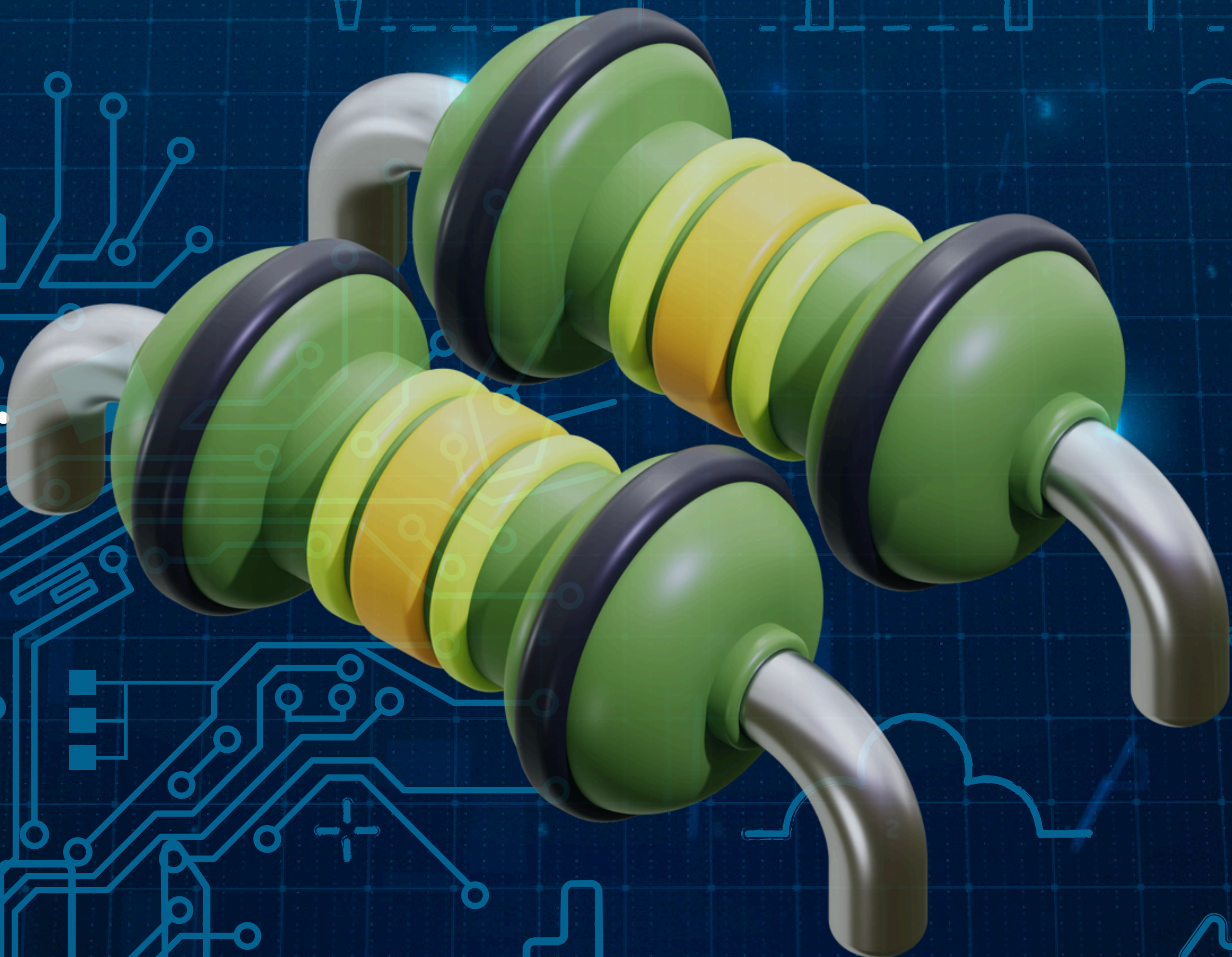
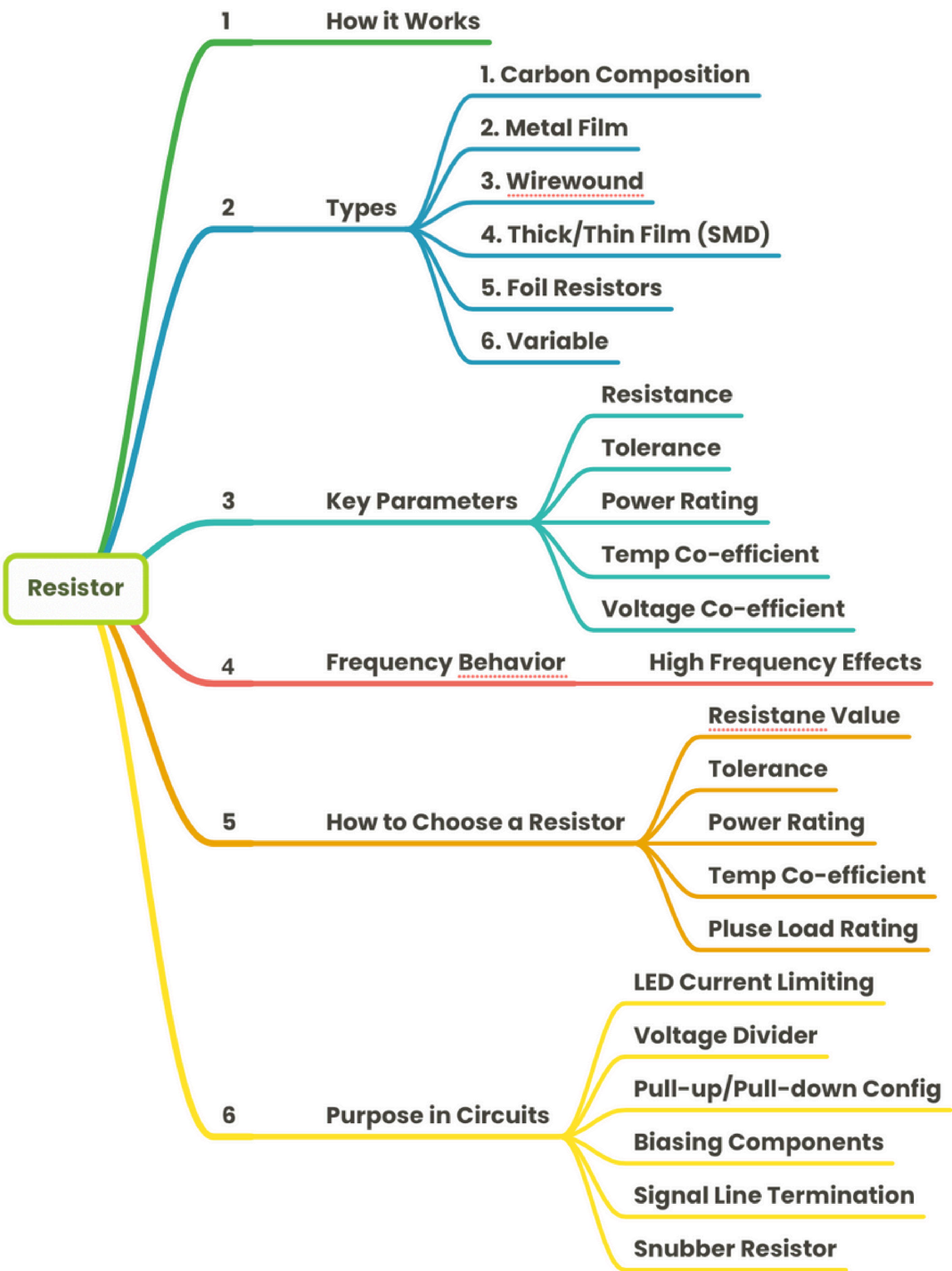
RESISTOR



By Bargunan Ponnusamy

INSIDE



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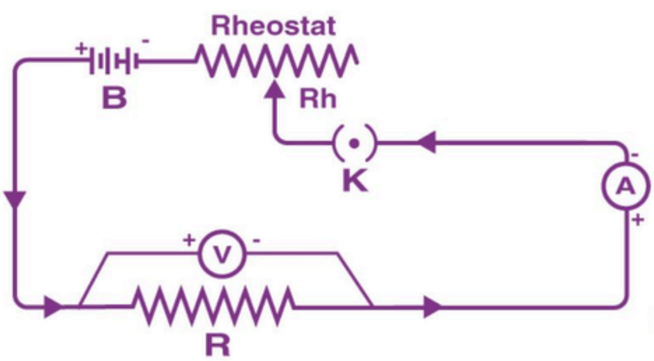
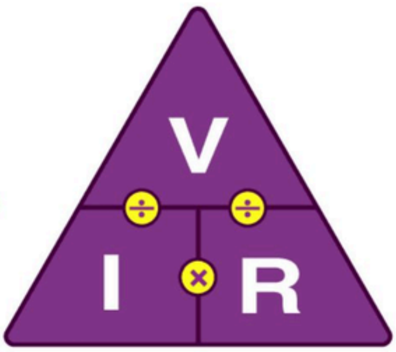
RESISTOR

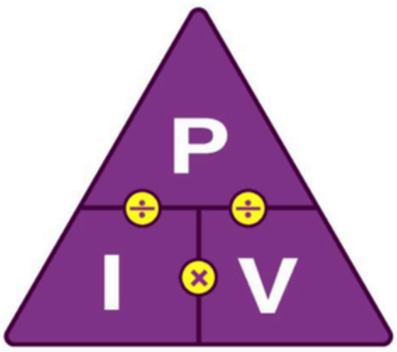
A resistor is a basic yet vital electronic component that limits or controls the flow of electric current in a circuit. It’s a passive device that plays a key role in managing voltage, current, and signal conditions across various electrical and electronic systems.

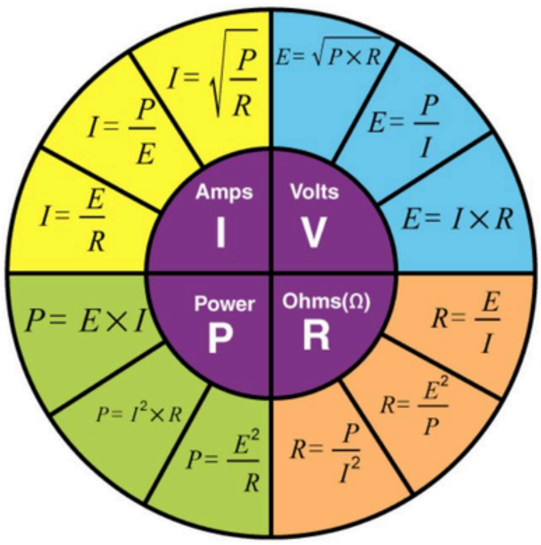
How it Works?

A **resistor** is a passive component used to oppose or limit current flow in an electrical circuit. The core principle is **Ohm's Law**









Known values	Resistance (R)	Current (I)	Voltage (V)	Power (P)
Current & Resistance	....	....	$V = I \times R$	$P = I^2 \times R$
Voltage & Current	$R = \frac{V}{I}$	....	....	$P = V \times I$
Power & Current	$R = \frac{P}{I^2}$	....	$V = \frac{P}{I}$	....
Voltage & Resistance	....	$I = \frac{V}{R}$	....	$P = \frac{V^2}{R}$
Power & Resistance	....	$I = \sqrt{\frac{P}{R}}$	$V = \sqrt{P \times R}$	....
Voltage & Power	$R = \frac{V^2}{P}$	$I = \frac{P}{V}$	....	....

Where:

- V = Voltage across the resistor (Volts)
- I = Current through the resistor (Amps)
- R = Resistance (Ohms, Ω)

Resistors dissipate electrical energy as heat and are used for voltage division, biasing, signal conditioning, and protection.

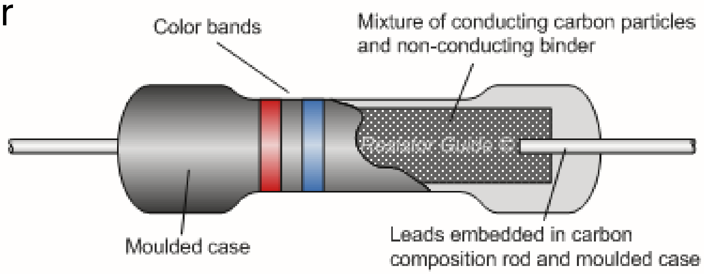
TYPES OF RESISTORS

1. Carbon Composition

Structure: Mixture of carbon + binder

Pros: Low cost, good for pulses

Cons: Poor tolerance, high noise



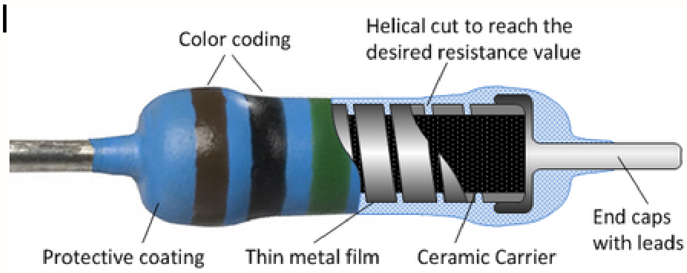
Applications: General purpose, surge protection

2. Metal Film

Structure: Vacuum-deposited metal

Pros: High accuracy, low noise

Cons: Costlier than carbon



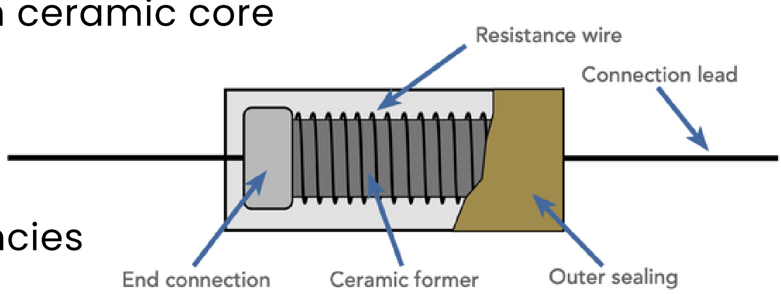
Applications: Precision analog circuits

3. Wirewound

Structure: Metal wire wound on ceramic core

Pros: High power, stable

Cons: Inductive at high frequencies



Applications: Power supplies, motor drives

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TYPES OF RESISTORS

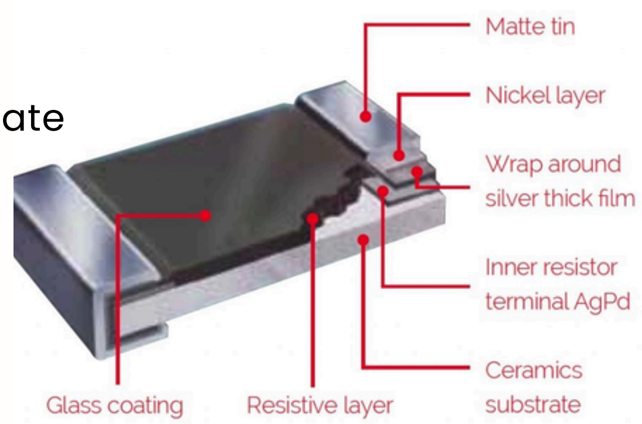
4. Thick/Thin Film (SMD)

Structure: Printed on ceramic substrate

Pros: Compact, cost-effective

Cons: Limited power rating

Applications: Consumer electronics, dense PCBs



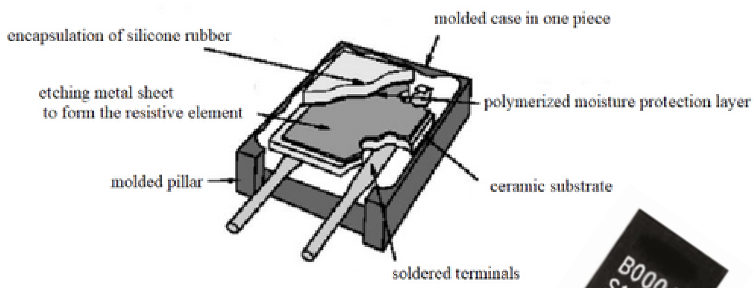
5. Foil Resistors

Structure: Etched metal foil

Pros: Extremely precise, low drift

Cons: Expensive

Applications: Instrumentation, medical devices



6. Variable (Potentiometer)

Structure: Movable contact on resistive track

Pros: Adjustable resistance

Cons: Mechanical wear

Applications: User-adjustable settings

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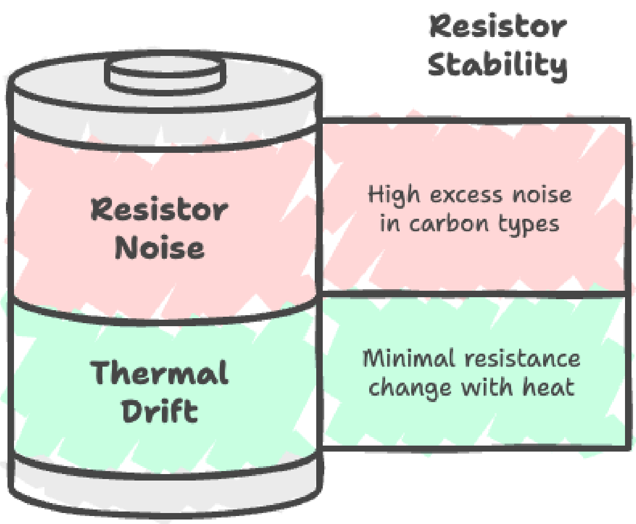
KEY PARAMETERS

Primary Parameters	Description
Resistance (Ω)	Value printed or color-coded
Tolerance (%)	Deviation from nominal value
Power Rating (W)	Max power without overheating
Temperature Coefficient (TCR)	Resistance change per °C
Voltage Coefficient	Resistance varies with voltage

Important Derived Values



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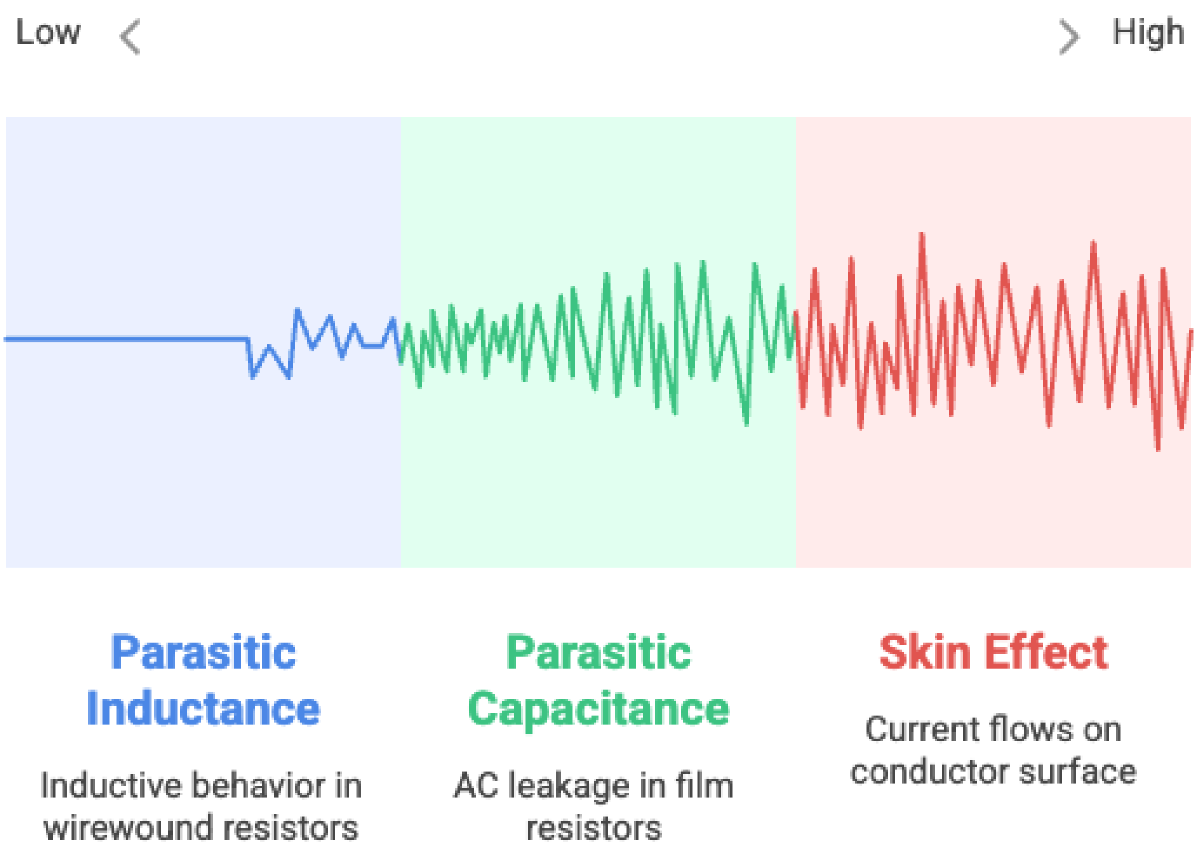
FREQUENCY BEHAVIOR

High Frequency Effects

Resistors behave ideally only at low frequencies. At high frequencies:

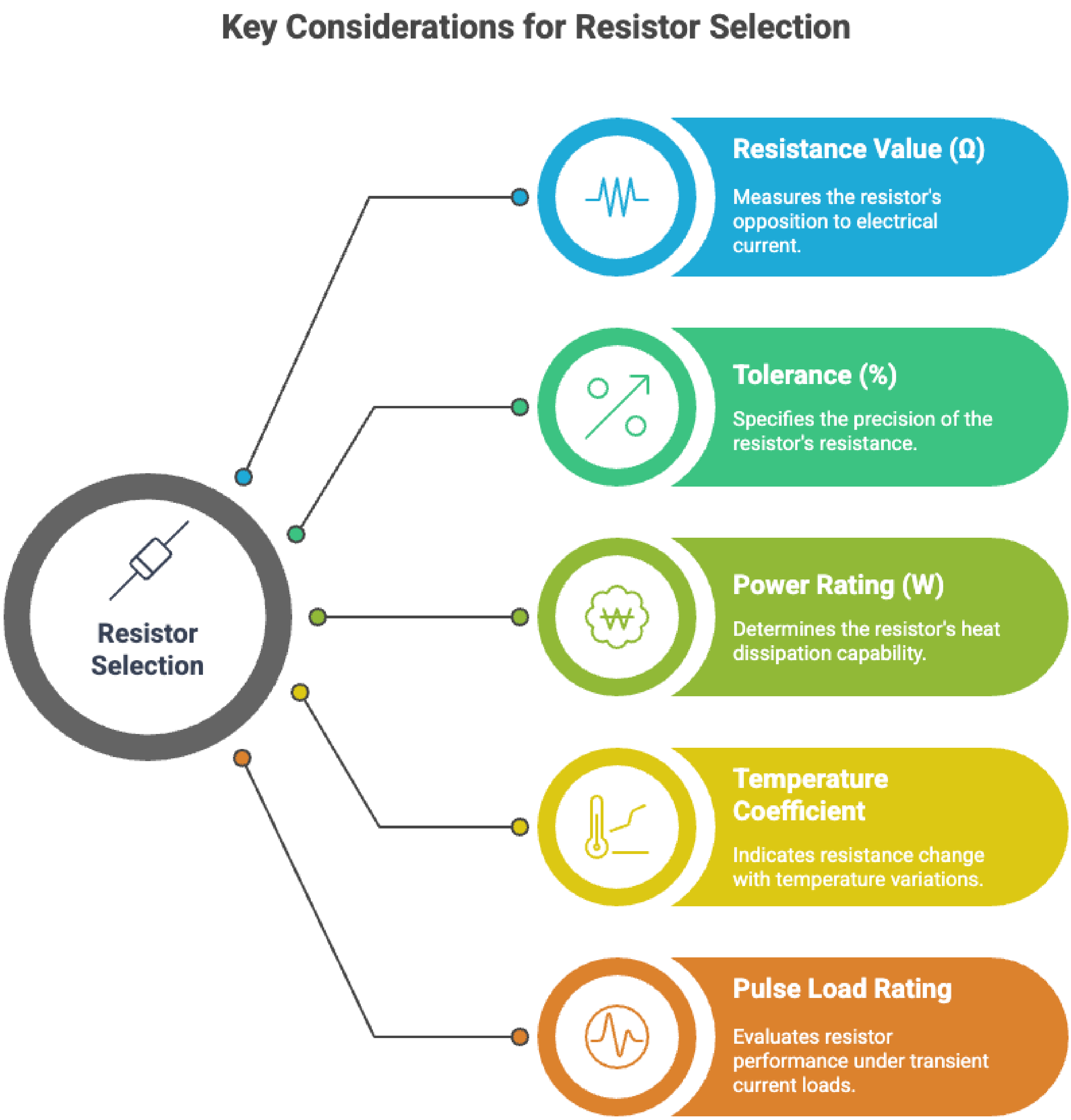


Rule of Thumb:

Use non-inductive resistors or surface mount resistors for RF and GHz applications.

HOW TO CHOOSE A RESISTOR

When selecting a resistor, consider the following:



Derating Rule:

Reduce power rating by 50% for every 25°C above 70°C ambient.

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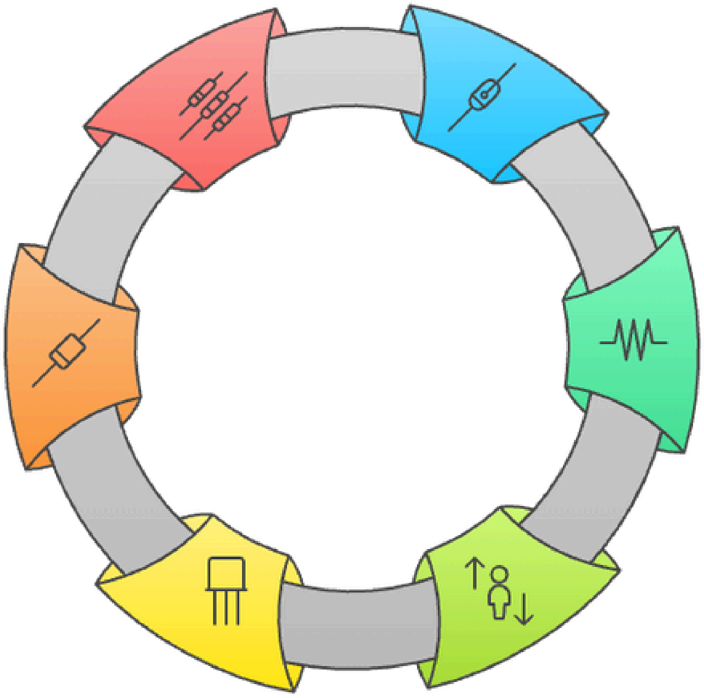
PURPOSE / APPLICATION IN CIRCUITS

Essential Circuit Applications



Function	Description	Real-Time Example
Voltage Divider	Used to scale down voltages to desired levels.	**Battery voltage monitor**: Divides 12V battery voltage to ~3.3V for ADC input on a microcontroller.
Pull-up / Pull-down	Ensures a logic input defaults to a known state (HIGH or LOW) when floating.	**I2C bus line**: 4.7kΩ pull-up resistors used on SDA and SCL lines to ensure proper logic levels.
Current Limiting	Protects LEDs and ICs by restricting the current flowing through them.	**LED indicator**: 330Ω resistor used to limit current from a 5V source to an LED (5V → LED + R).
Feedback Network	Sets gain in amplifiers or determines filter behavior.	**Op-amp amplifier**: 10kΩ and 1kΩ resistors in feedback loop for a gain of 11 in an audio preamp.
Load Termination	Prevents signal reflections on high-speed transmission lines.	**Ethernet PHY**: 49.9Ω resistors used to match 50Ω impedance of differential data lines.
Snubber Circuits	Protects switches or relays from voltage spikes caused by inductive loads.	**Relay driver circuit**: 100Ω resistor with 100nF capacitor across relay coil to suppress transients.

CURRENT LIMITING RESISTOR

A Current Limiting Resistor is used in circuits to restrict the current flowing to a specific component, protecting it from excessive current that could cause damage or failure.

Purpose:

- Protect LEDs, ICs, transistors, and sensors from overcurrent
- Control current flow to safe levels
- Stabilize circuit operation in resistive and reactive loads

Key Formula:

For a current-limiting resistor in series with a load:

$$R = \frac{V_{supply} - V_{load}}{V_{desired}}$$

Where:

- R = Required resistor value (Ω)
- V_{supply} = Source voltage
- V_{load} = Voltage drop across the load (e.g., LED forward voltage)
- $V_{desired}$ = Target current through the load

Application

Application	Typical Current Range	Resistor Power Rating
LEDs	5 mA – 20 mA	0.125W – 0.25W
Microcontroller Inputs	<1 mA	0.125W
Base Resistor for	1 mA – 10 mA	0.125W
Inrush Current Limiting	Depends on load	0.5W – 5W (higher transient)

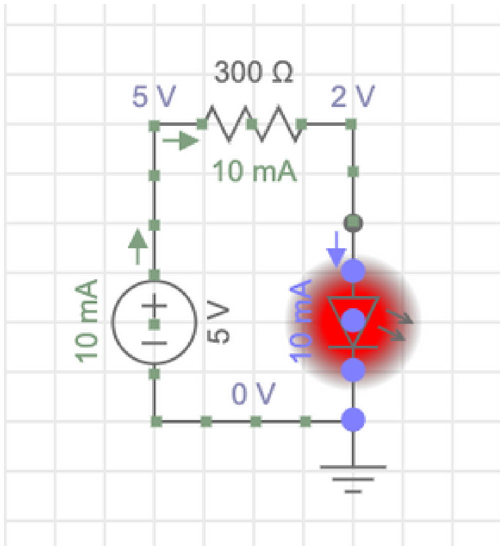
Design Considerations:

- Never undersize the resistor power rating. Always allow at least a 2× safety margin.
- For inrush current limiting, use higher wattage resistors or NTC thermistors.
- For fast switching circuits, account for resistor-induced delay or voltage drop
- Series resistor in op-amp inputs for current limiting.
- Current limiting for analog sensors to prevent overdriving input pins.
- Protection in USB, power rails, and high-side switches.

CURRENT LIMITING RESISTOR

Application:

Protecting an LED from overcurrent using a series resistor.



Parameters:

- Supply Voltage = 5V
- LED Forward Voltage = 2V
- Desired Current = 10mA

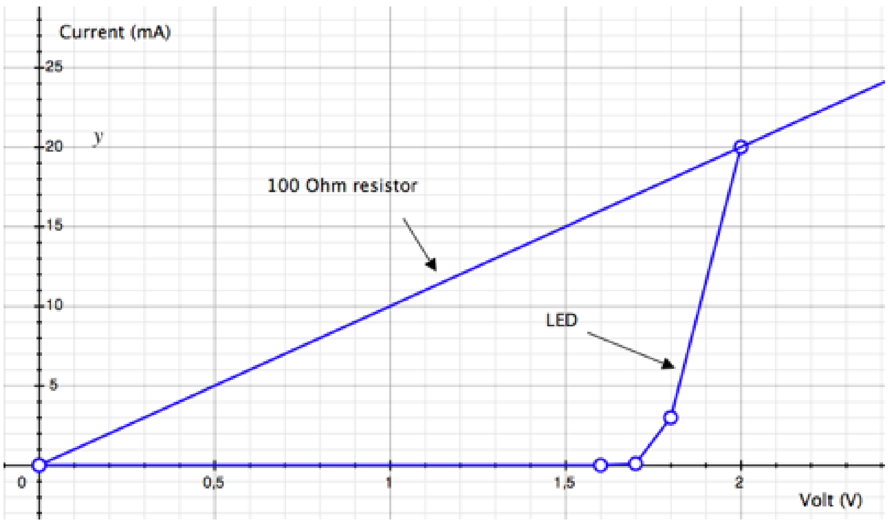
Calculation:

$$R = \frac{V_{supply} - V_f}{I} = \frac{5V - 2V}{0.01A} = 300\ \Omega$$

Power Dissipation:

$$P = I^2 \times R = (0.01)^2 \times 300 = 0.03W$$

LED with & without Resistor:



Result:

- Use a 300Ω, 0.25W resistor. This ensures the LED receives the correct current without damage.
- Choose a resistor with at least 0.125W (1/8W) rating for safety

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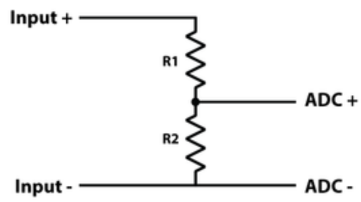
VOLTAGE DIVIDER FOR ADC INPUT

A Voltage Divider is a simple circuit using two resistors to scale down a higher input voltage to a lower level that is safe for the ADC (Analog-to-Digital Converter) of a microcontroller.

Purpose:

- To reduce a voltage source (e.g., 12V battery) to a voltage suitable for ADC input (usually <3.3V or <5V depending on the microcontroller).
- To safely monitor higher voltages using an ADC that has limited input voltage range.

Voltage Divider Formula:



$$V_{out} = V_{in} \times \frac{R2}{R1 + R2}$$

Where:

- Vin = Input voltage (e.g., 12V battery)
- Vout = Output voltage to ADC (must be < ADC max input, typically <3.3V)
- R1 = Resistor connected from Vin to Vout
- R2 = Resistor connected from Vout to Ground

Important Design Tips:

- Always ensure the voltage across the ADC pin is below the absolute maximum input (usually slightly less than the supply voltage, e.g., <3.3V for a 3.3V MCU).
- Use precision resistors (1% or better) for accurate voltage scaling.
- Consider adding a low-pass filter (capacitor in parallel with R2) to reduce ADC noise:
- Cutoff Frequency ≈ 723 Hz (Low-pass filter)
- Ensure input impedance of the ADC is significantly higher than the resistor network to avoid measurement errors.
- Check ADC datasheet guidelines for recommended source impedance.

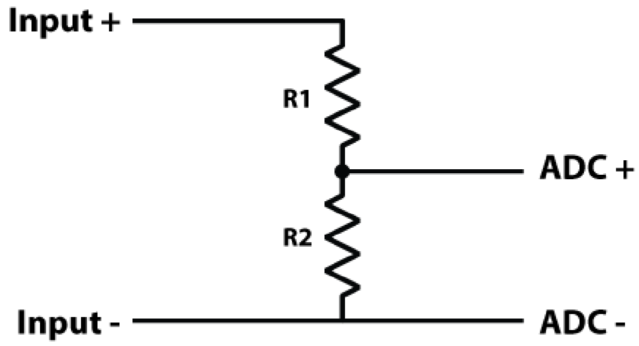
When to Use a Voltage Divider for ADC Input:

- Battery voltage monitoring
- Sensor signal scaling
- General-purpose voltage sensing in microcontroller systems

VOLTAGE DIVIDER FOR ADC INPUT

Application:

Scaling 12V battery voltage to <3.3V for microcontroller ADC.



Parameters:

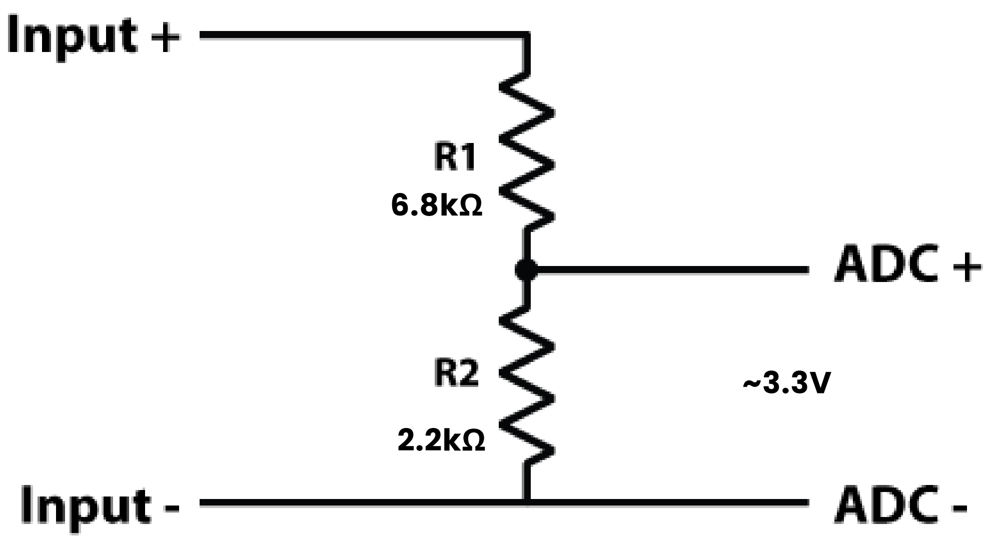
- Max battery voltage = 12V
- Desired ADC input = ≤3.3V
- Choose R1 = 6.8kΩ, find R2

Calculation:

$$V_{out} = V_{in} \times \frac{R2}{R1 + R2} \Rightarrow 3.3 = 12 \times \frac{R2}{6800 + R2} \Rightarrow R2 \approx 2.2k\ \Omega$$

Result:

Use 6.8kΩ (R1) and 2.2kΩ (R2) to safely scale 12V down to ~3.3V for the ADC.



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PULL-UP RESISTOR ON I2C LINE

In an I²C bus system, pull-up resistors are essential components that ensure the data (SDA) and clock (SCL) lines return to a logic HIGH level when no device is actively pulling them LOW.

Why Pull-Up Resistors Are Needed on I²C:

- I²C is an open-drain (open-collector) bus: devices can pull the lines LOW, but cannot drive them HIGH.
- Without pull-up resistors, the lines would float and logic levels would be undefined.
- Pull-up resistors define the idle (HIGH) state and enable proper logic transitions.

Basic I²C Pull-Up Configuration:

Each I²C line:

- SDA (Serial Data)
- SCL (Serial Clock)

has a resistor connected from the line to Vcc (typically 3.3V or 5V).

How to Calculate I²C Pull-Up Resistor Value:

The pull-up resistor value must satisfy:

1. Rise Time Requirements (depends on bus capacitance)
2. Sinking Current Capability of the devices

How to Calculate I²C Pull-Up Resistor Value:

$$\tau = R \times C$$

Where:

- τ\tauτ = RC time constant (~ 0.3 × max rise time allowed)
- R = Pull-up resistor (Ω)
- C = Bus capacitance (pF)

I²C Timing Reference:

Speed Mode	Max Rise Time (tr)	Typical Pull-Up Resistor
Standard (100 kHz)	1000 ns	4.7 kΩ to 10 kΩ
Fast (400 kHz)	300 ns	2.2 kΩ to 4.7 kΩ
Fast+ (1 MHz)	120 ns	1 kΩ to 2.2 kΩ

PULL-UP RESISTOR ON I2C LINE

Key Design Considerations:

- Lower resistor values → Faster rise times but higher current consumption.
- Higher resistor values → Slower rise times, less current drain, but possible signal integrity issues.
- Maximum current sinking per I²C spec is 3mA:
  - Example:
    - If Vcc = 3.3V, and R = 1kΩ → Current = 3.3mA → Too high for typical I²C drivers.
  - ✓ Recommended minimum: R ≥ 1.1kΩ for 3.3V systems.
- Consider total bus capacitance, trace length, and number of devices.

Parameters:

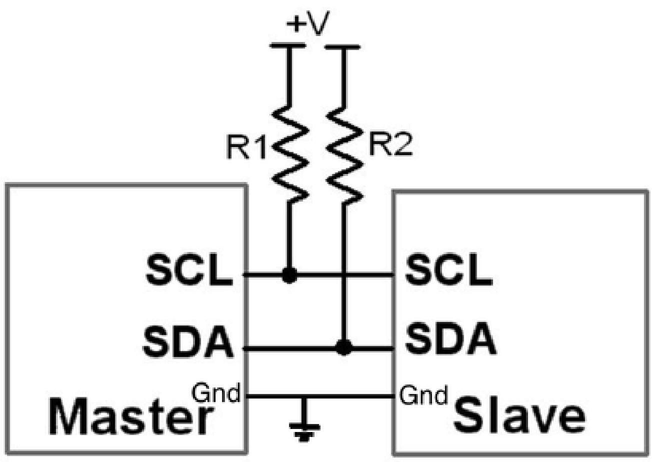
- Vcc = 3.3V
- Recommended Pull-up = 4.7kΩ
- Bus capacitance = ~100pF
- I2C clock speed = 100kHz

Check Rise Time:

$$\tau = R \times C = 4.7k \times 100pF = 470ns$$

Result:

Rise time is well within I2C spec (1000ns @ 100kHz).
Use 4.7kΩ pull-ups on both SDA and SCL lines.



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OP-AMP FEEDBACK RESISTOR

The Op-Amp Feedback Resistor is a critical component that controls the gain, bandwidth, and stability of operational amplifier circuits. It is typically placed in the feedback path to regulate how much of the output signal is returned to the input.

Purpose of Feedback Resistor:

- Sets voltage gain of the Op-Amp circuit.
- Stabilizes the amplifier.
- Shapes the frequency response (in filters).
- Controls input/output impedance characteristics.

Key Configurations:

1. Non-Inverting Amplifier

Gain Formula: $Gain(A_v) = 1 + \frac{R_f}{R_{in}}$

Where:

- Rf = Feedback resistor (from output to inverting input)
- Rin = Resistor from inverting input to ground

Example:

- Rf=10kΩ, Rin=1kΩ Gain = $1 + \frac{10k\Omega}{1k\Omega} = 11\times$

2. Inverting Amplifier

Gain Formula: $Gain(A_v) = -\frac{R_f}{R_{in}}$

The negative sign indicates 180° phase inversion.

Example:

- Rf=10kΩ, Rin=2kΩ Gain = $-\frac{10k\Omega}{2k\Omega} = -5\times$

3. Voltage Follower (Buffer):

- Feedback resistor is replaced with a direct connection (zero resistance).
- Gain = 1 (Unity Gain)
- Purpose: Impedance matching, signal buffering.

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OP-AMP FEEDBACK RESISTOR

Purpose of Feedback Resistor:

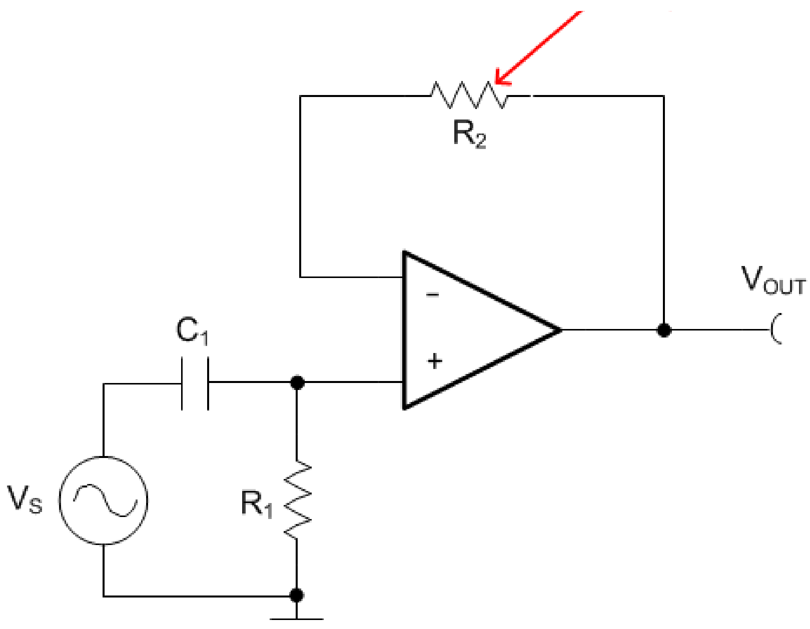
Parameter	Recommended Range
Feedback Resistor (R_f)	1kΩ – 100kΩ (typical)
Input Resistor (R_in)	1kΩ – 10kΩ (typical)
Resistor Tolerance	1% or better for precision
Noise Sensitivity	Lower resistor values preferred
Power Handling	Standard 1/8W or 1/4W resistors

Practical Design Considerations:

- Higher resistor values → Increase thermal noise, input offset currents may cause errors.
- Lower resistor values → Draw more current, increase power consumption.
- Use precision resistors (1% or 0.1%) for accurate and stable gain.
- For high-speed Op-Amps, keep resistor values low (1kΩ – 10kΩ) to minimize parasitic effects.

Common Applications:

- **Signal Amplification:** Audio preamps, sensor signal processing.
- **Active Filters**: Low-pass, high-pass, band-pass.
- **Voltage Scaling:** Precision voltage references.
- **Oscillator Circuits:** Involving feedback control loops.



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OP-AMP FEEDBACK RESISTOR

Application:

Designing a gain = 10 non-inverting amplifier.

Parameters:

- Vcc = 3.3V
- Recommended Pull-up = 4.7kΩ
- Bus capacitance = ~100pF
- I2C clock speed = 100kHz

Calculation:

$$10 = 1 + \frac{R2}{1k} \Rightarrow R2 = 9k\ \Omega$$

Result:

Use R1 = 1kΩ, R2 = 9kΩ.
This provides a voltage gain of 10× in audio preamps or signal conditioning circuits.

SIGNAL LINE TERMINATION

Signal Line Termination is a technique used to prevent signal reflections in high-speed or long PCB trace designs, especially when the trace length is electrically significant relative to the signal's wavelength.

Why Terminate Signal Lines?

When a signal travels along a PCB trace (transmission line), if the trace is not properly terminated, part of the signal can reflect back towards the source, causing:

- Data errors
- Signal integrity problems
- Increased EMI

When Is Termination Needed?

- High-speed signals (rise times < 1-2 ns)
- Long trace lengths relative to signal wavelength
- Interfaces like DDR, SPI, UART, Ethernet, CAN, PCIe, HDMI, USB, RF signals

Types of Signal Termination

Termination Type	Configuration	Use Case
Parallel Termination	Resistor to ground or Vcc at receiver	DDR, SDRAM, some clock lines
Series Termination	Resistor in series near driver	Point-to-point, short traces
Thevenin Termination	Pull-up and pull-down resistor combo	Bidirectional buses
AC Termination	Resistor + capacitor to ground	RF, clock lines
End-Termination (Matched)	Resistor equal to trace impedance	Ethernet, PCIe, differential signals

Example: Series Termination Calculation

- Trace impedance: 50 Ω
- Driver output impedance: 20 Ω
- Required series resistor: 50Ω−20Ω=30Ω50Ω - 20Ω = 30Ω50Ω−20Ω=30Ω

✓ Place the 30Ω resistor close to the driver.

SIGNAL LINE TERMINATION

Typical Termination Values

Signal Type	Termination Resistor
Single-ended (TTL/CMOS)	33Ω – 100Ω
Differential (Ethernet, USB)	49.9Ω – 100Ω per line
High-speed clocks	33Ω – 50Ω
RF lines (50Ω traces)	50Ω matched termination

Practical Tips:

- Always match the termination resistor to the trace impedance.
- Place series resistors near the driver to absorb reflections.
- For differential signals (e.g., Ethernet, CAN), terminate at the receiver with resistors equal to the differential impedance (commonly 100Ω).
- Use simulation tools (SI/PI analysis) for critical high-speed designs.
- Check interface-specific standards (e.g., PCIe, HDMI) for required termination details.

Application:

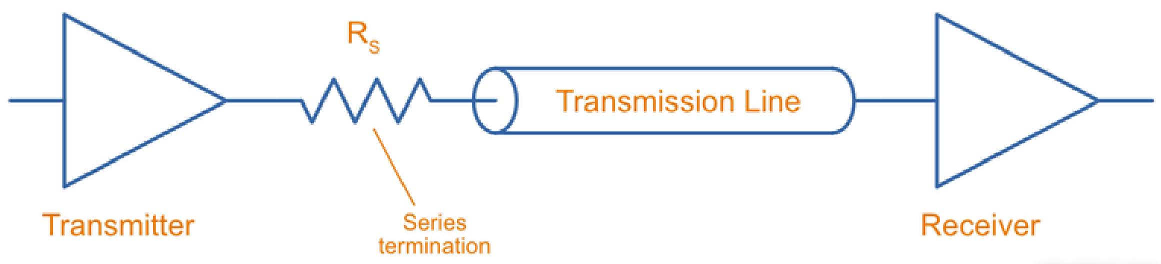
Matching impedance of 50Ω transmission line in RF design.

Parameters:

- Characteristic impedance (Z_0) = 50Ω
- Terminating resistor = 50Ω

Result:

Place a 50Ω resistor at the receiving end of the coaxial or differential line (e.g., Ethernet, RF antenna) to prevent reflections and ensure clean signal reception.



SNUBBER RESISTOR IN RELAY DRIVER

When driving inductive loads like relays, turning off the switch (transistor or MOSFET) can generate high-voltage spikes due to the collapsing magnetic field.

A snubber resistor (often used with a capacitor) helps to absorb or dissipate this energy to protect the switching device.

Why Use a Snubber Resistor?

- Limits voltage spikes across switching transistors.
- Protecting a transistor from inductive kickback.
- Reduces EMI (Electromagnetic Interference).
- Protects against arcing across the switch contacts.
- Improves relay life and system reliability.

Typical Snubber Circuit Configurations:

1. **RC Snubber:** Resistor and capacitor in series across the relay coil.
2. **RCD Snubber:** Adds a diode for more precise energy dissipation.
3. **Freewheeling Diode (Standard Protection):** A diode placed across the relay coil to provide a path for the coil current when switching off (most common).

👉 **Note:** A diode is usually sufficient, but a snubber is added for faster switching or reduced EMI.

Snubber Resistor Calculation Example:

Relay Coil Inductance: 1 mH
Operating Current: 0.5 A
Target Time Constant (τ): 10 µs

Step 1: Select Snubber Capacitor: Choose C = 100 nF

Step 2: Calculate Snubber Resistor $R = \frac{\tau}{C} = \frac{10 \times 10^{-6}}{100 \times 10^{-9}} = 100\,\Omega$

✔ Choose a 100Ω, 0.5W resistor in series with the 100nF capacitor.

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SNUBBER RESISTOR IN RELAY DRIVER

Snubber Resistor Calculation Example:

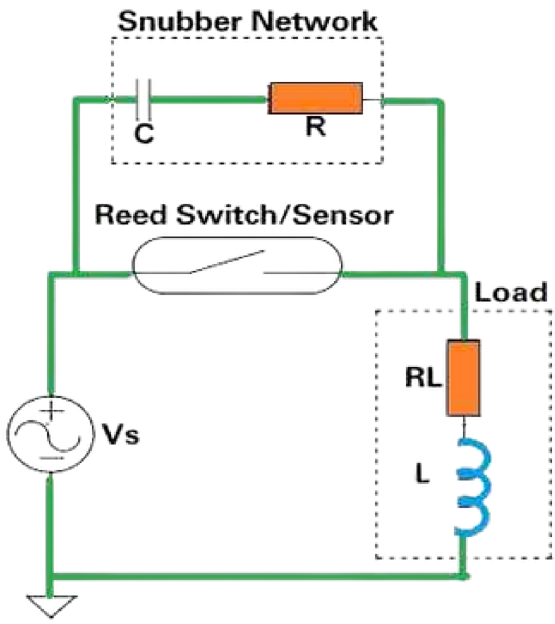
- A flyback diode (fast recovery preferred) is often enough for basic protection.
- RC snubbers are used for faster switching or reduced relay contact bounce.
- Snubbers may increase power loss, so sizing them properly is essential.
- For high-speed or sensitive circuits, simulate the switching behavior.

Comparison: Snubber vs. Diode

Protection Type	Voltage Spike Suppression	Switching Speed Impact	Power Dissipation
Flyback Diode	Very effective	Slower switching	Minimal
RC Snubber	Effective	Faster switching	Moderate

Parameters:

- Vcc = 12V
- Relay coil inductance = 1mH
- Target RC time constant = ~1ms
- Choose C = 100nF → Find R



Calculation:

$$\tau = R \times C \Rightarrow 1ms = R \times 100nF \Rightarrow R = 10k\ \Omega$$

But for better damping

$$R = 100\ \Omega\ \text{(typical)} \Rightarrow \tau = 10\ \mu s$$

Result:

Use 100Ω + 100nF RC snubber across the relay coil or transistor collector to suppress high-voltage spikes.