More Circuit Components: Capacitors, Inductors, and Diodes

- Practical circuits contain many components:
- Resistors (discussed last week)
- Capacitors, Inductors, and Diodes (to be discussed this week)
- Op Amps, Timers, etc (to be discussed next week)
Categories of Components:
Passive vs. Active, Lossy vs. Non-Lossy

Electronic Components

- Passive Components
  - Lossy Passives
    - Resistors, Diodes
  - Non-lossy Passives
    - Capacitors, Inductors

- Active Components
  - Needs power supply?
  - Doesn’t burn power?
Capacitors and Inductors

- Are not resistors. They:
  - Store energy
    - Capacitor in electric field, Inductor in magnetic field
  - Are non-lossy (*reactive* vs. *resistive*)
  - Have a time-varying behavior
    - Different from resistors
Capacitors

- Capacitors store energy in the form of an electric field
- Constructed from closely spaced conductors
- They act like small rechargeable batteries, able to store and release electrical energy.

Symbols:
Capacitor Construction

- Different types for different applications
- Choose for capacitance, size, voltage rating, leakage, series resistance...

Metal film capacitor
Variable capacitor
Electrolytic capacitor
Capacitor Equations

• A capacitor holds charge $Q$ proportional to the voltage across it:
  \[ C = \frac{Q}{V} \]

• The capacitance $C$ (units of \textit{Farads}) is set by the construction of the capacitor:
  \[ C \approx \frac{\epsilon A}{d}; \quad A \gg d^2 \]
Capacitor behavior

- Current through capacitor proportional to rate of change in voltage across it:
  \[ i = \frac{\Delta Q}{\Delta t} = C \frac{\Delta V}{\Delta t} \]

- Capacitors act to resist changes in voltage
- Capacitor current can change (very) quickly
- Capacitors store energy:
  \[ E_{\text{stored}} = \frac{1}{2} CV^2 \iff E_{\text{stored}} = \frac{1}{2} \frac{Q^2}{C} \]
Basic Resistor Capacitor (RC) Circuit

- Initially, capacitor is “uncharged.”

![Diagram of RC Circuit]

- Capacitor
- Resistor
- Battery
- Switch in Off position

No Voltage on Capacitor
Basic Resistor Capacitor (RC) Circuit

- When current flows, capacitor becomes charged to the voltage of the battery.

Switch in On position

Switch

Capacitor

Electron flow

Resistor

Battery
RC circuit: Time response

- Inherent time scale is: \( \tau = RC \) (RC time constant)
- Capacitors act to resist changes in voltage
- Capacitor current can change quickly
A capacitor stores energy

• And can release it very quickly
A capacitor stores energy

• And can release it very quickly
“Bypass” capacitors

• Digital electronics contain many transistor switches which require bursts of current when they switch
• Can cause troublesome power supply noise
“Bypass” capacitors

• A small capacitor, close to and in parallel with a digital device smoothes out the voltage by providing a low resistance “backup” voltage source
Voltage multiplication with capacitors

• Resistors can only decrease circuit voltages
• Capacitors can be used like batteries in series to increase voltages...

\[9V \times 3 = 27V\]
Switched-capacitor circuits

- Switch circuits can “rearrange” capacitors to achieve many useful effects...
- Example: voltage doubler

Step 1: Charge two capacitors in parallel

Step 2: Switch the two capacitors to be in series
Inductors

- Inductors store energy in the form of a magnetic field
- Made from coils of wire
Inductor construction

- Can have various geometries, big and small

- Coils can be wrapped around *high-permeability* materials to increase inductance

- It is a lot harder to make a good inductor than a good capacitor or resistor
  - Lossy
  - Big
  - “Parasitics”

- Inductors are mostly used for only a few applications
  - Radio circuits
  - Power conversion

*Air core (permeability = 1)*

*Soft iron core (permeability = 600)*

*Less inductance*

*More inductance*
Inductor Equations

• An inductor stores *magnetic flux* proportional to the current through it:

\[ L = \frac{\Phi}{i} \]

• The inductance \( L \) (units of *Henries*) is set by the construction of the inductor:

\[ L = \frac{\mu_0 \mu_r N^2 A}{l} \]

\( \mu_0 \) = permeability of free space = \( 4\pi \times 10^{-7} \) H/m

\( \mu_r \) = relative permeability of core material

\( N \) = number of turns

\( A \) = area of cross-section of the coil in *square metres* (m²)

\( l \) = length of coil in *metres* (m)
Inductor behavior

• Voltage across inductor is proportional to the rate of change of current through it:

\[ V = L \frac{\Delta I}{\Delta t} \]

• Inductors act to resist changes in current
• Inductor voltage can change quickly
• Inductors store energy:

\[ E_{\text{stored}} = \frac{1}{2} LI^2 \]
Inductor/Resistor (RL) Circuit

- Inductors act to resist changes in current
- Inductor voltage can change quickly
- Inherent time scale is: $\tau = \frac{L}{R}$
Inductor Applications: Filtering

• Because inductors tend to reject the flow of rapidly changing currents, they can be used to filter out high-frequency signals

• Ex: Lumps on computer cables are *ferrite beads* which add inductance to the cable.
Transformer

- An inductor’s magnetic field can pass through more than one coil.
- This is called a transformer.
- For AC (time-varying) signals, it transforms the voltage observed between its coils according to its turns ratio.
- A transformer isolates the two sides of the transformer – no physical connection other than through the magnetic field. This is often desirable for safety reasons.
Engine Ignition Circuit

- A transformer is used to generate 40,000V to fire the engine spark plugs
• “Coil” has high secondary-to-primary turns ratio.
• When the points first close, current starts to flow in the primary winding and eventually reaches the final value set by the 12V battery.
• When the points open, the current in the primary winding collapses very quickly, causing a large voltage to appear across this winding. This voltage on the primary is magnetically coupled to (and stepped up by) the secondary winding, generating a voltage of 30 kV - 40 kV on the secondary side.
• In the automobile ignition, a capacitor is placed across the points to minimize damage due to arcing when the points "break" the current flowing in the low-voltage coil winding (in car manuals, this capacitor is referred to as a "condenser")
Inductor Applications: Switching power supplies

- Inductors make possible many types of efficient DC-DC converters which convert an input voltage to a different voltage (either higher or lower)
- Can be >90% efficient

Switch: on “D”% of the time
(D = duty cycle)

- **“Buck” configuration**
  \[ \frac{V_o}{V_g} = D \]

- **“Boost” configuration**
  \[ \frac{V_o}{V_g} = \frac{1}{1-D} \]
The Diode: A one-way street

• Diodes are electronic components that conduct current in one direction only, from *anode* to *cathode*
The diode as a switch

- Diodes can be used as passive switches – to conduct positive voltages along one path and negative voltages along another.
- Ex: voltage doubler

![Diode as a switch diagram]
Voltage multipliers

• The voltage doubler principle can be generalized to make voltage *multipliers* capable of generating very high voltages

• One popular type was developed by Cockcroft and Walton to produce 800 kV needed for their particle accelerator (1932)

• Nobel Prize: First demonstration of a nuclear reaction caused by accelerated particles
Series and Parallel Combinations

• Any circuit constructed using just resistors also acts like a resistor. Same for capacitors and inductors.
• The circuit has an equivalent resistance (or capacitance, or inductance) which depends upon the details of the network.
Series Inductors

Series Inductances

\[ L_{\text{total}} = L_1 + L_2 + \ldots + L_n \]
Parallel Capacitors

less capacitance

more capacitance

\[ C_1 \parallel C_2 \rightarrow C_{\text{total}} \]

Parallel Capacitances

\[ C_{\text{total}} = C_1 + C_2 + \ldots + C_n \]
Parallel Inductors

Parallel Inductances

\[ L_{\text{total}} = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2} + \ldots + \frac{1}{L_n}} \]
Series Capacitors

$C_{\text{total}} = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \ldots + \frac{1}{C_n}}$