Beginner to Advanced Electronics

Foundations

By Apowware

Ref. The Art of Electronics by Paul Horowitz & Winfield Hill 3rd Edition
Electric Circuits by James Nilsson & Susan Riedel 10th Edition

Outline

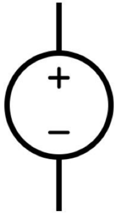
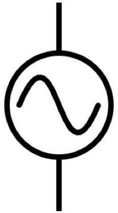
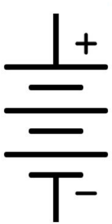
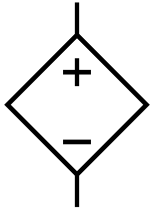
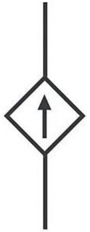
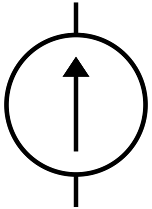
- Voltage, Current, & Resistance
- Signals
- Capacitors & AC Circuits
- Inductors & Transformers
- Diodes & Diode Circuits
- Impedance & Reactance
- Other Passive Components

Voltage, Current, & Resistance

Voltage & Current Sources

A **voltage source** is a device or component that provides a fixed or controlled **potential difference** (voltage) between its terminals, regardless of the current drawn (within its limits). It “pushes” electric charge through a circuit by maintaining a set voltage. It can be **independent** (e.g., a battery, power supply) or **dependent/controlled** (voltage depends on another circuit variable). An **ideal voltage source** maintains constant voltage no matter the current drawn; it has zero internal resistance. A **real voltage source** has some internal resistance, so voltage may drop under high load.

A **current source** is a device or component that delivers or maintains a constant current to a circuit, regardless of the voltage across it (within its operating limits). It “pushes” a fixed amount of electric charge per unit time. It can be **independent** (provides a set current) or **dependent/controlled** (current depends on another circuit variable). An **ideal current source** maintains constant current regardless of the load’s resistance; has infinite internal resistance. A **real current source** can only maintain the current within a certain voltage range before its output changes.

Voltage & Current

Voltage is the **electrical potential difference** between two points in a circuit. It tells you **how much potential energy per unit charge** is available to move electrons from one point to another, much like the pressure that pushes water through a pipe. Voltage has the symbol, V and is measured in **Volts.**

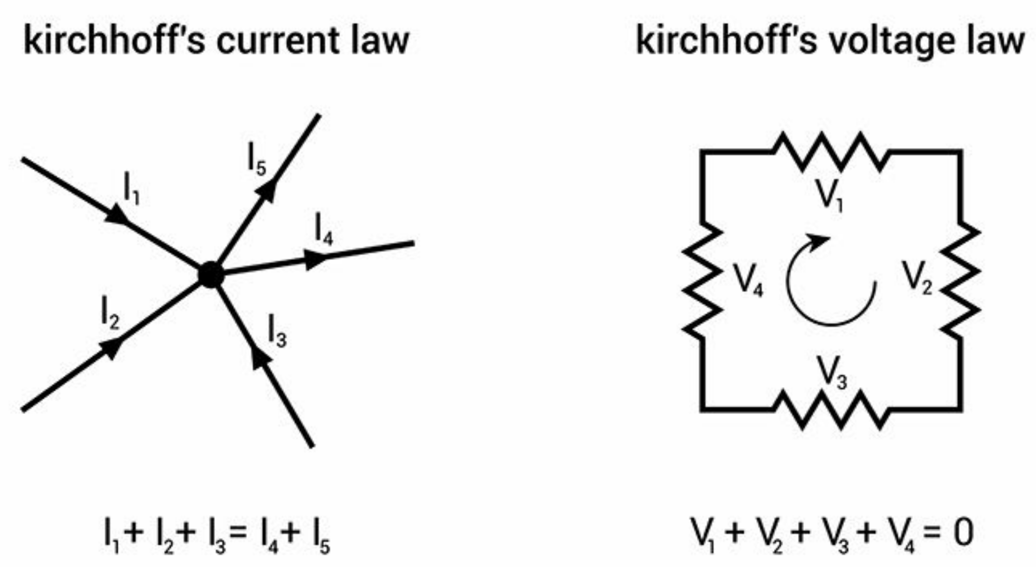
Electrical **current** is the **flow of electric charge** through a conductor or circuit. It measures **how many charges pass a point per unit time**, similar to the flow rate of water in a pipe. Current has the symbol, ***I*** and is measured in **Amps**.

Kirchhoff's Current Law (KCL) states that: **The total current entering a junction (node) in an electrical circuit is equal to the total current leaving that junction.** Mathematically, $\sum I_{in} = \sum I_{out}$. It's based on the **principle of conservation of electric charge**; charge cannot accumulate at a node, so whatever current enters must leave.

Kirchhoff's Voltage Law (KVL) states: **The algebraic sum of all voltages around any closed loop in a circuit is zero.** Mathematically $\sum V = 0$. As you travel around a closed loop in a circuit, the total energy gained by charges (from sources like batteries) equals the total energy lost (across resistors, capacitors, etc.). This is a consequence of the **conservation of energy**.

Electrical power is the **rate at which electrical energy is transferred or converted** in a circuit. It tells you how quickly electrical energy is being supplied by a source or used by a load. Power has the symbol, **P** and is measured in Watts. Formula, $P=VI$. Power goes into heat (usually), or sometimes mechanical work (motors), radiated energy (lamps, transmitters), or stored energy (batteries, capacitors, inductors).

KCL & KVL


kirchhoff's current law
I_1
I_2
I_3
I_4
I_5
$I_1 + I_2 + I_3 = I_4 + I_5$
kirchhoff's voltage law
V_1
V_2
V_3
V_4
$V_1 + V_2 + V_3 + V_4 = 0$

Example - KCL

Sum the currents at each node in the circuit shown in Fig. 2.16. Note that there is no connection dot (•) in the center of the diagram, where the 4 Ω branch crosses the branch containing the ideal current source i_a.

Solution

In writing the equations, we use a positive sign for a current leaving a node. The four equations are

node a $\quad i_1 + i_4 - i_2 - i_5 = 0,$

node b $\quad i_2 + i_3 - i_1 - i_b - i_a = 0,$

node c $\quad i_b - i_3 - i_4 - i_c = 0,$

node d $\quad i_5 + i_a + i_c = 0.$

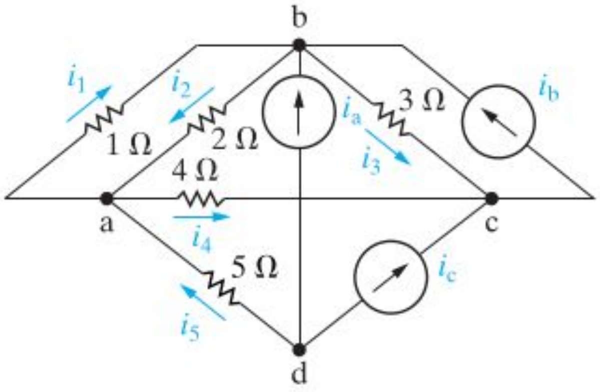


Figure 2.16 ▲ The circuit for Example 2.6.

Example - KVL

Sum the voltages around each designated path in the circuit shown in Fig. 2.17.

Solution

In writing the equations, we use a positive sign for a voltage drop. The four equations are

path a $\quad -v_1 + v_2 + v_4 - v_b - v_3 = 0,$

path b $\quad -v_a + v_3 + v_5 = 0,$

path c $\quad v_b - v_4 - v_c - v_6 - v_5 = 0,$

path d $\quad -v_a - v_1 + v_2 - v_c + v_7 - v_d = 0.$

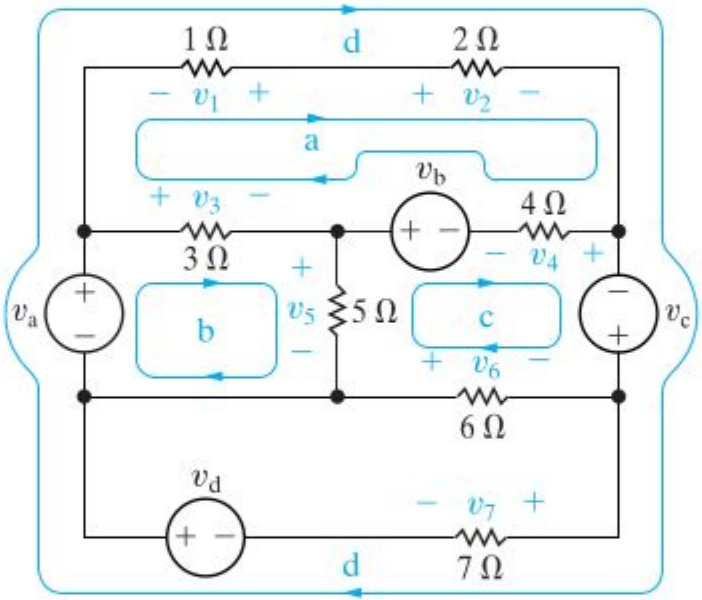


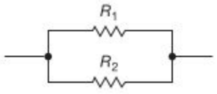
Figure 2.17 ▲ The circuit for Example 2.7.

Relationship Between Voltage & Current: Resistors

A **resistor** is an electrical component that **opposes the flow of electric current**, converting some of the electrical energy into heat. The symbol for resistance is R and has the unit Ohm (Ω). **Ohm's law** is $V=IR$ where V is **voltage** and I is **current**. Resistors are used to control current in a circuit, divide voltage, protect components, and to convert electrical energy into heat. A resistor is made out of some conducting stuff (carbon, or a thin metal or carbon film, or wire of poor conductivity), with a wire or contacts at each end.

The total resistance of resistors in **series** is $R_{total}=R_1+R_2+R_3+\ldots$ and the total resistance of resistors in **parallel** is $R_{total} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots}$

2 Resistors in parallel is $R = \frac{R_1 R_2}{R_1 + R_2}$



Using Ohm's Law the Power in a resistor is defined as

$$P = IV = I^2 R = \frac{V^2}{R}$$

Example: You have a 5k resistor and a 10k resistor. What is their combined resistance (a) in series and (b) in parallel?

In series $R=R_1+R_2 = 5000 + 10000= 15000.$

In parallel $$R = \frac{R_1 R_2}{R_1 + R_2} = \frac{5k(10K)}{5k + 10K} = 3333.33$$

Example - Applying Ohm's Law and Kirchhoff's Laws to Find an Unknown Current

a) Use Kirchhoff's laws and Ohm's law to find i_o in the circuit shown in Fig. 2.18.

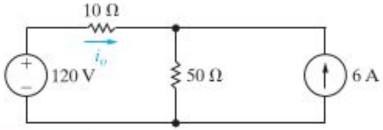


Figure 2.18 ▲ The circuit for Example 2.8.

b) Test the solution for i_o by verifying that the total power generated equals the total power dissipated.

Solution

a) We begin by redrawing the circuit and assigning an unknown current to the 50 Ω resistor and unknown voltages across the 10 Ω and 50 Ω resistors. Figure 2.19 shows the circuit. The nodes are labeled a, b, and c to aid the discussion.

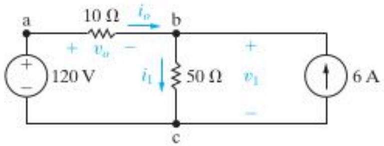


Figure 2.19 ▲ The circuit shown in Fig. 2.18, with the unknowns i_1, v_o, and v_1 defined.

Because i_o also is the current in the 120 V source, we have two unknown currents and therefore must derive two simultaneous equations involving i_o and i_1. We obtain one of the equations by applying Kirchhoff's current law to either node b or c. Summing the currents at node b and assigning a positive sign to the currents leaving the node gives

$$i_1 - i_o - 6 = 0.$$

We obtain the second equation from Kirchhoff's voltage law in combination with Ohm's law. Noting from Ohm's law that v_o is $10i_o$ and v_1 is $50i_1$, we sum the voltages around the closed path cabc to obtain

$$-120 + 10i_o + 50i_1 = 0.$$

In writing this equation, we assigned a positive sign to voltage drops in the clockwise direction. Solving these two equations for i_o and i_1 yields

$$i_o = -3 \text{ A} \quad \text{and} \quad i_1 = 3 \text{ A}.$$

b) The power dissipated in the 50 Ω resistor is

$$p_{50\Omega} = (3)^2(50) = 450 \text{ W}.$$

The power dissipated in the 10 Ω resistor is

$$p_{10\Omega} = (-3)^2(10) = 90 \text{ W}.$$

The power delivered to the 120 V source is

$$p_{120\text{V}} = -120i_o = -120(-3) = 360 \text{ W}.$$

The power delivered to the 6 A source is

$$p_{6\text{A}} = -v_1(6), \quad \text{but} \quad v_1 = 50i_1 = 150 \text{ V}.$$

Therefore

$$p_{6\text{A}} = -150(6) = -900 \text{ W}.$$

The 6 A source is delivering 900 W, and the 120 V source is absorbing 360 W. The total power absorbed is 360 + 450 + 90 = 900 W. Therefore, the solution verifies that the power delivered equals the power absorbed.

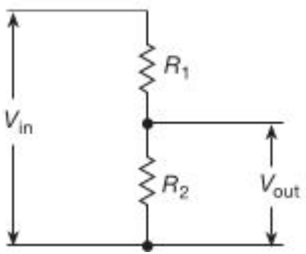
Voltage Divider

A voltage divider is a simple circuit that uses **two or more resistors in series** to produce an output voltage that is a fraction of the input voltage. It works by dividing the total voltage in proportion to the resistances.

If R_1 and R_2 are in series, and the input voltage V_{in} is applied across them, the voltage across R_2 (output) is: $V_{out} = V_{in}\frac{R_2}{R_1 + R_2}$

Voltage dividers are used to scale down voltages for sensors, measurement circuits, or biasing transistors. They only work well when the load connected to V_{out} draws a negligible amount of current.

Additionally, $I = \frac{V_{in}}{R_1 + R_2}$



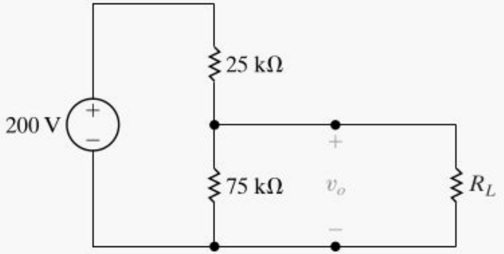
Example - Voltage Divider

3.2 a) Find the no-load value of v_o in the circuit shown.

b) Find v_o when R_L is 150 kΩ.

c) How much power is dissipated in the 25 kΩ resistor if the load terminals are accidentally short-circuited?

d) What is the maximum power dissipated in the 75 kΩ resistor?



[a] We can use voltage division to calculate the voltage v_o across the 75 kΩ resistor:

$$v_o(\text{no load}) = \frac{75{,}000}{75{,}000 + 25{,}000}(200\ \text{V}) = 150\ \text{V}$$

[b] When we have a load resistance of 150 kΩ then the voltage v_o is across the parallel combination of the 75 kΩ resistor and the 150 kΩ resistor. First, calculate the equivalent resistance of the parallel combination:

$$75\ \text{k}\Omega \| 150\ \text{k}\Omega = \frac{(75{,}000)(150{,}000)}{75{,}000 + 150{,}000} = 50{,}000\,\Omega = 50\ \text{k}\Omega$$

Now use voltage division to find v_o across this equivalent resistance:

$$v_o = \frac{50{,}000}{50{,}000 + 25{,}000}(200\ \text{V}) = 133.3\ \text{V}$$

[c] If the load terminals are short-circuited, the 75 kΩ resistor is effectively removed from the circuit, leaving only the voltage source and the 25 kΩ resistor. We can calculate the current in the resistor using Ohm's law:

$$i = \frac{200\ \text{V}}{25\ \text{k}\Omega} = 8\ \text{mA}$$

Now we can use the formula $p = Ri^2$ to find the power dissipated in the 25 kΩ resistor:

$$p_{25k} = (25{,}000)(0.008)^2 = 1.6\ \text{W}$$

[d] The power dissipated in the 75 kΩ resistor will be maximum at no load since v_o is maximum. In part (a) we determined that the no-load voltage is 150 V, so be can use the formula $p = v^2/R$ to calculate the power:

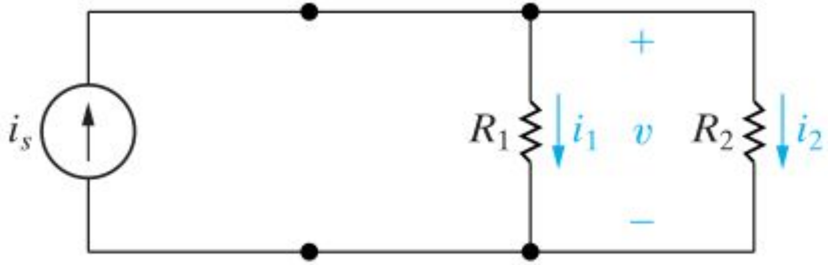
$$p_{75k}(\max) = \frac{(150)^2}{75{,}000} = 0.3\ \text{W}$$

Current Divider

A **current divider** is a circuit (usually resistors in parallel) that divides an input current into two or more branch currents **in inverse proportion to the branch resistances**. The branch with a **lower resistance** gets **more current**. The branch with a **higher resistance** gets **less current**.

For two resistors $\boldsymbol{R_1}$ and $\boldsymbol{R_2}$ in parallel, with total current, I_s

$$I_1 = I_s \frac{R_2}{R_1 + R_2} \quad I_2 = I_s \frac{R_1}{R_1 + R_2}$$



Example - Current Divider

Find the power dissipated in the 6 Ω resistor shown in Fig. 3.16.

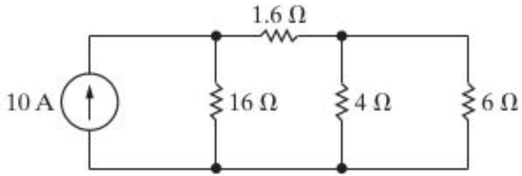


Figure 3.16 ▲ The circuit for Example 3.3.

Solution

First, we must find the current in the resistor by simplifying the circuit with series-parallel reductions. Thus, the circuit shown in Fig. 3.16 reduces to the one shown in Fig. 3.17. We find the current i_o by using the formula for current division:

$$i_o = \frac{16}{16 + 4}(10) = 8 \text{ A}.$$

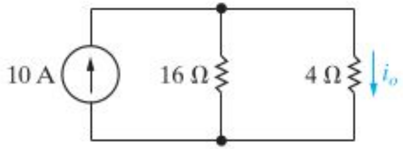


Figure 3.17 ▲ A simplification of the circuit shown in Fig. 3.16.

Note that i_o is the current in the 1.6 Ω resistor in Fig. 3.16. We now can further divide i_o between the 6 Ω and 4 Ω resistors. The current in the 6 Ω resistor is

$$i_6 = \frac{4}{6 + 4}(8) = 3.2 \text{ A},$$

and the power dissipated in the 6 Ω resistor is $p = (3.2)^2(6) = 61.44$ W.

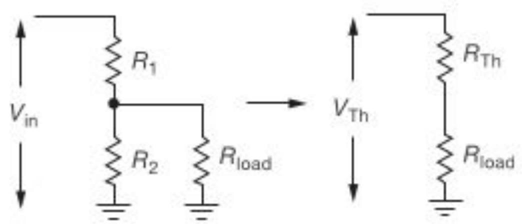
Thévenin Equivalent Circuit

A **Thévenin equivalent circuit** is a simplified representation of a complex linear electrical network, seen from two terminals, that makes analysis easier. It replaces the original network with **a single voltage source** V_{TH} (Thevenin voltage) in series with **a single resistor** R_{TH} (Thévenin resistance). V_{Th} = the **open-circuit voltage** measured at the two terminals (no load connected). R_{TH} = the resistance seen at the terminals with all independent voltage sources replaced by short circuits and all independent current sources replaced by open circuits.The Thévenin model makes it much easier to analyze how a load will behave when connected to a complex network; you only deal with a simple voltage source and resistor.

$V_{TH} = V_{oc}$ & $R_{TH} = \frac{V_{oc}}{I_{sc}}$

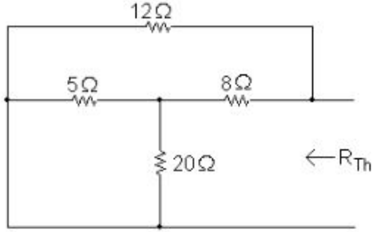
For example, in a voltage divider the open-voltage is $V_{oc} = V_{in}\frac{R_2}{R_1 + R_2}$ and the short-circuit current is $I_{sc} = \frac{V_{in}}{R_1}$

So the Thévenin equivalent circuit is a voltage source, $V_{TH} = V_{in}\frac{R_2}{R_1 + R_2}$ in series with a resistor $R_{TH} = \frac{R_1 R_2}{R_1 + R_2}$



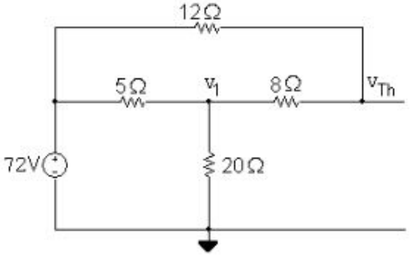
Example - Thevenin Circuits

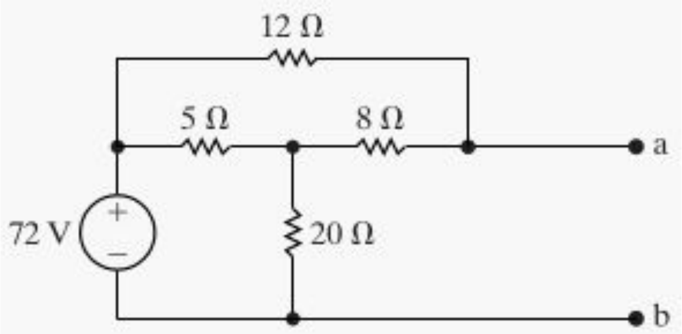
To find R_{Th}, replace the 72 V source with a short circuit:



Note that the $5\,\Omega$ and $20\,\Omega$ resistors are in parallel, with an equivalent resistance of $5\|20 = 4\,\Omega$. The equivalent $4\,\Omega$ resistance is in series with the $8\,\Omega$ resistor for an equivalent resistance of $4 + 8 = 12\,\Omega$. Finally, the $12\,\Omega$ equivalent resistance is in parallel with the $12\,\Omega$ resistor, so $R_{\text{Th}} = 12\|12 = 6\,\Omega$.

Use node voltage analysis to find v_{Th}. Begin by redrawing the circuit and labeling the node voltages:





The node voltage equations are

$$\frac{v_1 - 72}{5} + \frac{v_1}{20} + \frac{v_1 - v_{\text{Th}}}{8} = 0$$

$$\frac{v_{\text{Th}} - v_1}{8} + \frac{v_{\text{Th}} - 72}{12} = 0$$

Place these equations in standard form:

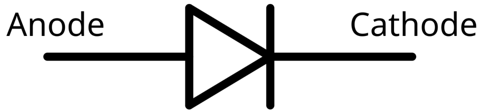
$$v_1\left(\frac{1}{5} + \frac{1}{20} + \frac{1}{8}\right) + v_{\text{Th}}\left(-\frac{1}{8}\right) = \frac{72}{5}$$

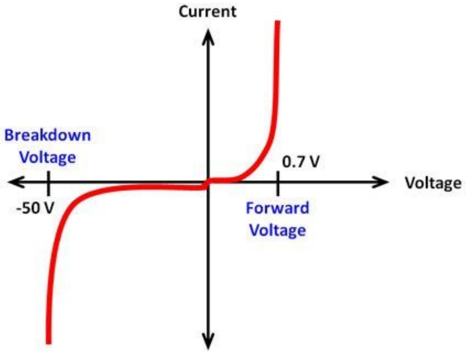
$$v_1\left(-\frac{1}{8}\right) + v_{\text{Th}}\left(\frac{1}{8} + \frac{1}{12}\right) = 6$$

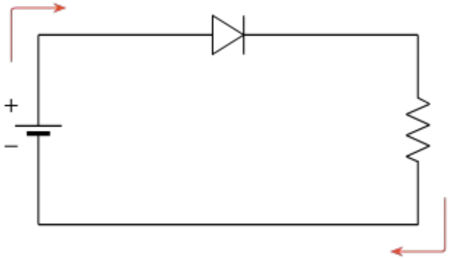
Solving, $v_1 = 60$ V and $v_{\text{Th}} = 64.8$ V. Therefore, the Thévenin equivalent circuit is a 64.8 V source in series with a $6\,\Omega$ resistor.

Diodes

A **diode** is an electronic component that allows current to flow **in one direction only** while blocking it in the opposite direction (under normal operating conditions). A diode is a triangle (pointing in the direction of conventional current) touching a vertical bar. A diode is **forward biased** when the anode is at a higher voltage than the cathode, the diode conducts after a certain threshold (about 0.7 V for silicon, 0.3 V for germanium). A diode is **reverse biased** when the cathode is at a higher voltage, the diode ideally blocks current (except for a tiny leakage). A diode **breaks down** if the reverse voltage exceeds the diode's breakdown rating, it can conduct heavily (often damaging the diode, unless it's a Zener or special type). Diodes are **commonly used** for rectification (AC to DC conversion), protecting circuits from reverse polarity, signal demodulation, and voltage regulation (Zener diodes).

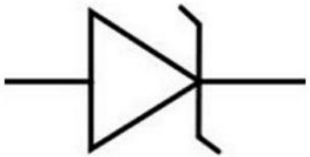


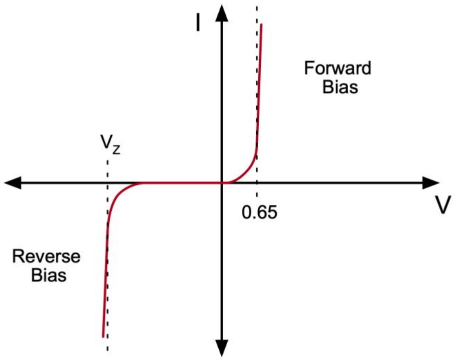


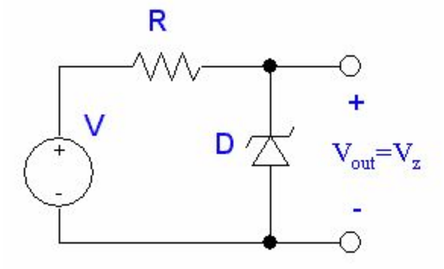


Zener Diodes

A **Zener diode** is a special type of diode designed to allow current to flow **not only in the forward direction** (like a regular diode) but also **in the reverse direction** when the reverse voltage reaches a specific value called the **Zener breakdown voltage**. It looks **s**imilar to a diode, but with bent edges on the bar. The **Zener voltage (**V_Z**)** is the fixed voltage at which the diode conducts in reverse. In the reverse breakdown region, the voltage across the diode stays nearly constant, even if the current changes which makes it useful as a **voltage regulator**. Typical V_Z values range from a few volts to tens of volts. They are mainly used for voltage regulation (keeping output voltage constant), as a reference voltage in circuits and overvoltage protection. For example, s 5.1 V Zener diode will start conducting in reverse when the voltage across it reaches about 5.1 V, clamping the voltage at that level.







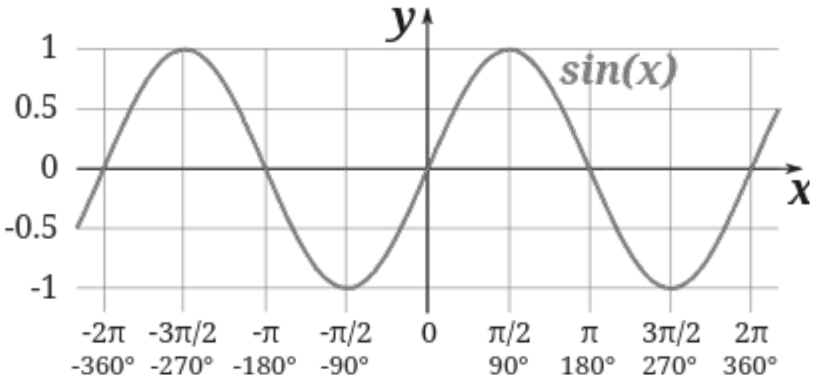
Signals

Sinusoidal Signals

A **sinusoidal signal** is a type of continuous waveform that varies with time following a **sine (or cosine) mathematical function**. It is one of the most fundamental signals in electrical engineering and physics. It is defined by the equation

$$x(t) = Asin(\omega t + \phi)$$

Where *A* is the amplitude (maximum value of the signal), ω (or $2\pi f$) is the angular frequency (rad/s), *f* is frequency, ϕ is the phase angle (radians or degrees, *t* is time.



Decibels (dB)

A **decibel (dB)** is a **logarithmic unit** used to express the ratio between two quantities, most commonly power or voltage. It's widely used in electronics, acoustics, and signal processing because it can represent very large or small ratios in a compact way.

$$L_{dB} = 10log_{10}(\frac{P}{P_{ref}})$$

Where P is the measured power, P_{ref} is the reference power, and L_{dB} is the level in decibels.

For voltage and current, since power is proportional to V^2 or I^2.

$$L_{dB} = 20log_{10}(\frac{V}{V_{ref}}) \quad L_{dB} = 20log_{10}(\frac{I}{I_{ref}})$$

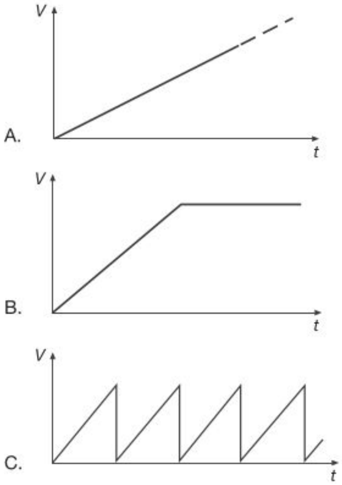
In the context of digital filters the **gain** (amplitude response) is expressed in dB. When the dB is **positive** the gain is called **amplification**. When the dB is **negative** the gain is called **attenuation**.

A **-3 dB point** means the output power has dropped to **half** of the input power. In terms of amplitude (voltage/magnitude), it means output is at about **70.7%** of input. In filter design, the **-3 dB frequency** is called the **cutoff frequency** (or half-power point). It's the boundary where the filter starts to significantly attenuate the signal.

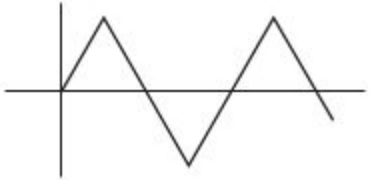
A **+3 dB gain** means the output power is **doubled** compared to the input power. In terms of amplitude, it's about **1.414 times** the input amplitude. In digital filters, this may indicate **resonance** or an **amplification band** (for example, in a band-pass filter with a peak).

A **low-pass filter** might pass low frequencies unchanged (≈ 0 dB), then at the cutoff frequency the response is down to -3 dB, and higher frequencies are attenuated further. A **band-pass filter** might have a peak gain of +3 dB at the center frequency, meaning it slightly boosts signals there, while attenuating others.

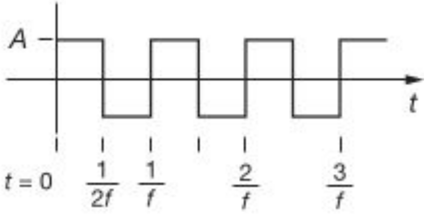
Other Signals



A: Voltage-ramp waveform. B: Ramp with limit. C: Sawtooth wave.

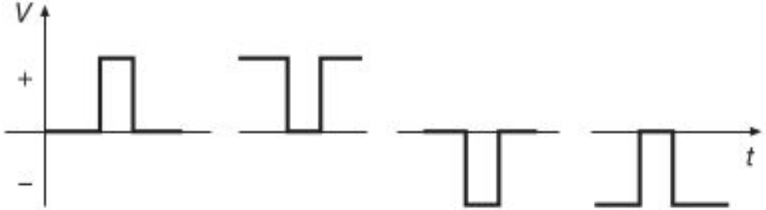


Triangle Wave



Square Wave

Noise



Positive and negative pulses of both polarities

Step and spike signals

Logic Levels

Logic levels are the specific voltage ranges in a digital circuit that represent the two binary states: **logic 0 (LOW)** and **logic 1 (HIGH)**.

Example: TTL (Transistor–Transistor Logic)

- **Logic 0 (LOW):** 0V to about 0.8V.
- **Logic 1 (HIGH):** 2.0V to 5.0 V5.0
- Between 0.8 V and 2.0 V is undefined — signals there are not guaranteed to be read correctly.

Why voltage ranges (not exact numbers)?

- Real circuits have noise, voltage drops, and variations in components.
- By allowing a margin (called **noise margin**), digital systems stay reliable.

Signal Sources

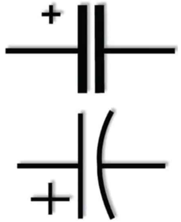
A **signal generator** is an electronic device that produces repeating or non-repeating waveforms. It is used to provide test signals for analyzing and troubleshooting circuits. **Common outputs:** Sine waves, square waves, or simple periodic signals. **Use cases:** Testing amplifiers, communication circuits, and measuring frequency response.

A **pulse generator** is a specialized signal source that produces **pulses**, short-duration signals with defined amplitude, duration, and repetition rate. It usually produces square or rectangular pulses. **Control parameters:** Pulse width, repetition frequency, rise/fall time, amplitude. **Use cases:** Clock signals for digital circuits, trigger signals in oscilloscopes, timing and synchronization applications.

A **function generator** is a versatile signal source capable of producing multiple standard waveforms. **Common outputs:** Sine wave, Square wave, Triangle wave, Sawtooth wave, Pulse trains **Features:** Adjustable frequency, amplitude, offset, and sometimes modulation (AM, FM, sweep). **Use cases:** Testing filters (sine and triangle inputs), Driving digital circuits (square waves), General-purpose testing in labs.

Capacitors & AC Circuits

Capacitors



A **capacitor** is a two-terminal passive electronic component that stores **electrical energy in an electric field**. They are made of **two conductive plates** separated by an **insulating material** (dielectric). When a voltage is applied across the plates, opposite charges accumulate on each plate, creating an electric field. **Capacitance (C)** (**Farads**, ***F***) is the ability to store charge per unit voltage.

$$C = \frac{Q}{V}$$

Where *C* is **Capacitance**, *Q* is stored **charge** (coulombs), and *V* is the **voltage** across the capacitor.

The energy stored is $E = \frac{1}{2}CV^2$

For **DC,** after the capacitor is charged it acts like an **open circuit** (blocks steady current). For **AC,** the capacitor allows **alternating current** to pass (impedance decreases with frequency). $X_C = \frac{1}{2\pi f C}$

Capacitors are used for energy storage (camera flashes, power supplies), filtering (smoothing ripples in DC power), coupling/decoupling signals in amplifiers, timing circuits (together with resistors, e.g., in oscillators).

Capacitor Types

Type	**Capacitance Range**	**Polarized?**	**Typical Use**
Ceramic	1pF ~ 1µF	No	RF, decoupling
Electrolytic	1µF ~ 10,000µF	Yes	Power supply filtering
Tantalum	0.1µF ~ 1000µf	Yes	Stable decoupling
Film	1nF ~ 1µF	No	Audio, precision filtering
Supercapacitor	1F >	Sometimes	Energy storage
Variable	pF ~ nF	No	Tuning circuits

Capacitors in Series vs. Parallel

When capacitors are connected in parallel or **side by side**, their **capacitances add up directly**, $C_{eq} = C_1 + C_2 + C_3 + \ldots$. The plate area effectively increases (like making one big capacitor). As a result, there is a higher total capacitance with the same voltage across each capacitor.

When capacitors are connected in series, the reciprocal capacitance add up $\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \ldots$

The distance between the plates effectively increases (reducing capacitance). Which means the total capacitance is smaller than the smallest capacitor in series.

RC Circuits - Voltage & Current vs. Time

An **RC circuit** is a resistor R and capacitor C connected in series (most common) or parallel. The key behavior comes from the **time constant** $\tau=RC$ where τ (tau) tells us how quickly the capacitor charges or discharges.

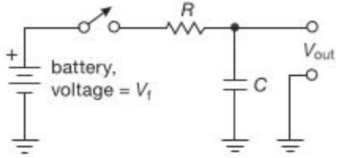
When a DC voltage source V_s is applied to an uncharged capacitor through a resistor the **Voltage across the capacitor** increases exponentially and the **Current through the capacitor** decreases exponentially.

$$V_c(t) = V_s\left(1 - e^{-\frac{t}{RC}}\right) \quad I(t) = \frac{V_s}{R}e^{-\frac{t}{RC}}$$

At $t=0$ the Capacitor behaves like a short circuit so max current flows. At $t\to\infty$ the Capacitor is fully charged so it acts like an open circuit and the current = 0.

If the capacitor is initially charged to V_o and then allowed to discharge through a resistor R then the **Voltage across the capacitor** decreases exponentially and the current also decreases exponentially

$$V_c(t) = V_o e^{-\frac{t}{RC}} \quad I(t) = \frac{V_o}{R}e^{-\frac{t}{RC}}$$



At $t=0$ the current is maximum. At $t\to\infty$ the capacitor is fully discharged and the voltage and current is 0.

The **time constant** $\tau=RC$ tells us how fast the response is. After **1τ**, the capacitor charges to ~63% of supply voltage (or discharges to ~37%). After **5τ**, charging/discharging is essentially complete (~99%). The **voltage is smooth (exponential curve)**, while **current starts high and decays**.

Example - Determining Current, Voltage, Power, and Energy for a Capacitor

The voltage pulse described by the following equations is impressed across the terminals of a 0.5 μF capacitor:

$$v(t) = \begin{cases} 0, & t \le 0 \text{ s}; \\ 4t \text{ V}, & 0 \text{ s} \le t \le 1 \text{ s}; \\ 4e^{-(t-1)} \text{ V}, & t \ge 1 \text{ s}. \end{cases}$$

a) Derive the expressions for the capacitor current, power, and energy.
b) Sketch the voltage, current, power, and energy as functions of time. Line up the plots vertically.
c) Specify the interval of time when energy is being stored in the capacitor.
d) Specify the interval of time when energy is being delivered by the capacitor.
e) Evaluate the integrals

$$\int_0^1 p\,dt \quad \text{and} \quad \int_1^\infty p\,dt$$

and comment on their significance.

Solution

a) From Eq. 6.13, $i = C\dfrac{dv}{dt}$,

$$i = \begin{cases} (0.5 \times 10^{-6})(0) = 0, & t < 0\text{s}; \\ (0.5 \times 10^{-6})(4) = 2\,\mu\text{A}, & 0\text{ s} < t < 1 \\ (0.5 \times 10^{-6})(-4e^{-(t-1)}) = -2e^{-(t-1)}\,\mu\text{A}, & t > 1 \text{ s}. \end{cases}$$

The expression for the power is derived from Eq. 6.16:

$$p = vi = Cv\frac{dv}{dt},$$

$$p = \begin{cases} 0, & t \le 0 \text{ s}; \\ (4t)(2) = 8t\,\mu\text{W}, & 0 \text{ s} \le t < 1 \text{ s}; \\ (4e^{-(t-1)})(-2e^{-(t-1)}) = -8e^{-2(t-1)}\,\mu\text{W}, & t > 1 \text{ s}. \end{cases}$$

The energy expression follows directly from Eq. 6.18:

$$w = \frac{1}{2}Cv^2.$$

$$w = \begin{cases} 0, & t \le 0 \text{ s}; \\ \frac{1}{2}(0.5)16t^2 = 4t^2\mu\text{J}, & 0 \text{ s} \le t \le 1 \text{ s}; \\ \frac{1}{2}(0.5)16e^{-2(t-1)} = 4e^{-2(t-1)}\,\mu\text{J}, & t \ge 1 \text{ s}. \end{cases}$$

b) Figure 6.11 shows the voltage, current, power, and energy as functions of time.

c) Energy is being stored in the capacitor whenever the power is positive. Hence energy is being stored in the interval 0−1 s.

d) Energy is being delivered by the capacitor whenever the power is negative. Thus energy is being delivered for all t greater than 1 s.

e) The integral of $p\,dt$ is the energy associated with the time interval corresponding to the limits on the integral. Thus the first integral represents the energy stored in the capacitor between 0 and 1 s, whereas the second integral represents the energy returned, or delivered, by the capacitor in the interval 1 s to ∞:

$$\int_0^1 p\,dt = \int_0^1 8t\,dt = 4t^2\Big|_0^1 = 4\,\mu\text{J},$$

$$\int_1^\infty p\,dt = \int_1^\infty (-8e^{-2(t-1)})dt = (-8)\frac{e^{-2(t-1)}}{-2}\Big|_1^\infty = -4\,\mu\text{J}.$$

The voltage applied to the capacitor returns to zero as time increases without limit, so the energy returned by this ideal capacitor must equal the energy stored.

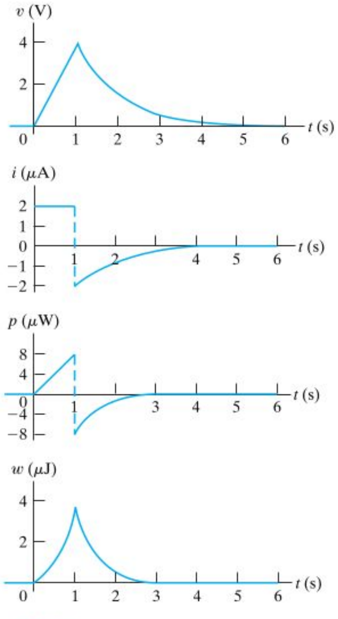
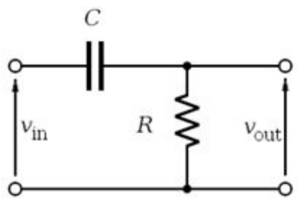


Figure 6.11 ▲ The variables v, i, p, and w versus t for Example 6.4.

RC Differentiator Circuits



An RC **Differentiator** is Built with a **capacitor in series** with the input signal and a **resistor to ground** (across which output is measured).

Capacitor current is proportional to the rate of change of input voltage: $i_c = C\frac{dV_{in}}{dt}$

That same current flows through the resistor: $V_{out} = I_C R = RC\frac{dV_{in}}{dt}$

For example, for a **DC input (constant voltage):** Derivative = 0 → output = 0.

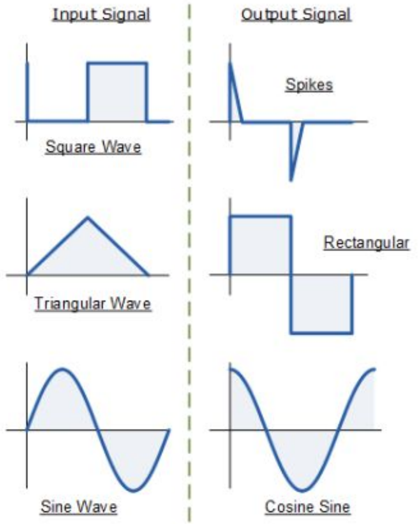
Square wave input, the output is a sharp pulse (spike), since derivative of a step is an impulse.

Triangle wave input, the output is a rectangular wave, since the derivative would show no rate of change

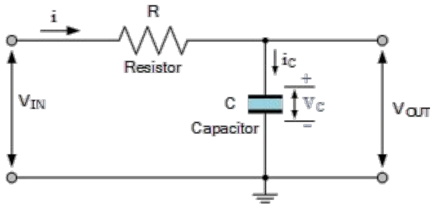
Sine wave input, if $V_{in}(t) = V_m sin(\omega t)$

then $V_{out} = \omega RCV_m cos(\omega t)$

which is a 90° phase shift.



RC Integrator Circuits



An RC **Integrator** circuit is Built with a **resistor in series** with the input signal and a **capacitor to ground** (across which output is measured).

From the capacitor voltage-current relation $i_C = C\frac{dV_C}{dt}$ but the current comes from the resistor $i_R = \frac{V_{in} - V_C}{R}$

Since $i_R = i_C$ $\frac{V_{in}}{R} \approx C\frac{dV_{out}}{dt}$ Rearranging ($V_{out} << V_{in}$) $V_{out}(t) \approx \frac{1}{RC}\int V_{in}(t)dt$

For a **Square wave input** the output is a **triangle wave** (since integration of a constant is a ramp).

For a **Sine wave input:** $V_{in}(t) = V_m sin(\omega t)$ then $V_{out}(t) = -\frac{V_m}{\omega RC}cos(\omega t)$ which is a sine wave shifted by -90°.

Step input: Output is a **ramp (linear increase/decrease)**.

DC input (constant): Output = linear ramp until capacitor saturates.

RC Integrators only work well when the input signal's period is **much smaller than RC.** For precision, active RC integrators using op-amps are used (to minimize errors and capacitor leakage).

In summary, RC integrator uses the **resistor first and then the capacitor**. The output is the **integral of the input**, scaled by *1/RC*. The RC integrator converts square waves → triangle waves, sine waves → phase-shifted sine waves, steps → ramps.

Inductors & Transformers

Inductors

An **inductor** is a **passive electrical component** that stores energy in the form of a **magnetic field** when current flows through it. It usually consists of a coil of wire wound around a core (air, iron, or ferrite). **Inductance (*L*)** is the ability of an inductor to oppose changes in current and is measured in **Henrys (*H*)**

Voltage-Current Relationship: $V_L = L\frac{dI}{dt}$ **Energy Storage:** $E = \frac{1}{2}LI^2$

Voltage across an inductor is proportional to the **rate of change of current**. Current through an ideal inductor **cannot change instantly** (unlike capacitors where voltage cannot change instantly). Energy stored in the magnetic field depends on current.

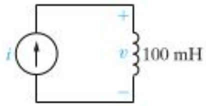
In **DC steady state** → behave like a short circuit (just a wire). In **AC circuits** → oppose current flow with inductive reactance: $X_L = 2\pi f L$

Applications

- Chokes (filtering AC, passing DC)
- Transformers (when paired with another coil)
- Energy storage in power supplies
- Radio tuning circuits (LC circuits)
- Inductive sensors and motors

Example - Determining the Voltage, Given the Current, at the Terminals of an Inductor

The independent current source in the circuit shown in Fig. 6.2 generates zero current for $t < 0$ and a pulse $10te^{-5t}$A, for $t > 0$.



$$i = 0, \qquad t < 0$$

$$i = 10te^{-5t}\text{A}, \qquad t > 0$$

Figure 6.2 ▲ The circuit for Example 6.1.

a) Sketch the current waveform.

b) At what instant of time is the current maximum?

c) Express the voltage across the terminals of the 100 mH inductor as a function of time.

d) Sketch the voltage waveform.

e) Are the voltage and the current at a maximum at the same time?

f) At what instant of time does the voltage change polarity?

g) Is there ever an instantaneous change in voltage across the inductor? If so, at what time?

Solution

a) Figure 6.3 shows the current waveform.

b) $di/dt = 10(-5te^{-5t} + e^{-5t}) = 10e^{-5t}(1 - 5t)$ A/s; $di/dt = 0$ when $t = \frac{1}{5}$ s. (See Fig. 6.3.)

c) $v = L\,di/dt = (0.1)10e^{-5t}(1 - 5t) = e^{-5t}(1-5t)$ V, $t > 0$; $v = 0$, $t < 0$.

d) Figure 6.4 shows the voltage waveform.

e) No; the voltage is proportional to di/dt, not i.

f) At 0.2 s, which corresponds to the moment when di/dt is passing through zero and changing sign.

g) Yes, at $t = 0$. Note that the voltage can change instantaneously across the terminals of an inductor.

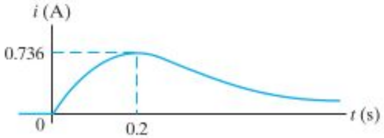


Figure 6.3 ▲ The current waveform for Example 6.1.

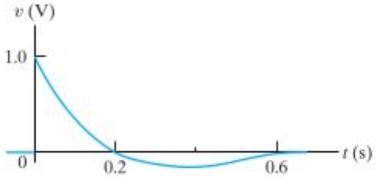


Figure 6.4 ▲ The voltage waveform for Example 6.1.

Transformers

A **transformer** is an electrical device that uses the principle of **electromagnetic induction** to transfer electrical energy between two or more circuits, usually with different voltage and current levels, but the same frequency. It consists of **two (or more) coils of wire**, called the **primary winding** and **secondary winding**, wound around a **magnetic core**.

An **AC voltage** applied to the **primary coil** produces a **changing magnetic flux** in the core. This flux induces a voltage in the **secondary coil** (Faraday's Law of Induction). The ratio of voltages depends on the **turns ratio** of the windings. The power is also conserved.

$$\frac{V_s}{V_p} = \frac{N_s}{N_p} \quad \frac{I_s}{I_p} = \frac{N_s}{N_p}$$

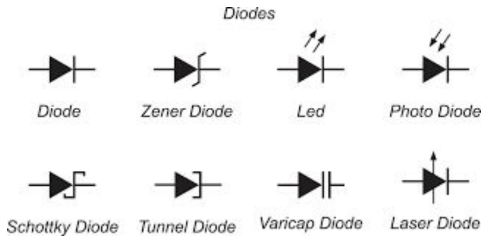
Where V_s & V_p are the secondary and primary voltages and N_s & N_p.

There are 3 types of transformers a **step-up Transformer:** $N_s > N_p$ (increases voltage and decreases current), a **Step-down Transformer:** $N_s < N_p$ (decreases voltage and increases current), and an **Isolation Transformer:** $N_s = N_p$ (same voltage, used for electrical isolation).

Transformers, are used in Power transmission (stepping voltage up for long-distance transmission, then stepping down for safe use), Power supplies (converting AC mains to usable voltages), Impedance matching in communication systems, and Isolation for safety in sensitive circuits.

Diodes & Diode Circuits

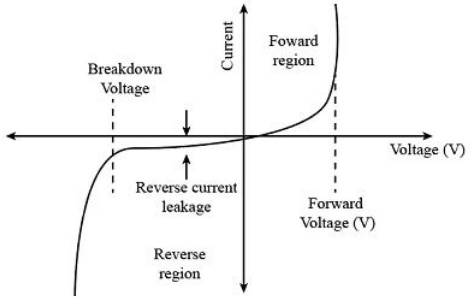
Diodes



A **diode** is a **two-terminal semiconductor device** that allows current to flow **in only one direction** (forward) and blocks it in the opposite direction (reverse), under normal operation. It's the simplest semiconductor device, made by joining **p-type** and **n-type** materials → forming a **p–n junction**. Diodes have a **Anode (A)** (Positive side (p-type)) and a **Cathode (K)** (Negative side (n-type)). They look like a triangle (points in current flow direction) against a vertical bar (blocking reverse flow).

Diodes have 3 operation modes. In **forward bias** the Anode is connected to positive and the cathode to negative. The diode conducts after a **threshold voltage** is reached which is ~0.7 V for **silicon** and ~0.3 V for **germanium.** The diode acts like a **closed switch** above threshold. In **reverse bias** the Anode is connected to negative and the cathode is connected to positive. The diode ideally blocks current (acts like an **open switch**). Only a tiny **leakage current** flows. The diode goes into the **breakdown region** if reverse voltage exceeds the breakdown rating, diode conducts heavily. This normally damages the diode (unless it's a **Zener diode**, which is designed for this).

Diodes are normally used as **Rectifiers** (Converting AC to DC (half-wave & full-wave)), in **Clamping & Clipping** (Shaping voltage waveforms), **Voltage Regulation** (With Zener diodes), **Switching (**In digital and power circuits), and **Protection** (Against reverse polarity or voltage spikes (flyback diodes)).

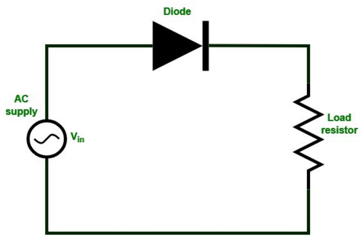


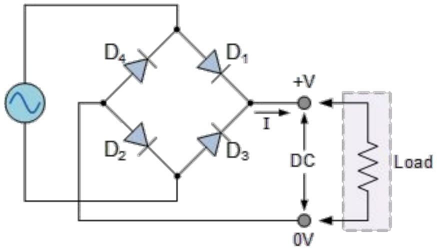
Rectification

Rectification is the process of converting an **alternating current (AC)** signal into a **direct current (DC)** signal. This is achieved using **diodes**, since they allow current to flow only in one direction. Most electrical power is supplied as **AC**, but many devices (radios, computers, chargers, etc.) require **DC**. Rectifiers are used inside **power supplies** to perform this conversion.

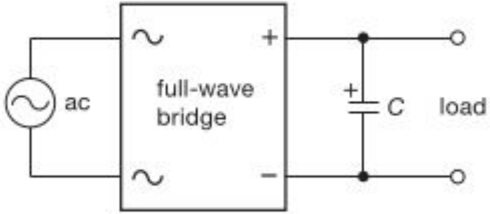
There are 3 types of rectifiers. A **Half-Wave Rectifier** uses **one diode**, passes only the **positive half-cycles** (or negative, depending on orientation) of AC, outputs a pulsating DC with large gaps. It is simple but inefficient. A **Full-Wave Rectifier (Center-Tap)** uses **two diodes** and a center-tapped transformer, and both halves of AC are rectified, producing pulsating DC. It has better efficiency than half-wave. A **Full-Wave Bridge Rectifier** uses **four diodes** in a bridge arrangement, no center-tap is required, and both halves of the AC are rectified → continuous pulsating DC. They are most common in power supplies. To smooth the output we add a capacitor.

For a half-wave rectifier the average DC voltage $V_{DC} = \dfrac{V_m}{\pi}$ and for a full-wave rectifier the average DC voltage is $V_{DC} = \dfrac{2V_m}{\pi}$





Power Supply Filtering



Filtering is the process of reducing the **ripple** (fluctuations) in a rectified DC signal to produce a **smoother, more stable DC output**. After **rectification**, the output is *pulsating DC* (not steady). Filtering circuits (typically using **capacitors, inductors, or both**) smooth this into usable DC.

A **Capacitor Filter ("Reservoir Capacitor")** is when a large **electrolytic capacitor** is connected across the rectifier output. The capacitor **charges** during voltage peaks and **discharges** when voltage drops. This "fills in the gaps" between pulses thereby reducing the ripple. This filter works best for light to moderate loads.

An **Inductor Filter (Choke Input Filter)** is when an **inductor** is placed in series with the rectifier output. Inductors resist changes in current so they smooth the pulsating DC by averaging current flow. This filter works well for **heavy loads** but, inductors can be bulky.

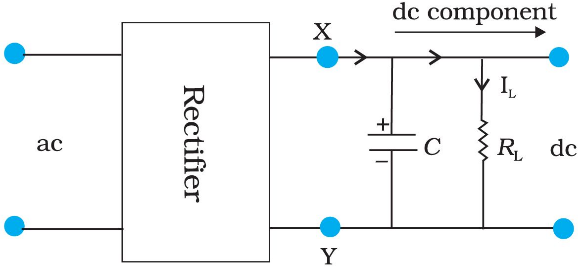
A **LC (Inductor-Capacitor) Filter** is the combination of a **series inductor** and **shunt capacitor**. An inductor smooths current and the capacitor smooths voltage. This filter has much better ripple reduction than either one alone.

A **π (Pi) Filter** looks like the Greek letter π with a **capacitor, inductor,** and **capacitor**. The first capacitor reduces high-frequency ripple. The inductor smooths current. The second capacitor removes residual ripple. It is very effective filter and is widely used in regulated power supplies.

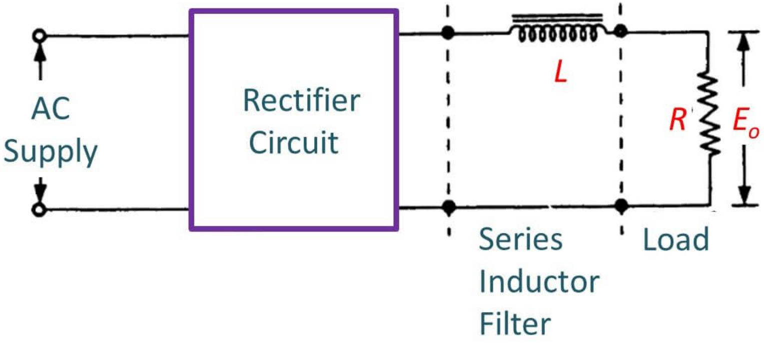
The goal is to reduce **ripple voltage (V_r)**, defined as the variation of DC voltage after filtering. For a **capacitor filter** on a **full-wave rectifier**:

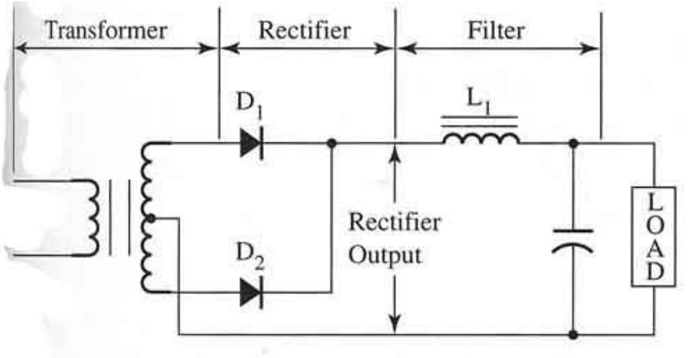
$$V_r = \frac{I_{load}}{2fC}$$

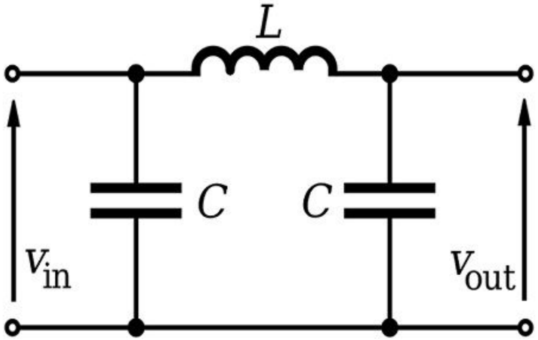
Power Supply Filters



(a)







Voltage Regulator

A **voltage regulator** is an electronic circuit or device that maintains a **constant DC output voltage**, even if the **input voltage** varies, and/or the **load current** changes. This ensures electronic devices receive a **stable supply voltage**. Since the rectifier and filter output of a voltage source is still not perfectly steady regulators are used to maintain a steady voltage like 5V or 3.3V.

Linear Regulators are simple and low-noise. They work like an **automatic variable resistor** that drops extra voltage. Examples include the **78xx series** of chips (e.g., 7805 → fixed 5V). They are considered to be cheap, low noise, and easy to use (just 2 capacitors needed). However, they are inefficient at high currents (dissipates excess power as **heat**).

A **Zener Diode Regulator** is when a **Zener diode** in reverse breakdown clamps voltage to a set level. Used for **simple, low-current regulation**.

Switching Regulators (SMPS) use high-frequency **transistors and inductors/capacitors** to efficiently step voltage **up, down, or invert** it. They include **Buck (step-down), Boost (step-up),** and **Buck-Boost (inverts or regulates up/down)** regulators. They are very efficient (80–95%) and can output higher or lower voltage than input. However, they are more complex and produce noise (need filtering).

Inductive Load Protection

An **inductive load** is any device that contains a coil of wire and therefore stores energy in a **magnetic field** when current flows. **Examples** include Relays, Motors, Solenoids, and Transformers.

The problem with inductive loads is inductors resist sudden changes in current. When you **turn off** current to an inductor, the magnetic field collapses. This collapsing field induces a **large voltage spike**. The spike can be **much higher than the supply voltage** and can **damage transistors, switches, or ICs** controlling the load. This is often called **back EMF (electromotive force)**.

To protect circuits from this high-voltage spike, we use a **diode (flyback diode) across the inductive load**. The diode is placed in **reverse bias** relative to the supply voltage. During normal operation, the diode does nothing (no current flows through it). When the current is suddenly interrupted, the inductor’s collapsing field drives current in the opposite direction. The diode provides a **safe path** for this current, allowing it to circulate until the energy is dissipated. This clamps the voltage spike to about **0.7 V (for a silicon diode)**, protecting the switch or transistor.

Other Protection Methods include **Snubber circuits** (RC networks) for AC inductive loads, **TVS (Transient Voltage Suppression) diodes** for fast clamping, and **MOVs (Metal-Oxide Varistors)** for surge protection.

Impedance & Reactance

Impedance & Reactance Overview

In **AC circuits**, capacitors and inductors oppose current flow, but in a **frequency-dependent** way. This opposition (without energy loss, just phase shift) is called **reactance** (*X*).

Inductive reactance (X_L) is $X_L = 2\pi fL$ It increases with frequency. Inductors resist high-frequency AC more strongly.

Capacitive reactance (X_C) is $X_C = \dfrac{1}{2\pi f C}$ It decreases with frequency. Capacitors resist low-frequency AC more strongly.

Impedance (*Z*) is the **total opposition** to AC, combining: **Resistance (*R*)** (real part (dissipates energy as heat)) and **Reactance (X)** (imaginary part (stores energy in fields)). $Z = R + jX$ where $j = \sqrt{-1}$ If $X = X_L - X_C > 0$ then the circuit is **inductive** (current lags voltage). If $X < 0$ then the circuit is **capacitive** (current leads voltage). The **magnitude of impedance** is $|Z| = \sqrt{R^2 + X^2}$

Frequency Analysis of Reactive Circuits

Reactive components (**capacitors** and **inductors**) don’t behave like fixed resistors. Their **opposition to current (reactance)** depends on frequency. An inductor **blocks high** frequencies and **passes low** frequencies. A capacitor **blocks low** frequencies and **passes high** frequencies.

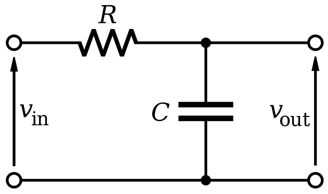
A **Low-Pass RC Filter** is when a capacitor shunts high-frequency signals to ground. Low frequencies pass through and high frequencies are attenuated. The cutoff frequency for a RC filter is $f_c = \frac{1}{2\pi RC}$

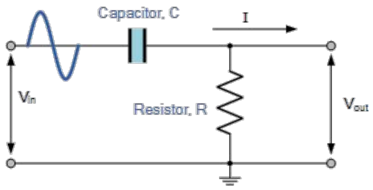
A **High-Pass RC Filter** is when a capacitor and resistor are in series. High frequencies pass through and low frequencies are attenuated. The cutoff frequency is the same as above.

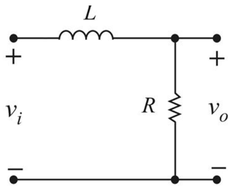
A **Low-Pass RL Filter** is when a inductor and resistor are in series. The cutoff frequency for a RL filter is $f_c = \frac{R}{2\pi L}$

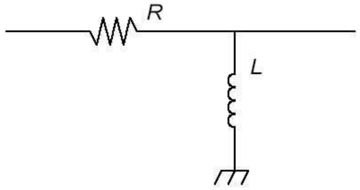
A **High-Pass RL Filter** is when a resistor and inductor are in series.

When resistors, capacitors, and inductors combine in RLC Circuits (Resonant circuits) at resonance, $X_L = X_C$ the impedance is purely resistive. For a **series resonance** there is minimum impedance which means there is maximum current. For a **parallel resonance** there is maximum impedance which means the circuit will block the resonant frequency. The resonant frequency for RLC circuits is $f_c = \frac{1}{2\pi\sqrt{LC}}$









Voltages & Currents as Complex Numbers

In **AC Circuits**, voltages and currents are sinusoids: $v(t) = V_m sin(\omega t + \phi_v)$ $i(t) = I_m sin(\omega t + \phi_i)$

Where V_m, I_m are magnitudes, ω is the angular frequency, and $\varphi_v \varphi_i$ are phase angles.

Handling sine waves with phase shifts gets messy in the time domain so we use **phasors**. A sinusoid can be written as a **rotating complex vector**

$$\widetilde{V} = V_m e^{j\phi_v} \qquad \widetilde{I} = I_m e^{j\phi_i} \qquad j = \sqrt{-1}$$

For example,

$$v(t) = 10sin(\omega t + 30^\circ) \rightarrow \widetilde{V} 10\angle 30^\circ$$

For Ohm's law we write $\tilde{V} = \tilde{I}Z$

For a **resistor** the voltage and current are in **phase** ($Z = R$). For an **inductor** the voltage **leads** the current by 90° ($Z = jX_L$). For a **capacitor** the voltage **lags** the current 90° ($Z = -jX_C$).

For example if $V = 10\angle 0°$ and the load is $Z = 4 + j3$□ then the current is $\tilde{I} = \frac{\tilde{V}}{Z} = \frac{10\angle 0^\circ}{5\angle 36.87^\circ} = 2\angle - 36.87^\circ$

Power in Reactive Circuits

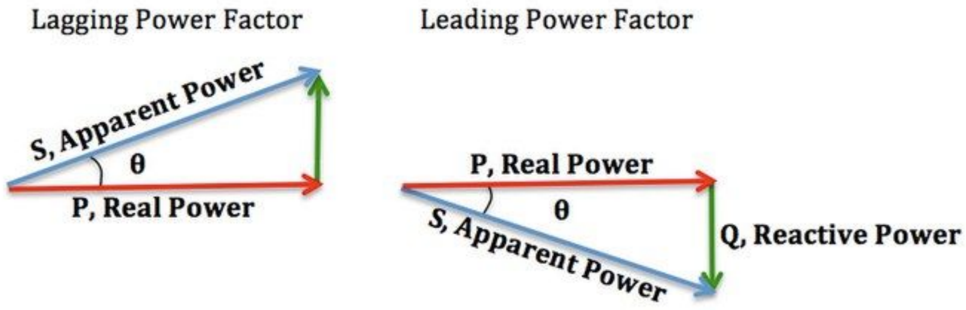
For **instantaneous** power in AC circuits $p(t) = v(t)i(t)$ If the voltage and current are not in phase, the power oscillates between positive (delivered to load) and negative (returned to source).

The **average (real)** power, ***P*** is the true power dissipated as heat, light, or mechanical work $P = V_{rms}I_{rms}cos\varphi$ where φ is the phase difference between voltage and current.

The **reactive** power, ***Q*** is the power alternatively stored and released by inductors and capacitors $Q = V_{rms}I_{rms}sin\varphi$ where a **positive *Q*** is inductor-dominated (lagging power factor) and a **negative *Q*** is capacitor-dominated (leading power factor).

The **apparent** power, ***S*** is the total power flow in the circuit (combination of real and reactive) $S = V_{rms}I_{rms}$. The units are **VA (Volt-amps)**. It is expressed as a complex number $S = P + jQ$

The power factor is $pf = cos\phi = \dfrac{P}{S}$



Other Passive Components

Switches

There are **manual** switches (toggle, pushbutton, and rotary) and **automatic** switches (relays, thermostats, and circuit breakers).

SPST (Single Pole, Single Throw) is the simplest on/off switch and controls one circuit. **DPST (Double Pole, Single Throw)** is when two inputs controlled together, each with one path. **DPDT (Double Pole, Double Throw)** is when two inputs, each can connect to two outputs. DPDT switches are used in motor reversing, complex control.

Switches **based on Actuation** include the **Toggle Switch** – lever flipped up/down, **Push-Button Switch** – pressed to make/break (momentary or latching), **Rotary Switch** – knob rotated to select one of many connections, **Rocker Switch** – see-saw style (like many power strips), **Slide Switch** – sliding contact back and forth, and the **Joystick Switch** – multidirectional control (used in cranes, video games).

Special Types of switches include the **Relay** – electrically controlled switch (coil + contacts), **Contactor** – heavy-duty relay for motors/industrial loads, **Limit Switch** – actuated by mechanical movement (used in machinery safety), **Reed Switch** – magnetic field operated, **Mercury Switch** – tilt-based, uses liquid mercury to make contact, **DIP Switches** – small SPST switches in arrays for circuit configuration, **Membrane Switches** – flat, flexible switches in keypads, and **Touch Switches** – activated by human touch (capacitive sensors).

Automatic Protection Switches include **Circuit Breakers** – open when current exceeds safe limit, **Thermal Switches** – trip on overheating, and **Pressure Switches** – used in pumps/compressors.

Connectors

Power Connectors are designed to safely carry electrical power. They include **Barrel Connectors (DC Jacks/Plugs)** – common in wall adapters for electronics, **Molex Connectors** – used in computers (HDD, fans, power distribution), **Anderson Powerpole** – modular DC connectors for high current, and **Banana Plugs/Jacks** – used in lab equipment and power supplies.

Signal/Data Connectors carry communication signals (digital or analog). They include **USB (A, B, C, Micro, Mini)** – universal standard for data + power, **HDMI** – video + audio for displays, **Ethernet (RJ45)** – networking, **Audio Jacks (3.5 mm, 1/4 inch, RCA)** – headphones, speakers, AV, **DisplayPort / DVI / VGA** – monitor connectors, and **Lightning (Apple)** – proprietary mobile connector.

RF (Radio Frequency) Connectors are specialized for high-frequency signals (antennas, radios, Wi-Fi). They include **BNC** – lab equipment, oscilloscopes, RF test gear, **SMA** – antennas, cellular/Wi-Fi modules, **N-type** – outdoor RF applications (durable, weatherproof), and **F-type** – cable TV connectors.

Board-to-Board & Wire-to-Board Connectors are used inside devices to connect circuit boards and wires. They include **Pin Headers (male/female)** – common in Arduino, Raspberry Pi, **Berg/IDC Ribbon Cable Connectors** – used in old PCs, printers, **JST Connectors** – compact power/signal connectors (batteries, drones), **Card Edge Connectors** – PCIe, RAM slots, and **Zero Insertion Force (ZIF) Connectors** – for flat flex cables in laptops/phones.

Specialized Connectors include **DIN / Mini-DIN** – MIDI, old keyboard/mouse connectors, **D-sub (DB9, DB25, etc.)** – serial ports, VGA, **Magnetic Connectors** – like MacBook MagSafe,**Waterproof/Sealed Connectors** – for outdoor/automotive use, and **Coaxial Power Connectors** – for CCTV cameras.

Industrial & High-Power Connectors include **XLR** – professional audio/microphones, **Speakon** – speakers and amplifiers (locking, high current), **Camlock** – industrial power distribution, **Terminal Blocks** – screw-based, used in control panels, and **Heavy-Duty Circular Connectors** – used in aviation, military, robotics.

Indicators

Visual Indicators use light or display symbols to show circuit status. **Lamps & Bulbs** include **Incandescent Lamps** – early indicators, glow when current passes and **Neon Lamps** – used as small “power on” lights in mains-powered devices. **LEDs (Light Emitting Diodes)** are the most common electronic indicators today. They are small, efficient, durable, and available in many colors (red, green, blue, yellow, white, RGB). **LED Displays** include **7-Segment Displays** – show numbers (digital clocks, meters, calculators), **14/16-Segment Displays** – show letters + numbers, and **Dot-Matrix Displays** – scrolling text or graphics. **LCD (Liquid Crystal Display) Indicators** are Low-power and used in calculators, watches, and multimeters. They can be alphanumeric or symbolic. **OLED Indicators** are brighter than LCDs and can show text/graphics. They are used in wearables, small control panels. **Bar Graph Indicators** are a series of LEDs arranged in a line. They show levels (e.g., audio volume meters, battery level).

Audible Indicators give sound feedback instead of (or in addition to) light. **Buzzers** (electromechanical or piezo) are used for alarms, notifications, and timers. They are found in appliances, timers, warning systems. **Speakers/Tone Generators** provide more complex sounds or beeps in equipment.

Electromechanical Indicators physically move parts to indicate status. **Analog Meters (Galvanometers)** is when a Needle moves to show voltage, current, etc. **Flip-dot Displays** are used in old buses/trains: small magnetic dots flip color.

Specialized Indicators include **status LEDs in Connectors** (Ethernet ports have “link/activity” LEDs), **Pilot Lights** (industrial control panels), and **Smart Indicators** (with microcontrollers, multicolor status).

Variable Components

Variable Resistors are resistors whose resistance can be adjusted. **Potentiometers (Pots)** are 3-terminal devices: acts as adjustable voltage divider. They are used in volume knobs, dimmers, tuners. **Rheostats** 2-terminal variable resistors (higher current than pots). They are used in motor control, heater regulation. **Digital Potentiometers (Digipots)** are potentiometers where resistance can be adjusted electronically (via I^2C/SPI). They are used in modern microcontroller systems. For **Photoresistors (LDR – Light Dependent Resistors)** the resistance changes with light intensity. They are used in light sensors, street lamps. For **Thermistors (NTC/PTC)** the resistance changes with temperature. They are used in temperature sensors, inrush current limiters.

Variable Capacitors are capacitors whereby the Capacitance can be tuned. **Air-Dielectric Variable Capacitors** are when mechanical plates move to vary capacitance. They are used in old radios (tuning). **Trimmer Capacitors** are small adjustable capacitors (set with screwdriver). They are used for calibration in RF circuits. **Varactor (Varicap) Diodes** are Semiconductor diodes that act as voltage-controlled capacitors. They are used in modern RF tuning circuits.

Variable Inductors are inductors where inductance is adjusted (though less common than resistors/capacitors). **Adjustable Core Inductors** have a Ferrite/iron core that can be moved in/out of the coil. They are used in RF circuits, oscillators. For **Saturable Reactors** the inductance is controlled by DC bias current. They are used in specialized power electronics.

Other Variable Components include **Varistors (VDRs)** - resistance changes with applied voltage, **MEMS Variable Devices** - Micro-electromechanical switches and capacitors, and **FETs/MOSFETs as Variable Resistors** - Operate in linear mode so they act as voltage-controlled resistors.