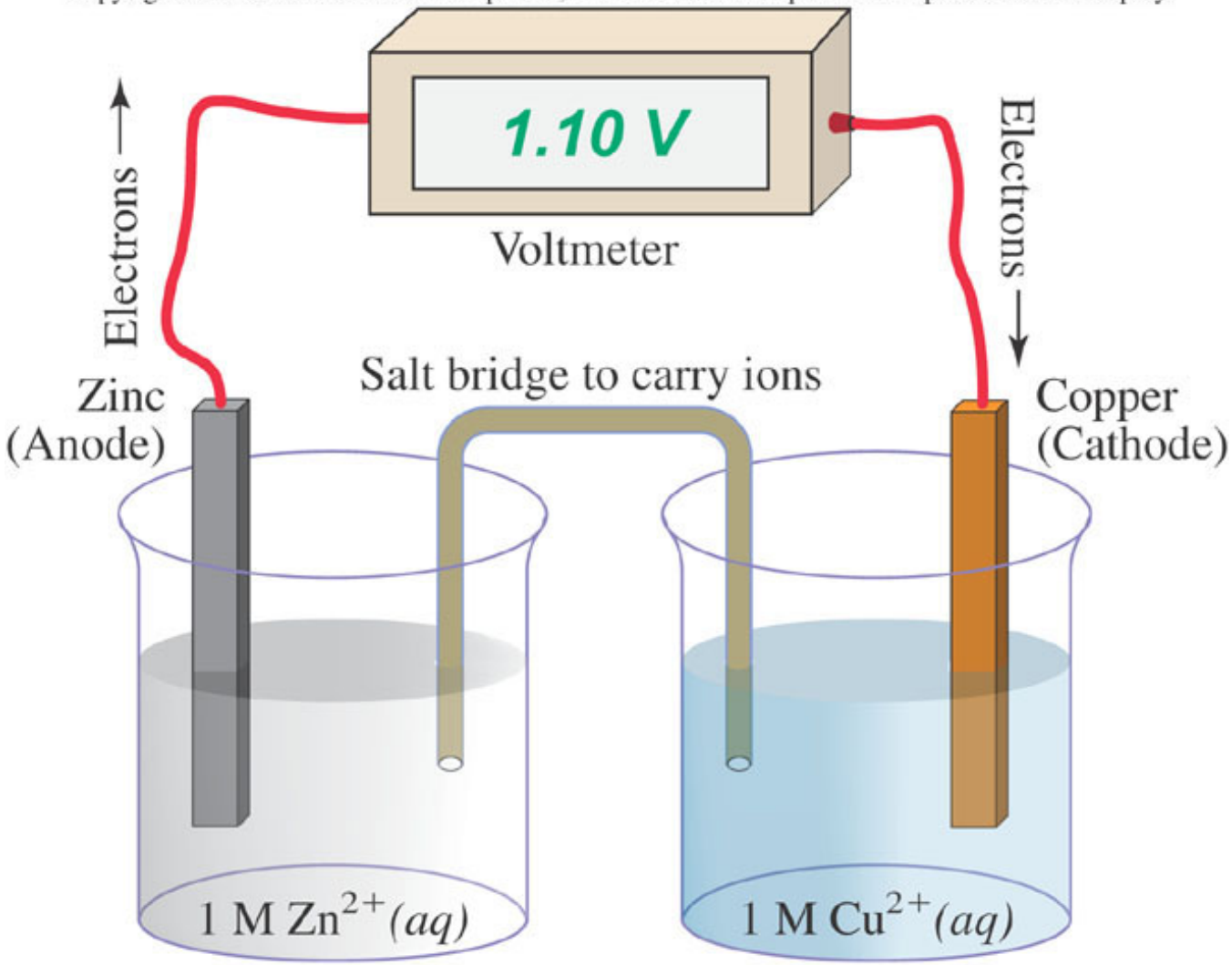
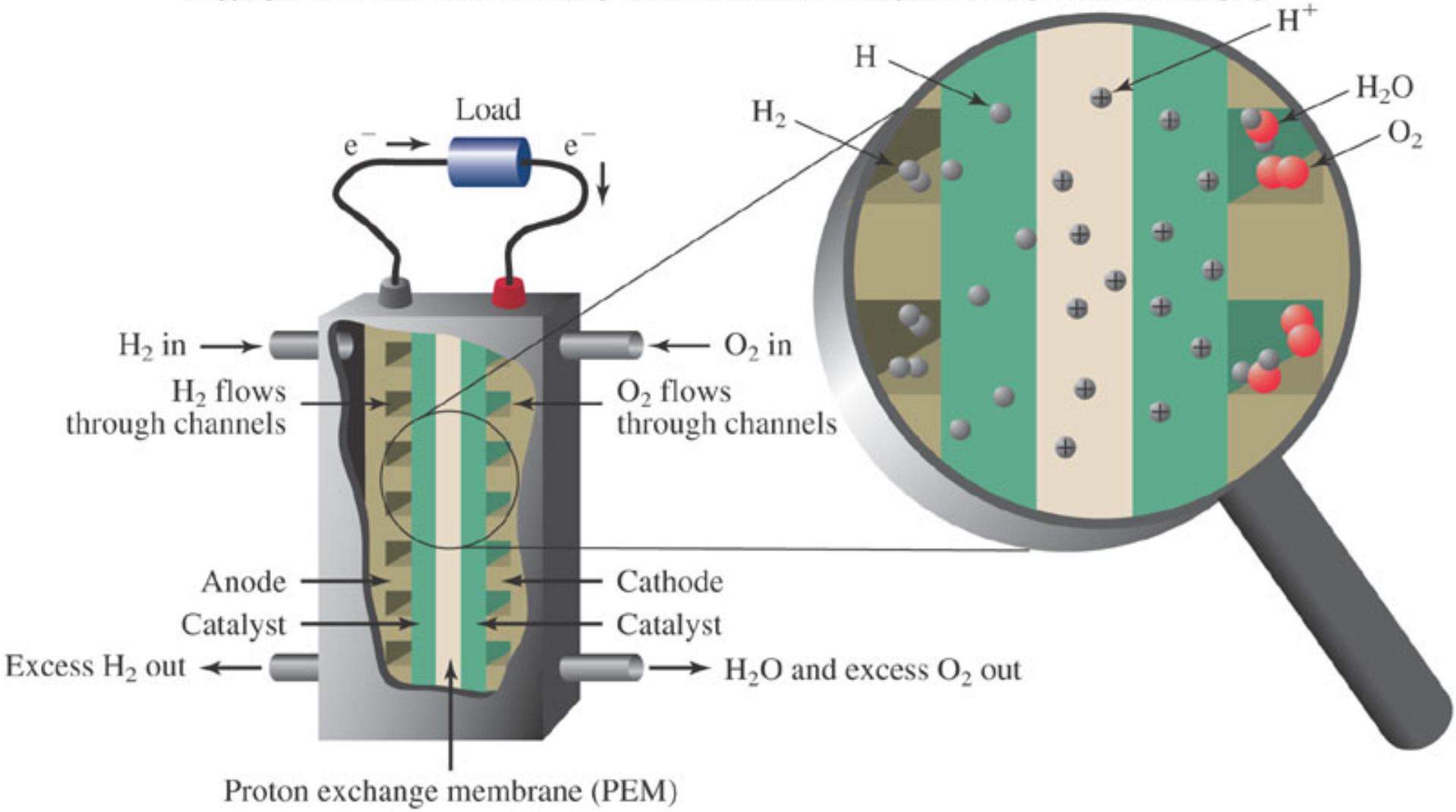


$$Zn(s) + Cu^{2+}(aq) \longrightarrow Zn^{2+}(aq) + Cu(s)$$

$Zn(s) \rightarrow Zn^{2+}\ (aq) + 2\ e^-$	Oxidation	Anode
$Cu^{2+}\ (aq) + 2\ e^- \rightarrow Cu\ (s)$	Reduction	Cathode

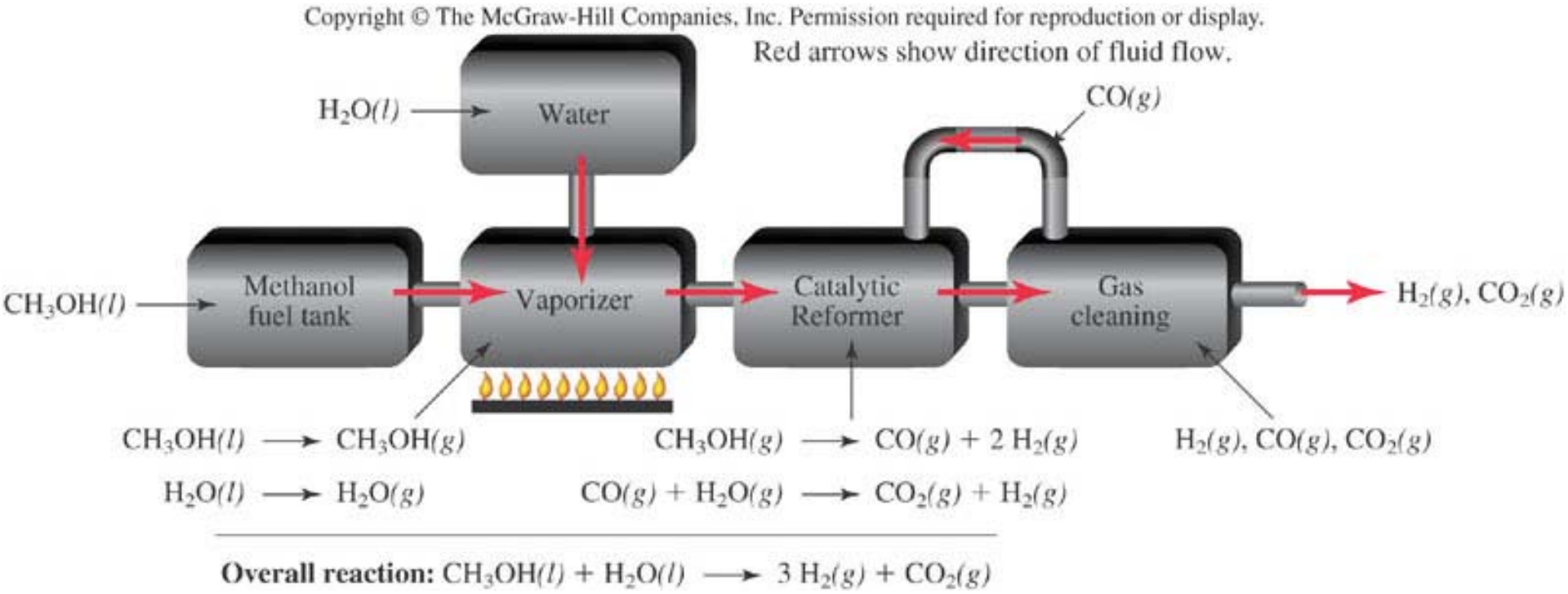


Anode: $H_2(g) \rightarrow 2\ H^+(aq) + 2\ e^-$

Cathode: $\frac{1}{2}\ O_2(g) + 2\ H^+(aq) + 2\ e^- \rightarrow H_2O(l)$

Net: $\frac{1}{2}\ O_2(g) + H_2(g) \rightarrow H_2O(l)$

One obstacle: Where do you get a constantly replenished source of H_2?



One possibility is the extraction of H_2 from methanol (CH_3OH) via the **reforming process**

Other reforming processes exist for gasoline, diesel

Table 8.2 Comparison of Combustion with Fuel Cell Technology

Process	Fuel*	Oxidant	Products	Other Considerations
Combustion	H_2	O_2 from air	H_2O, heat, light, and sound	Rapid process, flame present, lower efficiency, most useful for producing heat
Fuel cell	H_2	O_2 from air	H_2O, electricity, some heat	Slower process, no flame, quiet, higher efficiency, most useful for generating electricity

*Compounds containing hydrogen, such as natural gas or alcohols, can be used as fuels. Since these compounds contain carbon as well, CO or CO_2 (or both) are released as products.

The combustion of H_2 through either method "should" produce 286 kJ/mole

But in both cases, some of that energy is "lost" as heat

In a combustion engine, efficiency is ~ 25%

In a fuel cell, efficiency can be as high as 55%

The Electric Car

GM's Saturn EV-1 was, indeed, a ZEV, but...

- Lead storage batteries struggle at low T
- Recharging the batteries required plugging them in to the power grid
- Local power stations are NOT ZE plants
- In fact, calculations show that while CO2 emissions do go down if lead battery electric cars replace combustion engines...
- ... SO_2 and NO_x go up, due to the additional load at local power plants

So, the future of the electric car must lie elsewhere

Perhaps in the refinement of fuel cell technology, or perhaps in the form of the **hybrid vehicle**

The Hybrid Car

The first available hybrid was the Toyota Prius

Available in Japan in 1997, then in the U.S. in 2000

Combines a 1.5 L gasoline engine with a stack of nickel-metal hydride batteries, an electric motor and an electric generator

Needs no recharging – done during travel

Batteries start the engine, and operate the vehicle at low speeds

The combustion engine takes over for high speeds and rapid acceleration

Running the combustion engine drives the generator, which recharges the batteries

In addition, kinetic energy is used to recharge the batteries during deceleration and braking

The Hybrid Car

- The first available hybrid was the Toyota Prius
- Emits 50% less CO_2 than conventional engines
- Obtains 52 mpg gasoline in town, 45 mpg on the highway
- Newer models do even better – 70-80 mpg
- But there will be no mass market for alternative fuel vehicles until they can match the performance and price of conventional cars
- The current trend is to develop hybrid SUVs
- Research goes on to develop a viable hydrogen car – or truck

Hydrogen as Fuel

Why?

It's plentiful

It's clean

It provides tremendous amounts of energy:

½ $O_2(g)$ + $H_2(g)$ → H_2O (l) produces 286 kJ/mole of energy

1 mole of H_2 weighs 2 g

That makes for 143 kJ/g

- Coal: 30kJ/g
- Gasoline: 46 kJ/g
- Methane: 54 kJ/g

In fact, gram-for-gram, H_2 has the highest heat of combustion of any known substance

Hydrogen as fuel

One of the obstacles to using hydrogen fuel cells is that hydrogen is hard to come by

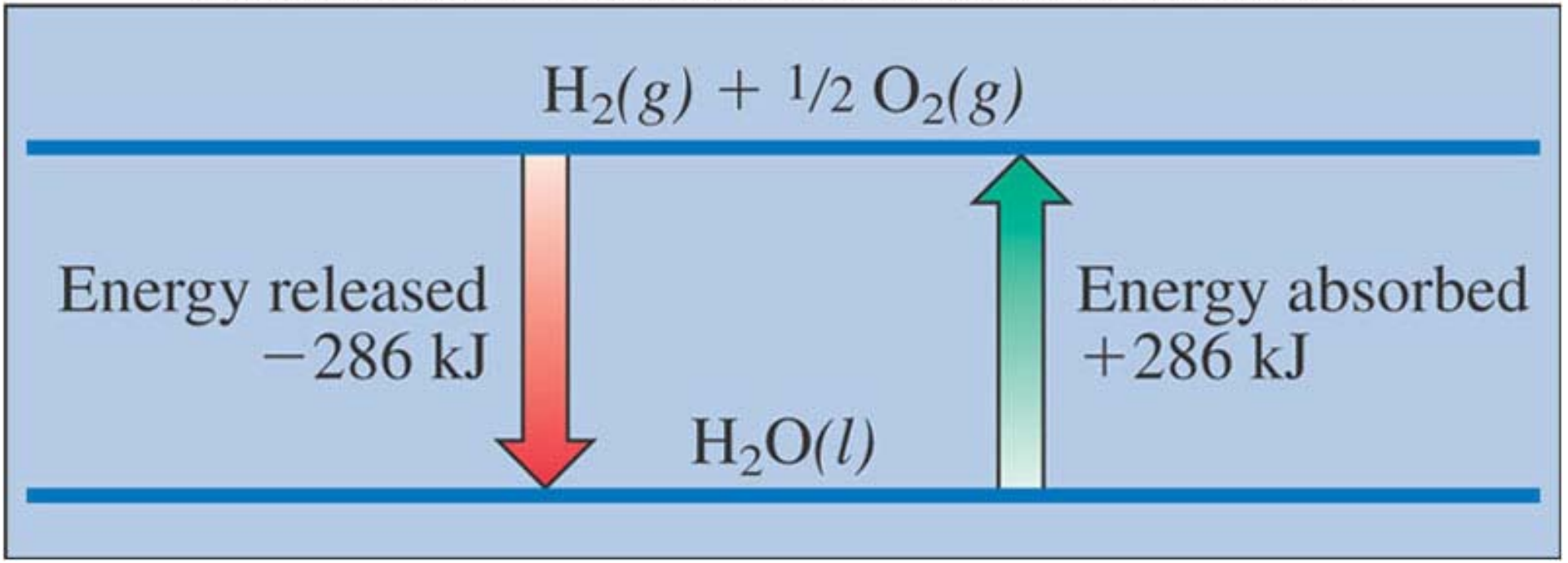
93% of atoms in the universe are hydrogen atoms

There are **vast** amounts of hydrogen atoms on Earth

But very few of them are present as $H_2(g)$

H_2 is too reactive to survive for long

So we have to **extract** H_2 from compounds which contain it, and that requires us to put energy in



If we can put 286 kJ/mol of energy IN to *water*, we should be able to separate the hydrogen and the oxygen

One method of doing this: electrolysis!

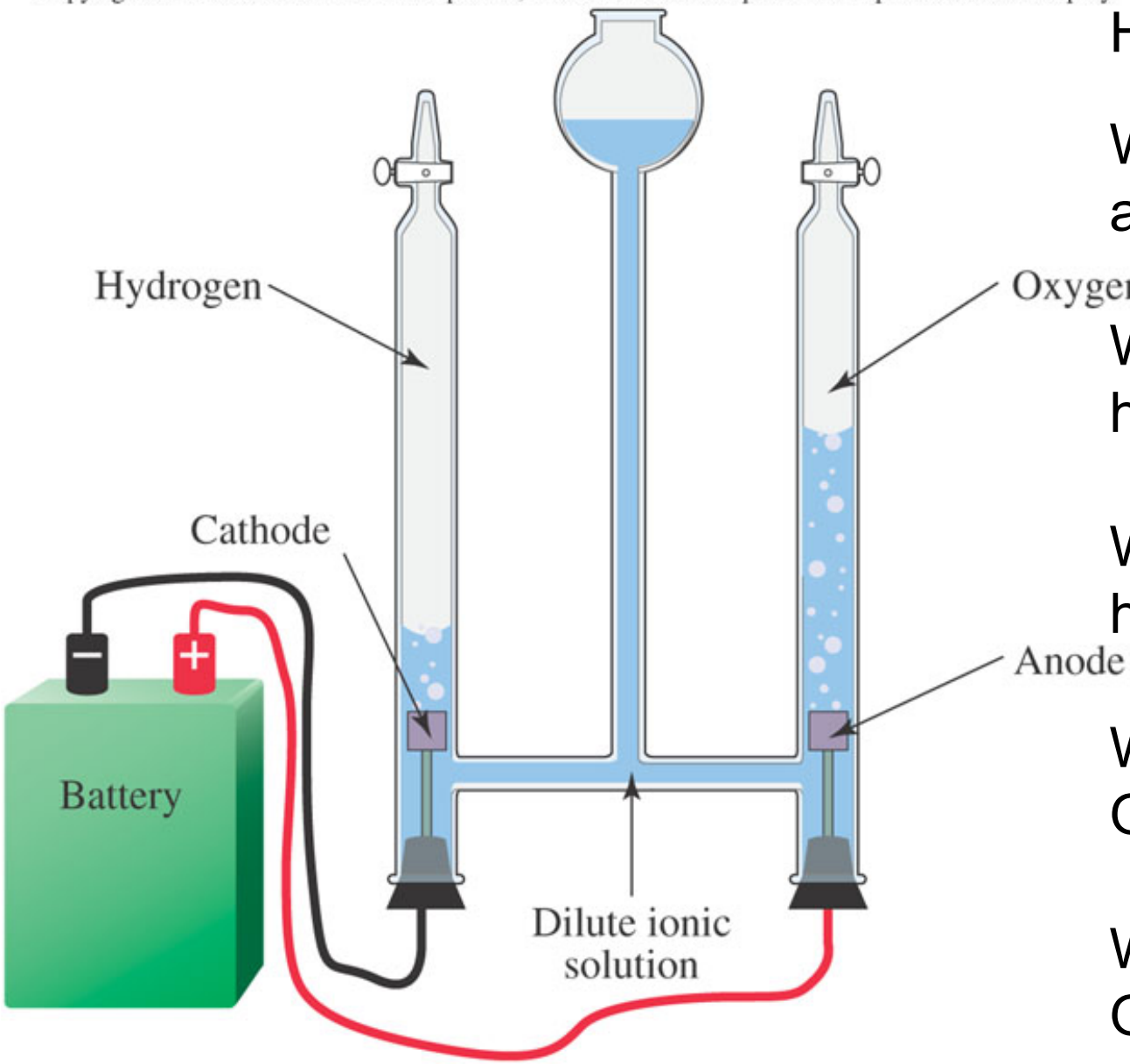
Electrochemistry: Some Definitions

A Battery: A system which converts chemical energy into electrical energy

More correctly, a battery is an **electrochemical cell**:

Galvanic Cells convert the energy from spontaneous chemical reactions into electricity

Electrolytic Cells use electricity to drive non-spontaneous chemical reactions



$H_2O \rightarrow H_2 + ½\ O_2$

Which is oxidized, and which reduced?

What's the charge on hydrogen in H_2O?

+1

What's the charge on hydrogen in H_2?

0

What's the charge on O in H_2O?

-2

What's the charge on O in O_2?

0

So hydrogen is **reduced**, and oxygen is **oxidized**

Hydrogen as fuel

- But the electrolysis of water still requires 286 kJ/mol of energy to be put in
- Where does that energy come from?
- Presumably from local power plants
- And combustion-driven power plants are so inefficient that we'd have to burn twice as much energy as that in fossil fuels in order to obtain the hydrogen
- That's not sustainable on a large scale
- So we need to find other reactions to do the job

Hydrogen as fuel

The electrolysis of water still requires 286 kJ/mol of energy to be put in

Recall the production of "water gas":

$H_2O(g) + C(s) \rightarrow H_2(g) + CO(g)$

This reaction at 800°C requires only 131 kJ/mol

The H_2 can be separated out and used as needed

Current research is focused on finding catalysts to reduce the temperature

Hydrogen as fuel

While we wait for that catalyst, most hydrogen is produced by:

$2\ H_2O(g) + CH_4(g) \rightarrow 4\ H_2(g) + CO_2(g)$

This reaction requires only 165 kJ/mol

But it consumes fossil fuels, and is fairly inefficient

Hydrogen Storage

IF we can establish a means to freely produce hydrogen, there remain significant obstacles.

One of these is the problem of storage

$H_2(g)$ occupies 12 L per gram, and would thus require bulky storage containers

It can be compressed into a liquid, but that requires it to be cooled to -253 °C … and kept there!

What other options are there?

Hydrogen Storage

What other options are there?

- Activated carbon
- Lithium hydride
- Fullerenes

Hydrogen Storage

What other options are there?

Activated carbon

Derived from charcoal, burned in the absence of air

Forms a black powder with **tremendous** surface area – up to 1500 square meters for one gram! (Six tennis courts worth)

Used as a filtration element for drinking water, vodka, gas purification

Can absorb huge amounts of hydrogen on its surface at low temperatures, and then release it as the carbon is heated

Hydrogen Storage

What other options are there?

Lithium hydride

$Li(s) + ½ H_2(g) \rightarrow LiH(s)$

This converts 12 L of hydrogen gas into a solid with the volume of a teaspoon

$LiH(s) + H_2O(l) \rightarrow H_2(g) + LiOH(aq)$

Reacting LiH with water re-produces the hydrogen gas

Prototypes cars based on this method have proven safe and successful

Hydrogen Storage

What other options are there?

- Fullerenes

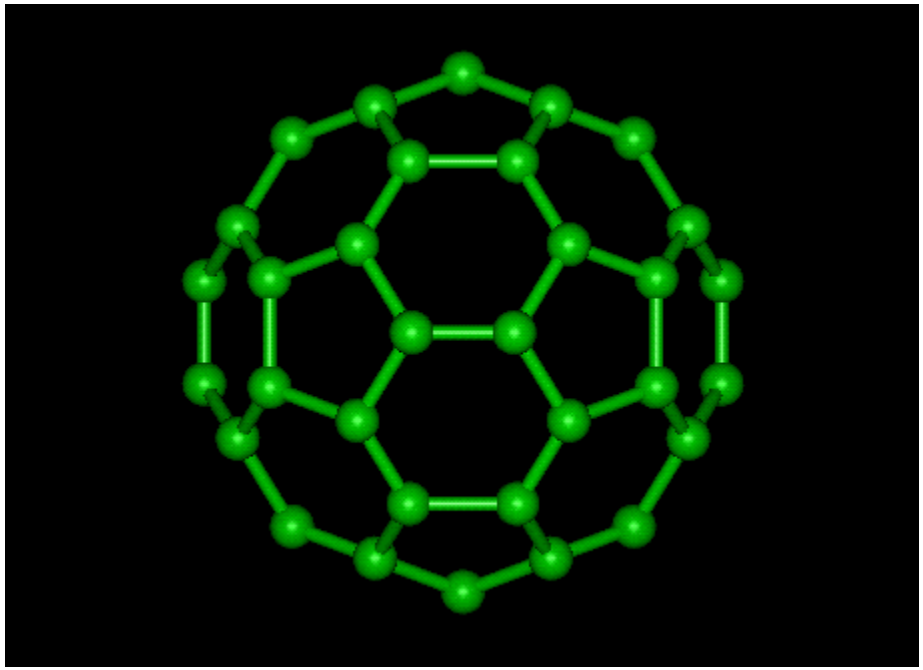
What's fullerene?!?

It's an *allotrope* of carbon – in the same way that ozone is an allotrope of oxygen

The simplest fullerene is C_{60}

C_{60} forms a soccer-ball shape – complete with pentagons and hexagons

C_{60} – “Buckminster Fullerene”



Named for Robert Buckminster Fullerene, the architect who invented the geodesic dome – like Epcot Center

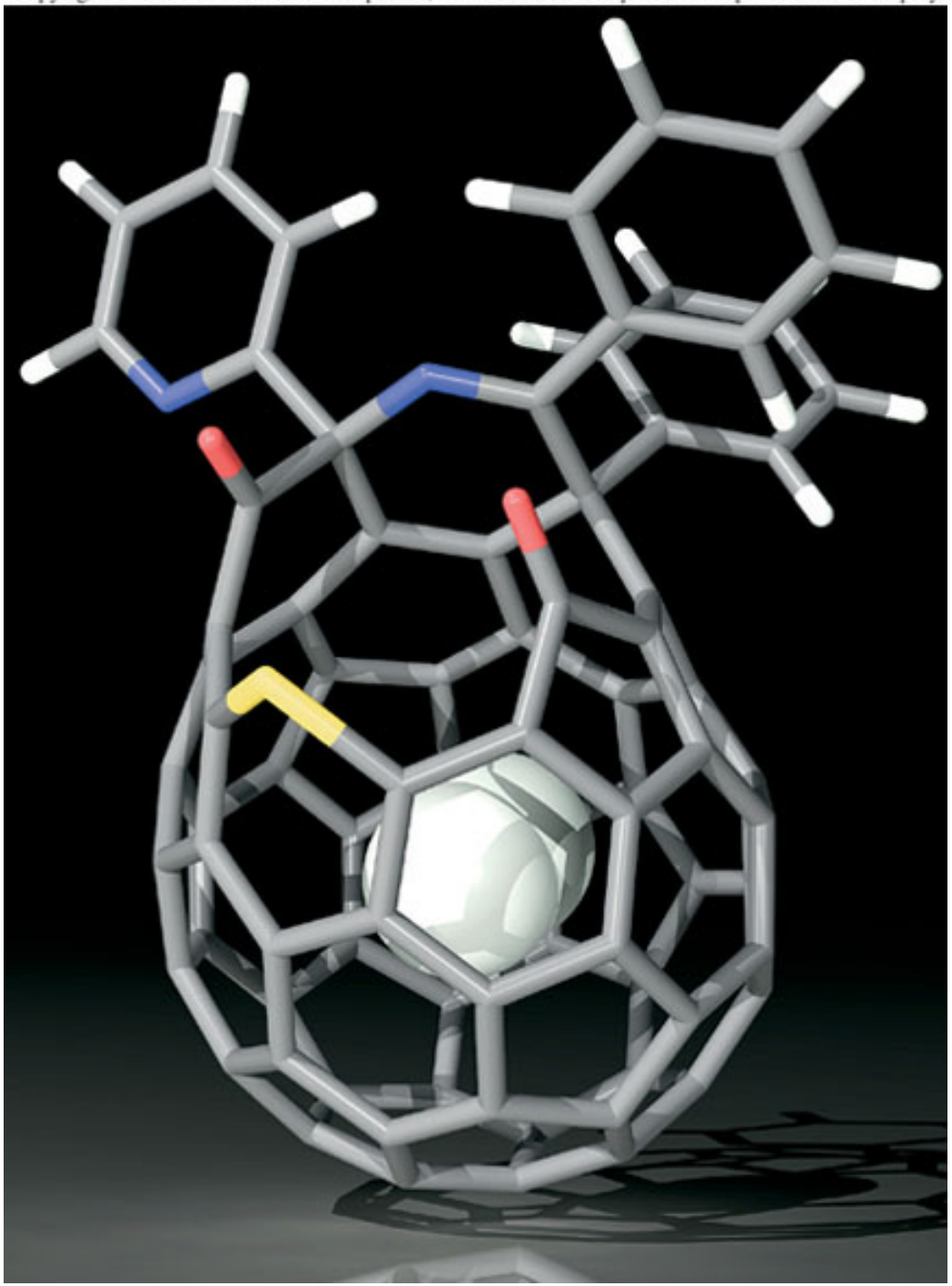
Hydrogen Storage

The simplest fullerene is C_{60}

But other fullerenes exist

Some include S, N, O

Some have openings in the sphere that allow other atoms to enter and occupy the central volume



One such fullerene is shown here, with an H_2 molecule trapped inside

Such structures can absorb huge amounts of H_2 at low temperatures, and then release the H_2 as temperatures are raised above 160°C

Hydrogen as fuel

All of these technologies are still under development

So hydrogen appears unlikely to be a solution to our energy crunch any time soon

The only solution seems to be to combine several different alternative fuels

Nuclear, geothermal, wind, hydroelectric, tidal… and solar

It turns out that solar power, too, is driven by electron transfer

We'll learn about that next week