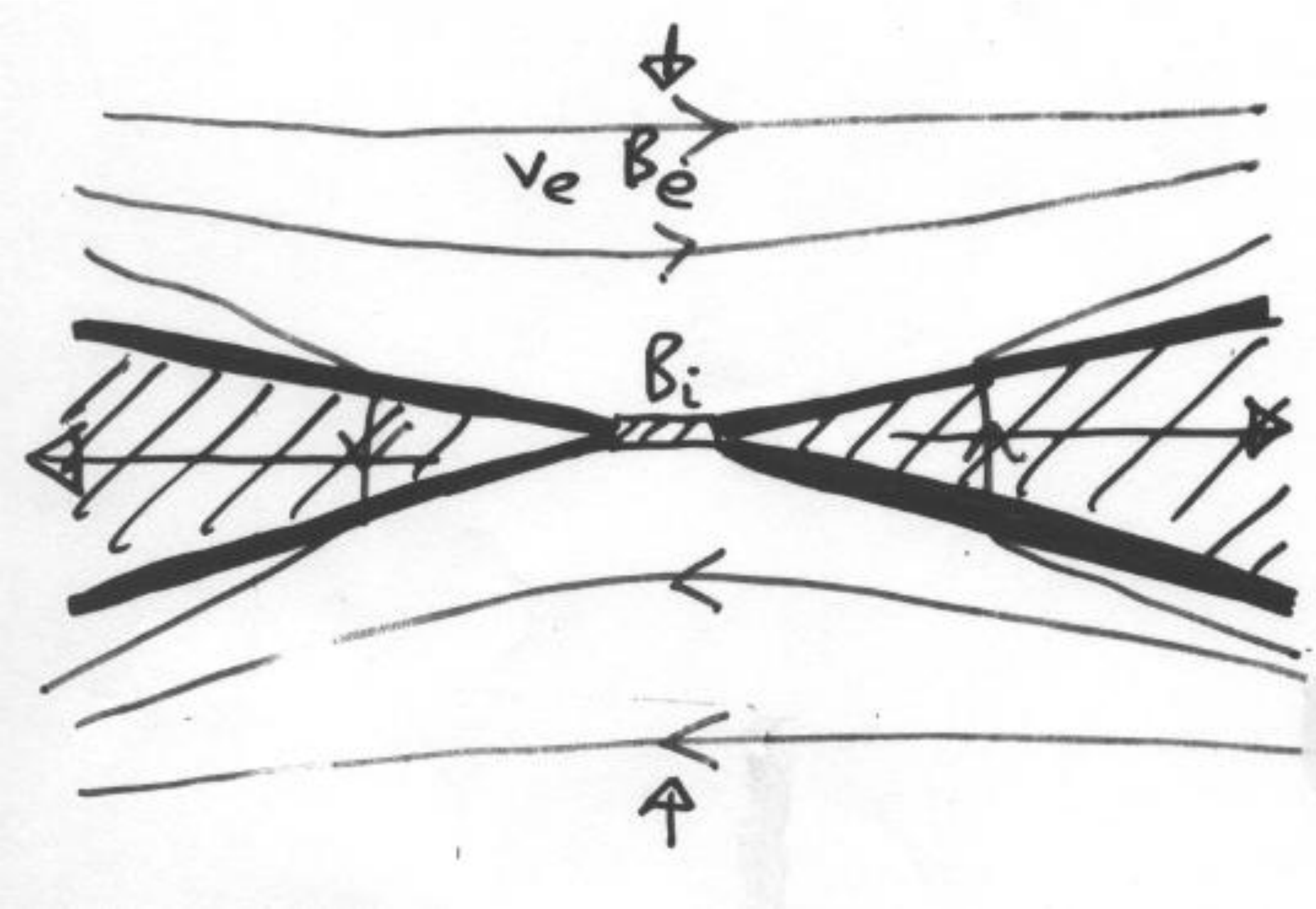
Petschek (1964)

- **Sheet bifurcates -**

Slow shocks - most of energy

- **Reconnection speed $\mathbf{v}_e$** --

any rate up to maximum



$$\boxed{v_e = \frac{\pi v_A}{8 \log R_{me}} \approx 0.1 v_A}$$

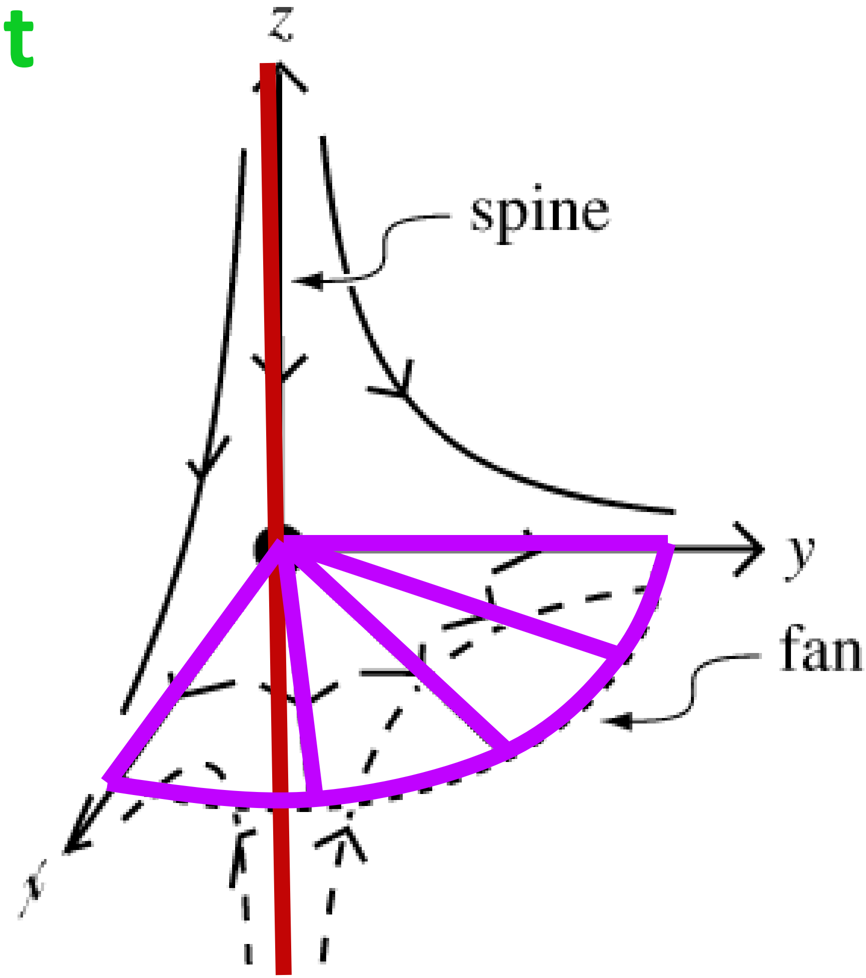
8. 3D RECONNECTION

Many New Features

(i) Structure of Null Point

Simplest

$$\mathbf{B} = (x, y, -2z)$$



2 families of field lines through null point:

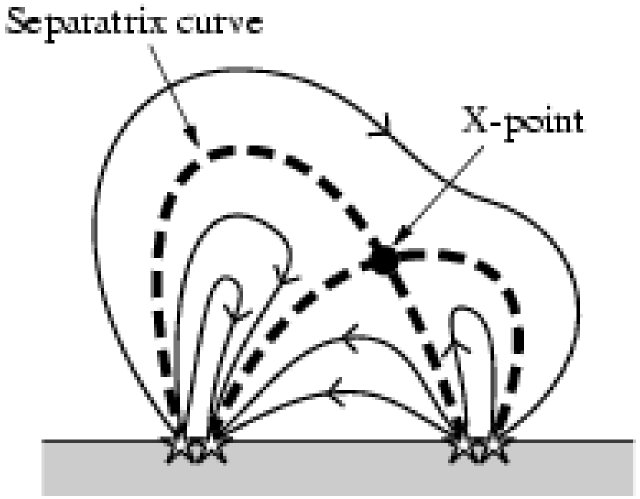
Spine Field Line

Fan Surface

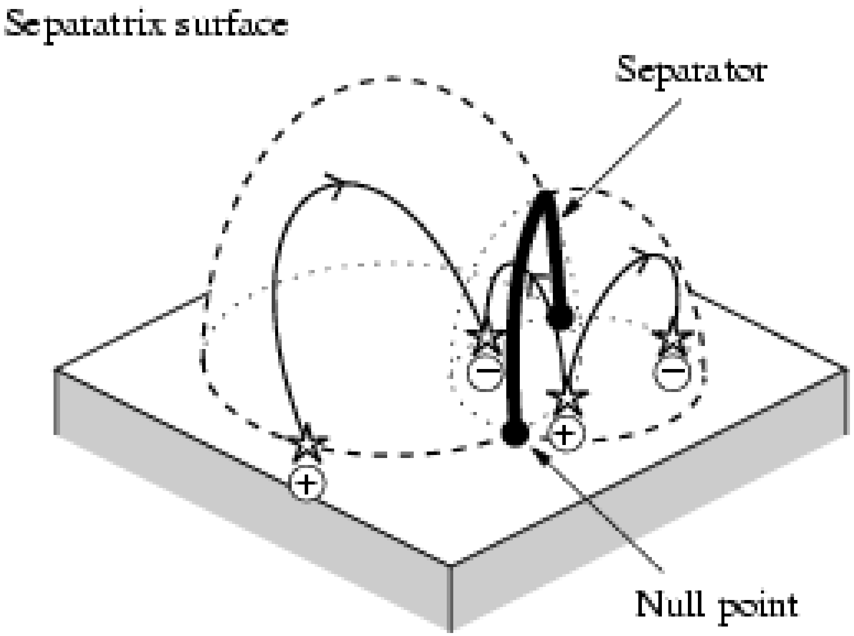
(ii) Global Topology of Complex Fields

In 2D -- **Separatrix curves**

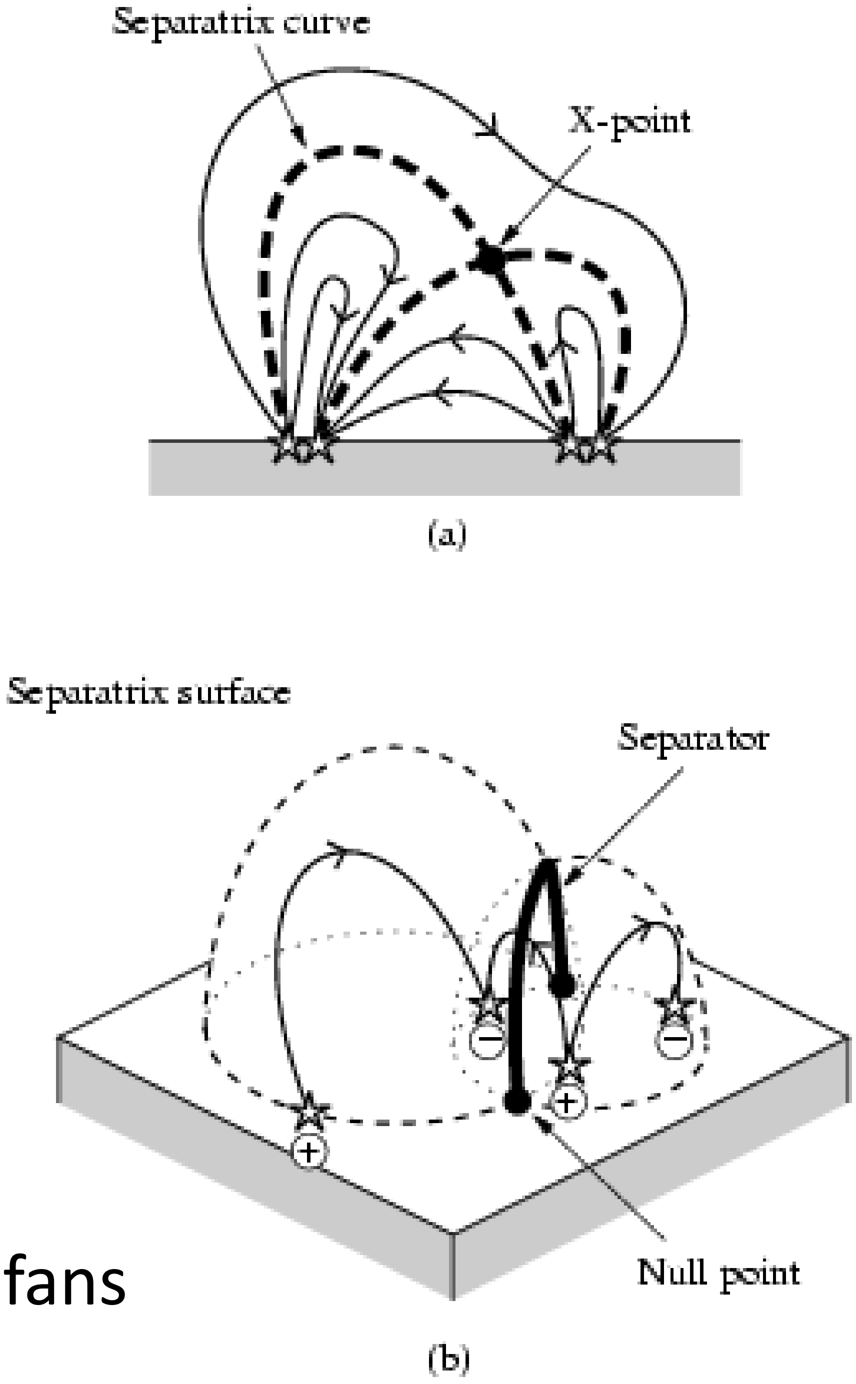
In 3D -- **Separatrix surfaces**



(a)



(b)



In 2D, reconnection at X

transfers flux from one
2D region to another.

In 3D, reconnection at
separator

transfers flux from one

3D region to another.

In complex fields we form the
SKELETON --
set of nulls, separatrices -- from fans

(iii) 3D Reconnection

Can occur

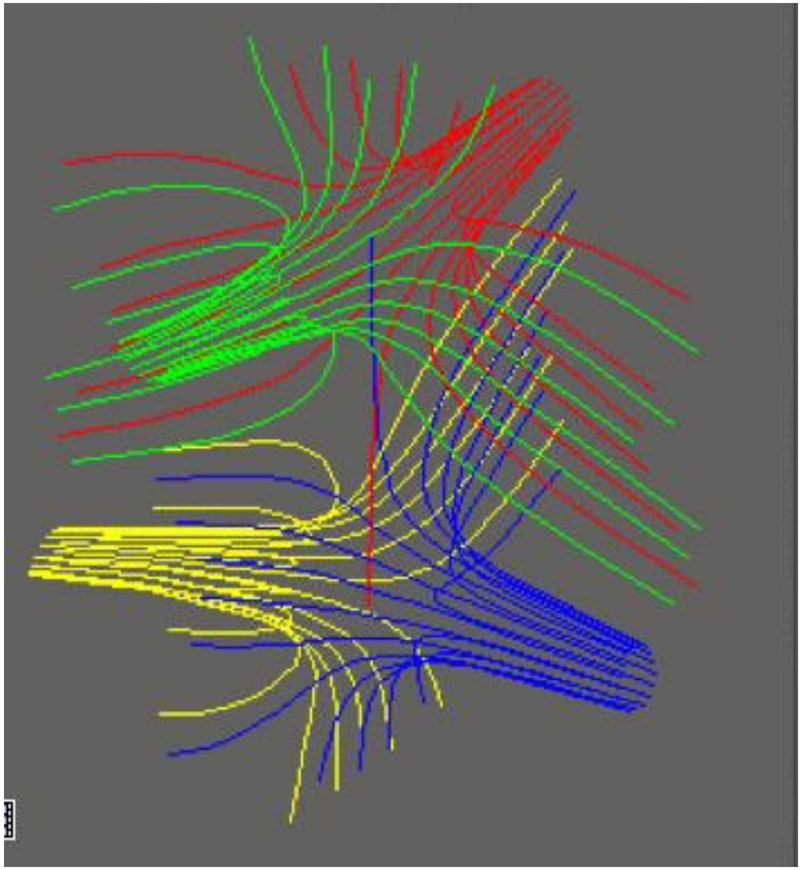
at a null point **or in absence of null**

At Null -- 3 Types of Reconnection:

Spine reconnection

Fan reconnection

Separator reconnection



Numerical Exp^t (Linton & Priest)

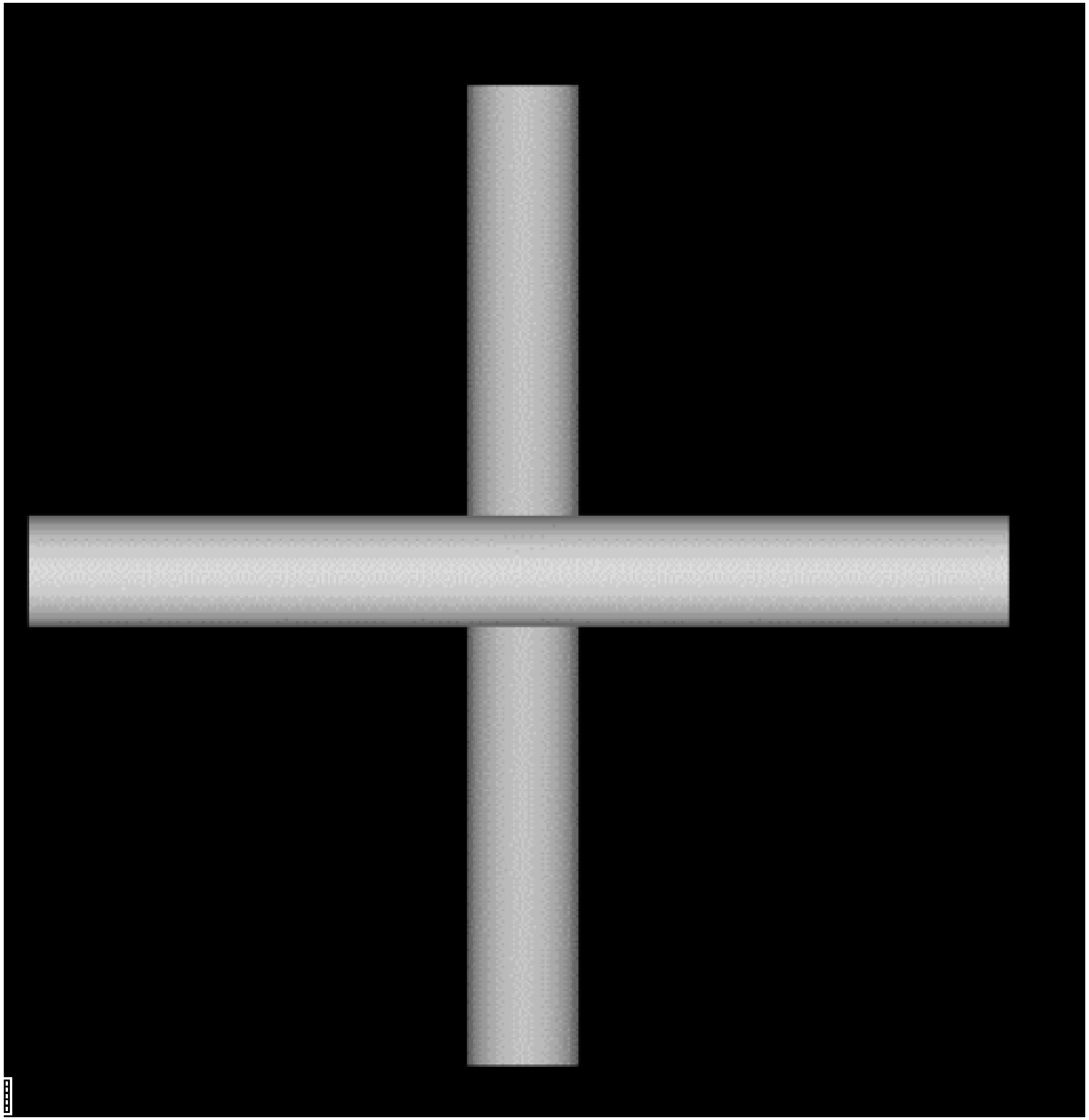
[3D pseudo-spectral code, 256^3 modes.]

Impose initial stag^n-pt flow

$v = v_A/30$

$R_m = 5600$

Isosurfaces of B^2:



B-Lines for 1 Tube

Colour shows locations of

strong E_p

stronger E_p

Final twist π

QuickTime™ and a
decompressor
are needed to see this picture.

9. CONCLUSIONS

- Reconnection fundamental process -
  - 2D theory well-developed
  - 3D new voyage of discovery:
    - topology
    - reconnection regimes (+ or - null)

- **Coronal heating**
  Solar flares