The reaction at the Anode is:

\[ \text{Zn}(s) \rightarrow \text{Zn}^{2+} (aq) + 2 \text{e}^- \]

The reaction at the Cathode is:

\[ \text{Cu}^{2+} (aq) + 2 \text{e}^- \rightarrow \text{Cu} (s) \]
<table>
<thead>
<tr>
<th>Type</th>
<th>Voltage</th>
<th>Rechargeable?</th>
<th>Examples of Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkaline</td>
<td>1.54</td>
<td>No</td>
<td>Flashlights, small appliances</td>
</tr>
<tr>
<td>Lithium–iodine</td>
<td>2.8</td>
<td>No</td>
<td>Camera batteries, pacemakers</td>
</tr>
<tr>
<td>Lithium ion</td>
<td>3.7</td>
<td>Yes</td>
<td>Laptop computers, cell phones, digital music players</td>
</tr>
<tr>
<td>Lead–acid</td>
<td>2.0</td>
<td>Yes</td>
<td>Automobiles</td>
</tr>
<tr>
<td>Nickel-cadmium</td>
<td>1.25</td>
<td>Yes</td>
<td>Consumer electronics</td>
</tr>
<tr>
<td>(NiCd)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nickel-metal</td>
<td>1.25</td>
<td>Yes</td>
<td>Replacing NiCad for many uses; hybrid vehicles</td>
</tr>
<tr>
<td>hydride (NiMH)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mercury</td>
<td>1.3</td>
<td>No</td>
<td>Formerly widely used in cameras, other appliances</td>
</tr>
</tbody>
</table>
Limitations of Traditional Batteries

Eventually, all batteries run down
If they are not rechargeable, then they simply run out of material at either the anode or the cathode (or both)
If they are rechargeable, then eventually the physical mechanism of keeping products attached to the electrodes fails
Many people believe that this will be the downfall of batteries, and that they will be replaced by something that doesn’t ever run down
One such possibility is the Fuel Cell
The Fuel Cell

A Fuel Cell is a galvanic cell which converts the chemical energy from a fuel into electrical energy \textit{without burning the fuel}. Fuel is still \textit{consumed}, but not \textit{combusted}. Sometimes referred to as “flow batteries”, because they must have a constantly replenished flow of both fuel and oxidizer.

Fuel cells were invented in 1839 (!), but were just a novelty until there was a reason to worry about combusting fuels… The U.S. space missions
The Fuel Cell

Fundamentally, a fuel cell is much like a traditional battery. There are two separate compartments. Oxidation happens in one, reduction in the other. Electrons are transferred from one electrode to the other. *Something* gets consumed... but in a fuel cell, it is immediately replaced.
The Fuel Cell

An example fuel cell: the hydrogen fuel cell

Hydrogen is the fuel from which the chemical energy is to be extracted

Oxygen is the oxidant

Anode: \( \text{H}_2(\text{g}) \rightarrow 2 \text{ H}^+ (\text{aq}) + 2 \text{ e}^- \)

Cathode: \( \frac{1}{2} \text{O}_2(\text{g}) + 2 \text{ H}^+ (\text{aq}) + 2 \text{ e}^- \rightarrow \text{H}_2\text{O} (\text{l}) \)

Net: \( \frac{1}{2} \text{O}_2(\text{g}) + \text{H}_2(\text{g}) \rightarrow \text{H}_2\text{O} (\text{l}) \)

What could be “cleaner” than that?

Hydrogen’s energy is extracted by interaction with oxygen from the air, and the only product is water

Note that this is the same equation as combustion
The Fuel Cell

Note that this is the same equation as combustion

But rather than applying a flame, the fuel cell uses a **catalyst** to lower the activation energy of the reaction

Charge is transferred through a **polymer electrolyte membrane** (PEM) also called a **proton exchange membrane**

This membrane has very small holes which are small enough to allow $H^+$ to pass through, but nothing else

It is coated on both sides with the catalyst – current versions require a platinum catalyst
Anode: \( \text{H}_2(\text{g}) \rightarrow 2 \text{H}^+ (\text{aq}) + 2 \text{e}^- \)

Cathode: \( \frac{1}{2} \text{O}_2(\text{g}) + 2 \text{H}^+ (\text{aq}) + 2 \text{e}^- \rightarrow \text{H}_2\text{O} (\text{l}) \)

Net: \( \frac{1}{2} \text{O}_2(\text{g}) + \text{H}_2(\text{g}) \rightarrow \text{H}_2\text{O} (\text{l}) \)
The PEM has to remain moist for the reaction to proceed.

Water produced at the anode is recycled to wet the membrane.

Operation at high temperatures is difficult, because it is hard to keep the water from evaporating/boiling.
The combustion of H₂ 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%.
One obstacle: Where do you get a constantly replenished source of H₂?

One possibility is the extraction of H₂ from methanol (CH₃OH) via the **reforming process**

Other reforming processes exist for gasoline, diesel
The PEM has to remain moist for the reaction to proceed.
In addition, the PEM requires platinum as a catalyst.
Platinum is expensive.
Scientists estimate that there is not enough platinum on the planet to build enough fuel cells to replace combustion engines in cars.
New models have been proposed using solid oxide electrolytes – ZrO$_2$ and CaO.
More resistant to temperature and impurities in fuel.
The Fuel Cell: Applications

**Distributed generation** – providing fuel cells to locations which are not on a standard power grid, or which need backup power for when the grid goes down

Beginning to flourish in the U.S. and Japan

Cleaner use of fossil fuels

In Japan, 26% of homes are powered by kerosene power plants

Using a kerosene reforming process, the same fuel can be used in a zero-emissions* plant

* - is it really zero-emissions if the by-products include CO$_2$?
The Fuel Cell: Applications

Microcells may be even closer to widespread application. Some Japanese laptops already run on fuel cell technology. Some predict that they may be in circulation as battery replacements by 2011. Most fuel cell discussions focus on applications in commercial vehicles.
The Fuel Cell: Applications in Motor Vehicles

It is possible to run automobiles on electrical power from hydrogen fuel cells. There have been some holdups in their widespread use. Safely storing hydrogen gas is a challenge, but working prototypes exist.
The Fuel Cell: Applications in Motor Vehicles

Other options include on-board reformers to convert methanol to hydrogen as needed. This eliminates the need for bulky/dangerous hydrogen storage. BUT it means that the car is no longer a ZEV.

On the other hand...

- The amount of energy per gram of CO$_2$ is larger.
- Engines run at lower T, reducing NO emission.
- Methanol is a renewable fuel.
- The engine has few moving parts, requires little service.
The Electric Car

Electric cars powered by fuel cells are not far off

There are already electric buses in Chicago, D.C. and New York – all using methanol and PEM cells

In 2000, DaimlerChrysler released the New Electric Car 5

A Mercedes-Benz model run on a methanol fuel cell

Averages 25 mpg of methanol
Can drive 250 miles without refueling
Can reach speeds over 90 mph
Has been driven cross country
Carries a hefty price tag
The Electric Car

Earlier models had relied solely on the lead storage battery

GM’s Saturn EV-1

Debuted in 1997

Powered by 26 lead storage batteries...

... weighing a total of 1100 pounds

Developed in response to legislation in California, Massachusetts and New York requiring ZEVs

(Now mostly repealed, as technology was unprepared)
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 Final Exam
May 25th at 9:00 am
Here!
Letters

Well done!
The average score was 81%
If you scored less than 160/200 on the letter, you may re-submit it
This is entirely optional!
Due our last day of class (May 15)
Turn in your original letter, your original score sheet, and your second draft
You can earn back a maximum of half the points between you and the average score of 162.