Rechargeable battery types

- **Nickel Cadmium (NiCd)**
  - long cycle life, high load current and economical

- **Nickel-Metal Hydride (NiMH)**
  - higher energy density than NiCd at the expense of reduced cycle life and lower load current

- **Lead Acid**
  - cheap, easily rechargeable and capable of high current pulses, but heavy

- **Lithium Ion (Li-ion) and Lithium Ion Polymer (Li-on polymer)**
  - high energy density making them very compact, but low load current, expensive and difficult to charge
<table>
<thead>
<tr>
<th>Characteristics of rechargeable batteries</th>
<th>NiCd</th>
<th>NiMH</th>
<th>Lead Acid</th>
<th>Li-ion</th>
<th>Li-ion polymer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravimetric Energy Density (Wh/kg)</td>
<td>45-80</td>
<td>60-120</td>
<td>30-50</td>
<td>110-160</td>
<td>100-130</td>
</tr>
<tr>
<td>Internal Resistance (in mΩ) (includes peripheral circuits)</td>
<td>100 to 200(^1) 6V pack</td>
<td>200 to 300(^1) 6V pack</td>
<td>&lt;100(^1) 12V pack</td>
<td>150 to 250(^1) 7.2V pack</td>
<td>200 to 300(^1) 7.2V pack</td>
</tr>
<tr>
<td>Cycle Life (to 80% of initial capacity)</td>
<td>1500(^2)</td>
<td>300 to 500(^2,^3)</td>
<td>200 to 300(^2)</td>
<td>500 to 1000(^3)</td>
<td>300 to 500</td>
</tr>
<tr>
<td>Fast Charge Time</td>
<td>1h typical</td>
<td>2-4h</td>
<td>8-16h</td>
<td>2-4h</td>
<td>2-4h</td>
</tr>
<tr>
<td>Overcharge Tolerance</td>
<td>moderate</td>
<td>low</td>
<td>high</td>
<td>very low</td>
<td>low</td>
</tr>
<tr>
<td>Self-discharge / Month (room temperature)</td>
<td>20%(^4)</td>
<td>30%(^4)</td>
<td>5%</td>
<td>10%(^5)</td>
<td>~10%(^5)</td>
</tr>
<tr>
<td>Cell Voltage (nominal)</td>
<td>1.25V(^6)</td>
<td>1.25V(^6)</td>
<td>2V</td>
<td>3.6V</td>
<td>3.6V</td>
</tr>
<tr>
<td>Load Current</td>
<td>- peak</td>
<td>20C</td>
<td>5C</td>
<td>5C(^7)</td>
<td>&gt;2C</td>
</tr>
<tr>
<td></td>
<td>- best result</td>
<td>1C</td>
<td>0.5C or lower</td>
<td>0.2C</td>
<td>1C or lower</td>
</tr>
<tr>
<td>Operating Temperature (discharge only)</td>
<td>-40 to 60°C</td>
<td>-20 to 60°C</td>
<td>-20 to 60°C</td>
<td>-20 to 60°C</td>
<td>0 to 60°C</td>
</tr>
<tr>
<td>Maintenance Requirement</td>
<td>30 to 60 days</td>
<td>60 to 90 days</td>
<td>3 to 6 months(^9)</td>
<td>not req.</td>
<td>not req.</td>
</tr>
<tr>
<td>Typical Battery Cost (US$, reference only)</td>
<td>$50 (7.2V)</td>
<td>$60 (7.2V)</td>
<td>$25 (6V)</td>
<td>$100 (7.2V)</td>
<td>$100 (7.2V)</td>
</tr>
<tr>
<td>Cost per Cycle (US$)(^1)</td>
<td>$0.04</td>
<td>$0.12</td>
<td>$0.10</td>
<td>$0.14</td>
<td>$0.29</td>
</tr>
</tbody>
</table>

Battery capacity

- **capacity** - amount of stored energy
  - typically specified in (misleading) unit of *ampere-hours* (A·hr)
  - multiply A·hr rating by battery voltage V to get energy units Watt·hr
    - recalling
      - unit of energy is Joule = Watt·sec
      - power P is rate energy E is being generated or dissipated, \( P = \frac{dE}{dt} \)
  - given a 12V lead acid battery rated at 2.0A·hr – approximately how long would the battery be able to supply a fixed current of 1.5A to a device?

\[
P = 12V \times 1.5A = 18W
\]

\[
E - E(0) = 2.0A \cdot hr \times 12V = 24W \cdot hr
\]

\[
= \int_{\lambda=0}^{t} Pd\lambda = 18W \cdot t
\]

\[
\Rightarrow t = 24W \cdot hr / 18W = 1.3hr
\]

or using A·hr rating
(reason for A·hr units now seen)

\[
t = \frac{2.0A \cdot hr}{1.5A} = 1.3hr
\]
Power budget

battery “size” determined by operation time and current draw

- node equation: \( I = I_1 + I_2 + I_3 + I_4 \)
- multiply by battery voltage \( V \) to get power equation:
  \[ P = VI = VI_1 + VI_2 + VI_3 + VI_4 \]
- assuming constant power \( P \) and given a specified run-time \( t \), battery capacity can be found via \( P \cdot t \)
Power regulation

• goal: provide constant voltage to a load even as input voltage and load vary

• **linear regulator**
  – cheap, dropout voltage ⇒ $V_{in} > V_{out}$, linear ⇒ $I_{in} = I_{out}$ ⇒ lost power
    $= I_{in}(V_{in} - V_{out})$ ($= 0.5\text{A} (12\text{V} - 5\text{V}) = 3.5\text{W}$ for 12V battery, 5V linear regulator and 0.5A current draw)

• **dc-dc converter (switching regulator)**
  – expensive, capacitors or inductors are switched in such a way that $V_{out} \geq V_{in}$ or $V_{out} \leq V_{in}$, often over 80% efficient