In a typical capacitor, electrons are removed from one plate and deposited on the other. Polarized molecules in the dielectric concentrate the electric field. One major factor determining capacitance is the surface area of the plates.
An ultracapacitor can store more charge than a capacitor can, because the activated carbon has a pocked interior, much like a sponge. This means that ions in the electrolyte can cling to more surface area.
With finer dimensions and more uniform distribution, carbon nanotubes enable greater energy storage in ultracapacitors than activated carbon does.
HOW TO ULTRACAP A CAR

Ultracapacitors can power a number of a car's functions locally. The orange arrows show how an ultracapacitor discharges to power acceleration, while the blue arrows show energy flowing back during braking. The red squares indicate places where ultracapacitors can be used.
ELECTRIC SHAG: A cross section of an electrode made with carbon nanotubes.
Figure 13. Generalized capacitor.
What do you get?

**Fig. 2.** Actual capacitors have parasitic inductance and resistance.

Real 

C

$X_C$
Figure 15.
Simplified equivalent capacitor circuit.
Capacitor Technologies

Vacuum Cap: High Q, high, high voltage
Capacitor Fundamentals

- In conventional capacitors, capacitance is measured as the amount of charge divided by the voltage, and charge is proportional to area of the plates.

- Traditional capacitors require a large surface area plate to have more capacitance.

- Ideally, to get a very large capacitance one wants a very large surface area with as little distance between the plates as possible.

\[ C = \]
Impedance vs. Frequency

Following graph illustrates how characteristic of some capacitors vary over frequency.

- Capacitive: $X_C > X_L$
- Inductive: $X_C < X_L$
- Mixed including Resistance: $X_C = X_L$, $Z/I = E.S.R.$

$\frac{f_{SRF}}{1/2\pi} = (L/C)^{1/2}$
The sheet resistance of the conductive plates of the capacitor and the wires that link these conductive plates to the terminals of the capacitors lead to a parasitic resistance that is called the ESR (Equivalent Series Resistance). The termination loop of the terminal wires also lead to a small and often negligible parasitic inductance called the ESL (Equivalent Series Inductance). Thus, the total impedance of a capacitor varies over the frequency at which it is used.

\[ \frac{1}{C} \]

ESL small but \( \frac{1}{2\pi f \cdot R} \) as \( f \) increases.
Fig. 3. As frequency increases, the parasitic inductance of a capacitor becomes dominant.
Table 3: Ripple characteristics of output capacitor in a step-down converter.

<table>
<thead>
<tr>
<th>Nominal C</th>
<th>Minimum C</th>
<th>Dielectric</th>
<th>C (µF)</th>
<th>Vc</th>
<th>Vout</th>
<th>ΔVESL</th>
<th>ΔVESR</th>
<th>ΔL/8Cf</th>
<th>ESL ΔL</th>
<th>ESR ΔL</th>
</tr>
</thead>
<tbody>
<tr>
<td>10µF</td>
<td>7µF</td>
<td>MK</td>
<td>6.5mV</td>
<td>2.6mV</td>
<td>3mV</td>
<td>0.4mV</td>
<td>0.7mV</td>
<td>0.8Cf</td>
<td>6.5mV</td>
<td>3mV</td>
</tr>
<tr>
<td>22µF</td>
<td>16µF</td>
<td>MK</td>
<td>2.8mV</td>
<td>1.9mV</td>
<td>1.4mV</td>
<td>0.7mV</td>
<td>1.7mV</td>
<td>1.8Cf</td>
<td>2.8mV</td>
<td>1.4mV</td>
</tr>
<tr>
<td>47µF</td>
<td>34µF</td>
<td>MK</td>
<td>1.4mV</td>
<td>1.4mV</td>
<td>1.7mV</td>
<td>0.7mV</td>
<td>1.7mV</td>
<td>2.0Cf</td>
<td>1.4mV</td>
<td>1.7mV</td>
</tr>
<tr>
<td>33µF</td>
<td>27µF</td>
<td>TPA</td>
<td>1.7mV</td>
<td>1.7mV</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

- \( V_{in} = +5V \)
- \( V_{out} = +1.8V \)
- \( l_{peak} = 0.72A \)
- \( F = 650 \text{ kHz} \)
- \( \Delta L = 0.24A \)
- \( \Delta L = 0.7\mu s \)
- \( \Delta L = 0.9\mu s \)
- \( F = 650 \text{ kHz} \)  
- \( V_{in} = +5V \)  
- \( V_{out} = +1.8V \)  
- \( l_{peak} = 0.72A \)  
- \( F = 650 \text{ kHz} \)
All capacitors have a lead inductance of 15 nH.

Figure 16: Plot of frequency dependent behavior of equivalent circuit for various capacitors.
Most of the parasitic inductances that we are concerned with here are those associated with traces, bond-wires, lead terminations, etc. From an applications point of view, we need to be concerned about PCB trace inductances in particular --- for that is what we can minimize easily.

But not all PCB trace inductances are "trouble-makers". For example, the traces connected in series with the inductor are "benign" --- because they can be looked at as just being lumped together with the main inductor. A freewheeling path is available for them too --- the same as the freewheeling path of the main inductor.

However, certain other trace inductances do not have any freewheeling path, and will therefore "complain" --- in the form of voltage spikes across the board, as per the basic equation $V=\text{L}dI/dt$. These traces are considered "high-frequency" or "critical traces" from the viewpoint of PCB layout, and their associated inductances are considered to be "uncoupled" or "leakage" inductances.
20 ft. from a network analyzer

Reactance [ohm] Absolute Value

Frequency [MHz]

G Hz
(a)
Fig. 5. Equivalent circuit, impedance and frequency dependence of bulk capacitors.
<table>
<thead>
<tr>
<th>Capacitor characteristics</th>
<th>Technology</th>
<th>V_Range (V)</th>
<th>Leakage nA x μF x V</th>
<th>Temperature Range (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Standard MnO₂</td>
<td>4 to 50</td>
<td>10</td>
<td>-55 to +125</td>
</tr>
<tr>
<td></td>
<td>Low-ESR MnO₂</td>
<td>4 to 50</td>
<td>10</td>
<td>-55 to +125</td>
</tr>
<tr>
<td></td>
<td>Standard 3f Multianode</td>
<td>4 to 50</td>
<td>0.1</td>
<td>-55 to +125</td>
</tr>
<tr>
<td></td>
<td>Polymer</td>
<td>2.5 to 10</td>
<td>0.035</td>
<td>-55 to +105</td>
</tr>
<tr>
<td></td>
<td>Polymer Multianode</td>
<td>2.5 to 6.3</td>
<td>0.01</td>
<td>-55 to +105</td>
</tr>
<tr>
<td></td>
<td>Standard MnO₂</td>
<td>3.3 to 1000</td>
<td>0.1</td>
<td>470 to 1000</td>
</tr>
<tr>
<td></td>
<td>Standard 3f Multianode</td>
<td>330 to 1000</td>
<td>0.035</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Polymer</td>
<td>2.5 to 10</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Polymer Multianode</td>
<td>2.5 to 6.3</td>
<td>0.01</td>
<td></td>
</tr>
</tbody>
</table>
Various C all show ESR, ESR, ESR, ESR.
Several factors affect the ESR:

- Thickness and material of the electrodes
- Area and aspect ratio of the electrodes
- Number of layers and parallel termination that form the electrodes
- Electrode surface flatness and metallization density
- Distributed resistance of the dielectric
- Frequency of operation

Below is a plot of ESR for various capacitors. Note that the ESR for ceramics can be as small as 1% of that of the Tantalum capacitors.
Inherent to any conducting wire is an element of resistance. Also, the insulating material added around the wire, to prevent short circuit from one turn of the coil to another, acts as a dielectric that adds capacitance between the turns. So, each inductor comes with an inherent resistance and capacitance. In addition, at higher frequencies, current tends to flow closer to the conductor surface, an effect known as the skin effect. Thus, the total impedance offered by an inductor varies with voltage and frequency applied to it. An example inductor impedance vs frequency graph is shown below.

![Typical AC Resistance vs Frequency](image-url)
<table>
<thead>
<tr>
<th>Vout</th>
<th>AVout</th>
<th>AVEsl</th>
<th>ESR</th>
<th>ESL * ALf/ton</th>
<th>TPA</th>
<th>MK</th>
<th>27 uf</th>
<th>33 uf</th>
<th>39 uf</th>
<th>47 uf</th>
<th>4 uf</th>
<th>16 uf</th>
<th>22 uf</th>
<th>2 uf</th>
<th>1 uf</th>
<th>Nominal C</th>
<th>Minimum C</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7 MV</td>
<td>7.7 MV</td>
<td>5.4 MV</td>
<td>2.0 MV</td>
<td>7.1 MV</td>
<td>6.9 MV</td>
<td>15.9 MV</td>
<td>15.9 MV</td>
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<td>15.9 MV</td>
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</tr>
<tr>
<td>1.8 MV</td>
<td>8.0 MV</td>
<td>0.4 MV</td>
<td>4.3 MV</td>
<td>5.8 MV</td>
<td>3.3 MV</td>
<td>3.3 MV</td>
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</tr>
<tr>
<td>3.6 MV</td>
<td>8.0 MV</td>
<td>0.2 MV</td>
<td>7.9 MV</td>
<td>7.7 MV</td>
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<td>7.7 MV</td>
<td></td>
</tr>
<tr>
<td>Graphic estimation</td>
<td>ESL * ALf/ton</td>
<td>ESR</td>
<td>Vout</td>
<td>Ioff = 0.7 MA</td>
<td>Ioff = 0.7 MA</td>
<td>Ioff = 0.7 MA</td>
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<td>Ioff = 0.7 MA</td>
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<tr>
<td>Vout</td>
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<td>2 uf</td>
<td>1 uf</td>
<td>Nominal C</td>
<td>Minimum C</td>
</tr>
</tbody>
</table>

\[
\frac{\tau_{on}}{\tau_{off}} > \frac{ESL}{\Delta V} = \frac{ESL}{V_{in}} = \frac{ESL}{1.8V} = \frac{ESL}{24A} = \frac{ESL}{600mA} = \frac{ESL}{0.9A} = \frac{ESL}{0.7A}
\]

Trent is linear and equal to ALf/ton:

\[
\tau_{on} = \frac{ESL}{\Delta V} = \frac{ESL}{V_{in}} = \frac{ESL}{1.8V} = \frac{ESL}{24A} = \frac{ESL}{600mA} = \frac{ESL}{0.9A} = \frac{ESL}{0.7A}
\]

\[
\tau_{off} = \frac{ESL}{\Delta V} = \frac{ESL}{V_{in}} = \frac{ESL}{1.8V} = \frac{ESL}{24A} = \frac{ESL}{600mA} = \frac{ESL}{0.9A} = \frac{ESL}{0.7A}
\]

\[
\tau_{on} + \tau_{off} = \frac{ESL}{\Delta V} = \frac{ESL}{V_{in}} = \frac{ESL}{1.8V} = \frac{ESL}{24A} = \frac{ESL}{600mA} = \frac{ESL}{0.9A} = \frac{ESL}{0.7A}
\]
Capacitance vs Frequency

- Area and aspect ratio of the electrodes
- Number of layers and parallel termination that form the electrodes
- Cover layer thickness
- Case size

\[ 15 \leq f \leq 3 \text{ MHz} \]
\[ ESL = f(f) \]
\[ f > 2 \text{ MHz}, \quad ESL \neq f(f) \]
Industry's First Non-Volatile Digitally Controlled Capacitor

Features
- 32-tap Digital capacitor
- Non-volatile EEPROM Storage of capacitor value with Power-On-Recall
- Fast setting time of 5µsec
- Excellent Linearity
- Simple Digital interface to program & store
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X90100 Replaces variable capacitors used to tune the frequency response of electronic systems up to 400MHz
Features

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- Excellent Linearity
- Simple Digital interface to program & store
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Xicor X90100 Linearity Over Capacitive Range

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