

# ANALOG HARDWARE DESIGN CHEAT SHEET

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## **Comprehensive One-Page Study Guide**

Covering fundamental concepts, formulas, examples,  
and interview-focused key points

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# Section 01: Welcome to Electronics I

## Introduction

### TL;DR (The Gist)

- Electronics is a fascinating field that builds on childhood curiosity about how devices work, from experimenters kits to modern computers and satellites
- This course provides clear, concise explanations of fundamental electronic concepts for those interested but without a career background in electronics
- No prior knowledge assumed - only curiosity about how electronics works and enthusiasm for hands-on learning through practical projects

### Detailed Explanation

2. Detailed Explanation

**Course Purpose:**

- Introduction to electronics for enthusiasts who didn't pursue it professionally
- Covers nature of electricity, voltage/ampereage/wattage, and basic components (resistors, capacitors, diodes, transistors)
- Combines theory with practical circuit building using simulator

**Prerequisites:**

- Curiosity about electronics (how radio works, what makes computers possible)
- Interest in building things hands-on
- No prior electronics classes, circuit assembly, or advanced math required

### Key Points

4. Key Points (Interview Focus)

1. Learning electronics is best done through doing - hands-on projects reinforce theoretical knowledge
2. Course uses powerful simulator for safe, practical experimentation
3. No assumptions about prior knowledge - designed for beginners with curiosity

## The Story of Electricity

### TL;DR (The Gist)

- Edison's 1883 discovery of electron flow from heated filaments (Edison Effect) marked the birth of electronics as distinct from electrical technology
- Electronics began 100+ years after electrical devices like batteries (1800) and telegraph (1830s) were invented
- The Edison Effect device was the world's first electronic component, enabling voltage monitoring and regulation

### Detailed Explanation

2. Detailed Explanation

**Historical Context:**

- 1800: Volta invents electric battery (Volt named after him)
- 1830s: Electric telegraph invented, Morse code developed
- 1850: Franklin publishes kite experiment idea (wisely let others test it first!)
- 1866: Transatlantic telegraph cable laid
- 1880: Edison patents improved light bulb

- 1883: Edison Effect discovered - BIRTH OF ELECTRONICS

#### The Discovery:

- Problem: Carbon-coated filaments shed particles, darkening bulb interior
- Observation: Darkening occurred only on one end of filament
- Hypothesis: Electric charge escaping from filament
- Test: Third wire inserted to "catch" the charge
- Result: Current flowed from heated filament to third wire; hotter filament = more current

### Key Points

#### 4. Key Points (Interview Focus)

1. Edison Effect (Nov 15, 1883): First electronic device - could monitor and regulate voltage
2. Electronics vs Electrical: Electrical devices existed 100+ years before electronic devices
3. Edison's discovery was accidental - solving light bulb darkening problem led to electronics
4. Without electronics, modern life would be unimaginable (TV, cameras, computers, phones)

## What is Electricity

### TL;DR (The Gist)

- Electricity is both familiar (household power, batteries, lightning) and mysterious in its exact nature
- We know what electricity does practically: powers devices, flows through wires, can be measured in volts/watts/amps, stored in batteries
- It's dangerous (can be lethal), valuable (we pay for it), and exists in forms like static electricity and lightning

### Detailed Explanation

#### 2. Detailed Explanation

##### Common Knowledge About Electricity:

- Flows through wires from power plants (coal, wind, nuclear) to homes via cables
- Reaches devices through outlets and power cords
- Not free - electric companies bill monthly; turn off service if unpaid
- Can be stored in batteries (limited amount, rechargeable or disposable)
- Creates lightning in thunderstorms (Ben Franklin's kite experiment)

##### Measurement Units:

- **Volts (V):** Household 120V, flashlight 1.5V, car battery 12V
- **Watts (W):** Light bulbs 60-100W, microwave/hair dryer 1000-1200W (more watts = brighter/faster)
- **Amps (A):** Typical household outlet 15A
- Most people don't know the difference between volts, watts, and amps

##### Forms of Electricity:

- Static electricity: Hangs in air, transferred by dragging feet on carpet or rubbing balloons
- Current electricity: Flows through conductors

### Key Points

#### 4. Key Points (Interview Focus)

1. Electricity is both familiar in practice and mysterious in exact nature
2. Three main measurements: Volts (electrical pressure), Watts (power), Amps (current flow)
3. Dangerous: Used in electric chair for 100 years; hundreds die annually from electrocution
4. Can be stored (batteries) or generated (power plants)
5. Understanding volts, watts, and amps is essential for electronics work

# What is Electric Current

## TL;DR (The Gist)

- Electric current is the flow of free electrons through conductors, motivated by voltage (electrical pressure)
- Atoms contain protons (nucleus), neutrons (nucleus), and orbiting electrons; valence electrons in outer orbit can escape and become free electrons
- Copper is excellent for wiring because its atoms have one loosely bound valence electron that's very easy to move

## Detailed Explanation

### 2. Detailed Explanation

#### Atomic Structure:

- **Nucleus:** Dense center containing protons (+) and neutrons (neutral)
- **Electrons:** Negatively charged particles orbiting nucleus
- **Atomic Number:** Count of protons (defines element - H=1, Cu=29, Pu=94)
- **Valence Electrons:** Outer orbit electrons that can escape with enough force

#### How Current Flows:

1. Atoms in conductors (like copper) have loosely bound valence electrons
2. Voltage applies "pressure" to push electrons in one direction
3. Free electrons escape atoms and flow through conductor
4. Millions of electrons flowing = electric current
5. We place devices (lamps, motors) in path to use this flow

#### Key Relationships:

- More voltage = more electrons can flow (like water pressure in pipe)
- Copper: 29 protons, 29 electrons, 1 valence electron (very mobile)
- Atoms are tiny: max 300 picometers ( $300 \times 10^{-12}$  m)

## Practical Example & Numerical

### Why Copper for Wiring?

Copper has atomic number 29, meaning:

Protons:	29
Electrons:	29 (neutral atom)
Valence electrons:	1 (outer shell)

That single valence electron is loosely bound and very easy to move. When voltage is applied across copper wire:

1. Free electrons from billions of copper atoms start flowing
2. We place a lamp in the electron path
3. Electrons flowing through lamp filament generate light and heat
4. Voltage keeps pushing more electrons through circuit

#### Atom Size Calculation:

$$\text{Maximum atom size} = 300 \text{ pm} = 300 \times 10^{-12} \text{ m} = 0.0000000003 \text{ m}$$

Incredibly tiny - you can't see individual atoms even under regular microscopes!

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

1. Electric current = flow of free electrons through conductors
2. Voltage is the "pushing force" (like water pressure) that motivates electron flow
3. Atoms have nucleus (protons + neutrons) surrounded by orbiting electrons

4. Atomic number = proton count (defines what element the atom is)
5. Valence electrons (outer orbit) can escape and become free electrons
6. Copper is popular for wiring: 1 loosely bound valence electron, very easy to move
7. Electricity exists everywhere: lightning, synapses in body, all modern devices

#### Interview Questions:

- **Q:** What is electric current at the atomic level?  
*A:* The flow of free valence electrons through conductor materials, motivated by voltage.
- **Q:** Why is copper commonly used for electrical wiring?  
*A:* Copper atoms have one loosely bound valence electron that's very easy to move, making excellent conductor.
- **Q:** What determines what element an atom is?  
*A:* The atomic number (number of protons in nucleus) defines the element.

#### Applications:

- Wiring in homes, buildings, devices (copper cables)
- Circuit boards use conductive traces to route current
- All electric gadgets: phones, computers, lights, air conditioners

## What is Electronics

### TL;DR (The Gist)

- **Electrical devices** convert electrical energy into heat, light, or motion (toasters, light bulbs, vacuum cleaners)
- **Electronic devices** manipulate the electrical current itself to add meaningful information or control (radios, computers, phones)
- Electronics began in 1883 with Edison Effect, 100 years after first electrical devices (battery 1800, telegraph 1830s)

### Detailed Explanation

## 2. Detailed Explanation

#### Historical Timeline:

- **1800:** Alessandro Volta invents electric battery ("Volt" named for him)
- **1830s:** Electric telegraph invented; Samuel Morse creates Morse code
- **1850:** Benjamin Franklin publishes kite experiment idea (wisely let others try first!)
- **1866:** Transatlantic telegraph cable laid (US-Europe instant communication)
- **1883:** Edison Effect - BIRTH OF ELECTRONICS

#### Electrical vs Electronic Devices:

*Electrical Devices (Simple energy conversion):*

- Light bulbs: electrical energy → light
- Toasters: electrical energy → heat
- Vacuum cleaners: electrical energy → motion (motor/pump)
- Simple transformation, no information processing

*Electronic Devices (Current manipulation):*

- Manipulate electrical current itself for interesting/useful tasks
- Add meaningful information to current (audio, video, data)
- Monitor and control voltage/current automatically
- Examples: radios, TVs, computers, cell phones

**Key Distinction:** The line is blurry - modern toasters may have electronic thermostats. But fundamentally:

- Electrical = energy conversion
- Electronic = current manipulation + information processing

### Practical Example & Numerical

#### Edison's First Electronic Device (1883):

Edison manipulated electrical current flowing through light bulb to create a device that could:

1. Monitor voltage provided to electrical circuit
2. Automatically increase voltage if too low
3. Automatically decrease voltage if too high

This was **current manipulation**, not just energy conversion - the birth of electronics!

#### Modern Examples:

##### *Audio Electronics:*

- Microphone converts sound waves to varying electrical current
- Amplifier manipulates current to strengthen signal
- Speaker converts manipulated current back to sound
- Information added: music, voice, sound effects

##### *Video Electronics:*

- Camera converts images to electrical signals
- Processor manipulates current to encode video information
- Display converts signals back to images
- Watch movies, video calls, TV shows

#### Timeline Calculation:

$$\text{Electronics delay} = 1883 - 1800 = \boxed{83 \text{ years after first battery}}$$

Electrical devices existed nearly a century before electronics was invented!

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

1. **Electrical devices:** Convert electrical energy to heat/light/motion (simple transformation)
2. **Electronic devices:** Manipulate current itself to add information and control
3. Electronics born 1883 (Edison Effect), 83 years after first battery (1800)
4. Electronic devices add meaningful information: audio (music, voice), video (images, movies)
5. First electronic device: Edison's voltage monitor/regulator (1883)
6. Ancient Parthians may have invented battery 150 BC, but invention was lost for 2000 years
7. Modern "electrical" devices often contain electronic components (blurry distinction)

#### Interview Questions:

- **Q:** What's the difference between electrical and electronic devices?  
*A:* Electrical devices convert energy to heat/light/motion. Electronic devices manipulate current to add information and perform complex control.
- **Q:** When was electronics invented and how?  
*A:* 1883, when Edison discovered he could manipulate current in light bulbs to monitor and regulate voltage - the Edison Effect.
- **Q:** Give examples of information added by electronic devices.  
*A:* Audio (music, voice), video (images, movies), data (computers), control signals (automation).

#### Applications:

- Communication: telegraph, telephone, cell phones, internet
- Entertainment: radio, TV, music players, gaming consoles
- Computing: computers, smartphones, calculators
- Control systems: thermostats, automotive electronics, industrial automation

## Looking Inside Electronic Devices

### TL;DR (The Gist)

- Circuit boards (PCBs) have two sides: component side (resistors, capacitors, diodes, transistors, ICs) and trace side (conductive pathways)
- Components manipulate current (restrict, amplify, direct, smooth); traces route current between components in specific order

- **DANGER:** Capacitors can store lethal electrical energy even when device is unplugged - never carelessly disassemble electronics!

## Detailed Explanation

### 2. Detailed Explanation

#### Circuit Board Structure:

*Component Side (The "Little City"):*

- Populated with electronic components like "little buildings"
- **Resistors:** Restrict current flow (like speed bumps on road)
- **Capacitors:** Smooth ripples/variations, store energy
- **Diodes:** Allow current flow in only one direction (one-way street)
- **Transistors:** Amplify current, make it stronger
- **Integrated Circuits (ICs):** Complex functions, thousands of components

*Trace Side (The "Streets"):*

- Silver/copper conductive pathways painted on board
- Connect components in specific order
- Route current from one component to next
- Create complete circuit paths

#### How It Works Together:

1. Current flows through traces (streets) to components (buildings)
2. Each component bends, twists, restricts, or strengthens the current
3. Modified current flows to next component via traces
4. Components work in sequence to achieve circuit function
5. Final output: useful work (audio, video, control, computation)

**Circuit Design Essence:** Connect components in *just the right way* so current flowing out of one component passes correctly to the next, creating desired functionality.

## Practical Example & Numerical

#### Typical Circuit Board Analysis:

When you open an old clock radio or VHS player, you'll see:

*Top Side (Components):*

- Various electronic components standing upright
- Cylindrical capacitors (often tall, near edges)
- Small resistors (color-coded bands)
- Black ICs with multiple pins
- Looks like miniature city with buildings

*Bottom Side (Traces):*

- Silver/copper lines connecting component pins
- Complex patterns like city streets
- Some traces thick (high current), some thin (signals)

#### Component Functions - Speed Analogy:

- **Resistor:** Speed bump - slows current flow
- **Capacitor:** Traffic smoother - evens out flow variations
- **Diode:** One-way street sign - current flows only one direction
- **Transistor:** Amplifier/switch - controls or strengthens current

**CRITICAL SAFETY WARNING:** Capacitors store energy:  $E = \frac{1}{2}CV^2$

Large capacitors in power supplies can hold **hundreds of volts** even after unplugging. Touching terminals = potentially **fatal shock**!

## Key Points (Interview Focus)

## 4. Key Points (Interview Focus)

1. Circuit boards have component side (parts) and trace side (connections)
2. Components manipulate current: resistors restrict, capacitors smooth, diodes direct, transistors amplify
3. Traces are conductive pathways (silver/copper) routing current between components
4. Circuit board resembles miniature city: components = buildings, traces = streets
5. Circuit design = connecting components in right order for desired function
6. **DANGER:** Capacitors store energy even when unplugged - can deliver fatal shock
7. Never carelessly disassemble electronics until you know what you're doing

### Interview Questions:

- **Q:** What are the two main parts of a circuit board?  
*A:* Component side (electronic parts that manipulate current) and trace side (conductive pathways connecting components).
- **Q:** What do resistors, capacitors, and diodes do?  
*A:* Resistors restrict current flow, capacitors smooth variations and store energy, diodes allow one-way current flow.
- **Q:** Why are capacitors dangerous even when device is unplugged?  
*A:* Capacitors store electrical energy and can hold lethal voltage/charge long after power is disconnected.

### Applications:

- All modern electronics: computers, phones, TVs, radios
- Automotive electronics: engine control, entertainment systems
- Industrial control systems and automation
- Consumer devices: microwaves, washing machines, thermostats

### Safety Limitations:

- Capacitor shock hazard (even when unplugged)
- Component heat sensitivity during operation
- Static electricity can damage sensitive ICs
- Requires proper knowledge before disassembly/repair

# Section 02: Understanding Electricity

## What You Will Learn

### TL;DR (The Gist)

- This section builds foundational understanding of electricity starting from atomic structure through to practical circuit operation
- You'll learn what electricity fundamentally is, how atoms create it, and why certain materials conduct while others insulate
- Core topics: atomic structure, charge, electromagnetic force, conductors/insulators, and how current actually flows

### Detailed Explanation

## 2. Detailed Explanation

**Section Overview:** This section answers fundamental questions:

- What is electricity at the atomic level?
- Why does electricity exist in all matter?
- How do atoms create electric charge?
- Why do some materials conduct and others insulate?
- What makes electrons flow as current?

**Learning Path:**

1. Pondering electricity's mysterious nature
2. Understanding atoms and their components
3. Exploring the periodic table of elements
4. Learning about electric charge and electromagnetic force
5. Distinguishing conductors from insulators
6. Understanding how electric current flows

**Prerequisites:**

- Curiosity about how things work
- No prior electronics knowledge required
- Basic awareness of atoms (middle/high school science)

### Key Points

## 4. Key Points (Interview Focus)

1. Builds from fundamentals (atoms) to practical concepts (current flow)
2. Answers "what is electricity?" at deepest level
3. Essential foundation for all future electronics topics
4. No math required - conceptual understanding focus

## Pondering the Wonder of Electricity

### TL;DR (The Gist)

- Electricity is both familiar (powers devices, exists in lightning/static) yet mysterious in its exact nature
- Ancient Greeks discovered "elektron" (amber) attracting objects when rubbed - root of word "electricity"
- We know what electricity does practically, but understanding *what it is* requires diving into atomic structure

### Detailed Explanation

## 2. Detailed Explanation

### Historical Discovery:

- Ancient Greeks: Rubbed amber (fossilized tree resin) with fur
- Observed: Amber attracted feathers, raised hair on arms
- Greek word for amber: *elektron*
- Latin: *electricus* (relating to amber)
- Early 1600s: William Gilbert (English scientist) studied this phenomenon
- Result: English word "electricity" derived from Greek *elektron*

### Common Knowledge About Electricity:

- Powers household devices (lights, appliances, computers)
- Stored in batteries (limited amount, rechargeable or disposable)
- Flows through wires from power plants to homes
- Manifests as lightning in thunderstorms
- Creates static electricity (carpet scuffing, balloon rubbing)
- Dangerous - can be lethal (electric chair, electrocution accidents)

### Measurement Units (Common Awareness):

- **Volts (V):** Household 120V, flashlight 1.5V, car battery 12V
- **Watts (W):** Light bulbs 60-100W, microwave 1000-1200W
- **Amps (A):** Typical household outlet 15A
- Most people don't know the precise difference between these units

**The Mystery:** Despite familiarity, most people can't answer: "What *is* electricity?" To truly understand, we must explore atomic structure and electromagnetic forces.

## Practical Example & Numerical

### Ancient Greek Experiment (Recreate at Home):

1. Get a piece of amber or plastic rod
  2. Rub vigorously with wool or fur for 30 seconds
  3. Bring near small pieces of paper or hair
  4. Observe: Papers jump toward the rod, hair stands up
- This is **static electricity** - electric charge building up on surfaces.

### Voltage Comparison:

Household outlet:	120 V
Flashlight battery:	1.5 V
Car battery:	12 V
Lightning bolt:	100,000,000 V (100 million volts!)

### Ratio Calculation:

$$\frac{\text{Lightning}}{\text{Household}} = \frac{100,000,000}{120} \approx \boxed{833,000 \times \text{more voltage}}$$

Lightning is incredibly powerful!

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

1. Word "electricity" comes from Greek *elektron* (amber) via Latin *electricus*
2. Ancient Greeks discovered static electricity by rubbing amber with fur
3. Electricity is familiar (powers devices, exists as lightning/static) yet mysterious in nature
4. Common measurements: Volts (pressure), Watts (power), Amps (current)
5. Understanding requires diving into atomic structure and charge
6. Electricity can be stored (batteries) or generated (power plants)
7. Dangerous: Used in electric chair, causes electrocution deaths

### Interview Questions:

- **Q:** What is the origin of the word "electricity"?  
*A:* From Greek *elektron* (amber) - Greeks discovered rubbed amber attracted objects.
- **Q:** What are the three main electrical measurements?  
*A:* Volts (electrical pressure), Watts (power), Amps (current flow).

# Atoms Introduction

## TL;DR (The Gist)

- Atoms are the smallest units of elements - from Greek "atomos" meaning "undividable"
- Structure: Dense nucleus (protons + neutrons) surrounded by electron cloud (not orbits!)
- Three particles: Protons (+charge), Neutrons (neutral), Electrons (-charge, 200,000× smaller than protons)

## Detailed Explanation

### 2. Detailed Explanation

#### Etymology & Concept:

- Greek: *atomos* = "a" (not) + "tomos" (cut) = "undividable"
- Ancient Greek philosophers theorized smallest indivisible units of matter
- Modern science: Atoms *can* be split (nuclear reactions), but doing so changes the element
- Atom = smallest unit retaining properties of an element

#### Atomic Structure:

- **Nucleus:** Dense center containing:
  - Protons: Positive electric charge
  - Neutrons: No electric charge (neutral)
- **Electron Cloud:** Surrounding nucleus:
  - Electrons: Negative electric charge
  - Exist in quantum electron cloud (NOT planetary orbits)
  - Much smaller than protons/neutrons (200,000× lighter)

#### Key Properties:

- Neutral atom: # electrons = # protons
- Atomic number = # protons (defines element)
- Electrons held in orbit by electromagnetic attraction to positive protons
- Valence electrons (outer shell) can escape and become free

#### Scale:

- Atoms: Maximum 300 picometers ( $300 \times 10^{-12}$  m)
- Invisible to naked eye, even regular microscopes
- Billions of atoms in a single grain of sand

## Practical Example & Numerical

### Copper Atom (Common in Wiring):

Element:	Copper (Cu)
Atomic number:	29
Protons:	29 (in nucleus)
Neutrons:	34 (most common isotope)
Electrons:	29 (neutral atom)

#### Electron Shell Structure:

- Shell 1: 2 electrons
- Shell 2: 8 electrons
- Shell 3: 18 electrons

- Shell 4: 1 electron (**valence electron** - loosely bound!)

#### Size Comparison:

$$\text{Electron mass} \approx \frac{\text{Proton mass}}{200,000}$$

If proton was size of basketball:

Electron  $\approx$  grain of sand

#### Atom Size:

Typical atom diameter =  $100\text{-}300 \times 10^{-12} \text{ m} = 0.1\text{-}0.3 \text{ nanometers}$

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

1. Atom from Greek *atomos* = "undividable" (smallest unit of element)
2. Structure: Nucleus (protons + neutrons) + electron cloud
3. Three particles: Protons (+), Neutrons (0), Electrons (-)
4. Electrons are  $200,000\times$  smaller/lighter than protons
5. Atomic number = proton count (defines element identity)
6. Neutral atom: equal numbers of protons and electrons
7. Valence electrons (outer shell) can escape to create current

#### Interview Questions:

- **Q:** What are the three components of an atom?  
A: Protons (positive, in nucleus), neutrons (neutral, in nucleus), electrons (negative, in cloud around nucleus).
- **Q:** What defines what element an atom is?  
A: The atomic number (number of protons in the nucleus).

## Examining the Elements - Periodic Table

### TL;DR (The Gist)

- An element is a specific type of atom defined by its atomic number (number of protons in nucleus)
- H=1 proton (hydrogen), He=2 (helium), Li=3 (lithium), Cu=29 (copper), etc.
- Neutral atoms have equal protons and electrons; electrons are the source of electric current

### Detailed Explanation

#### 2. Detailed Explanation

##### What Defines an Element:

- **Element:** Specific type of atom defined by number of protons
- **Atomic Number:** Count of protons in nucleus
- Each element has unique atomic number (cannot change without nuclear reaction)
- 118 known elements in periodic table

##### Common Elements:

- Hydrogen (H): 1 proton, atomic number 1
- Helium (He): 2 protons, atomic number 2
- Lithium (Li): 3 protons, atomic number 3
- Copper (Cu): 29 protons, atomic number 29 (important in electronics!)

##### Neutrons:

- Found in nucleus with protons (except hydrogen)
- Extremely important to chemists and physicists
- Don't play big role in how electric current works
- Usually slightly more neutrons than protons
- Can safely be ignored for electronics fundamentals

##### Electrons - The Star of Electricity:

- Source of electric current
- Unbelievably small:  $200,000\times$  smaller than proton
- Atoms usually have same number of electrons as protons
- Copper: 29 protons  $\rightarrow$  29 electrons (neutral atom)
- When atom gains/loses electron, things get interesting (charge!)

## Practical Example & Numerical

### Element Examples with Atomic Numbers:

Hydrogen (H):	1 proton, atomic # 1
Helium (He):	2 protons, atomic # 2
Lithium (Li):	3 protons, atomic # 3
Carbon (C):	6 protons, atomic # 6
Oxygen (O):	8 protons, atomic # 8
Copper (Cu):	29 protons, atomic # 29
Silver (Ag):	47 protons, atomic # 47
Gold (Au):	79 protons, atomic # 79

### Copper Atom Composition:

- Protons: 29 (in nucleus)
- Neutrons: 35 (in nucleus, more than protons)
- Electrons: 29 (orbiting in cloud)
- Net charge: 0 (neutral atom)

### Electron Size Calculation:

$$\text{Electron mass} = \frac{\text{Proton mass}}{200,000}$$

If proton mass = 1 kg (hypothetically):

$$\text{Electron mass} = \frac{1 \text{ kg}}{200,000} = 0.000005 \text{ kg} = 5 \text{ mg}$$

Incredibly tiny compared to protons!

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

1. Element = specific type of atom defined by atomic number (proton count)
2. Atomic number uniquely identifies element (H=1, He=2, Cu=29)
3. Neutrons exist in nucleus but don't affect electric current flow
4. Electrons are source of electric current (  $200,000\times$  smaller than protons)
5. Neutral atoms have equal protons and electrons
6. When atoms gain/lose electrons, they become charged
7. 118 known elements in periodic table

### Interview Questions:

- **Q:** What defines which element an atom is?  
A: The atomic number - the number of protons in the nucleus.
- **Q:** Why are electrons important for electricity?  
A: Electrons are the source of electric current - they move between atoms to create flow.
- **Q:** How many electrons does a neutral copper atom have?  
A: 29 electrons (equal to its 29 protons).

### Applications:

- Selecting conductor materials (copper, silver, aluminum)

- Understanding periodic table for electronics
- Predicting electrical properties based on element

# Charge and Electromagnetism

## TL;DR (The Gist)

- Electric charge is a fundamental property: electrons are negative (-), protons are positive (+)
- Opposite charges attract (+ and -), like charges repel (+ and +, - and -)
- Electromagnetic attraction holds electrons in orbit around protons in nucleus

## Detailed Explanation

### 2. Detailed Explanation

#### Electric Charge:

- Property of electrons and protons
- Two polarities: negative and positive
- Electrons: negative polarity (-)
- Protons: positive polarity (+)
- Neutrons: no charge (neutral)

#### Fundamental Law of Charge:

- **Opposite charges attract:**
  - Negative attracts positive
  - Positive attracts negative
- **Like charges repel:**
  - Negative repels negative
  - Positive repels positive

#### Effects of Charge:

- Electrons and protons attract each other
- Electrons repel other electrons
- Protons repel other protons
- This attraction/repulsion holds atoms together
- Keeps electrons orbiting around nucleus

#### Electromagnetism:

- Charge is a property of electromagnetic force
- One of four fundamental forces of nature
- Governs all electrical and magnetic phenomena
- Each proton attracts exactly one electron
- This is why neutral atoms have equal protons and electrons

## Practical Example & Numerical

#### Charge Attraction/Repulsion Examples:

##### *Attraction (Opposite Charges):*

- Proton (+) near Electron (-) → ATTRACT
- Electron (-) near Proton (+) → ATTRACT
- This holds atom together!

##### *Repulsion (Like Charges):*

- Electron (-) near Electron (-) → REPEL
- Proton (+) near Proton (+) → REPEL
- This is why protons packed in nucleus need neutrons (strong nuclear force overcomes repulsion)

### Electromagnetic Balance in Copper Atom:

Protons in nucleus: 29 (positive charges)  
Electrons in cloud: 29 (negative charges)  
Net charge: 0 (neutral)

Each of 29 protons attracts one electron:

$$29 \text{ protons} \times 1 \frac{\text{electron}}{\text{proton}} = 29 \text{ electrons}$$

Perfect electromagnetic balance!

**Static Electricity Example:** Rubbing balloon on hair transfers electrons:

- Balloon gains extra electrons → becomes negative
- Hair loses electrons → becomes positive
- Balloon and hair now attract each other (opposite charges!)

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

1. Electric charge has two polarities: negative (electrons) and positive (protons)
2. Fundamental law: opposite charges attract, like charges repel
3. Electromagnetic force holds electrons in orbit around nucleus
4. Charge is property of electromagnetism (fundamental force of nature)
5. Each proton attracts exactly one electron (why neutral atoms have equal numbers)
6. Electrons repel each other, protons repel each other
7. Attraction between protons and electrons keeps atom structure intact

#### Interview Questions:

- **Q:** What is electric charge?  
A: A fundamental property of particles with two polarities - negative (electrons) and positive (protons).
- **Q:** What is the fundamental law of electric charge?  
A: Opposite charges attract (+ and -), like charges repel (+ and +, - and -).
- **Q:** Why do neutral atoms have equal protons and electrons?  
A: Because electromagnetic force causes each proton to attract exactly one electron.
- **Q:** What holds electrons in orbit around the nucleus?  
A: The electromagnetic attraction between positive protons in nucleus and negative electrons.

#### Applications:

- Static electricity (balloon on hair, carpet scuffing)
- Understanding atomic structure stability
- Basis for all electrical phenomena
- Foundation of current flow in circuits

## Conductors and Insulators

### TL;DR (The Gist)

- **Conductors:** Elements that don't hold outer electrons tightly (silver, copper, aluminum) - electrons constantly skip between atoms
- **Insulators:** Elements that hold electrons very tightly (rubber, plastic, glass) - almost always stay neutral
- Without voltage, electron movement in conductors is completely random; with voltage applied, movement becomes organized = electric current

### Detailed Explanation

## 2. Detailed Explanation

### Conductors:

- Don't hold outermost electrons tightly
- Frequently lose or gain electrons
- Constantly cycling between positive, neutral, and negative charge states
- Best conductors: metals (silver, copper, aluminum)
- Electrons constantly skip between nearby atoms

### Insulators:

- Hold electrons very tightly
- Hard to lose or gain electrons
- Almost always stay neutral
- Common insulators: rubber, plastic, glass, wood, ceramic

### Random Electron Movement (No Voltage):

1. Electron jumps from Atom A to Atom B
2. Atom A becomes positive (lost electron)
3. Atom B becomes negative (gained electron)
4. Almost immediately, electron from Atom C jumps to Atom A
5. Atom A returns to neutral, Atom C becomes positive
6. Process continues constantly in all directions
7. Like "Keystone cops running aimlessly" - lots of motion, no net movement

### The Key Concept:

- Random movement: One electron left, another right, one up, one down
- Net effect: Although electrons move, collectively they go nowhere
- Atoms in perpetual turmoil: giving/receiving electrons constantly
- When randomness stops and electrons get organized → electric current!

## Practical Example & Numerical

### Conductor Example - Three Copper Atoms:

*Initial State (all neutral):*

Atom A: 29p, 29e (neutral)

Atom B: 29p, 29e (neutral)

Atom C: 29p, 29e (neutral)

*After electron jump A → B:*

Atom A: 29p, 28e (positive)

Atom B: 29p, 30e (negative)

Atom C: 29p, 29e (neutral)

*After electron jump C → A:*

Atom A: 29p, 29e (neutral again!)

Atom B: 29p, 30e (still negative)

Atom C: 29p, 28e (now positive)

This happens continuously in random directions!

### Best Conductors Ranking:

1. Silver (Ag) - Best conductor (expensive)
2. Copper (Cu) - Excellent conductor (affordable) ← Most common
3. Aluminum (Al) - Good conductor (lighter, used in power lines)

### Common Insulators:

- Rubber (wire coating)
- Plastic (electrical enclosures)
- Glass (power line insulators)
- Ceramic (spark plug insulators)
- Air (poor conductor at normal voltages)

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

1. Conductors have loosely bound outer electrons (silver, copper, aluminum)
2. Insulators hold electrons tightly (rubber, plastic, glass)
3. In conductors, electrons constantly skip randomly between atoms
4. Atoms cycle through positive → neutral → negative states continuously
5. Random electron movement has no net direction (like "Keystone cops running aimlessly")
6. When randomness becomes organized → electric current flows
7. Best conductors: Silver > Copper > Aluminum (copper most commonly used)

#### Interview Questions:

- **Q:** What's the difference between conductors and insulators?  
A: Conductors have loosely bound outer electrons that move easily; insulators hold electrons tightly and resist movement.
- **Q:** Why is copper the most common conductor?  
A: Excellent conductivity (loosely bound valence electron) at affordable cost. Silver is better but expensive; aluminum is cheaper but not as good.
- **Q:** What happens to atoms in a conductor at rest (no voltage)?  
A: Electrons constantly jump randomly between atoms, making atoms cycle between positive/neutral/negative states, but no net electron movement.
- **Q:** Name three common insulators.  
A: Rubber (wire insulation), plastic (enclosures), glass (power line insulators).

#### Applications:

- Wire design: copper core (conductor) + rubber coating (insulator)
- Circuit boards: copper traces (conductors) on plastic board (insulator)
- Power lines: aluminum conductors suspended by glass/ceramic insulators
- Safety equipment: rubber gloves (insulator) for electrical work

## Electric Current Flow

### TL;DR (The Gist)

- Electric current = organized flow of electrons in the same direction through a conductor
- Electromotive Force (EMF/voltage) from battery organizes random electron motion into directional flow
- Requires: voltage source (battery), conductors (copper wire), and closed loop circuit (no breaks for electrons to escape)

### Detailed Explanation

### 2. Detailed Explanation

#### What is Electric Current:

- Flow of electrons in a circuit
- Happens when random electron exchange becomes organized
- All electrons begin moving in same direction
- Like organized march vs. random wandering

#### Why Copper:

- Atoms have loosely bound valence electrons
- Free electrons naturally move between atoms randomly
- Very easy to move these free electrons
- Random motion in all directions = not useful
- Need force to organize movement in one direction

#### Electromotive Force (EMF):

- Force that acts on electrons to move them in particular direction
- Also called voltage, measured in volts (V)
- Like pressure in water pipe - pushes electrons

- More voltage = more electrons can flow
- Easiest source: battery

#### How Current Flows:

1. Place battery in closed loop copper wire circuit
2. Battery provides EMF (voltage)
3. Voltage organizes random electron movement
4. Electrons begin drifting in same direction
5. Electrons flow around and around the loop
6. Movement continues until battery energy depleted
7. Somewhat disorderly, but overall movement in one direction

#### Closed Loop Circuit Requirements:

- Must be closed (no breaks)
- Electrons cannot escape circuit
- Path for electrons to return to starting position
- Break in loop = current stops immediately

#### Using Current:

- Place useful devices (lamps, motors) in electron path
- Electrons flow through device
- Generate light, heat, motion, etc.
- This is where electronics begins!

### Practical Example & Numerical

#### Simple Lamp Circuit:

##### Components:

- Battery (voltage source): Provides EMF
- Copper wire (conductor): Forms circuit path
- Lamp (load): Uses electron flow to create light
- Closed loop: Battery → wire → lamp → wire → back to battery

##### Operation:

1. Battery creates voltage (EMF) across circuit
2. Free electrons in copper start drifting toward positive terminal
3. Electrons flow through lamp filament
4. Resistance in filament causes heating
5. Hot filament glows → light!
6. Electrons continue back to battery negative terminal
7. Cycle repeats continuously

#### Current Flow Comparison:

##### Without Voltage (Random Motion):

Net movement = 0    (electrons go all directions)

##### With Voltage (Organized Flow):

Net movement = Current    (electrons drift same direction)

#### Practical Voltage Sources:

AA battery:	1.5 V
Car battery:	12 V
USB charger:	5 V
Laptop battery:	11-15 V
Household outlet:	120 V (AC)

#### Water Pipe Analogy:

- Voltage ↔ Water pressure
- Current ↔ Water flow rate

- Wire  $\leftrightarrow$  Pipe
- Battery  $\leftrightarrow$  Water pump
- Closed loop  $\leftrightarrow$  Plumbing circuit

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

1. Electric current = organized directional flow of electrons
2. EMF (Electromotive Force) = voltage that pushes electrons in one direction
3. Voltage measured in volts (V)
4. Battery easiest way to provide EMF/voltage
5. Closed loop circuit required (no breaks for electrons to escape)
6. Copper used because valence electrons very easy to move
7. Random electron motion becomes organized when voltage applied
8. Current continues until energy source depleted

#### Interview Questions:

- **Q:** What is electric current?  
A: The organized flow of electrons in the same direction through a conductor.
- **Q:** What is EMF (Electromotive Force)?  
A: The force (voltage) that acts on electrons to move them in a particular direction, measured in volts.
- **Q:** What three things are required for current flow?  
A: (1) Voltage source (battery/power supply), (2) Conductor (copper wire), (3) Closed loop circuit (no breaks).
- **Q:** Why does current stop when circuit is broken?  
A: Electrons need continuous closed path to flow. Break means no return path, so organized flow stops.
- **Q:** How does a battery create current?  
A: Battery provides voltage (EMF) that organizes random electron motion in conductor into directional flow.

#### Applications:

- All battery-powered devices (flashlights, phones, laptops)
- Simple circuits: battery  $\rightarrow$  switch  $\rightarrow$  lamp  $\rightarrow$  back to battery
- Understanding why switches work (break = no closed loop = no current)
- Foundation for all electronics (need current to make anything work)

#### Key Concepts:

- Voltage = electrical pressure (like water pressure)
- Current = flow rate (like water flow rate)
- Closed loop = complete circuit (like plumbing loop)
- Open circuit = broken path (no current can flow)
- This is where electronics begins!

# Section 03: Simulator Tutorial

## Setting up the Simulator

### TL;DR (The Gist)

- Browser-based circuit simulator - completely free, no account needed
- Works on Chrome, Safari, Firefox, IE - just needs JavaScript enabled (default)
- Best beginner-friendly simulator for understanding electronics fundamentals

### Detailed Explanation

#### 2. Detailed Explanation

##### Access:

- Navigate to simulator website in browser
- Completely free - no registration required
- Demo circuit loads automatically upon access
- Works in any modern browser with JavaScript enabled

##### Why This Simulator:

- Most amazing and easy-to-use for beginners
- Straightforward visualization of circuit behavior
- Not designed for complex professional circuits
- Perfect for understanding electronics fundamentals
- Real-time visual feedback (electron flow, voltage, current)

##### System Requirements:

- Any modern web browser (Chrome, Safari, Firefox, IE)
- JavaScript enabled (enabled by default)
- Internet connection for web access
- No installation required

### Key Points

#### 4. Key Points (Interview Focus)

1. Browser-based, free, no account needed
2. Best for beginners - simple and visual
3. Not for complex professional design (basic circuits only)
4. JavaScript required (enabled by default in browsers)
5. Instant access - just navigate to website

## How to Get Started

### TL;DR (The Gist)

- Interface has 4 sections: Menu tab (top-left), component list, circuit canvas, controls (right side)
- Use keyboard shortcuts for fast component placement: R (resistor), W (wire), V (voltage source), G (ground)
- Yellow dots = electron flow; green wires = positive voltage; scopes show voltage (green) and current (yellow) over time

### Detailed Explanation

## 2. Detailed Explanation

### Interface Layout (4 Sections):

#### 1. Menu Tab (Upper-left):

- **File:** New circuit, open, save, export
- **Edit:** Undo, cut, copy (Ctrl+C/V), find component, center circuit, zoom
- **Draw:** All available components (categorized)
- **Scopes:** Oscilloscope settings
- **Options:** Simulation settings
- **Circuits:** Pre-built example circuits

#### 2. Component Categories (Draw Menu):

- **Wires and Resistors:** Basic connections and resistance
- **Passive Components:** Capacitors, inductors, transformers, fuses
- **Inputs & Sources:** Ground, DC/AC voltage, square wave, clock, current source
- **Outputs & Labels:** LED, lamp, text, voltmeter, ohmmeter, ammeter, wattmeter
- **Active Components:** Diodes, transistors (NPN/PNP), MOSFETs, JFETs, Darlington
- **Active Building Blocks:** Op-amps, analog switches, Schmitt triggers
- **Logic Gates & Digital:** (Not covered - digital electronics)

#### 3. Circuit Canvas (Center):

- Main workspace for building circuits
- Click-and-drag to place components
- Hover over component to see info (bottom-right)
- Visual feedback: yellow dots (electrons), green wires (positive voltage)

#### 4. Controls (Right Side):

- **Reset:** Reset circuit to initial state
- **Run/Stop:** Start/pause simulation
- **Simulation Speed:** Speed up/slow down simulation
- **Current Speed:** Control electron dot movement speed (visual only)

### Keyboard Shortcuts (Essential):

- **R:** Add resistor
- **W:** Add wire
- **V:** Add voltage source (battery)
- **G:** Add ground
- **Ctrl+C / Ctrl+V:** Copy/paste components

### Oscilloscope (Scope):

- Right-click component → "View in New Scope"
- Green line = voltage across component
- Yellow line = current through component
- Shows how signals change over time
- Can stack multiple scopes for comparison
- Most useful for AC circuits and reactive components
- Less useful for DC circuits (flat lines)

### Visual Indicators:

- **Yellow dots:** Electron flow (current direction)
- **Green wires:** Positive voltage applied
- **Gray wires:** Ground or zero voltage
- **Highlighted component:** Mouse hover shows scope attachment

### Component Editing:

- Double-click component to change value
- Double-click wire to show current/voltage
- Right-click component for scope or delete
- Hover to see info (bottom-right corner)

### Ground Reference:

- All voltages measured relative to ground
- Can use wire loop back to source OR ground symbols
- Ground symbols cleaner (fewer wires)

- Functionally identical

## Practical Example & Numerical

### Building Simple Resistor Circuit:

*Step-by-Step:*

1. Press **V** → drag/drop to place 12V battery
2. Press **R** → drag/drop to place resistor
3. Press **W** → connect battery positive to resistor
4. Press **W** → connect resistor to battery negative (or use ground)
5. Double-click resistor → set to 500Ω
6. Double-click battery → set to 12V

*Reading the Circuit:*

- Hover over wire → bottom-right shows current: 24mA
- Green wire indicates positive voltage
- Yellow dots flow from negative to positive terminal

### Ohm's Law Verification:

$$V = 12\text{ V}$$

$$R = 500\ \Omega$$

$$I = \frac{V}{R} = \frac{12}{500} = 0.024\text{ A} = \boxed{24\text{ mA}}$$

Simulator shows exactly 24mA - confirms Ohm's Law!

### Pre-built Example - Ohm's Law Demo:

- Circuits → Basics → Ohm's Law
- Shows 5V source with two branches:
  - Branch 1: 100Ω resistor (higher current)
  - Branch 2: 1kΩ resistor (lower current)
- Demonstrates: Lower resistance → higher current

### Using Scope on AC Circuit:

- Load capacitor circuit example
- Right-click capacitor → "View in New Scope"
- Green line (voltage) shows sinusoidal wave
- Yellow line (current) shows phase shift
- Adjust simulation speed slider to slow down visualization

### Wire Voltage Display:

- Double-click wire → check "Show voltage"
- Wire connected to 12V battery shows: 12V
- Same as using voltmeter: red probe on wire, black probe on ground

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

1. **4 Interface Sections:** Menu (top-left), component list (Draw menu), canvas (center), controls (right)
2. **Keyboard Shortcuts:** R (resistor), W (wire), V (voltage), G (ground), Ctrl+C/V (copy/paste)
3. **Visual Feedback:** Yellow dots (electrons/current), green wires (positive voltage), gray (ground)
4. **Oscilloscope:** Right-click component for scope - green (voltage), yellow (current) over time
5. **Component Editing:** Double-click to change values, right-click for options
6. **Information Display:** Hover over component/wire shows voltage/current in bottom-right
7. **Ground Reference:** All voltages relative to ground; can use wire loop OR ground symbols
8. **Simulation Controls:** Speed sliders affect visualization only (not circuit behavior)

### Interview Questions:

- **Q:** How do you add a resistor in the simulator?  
A: Press "R" key, then click-drag-release to place resistor. Or use Draw menu → Add Resistor.
- **Q:** What do the yellow dots represent?  
A: Electron flow or electric current moving through the circuit.
- **Q:** What's the difference between green and gray wires?  
A: Green wires have positive voltage applied; gray wires are at ground (zero voltage).
- **Q:** How do you view voltage and current on a component over time?  
A: Right-click component → "View in New Scope". Green line = voltage, yellow line = current.
- **Q:** What does the simulation speed slider control?  
A: How fast the simulation runs visually - doesn't affect circuit calculations, only visualization speed.

#### **Typical Applications:**

- Testing circuit designs before building physically
- Understanding Ohm's Law and basic circuit behavior
- Visualizing AC circuits and phase relationships
- Learning component behavior (capacitors, inductors, diodes, transistors)
- Debugging circuits by observing voltage/current at different points
- Experimenting safely without risk of component damage

#### **Limitations:**

- Not suitable for complex professional circuit design
- Limited component library compared to professional tools
- Idealized components (no parasitic effects, tolerances)
- No PCB layout capabilities
- Basic simulation (no thermal, electromagnetic interference modeling)
- Focus on analog electronics (digital capabilities limited)

#### **Tips for Effective Use:**

- Practice keyboard shortcuts for faster circuit building
- Use pre-built example circuits to learn
- Hover over components frequently to check voltage/current
- Use scopes on AC circuits and reactive components
- Save circuits locally for later modification
- Start simple, gradually add complexity
- Verify calculations manually to reinforce learning

# Section 04: FUNDAMENTALS

## So, What is Voltage Anyway?

TL;DR (The Gist)

- **Voltage = Motivation** - How motivated electrons are to move from one point to another in a circuit
- **Resistance = Difficulty** - How hard the path is between two points (cost of travel)
- **Current = Flow** - How many electrons actually travel through wire per second

### Detailed Explanation

## 2. Detailed Explanation

### What is Voltage:

- Often explained with vague terms: "potential difference," "electric field," "electric tension"
- Simple analogy: **Voltage is motivation for electrons to move**
- Like cost-of-living difference motivating people to relocate (Tel Aviv expensive → Berlin cheaper)
- Higher voltage = more motivation for electrons to flow
- Measured in Volts (V)

### Common Voltage Levels:

- AA battery: 1.5V
- USB connector/phone charger: 5V
- Electronics: typically 3.3V, 5V
- Car appliances: 12V
- Mains power: 110V or 220V (region dependent)

### The Three Fundamental Elements:

#### 1. Voltage (Motivation):

- How motivated electrons are to move from point A to point B
- Like price difference motivating relocation
- Symbol: V, measured in Volts (V)

#### 2. Resistance (Difficulty):

- How hard the path is between two points
- Like cost of flights between cities
- High resistance = fewer electrons flow (expensive flights)
- Low resistance = many electrons flow (cheap flights)
- Symbol: R, measured in Ohms ( $\Omega$ )

#### 3. Current (Flow):

- How many electrons actually travel through wire per second
- Like number of people relocating daily
- Symbol: I, measured in Amperes (A)

### Ohm's Law - The Fundamental Relation:

$$V = I \times R$$

This simple formula defines the relationship between voltage, current, and resistance.

### Circuit Scenarios:

#### Open Circuit (Disconnected Leads):

- No route for electricity to flow
- Resistance = infinite ( $R = \infty$ )
- Current = zero ( $I = 0$ )
- Like no flights available - can't travel even with high motivation

#### Short Circuit (Positive & Negative Connected Directly):

- Nearly zero resistance path ( $R \approx 0$ )
- Huge current flows ( $I$  very large)
- Dangerous! Can damage battery/components
- Like massive cheap flights - even slight motivation causes huge travel

#### Resistor Connected:

- Controlled resistance path
- Current limited by Ohm's Law:  $I = \frac{V}{R}$
- Safe, controlled electron flow

#### Adding Resistors:

*Parallel Connection:*

- Adds another path for electrons
- Like adding another daily flight (more capacity)
- Total resistance decreases
- Current increases (same voltage)

*Series Connection:*

- Electrons must pass through both resistors
- Like requiring connection flight (Tel Aviv → London → Berlin)
- Total resistance increases
- Current decreases (same voltage)

## Practical Example & Numerical

### Example 1: Basic Circuit Calculation

Given:

Battery voltage:  $V = 1.5 \text{ V}$

Resistor:  $R = 100 \Omega$

Find current using Ohm's Law:

$$V = I \times R$$

$$1.5 = I \times 100$$

$$I = \frac{1.5}{100} = 0.015 \text{ A} = \boxed{15 \text{ mA}}$$

### Example 2: Adding Parallel Resistor

When we add second  $100\Omega$  resistor in parallel:

- Two paths for current now
- Like adding second daily flight (doubled capacity)
- Total resistance decreases:  $R_{total} = \frac{100 \times 100}{100 + 100} = 50 \Omega$
- Current increases:  $I = \frac{1.5}{50} = 0.03 \text{ A} = \boxed{30 \text{ mA}}$
- Current doubled because resistance halved!

### Example 3: Adding Series Resistor

When we add second  $100\Omega$  resistor in series:

- Electrons must pass through both resistors
- Like requiring connection flight (higher travel cost)
- Total resistance increases:  $R_{total} = 100 + 100 = 200 \Omega$
- Current decreases:  $I = \frac{1.5}{200} = 0.0075 \text{ A} = \boxed{7.5 \text{ mA}}$
- Current halved because resistance doubled!

### Travel Analogy Summary:

- **Tel Aviv expensive, Berlin cheap:** High voltage (motivation to move)
- **Flight cost:** Resistance (barrier to movement)
- **Daily travelers:** Current (actual flow)
- **More/cheaper flights:** Lower resistance (parallel resistors)
- **Connection flights:** Higher resistance (series resistors)

## Key Points (Interview Focus)

## 4. Key Points (Interview Focus)

1. **Voltage (V):** Motivation for electrons to move between two points (measured in Volts)
2. **Current (I):** Number of electrons flowing per second (measured in Amperes)
3. **Resistance (R):** Difficulty of path between points (measured in Ohms)
4. **Ohm's Law:**  $V = I \times R$  (fundamental relationship)
5. **Open circuit:** Infinite resistance, zero current (no path)
6. **Short circuit:** Near-zero resistance, huge current (dangerous!)
7. **Parallel resistors:** Decrease total resistance, increase current
8. **Series resistors:** Increase total resistance, decrease current

### Interview Questions:

- **Q:** What is voltage in simple terms?  
*A:* Voltage is the motivation for electrons to move from one point to another, like a price difference motivating relocation.
- **Q:** State Ohm's Law and explain each term.  
*A:*  $V = I \times R$  where V is voltage (motivation), I is current (flow rate), R is resistance (difficulty of path).
- **Q:** What happens in a short circuit?  
*A:* Near-zero resistance causes huge current to flow, potentially damaging components or causing fire.
- **Q:** How do parallel resistors affect total resistance?  
*A:* Parallel resistors decrease total resistance by providing multiple paths for current.
- **Q:** If you double the resistance in a circuit with constant voltage, what happens to current?  
*A:* Current is halved (from Ohm's Law:  $I = \frac{V}{R}$ ).

### Applications:

- Circuit design: calculating current draw from batteries
- Component selection: choosing resistors to limit current
- Power calculations: determining heat dissipation
- Safety: understanding short circuit dangers

### Common Misconceptions:

- **Wrong:** Voltage and current are the same thing  
**Right:** Voltage is motivation (pressure), current is actual flow
- **Wrong:** High voltage always means high current  
**Right:** High resistance can limit current even with high voltage
- **Wrong:** Batteries "contain" current  
**Right:** Batteries provide voltage; current depends on circuit resistance

## Voltage Drop

### TL;DR (The Gist)

- **Voltage drop:** Work per unit charge consumed by component when current flows through it
- Resistor drops voltage: positive terminal where current enters, negative where it exits
- **Series resistors:** Sum of all voltage drops = source voltage (Kirchhoff's Voltage Law)
- Higher resistance  $\rightarrow$  larger voltage drop (for same current)

### Detailed Explanation

## 2. Detailed Explanation

### What is Voltage Drop?

#### Conceptual Definition:

- Voltage = ability to do work of moving charge from one point to another
- Voltage drop = amount of work per unit charge consumed by component
- Battery/source supplies energy; resistors consume energy
- Work performed by battery is divided among components in circuit

#### Energy Perspective:

- 5V battery can do 5 joules of work per coulomb of charge

- Current flowing through resistor requires work
- This work consumption = voltage drop across resistor
- Voltage drop accounts for portion of voltage generated by battery

### Polarity of Voltage Drop (Conventional Current Flow):

*Single Resistor:*

- Current flows from higher voltage to lower voltage
- **Positive (+) terminal:** Where current enters resistor
- **Negative (-) terminal:** Where current exits resistor
- Resistor functions as load (consumes energy)

*Multiple Resistors in Series:*

- Current direction doesn't change throughout series circuit
- Each resistor: positive where current enters, negative where exits
- Polarity pattern consistent with current flow direction
- Important for Kirchhoff's Voltage Law analysis

### Voltage Division in Series Circuits:

*Key Principles:*

- Same current flows through all series resistors
- More resistance → more work needed → larger voltage drop
- Sum of all voltage drops = source voltage
- Work performed by battery divided among components

*Mathematical Relationship:*

$$V_{drop} = I \times R \quad (\text{Ohm's Law})$$

For series circuit:

$$V_{source} = V_{R1} + V_{R2} + V_{R3} + \dots$$

This is the foundation of **Kirchhoff's Voltage Law (KVL)**: Conservation of energy in circuits.

### Parallel Circuits vs Series:

*Parallel components:*

- Same voltage drop across all parallel resistors
- Each parallel branch connects directly to source terminals
- Voltage drop = source voltage for each branch

*Series components:*

- Different voltage drops (unless resistances equal)
- Voltage drops add up to source voltage
- Larger resistor gets larger share of voltage

### Foundation for Voltage Divider:

- Voltage divider exploits proportional voltage drop behavior
- Resistor with more resistance has larger voltage drop (same current)
- Can create specific output voltages from fixed source
- Used extensively in sensor circuits, biasing, level shifting

### Energy Conservation Principle:

- Energy supplied by source = energy consumed by loads
- Voltage is energy per unit charge
- Total voltage drops = total energy consumed per coulomb
- Kirchhoff's Voltage Law formalized this observation

## Practical Example & Numerical

### Example: Two Resistors in Series

*Given:*

- Battery:  $V_{source} = 12 \text{ V}$
- Resistor 1:  $R_1 = 1 \text{ k}\Omega$
- Resistor 2:  $R_2 = 2 \text{ k}\Omega$
- Configuration: Series

*Task:* Calculate voltage drop across each resistor.

### Step 1: Find Total Resistance

$$R_{total} = R_1 + R_2 \quad (\text{series})$$
$$R_{total} = 1,000 + 2,000 = 3,000 \Omega = 3 \text{ k}\Omega$$

### Step 2: Calculate Circuit Current (Ohm's Law)

$$I = \frac{V_{source}}{R_{total}}$$
$$I = \frac{12}{3,000} = 0.004 \text{ A} = 4 \text{ mA}$$

*Note:* Same 4mA flows through both resistors (series property)

### Step 3: Calculate Voltage Drop Across R1

$$V_{R1} = I \times R_1$$
$$V_{R1} = 0.004 \times 1,000 = 4 \text{ V}$$

### Step 4: Calculate Voltage Drop Across R2

$$V_{R2} = I \times R_2$$
$$V_{R2} = 0.004 \times 2,000 = 8 \text{ V}$$

### Step 5: Verify Kirchhoff's Voltage Law

$$V_{source} = V_{R1} + V_{R2}$$
$$12 = 4 + 8$$
$$12 = 12 \quad \checkmark \quad (\text{Verified!})$$

### Observations:

- $R_2$  has twice the resistance of  $R_1$  (2k $\Omega$  vs 1k $\Omega$ )
- $R_2$  has twice the voltage drop (8V vs 4V)
- **Proportional relationship:** Voltage drop proportional to resistance (same current)
- Sum of drops (12V) equals source voltage (12V) - energy conservation!

### Voltage Drop Ratios:

$$\frac{V_{R1}}{V_{source}} = \frac{R_1}{R_{total}} = \frac{1,000}{3,000} = \frac{1}{3} = 33.3\%$$
$$\frac{V_{R2}}{V_{source}} = \frac{R_2}{R_{total}} = \frac{2,000}{3,000} = \frac{2}{3} = 66.7\%$$

### Verification:

$$V_{R1} = V_{source} \times \frac{R_1}{R_{total}} = 12 \times \frac{1}{3} = 4 \text{ V} \quad \checkmark$$
$$V_{R2} = V_{source} \times \frac{R_2}{R_{total}} = 12 \times \frac{2}{3} = 8 \text{ V} \quad \checkmark$$

This ratio method is the basis of voltage divider formula!

### General Series Circuit (3 Resistors):

*Given:* 9V battery,  $R_1 = 100 \Omega$ ,  $R_2 = 200 \Omega$ ,  $R_3 = 300 \Omega$

*Total resistance:*  $R_{total} = 100 + 200 + 300 = 600 \Omega$

*Current:*  $I = \frac{9}{600} = 0.015 \text{ A} = 15 \text{ mA}$

*Voltage drops:*

$$V_{R1} = 15 \times 10^{-3} \times 100 = 1.5 \text{ V}$$
$$V_{R2} = 15 \times 10^{-3} \times 200 = 3.0 \text{ V}$$
$$V_{R3} = 15 \times 10^{-3} \times 300 = 4.5 \text{ V}$$

*Verification:*  $1.5 + 3.0 + 4.5 = 9 \text{ V} = V_{source} \quad \checkmark$

#### 4. Key Points (Interview Focus)

1. **Voltage drop:** Work per unit charge consumed by component (Joules/Coulomb)
2. **Polarity:** Positive where current enters, negative where current exits
3. **Ohm's Law:**  $V_{drop} = I \times R$
4. **Series circuits:**  $V_{source} = V_{R1} + V_{R2} + \dots$  (Kirchhoff's Voltage Law)
5. **Proportional:** Larger resistance  $\rightarrow$  larger voltage drop (same current)
6. **Energy conservation:** Total voltage drops = source voltage
7. **Parallel circuits:** All parallel components have same voltage drop = source voltage
8. **Foundation:** Voltage divider circuits exploit this proportional behavior

##### Interview Questions:

- **Q:** What is voltage drop?  
A: Amount of work per unit charge consumed by a component when current flows through it.
- **Q:** In series circuit with 10V source and two equal resistors, what's voltage drop across each?  
A: 5V across each (equal resistances  $\rightarrow$  equal voltage drops).
- **Q:** Series circuit: 12V battery, 3k $\Omega$  and 1k $\Omega$  resistors. Find voltage drops.  
A: Current =  $12V/4k\Omega = 3mA$ .  $V_{3k} = 3mA \times 3k\Omega = 9V$ ,  $V_{1k} = 3V$ . Sum = 12V ✓
- **Q:** What's the polarity of voltage drop across resistor?  
A: Positive (+) where current enters, negative (-) where current exits.
- **Q:** Why do voltage drops sum to source voltage in series circuit?  
A: Energy conservation - total energy consumed = energy supplied by source.
- **Q:** In series, which resistor has larger voltage drop: 1k $\Omega$  or 3k $\Omega$ ?  
A: 3k $\Omega$  resistor (more resistance requires more work for same current).

##### Applications:

- Voltage divider circuits (creating reference voltages)
- Sensor interfaces (converting resistance changes to voltage)
- Biasing transistors and op-amps
- LED current limiting (voltage left after resistor drop)
- Power distribution analysis
- Troubleshooting circuits (measuring drops to find faults)

##### Common Mistakes:

- Forgetting to add all drops in series (must equal source)
- Confusing series (drops add) with parallel (same voltage)
- Incorrect polarity assignment
- Not using total resistance to find current first

##### Connection to Other Topics:

- Leads to Kirchhoff's Voltage Law (KVL)
- Foundation for voltage divider design
- Critical for circuit analysis and troubleshooting
- Explains why components in series share source voltage

## Ohm's Law

### TL;DR (The Gist)

- **Ohm's Law:**  $V = I \times R$  - Current through conductor is proportional to voltage over resistance
- Can rearrange:  $I = \frac{V}{R}$  (find current) or  $R = \frac{V}{I}$  (find resistance)
- Water pipe analogy: Voltage = pressure, Current = flow rate, Resistance = pipe size

### Detailed Explanation

## 2. Detailed Explanation

### Ohm's Law - The Fundamental Equation:

$$V = I \times R$$

Where:

- V = Voltage (Volts)
- I = Current (Amperes)
- R = Resistance (Ohms)

### Rearranged Forms:

$$I = \frac{V}{R} \quad (\text{Calculate current})$$

$$R = \frac{V}{I} \quad (\text{Calculate resistance})$$

Any one variable can be calculated if you know the other two!

### What Ohm's Law Describes:

- How current flows through resistance when voltage applied at each end
- Relationship between three fundamental electrical quantities
- Current is proportional to voltage (higher V → higher I)
- Current is inversely proportional to resistance (higher R → lower I)

### Water Pipe Analogy:

- **Voltage:** Water pressure (motivation for flow)
- **Current:** Amount of water flowing through pipe
- **Resistance:** Size/diameter of pipe
- More pressure + bigger pipe → more water flows
- Bigger pipe = lower resistance → more current flows
- Higher pressure = higher voltage → more current flows

### Understanding Relationships:

*If resistance increases (voltage constant):*

- Current decreases
- Like narrower pipe → less water flows
- $I = \frac{V}{R}$  - higher R means lower I

*If voltage doubles (resistance constant):*

- Current also doubles
- Like doubling water pressure → double flow rate
- $I = \frac{V}{R}$  - double V means double I

### Parallel Circuits & Voltage:

- Components in parallel with voltage source all have same voltage drop
- If source is 5V, each parallel resistor has 5V across it
- Each branch can have different current (based on individual resistance)
- Total current from source = sum of branch currents

### Historical Context:

- Named after German physicist George Ohm
- First explained the relationship between V, I, and R
- Foundation of electrical circuit analysis

### Measurement Tools:

- **Voltmeter:** Measures voltage (V)
- **Ammeter:** Measures current (I)
- **Ohmmeter:** Measures resistance (R)
- **Multimeter:** Measures all three (plus more) - most practical choice

### Applicability:

- Generally applied to DC (Direct Current) circuits
- NOT directly applicable to AC circuits without modification
- AC circuits have additional factors: capacitance, inductance, phase
- For AC, must consider impedance (complex resistance)

**Example 1: Finding Voltage**

Given:  $I = 2 \text{ A}$ ,  $R = 13 \Omega$ , Find:  $V = ?$

$$V = I \times R$$

$$V = 2 \times 13 = \boxed{26 \text{ V}}$$

**Example 2: Finding Current**

Given:  $V = 5 \text{ V}$ ,  $R = 100 \Omega$ , Find:  $I = ?$

$$I = \frac{V}{R}$$

$$I = \frac{5}{100} = 0.05 \text{ A} = \boxed{50 \text{ mA}}$$

**Example 3: Finding Resistance**

Given:  $V = 12 \text{ V}$ ,  $I = 0.5 \text{ A}$ , Find:  $R = ?$

$$R = \frac{V}{I}$$

$$R = \frac{12}{0.5} = \boxed{24 \Omega}$$

**Example 4: Parallel Circuit Analysis**

Circuit:  $5 \text{ V}$  source with two resistors in parallel ( $100 \Omega$  and  $1 \text{ k}\Omega$ )

*Step 1: Voltage across each resistor*

- Both resistors in parallel with  $5 \text{ V}$  source
- Voltage across  $R_1$  ( $100 \Omega$ ) =  $5 \text{ V}$
- Voltage across  $R_2$  ( $1 \text{ k}\Omega$ ) =  $5 \text{ V}$
- **Key principle:** Parallel components share same voltage

*Step 2: Current through each resistor*

$$I_1 = \frac{V}{R_1} = \frac{5}{100} = 0.05 \text{ A} = \boxed{50 \text{ mA}}$$

$$I_2 = \frac{V}{R_2} = \frac{5}{1,000} = 0.005 \text{ A} = \boxed{5 \text{ mA}}$$

*Step 3: Total current from battery*

$$I_{total} = I_1 + I_2 = 50 + 5 = \boxed{55 \text{ mA}}$$

*Observations:*

- Lower resistance ( $100 \Omega$ )  $\rightarrow$  higher current ( $50 \text{ mA}$ )
- Higher resistance ( $1 \text{ k}\Omega$ )  $\rightarrow$  lower current ( $5 \text{ mA}$ )
- Battery supplies total:  $55 \text{ mA}$
- Current splits:  $50 \text{ mA} + 5 \text{ mA}$  at junction
- Recombines:  $55 \text{ mA}$  returns to battery

**Example 5: Effect of Doubling Voltage**

Original:  $V = 10 \text{ V}$ ,  $R = 5 \Omega$ ,  $I = \frac{10}{5} = 2 \text{ A}$

After doubling voltage:  $V = 20 \text{ V}$ ,  $R = 5 \Omega$  (same)

$$I = \frac{20}{5} = 4 \text{ A}$$

Result: Current also doubles! ( $2 \text{ A} \rightarrow 4 \text{ A}$ )

**Example 6: Effect of Increasing Resistance**

Original:  $V = 12 \text{ V}$ ,  $R = 4 \Omega$ ,  $I = \frac{12}{4} = 3 \text{ A}$

After increasing resistance:  $V = 12 \text{ V}$  (same),  $R = 12 \Omega$

$$I = \frac{12}{12} = 1 \text{ A}$$

Result: Current decreases! ( $3 \text{ A} \rightarrow 1 \text{ A}$  when  $R$  tripled)

### 4. Key Points (Interview Focus)

1. **Ohm's Law:**  $V = I \times R$  (most important circuit equation)
2. **Three forms:**  $V = IR$ ,  $I = \frac{V}{R}$ ,  $R = \frac{V}{I}$
3. **Current  $\propto$  Voltage:** Double voltage  $\rightarrow$  double current (R constant)
4. **Current  $\propto \frac{1}{R}$ :** Double resistance  $\rightarrow$  half current (V constant)
5. **Parallel voltage rule:** Components in parallel have same voltage across them
6. **Current splits:** In parallel, total current = sum of branch currents
7. **Applicability:** DC circuits primarily; AC requires impedance consideration
8. **Named after:** German physicist George Ohm
9. **Measurement:** Voltmeter (V), Ammeter (I), Ohmmeter (R), or Multimeter (all)

#### Interview Questions:

- **Q:** State Ohm's Law.  
**A:**  $V = I \times R$  - Voltage equals current times resistance.
- **Q:** If resistance increases and voltage stays constant, what happens to current?  
**A:** Current decreases (inversely proportional:  $I = \frac{V}{R}$ ).
- **Q:** If voltage across a resistor doubles, what happens to current?  
**A:** Current also doubles (directly proportional:  $I = \frac{V}{R}$ ).
- **Q:** Calculate current:  $V=12V$ ,  $R=6\Omega$ .  
**A:**  $I = \frac{V}{R} = \frac{12}{6} = 2A$
- **Q:** What voltage is needed for 3A through 10 $\Omega$  resistor?  
**A:**  $V = I \times R = 3 \times 10 = 30V$
- **Q:** Two resistors in parallel with 5V source - what's voltage across each?  
**A:** Both have 5V across them (parallel components share same voltage).
- **Q:** Does Ohm's Law apply to AC circuits?  
**A:** Not directly - AC requires considering impedance (capacitance, inductance, phase).

#### Applications:

- Calculating current consumption (battery life estimates)
- Selecting resistors for current limiting (LED circuits)
- Power calculations:  $P = V \times I = I^2 \times R = \frac{V^2}{R}$
- Voltage divider design
- Circuit troubleshooting and verification
- Component selection and rating verification

#### Common Mistakes to Avoid:

- Forgetting to convert units (mA  $\rightarrow$  A, k $\Omega$   $\rightarrow$   $\Omega$ )
- Applying DC Ohm's Law directly to AC without considering impedance
- Confusing series (same current) with parallel (same voltage)
- Not recognizing when components are in parallel with source

#### Memory Aid - Ohm's Triangle:

- Draw triangle with V on top, I and R on bottom
- Cover variable you want to find
- Remaining shows formula:  $V \rightarrow I \times R$ ,  $I \rightarrow V/R$ ,  $R \rightarrow V/I$

## Resistors in Series & Parallel

### TL;DR (The Gist)

- **Series:** Add resistances:  $R_{total} = R_1 + R_2 + R_3 + \dots$  (same current through all)
- **Parallel:** Reciprocal formula:  $\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \dots$  (total always less than smallest resistor)
- **Mixed circuits:** Break down into series/parallel sections, solve step-by-step, replace with equivalent resistance

### Detailed Explanation

## 2. Detailed Explanation

### Why Combine Resistors:

- Create specific resistance values not available as single component
- Example: Need  $500\Omega$  but only have  $1k\Omega$  resistors
- Solution 1: Two  $1k\Omega$  in parallel =  $500\Omega$
- Solution 2: Two  $250\Omega$  in series =  $500\Omega$
- Cheaper/faster than buying exact value

### Series Connection:

*Definition:*

- Resistors connected end-to-end in a line
- Current flows through each resistor sequentially
- Same current through all resistors (no branching)

*Formula:*

$$R_{total} = R_1 + R_2 + R_3 + \dots + R_n$$

*Characteristics:*

- Simply add up all resistance values
- Total resistance always greater than largest individual resistor
- Current is identical at all points in series path
- Voltages add up across resistors (Kirchhoff's Voltage Law)

*Practical Application:*

- Can replace multiple series resistors with single equivalent resistor
- Circuit behaves identically (same current, same total voltage drop)
- Useful for circuit simplification and analysis

### Parallel Connection:

*Definition:*

- Resistors connected across from each other
- All resistors share same voltage across them
- Current splits between multiple paths

*Formula:*

$$\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \dots + \frac{1}{R_n}$$

*Two Resistors in Parallel (Simplified):*

$$R_{total} = \frac{R_1 \times R_2}{R_1 + R_2}$$

*Characteristics:*

- Total resistance always less than smallest individual resistor
- Each resistor provides additional path for current
- More paths = lower total resistance
- Voltage across each resistor is identical
- Currents through resistors add up (Kirchhoff's Current Law)

### Mixed Series-Parallel Circuits:

*Solution Strategy:*

1. Identify series sections - calculate equivalent resistance
2. Replace series sections with single equivalent resistor
3. Identify parallel sections - calculate equivalent resistance
4. Replace parallel sections with single equivalent resistor
5. Repeat steps until single total resistance remains
6. Work systematically from inside out

*Purpose of Finding Total Resistance:*

- Calculate total current from source:  $I = \frac{V}{R_{total}}$
- Determine battery life (current consumption)
- Check if components can handle current
- Simplify circuit analysis
- Verify circuit design meets specifications

### Example 1: Series Resistors

Two resistors in series:  $R_1 = 1.5 \text{ k}\Omega$ ,  $R_2 = 1.5 \text{ k}\Omega$

$$R_{total} = R_1 + R_2 = 1.5 + 1.5 = \boxed{3 \text{ k}\Omega}$$

### Example 2: Finding Missing Resistor

Given:  $V = 50 \text{ V}$ ,  $I = 2 \text{ A}$ , resistors:  $5\Omega$ ,  $3\Omega$ ,  $4\Omega$ ,  $7\Omega$ ,  $R = ?$

Step 1: Find total resistance using Ohm's Law

$$R_{total} = \frac{V}{I} = \frac{50}{2} = 25 \Omega$$

Step 2: Sum of series resistances

$$R_{total} = 5 + 3 + 4 + 7 + R$$

$$25 = 19 + R$$

$$R = 25 - 19 = \boxed{6 \Omega}$$

Key insight: Single  $25\Omega$  resistor gives same current as all five resistors in series!

### Example 3: Parallel Resistors

Three resistors in parallel:  $R_1 = 4\Omega$ ,  $R_2 = 5\Omega$ ,  $R_3 = 20\Omega$

$$\begin{aligned} \frac{1}{R_{total}} &= \frac{1}{4} + \frac{1}{5} + \frac{1}{20} \\ &= \frac{5}{20} + \frac{4}{20} + \frac{1}{20} = \frac{10}{20} = \frac{1}{2} \\ R_{total} &= \boxed{2 \Omega} \end{aligned}$$

Note:  $2\Omega < 4\Omega$  (smallest resistor) ✓ Always true for parallel!

### Example 4: Two Resistors in Parallel (Shortcut)

$R_1 = 1 \text{ k}\Omega$ ,  $R_2 = 1 \text{ k}\Omega$  (equal values)

$$R_{total} = \frac{R_1 \times R_2}{R_1 + R_2} = \frac{1,000 \times 1,000}{1,000 + 1,000} = \frac{1,000,000}{2,000} = \boxed{500 \Omega}$$

Special case: Two equal resistors in parallel = half the value!

### Example 5: Mixed Series-Parallel Circuit

Complex circuit with multiple resistors:

Step 1: Combine series sections on left and right

- Left:  $3 + 8 = 11 \Omega$
- Right:  $2 + 4 = 6 \Omega$

Step 2: Combine right parallel section ( $6\Omega$  and  $12\Omega$ )

$$R_{parallel} = \frac{6 \times 12}{6 + 12} = \frac{72}{18} = 4 \Omega$$

Step 3: Combine new series ( $11\Omega$  and  $4\Omega$ )

$$R_{series} = 11 + 4 = 15 \Omega$$

Step 4: Final parallel ( $15\Omega$  and  $10\Omega$ )

$$R_{total} = \frac{15 \times 10}{15 + 10} = \frac{150}{25} = \boxed{6 \Omega}$$

Step 5: Calculate total current ( $12\text{V}$  source)

$$I = \frac{V}{R_{total}} = \frac{12}{6} = \boxed{2 \text{ A}}$$

### Creating $500\Omega$ from Available Resistors:

Option 1: Two  $1\text{k}\Omega$  in parallel

$$R = \frac{1,000 \times 1,000}{1,000 + 1,000} = 500 \Omega$$

Option 2: Two  $250\Omega$  in series

$$R = 250 + 250 = 500 \Omega$$

### 4. Key Points (Interview Focus)

1. **Series formula:**  $R_{total} = R_1 + R_2 + R_3 + \dots$  (simple addition)
2. **Parallel formula:**  $\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \dots$  (reciprocals)
3. **Series characteristic:** Same current through all, total  $R$   $\geq$  largest individual  $R$
4. **Parallel characteristic:** Same voltage across all, total  $R$   $\leq$  smallest individual  $R$
5. **Two equal resistors in parallel:** Total = half the value
6. **Two resistors in parallel shortcut:**  $R_{total} = \frac{R_1 \times R_2}{R_1 + R_2}$
7. **Mixed circuits:** Solve step-by-step, series first, then parallel, repeat
8. **Purpose:** Find total resistance to calculate current, battery life, power consumption

#### Interview Questions:

- **Q:** How do you calculate total resistance for series resistors?  
A: Add them up:  $R_{total} = R_1 + R_2 + R_3 + \dots$
- **Q:** How do you calculate total resistance for parallel resistors?  
A: Use reciprocal formula:  $\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \dots$
- **Q:** If you have two  $1k\Omega$  resistors in parallel, what's the total resistance?  
A:  $500\Omega$  (two equal resistors in parallel = half the value).
- **Q:** Is total parallel resistance greater or less than the smallest resistor?  
A: Always less than the smallest resistor in the parallel combination.
- **Q:** Why would you combine resistors instead of buying the exact value?  
A: To create specific values not readily available, faster/cheaper than ordering exact value.
- **Q:** What's the current distribution in series vs parallel?  
A: Series: same current through all. Parallel: current splits based on resistance values.

#### Applications:

- Creating custom resistance values from standard resistors
- Calculating current consumption for battery life estimation
- Voltage divider design (series resistors)
- Current divider design (parallel resistors)
- Circuit simplification for analysis
- Impedance matching in RF circuits

#### Quick Reference:

- **Two equal  $R$  in series:** Total =  $2R$
- **Two equal  $R$  in parallel:** Total =  $\frac{R}{2}$
- **Three equal  $R$  in series:** Total =  $3R$
- **Three equal  $R$  in parallel:** Total =  $\frac{R}{3}$
- **$n$  equal  $R$  in series:** Total =  $nR$
- **$n$  equal  $R$  in parallel:** Total =  $\frac{R}{n}$

## Resistor Introduction

### TL;DR (The Gist)

- Resistors are critical components in nearly every circuit, limiting current flow based on Ohm's Law ( $V = I \times R$ )
- Resistance measured in Ohms ( $\Omega$ ):  $1\Omega$  = resistance where 1V pushes 1A of current
- Color bands indicate value (4-band: 2 digits + multiplier + tolerance); easier to measure with multimeter

### Detailed Explanation

#### 2. Detailed Explanation

##### Resistor Purpose:

- Control current flow in circuits
- Limit current to protect components (LEDs, ICs)
- Create voltage dividers

- Set bias points for transistors/op-amps
- Critical in nearly every electronic circuit
- Major role in Ohm's Law:  $V = I \times R$

#### Resistor Structure:

- Two terminals (one connection on each end)
- Non-polarized (can be inserted either direction)
- Made from carbon composition, metal film, or wire-wound

#### Schematic Symbols:

- **American style:** Zigzag line pattern
- **International style:** Rectangle box
- Either acceptable - choose one and be consistent
- Simulator allows switching: Options → European resistors
- Functionality identical regardless of symbol style

#### Naming Convention:

- Typically: R1, R2, R3, etc.
- Each resistor needs unique identifier
- Naming helps distinguish between multiple resistors
- 99% of cases use R + number scheme
- Can use any naming as long as consistent

#### Resistance - The Property:

- **"Resistor":** Name of component
- **"Resistance":** Intrinsic property (measured in ohms)
- Symbol:  $\Omega$  (Greek capital Omega)
- **Definition:**  $1\Omega$  = resistance where 1V pushes 1A
- Derived from Ohm's Law:  $R = \frac{V}{I}$

#### Unit Prefixes:

- **k $\Omega$  (kilo-ohm):**  $\times 1,000$  (very common)
- **M $\Omega$  (mega-ohm):**  $\times 1,000,000$  (common)
- **G $\Omega$  (giga-ohm):**  $\times 1,000,000,000$  (rare)
- **m $\Omega$  (milli-ohm):**  $\times 0.001$  (rare)
- Examples:  $4,700\Omega = 4.7k\Omega$ ;  $5,600,000\Omega = 5.6M\Omega$

#### Color Code (4-Band Resistors):

- **Band 1:** First significant digit
- **Band 2:** Second significant digit
- **Band 3:** Multiplier (power of 10)
- **Band 4:** Tolerance ( $\pm\%$ )
- Also 5-band and 6-band variants (higher precision)

#### Tolerance:

- Indicates manufacturing accuracy
- How much actual resistance can deviate from nominal value
- Common:  $\pm 5\%$ ,  $\pm 10\%$ ,  $\pm 20\%$
- Precision:  $\pm 1\%$ ,  $\pm 0.1\%$  (more expensive)
- Example:  $1k\Omega$  with 5% tolerance =  $0.95k$  to  $1.05k\Omega$  actual
- No resistor is perfect - all have tolerance
- Higher precision = more expensive (requires controlled manufacturing)

#### Measuring Resistance with Multimeter:

- Much easier than decoding color bands
- Many engineers don't memorize color codes - they measure!
- Set multimeter to ohms mode ( $20k\Omega$  good starting point)
- Touch probes to resistor legs
- Read displayed value

#### Multimeter Reading Interpretation:

- **Displays value (e.g., 0.97):** Resistance in selected range ( $970\Omega$  in  $20k$  mode)
- **Displays "1" or "OL":** Overload - resistance too high, switch to higher range
- **Displays "0.00":** Resistance too low for range, switch to lower range
- **More digits after decimal:** Lower ranges give higher resolution
- Rare to see resistors  $< 1\Omega$  (rule of thumb)

Example 1: Unit Conversion

Convert large values to readable format:

$$\begin{aligned} 4,700 \, \Omega &= 4.7 \, \text{k}\Omega \\ 47,000 \, \Omega &= 47 \, \text{k}\Omega \\ 5,600,000 \, \Omega &= 5,600 \, \text{k}\Omega = 5.6 \, \text{M}\Omega \end{aligned}$$

Example 2: Color Code Decoding

4-band resistor: Red-Green-Brown-Gold

$$\begin{aligned} \text{Band 1 (Red):} & \quad 2 \\ \text{Band 2 (Green):} & \quad 5 \\ \text{Band 3 (Brown):} & \quad \times 10 \\ \text{Band 4 (Gold):} & \quad \pm 5\% \end{aligned}$$

Calculation:

$$(2 \times 10 + 5) \times 10 = 25 \times 10 = \boxed{250 \, \Omega \pm 5\%}$$

Example 3: Tolerance Range

1kΩ resistor with 5% tolerance:

$$\begin{aligned} \text{Nominal:} & \quad 1,000 \, \Omega \\ \text{Tolerance:} & \quad \pm 5\% = \pm 50 \, \Omega \\ \text{Minimum:} & \quad 1,000 - 50 = 950 \, \Omega \\ \text{Maximum:} & \quad 1,000 + 50 = 1,050 \, \Omega \\ \text{Actual range:} & \quad \boxed{950 \, \Omega \text{ to } 1,050 \, \Omega} \end{aligned}$$

Example 4: Multimeter Measurement

Measuring unknown resistor:

- Set multimeter to 20kΩ range
- Display shows: 0.97
- Interpretation:  $0.97 \times 1,000 = \boxed{970 \, \Omega \approx 1 \, \text{k}\Omega}$

Switch to 2kΩ range for better resolution:

- Display shows: 0.973
- More precise:  $\boxed{973 \, \Omega}$

Switch to 200Ω range:

- Display shows: "1" or "OL" (overload)
- Resistor is 200Ω, range too low
- Must use higher range

Common Color Code Reference:

- Black = 0, Brown = 1, Red = 2, Orange = 3, Yellow = 4
- Green = 5, Blue = 6, Violet = 7, Gray = 8, White = 9
- Gold = ±5%, Silver = ±10%, None = ±20%

Key Points (Interview Focus)

4. Key Points (Interview Focus)

1. Resistors limit current flow, critical in nearly every circuit
2. Resistance measured in Ohms (Ω): 1Ω = 1V pushes 1A
3. Two schematic symbols: American (zigzag) and International (rectangle)
4. Named R1, R2, R3, etc. for unique identification
5. Common units: kΩ (kilo-ohm), MΩ (mega-ohm)
6. 4-band color code: 2 digits + multiplier + tolerance

7. Tolerance indicates manufacturing accuracy ( $\pm 5\%$ ,  $\pm 10\%$ , etc.)
8. Easier to measure with multimeter than decode color bands
9. No resistor is perfect - all have tolerance range
10. Higher precision resistors cost more

#### Interview Questions:

- **Q:** What is the definition of 1 Ohm?  
A: The resistance between two points where 1V of potential will push 1A of current.
- **Q:** What does a  $1k\Omega$  resistor with 5% tolerance mean?  
A: The actual resistance can be anywhere from  $950\Omega$  to  $1,050\Omega$  ( $950\Omega$  to  $1.05k\Omega$ ).
- **Q:** How do you quickly find a resistor's value?  
A: Use a multimeter in ohms mode - much faster than decoding color bands.
- **Q:** What do the 4 color bands on a resistor indicate?  
A: First two digits, multiplier (power of 10), and tolerance.
- **Q:** Why do resistors have tolerance?  
A: Manufacturing is imperfect - impossible to make exact values in mass production. Higher precision requires more time/cost.

#### Applications:

- Current limiting (protecting LEDs, ICs)
- Voltage dividers (creating reference voltages)
- Pull-up/pull-down resistors (digital logic)
- Biasing transistors and op-amps
- Filtering circuits (with capacitors)
- Setting gain in amplifiers

#### Practical Tips:

- Keep multimeter handy - faster than color code lookup
- Online calculators available for color code decoding
- 10-20% tolerance acceptable for most general electronics
- Precision applications need  $\pm 1\%$  or better
- Start with  $20k\Omega$  multimeter range, adjust as needed
- Resistors are non-polarized (can be installed either way)

## How to Measure Voltage and Current in a Circuit

### TL;DR (The Gist)

- **Current measurement:** Place ammeter in series (break circuit, insert ammeter so current flows through it)
- **Voltage measurement:** Place voltmeter in parallel (red probe at measurement point, black probe at ground)
- All voltage measurements are referenced to ground (0V) - ground is the common reference point

### Detailed Explanation

## 2. Detailed Explanation

#### Digital Multimeter (DMM):

- Most widely used test equipment for current/voltage measurements
- Widely available at reasonable prices
- Essential for home, hobbyists, and professional engineers
- Typical features: voltage, current, resistance measurement
- Often includes specialized features (capacitance, frequency, continuity, etc.)
- Invaluable in any electronics laboratory

#### Ammeter vs Multimeter:

- **Ammeter:** Only measures current
- **Multimeter:** Measures current, voltage, resistance, and more
- Most people buy multimeter (more features, same price range)
- Digital multimeter has ammeter function integrated

## Measuring Current:

### *Procedure:*

1. Break the circuit at desired measurement point
2. Insert ammeter in series (current must flow through it)
3. Electrons flowing through path also flow through ammeter
4. Location doesn't matter - same current everywhere in series path
5. Read current value on ammeter display

### *Why Series Connection:*

- Current must physically flow through ammeter
- Same electrons that flow in circuit flow through meter
- Cannot measure current without breaking circuit
- Current is same at all points in series path

### *In Real Life with Multimeter:*

- Use red and black probes
- Break circuit at measurement point
- Connect probes at both ends (completing circuit through meter)
- Current flows through multimeter
- Display shows current value

### *Simulator Shortcut:*

- Instead of placing ammeter component
- Double-click wire where current measurement desired
- Check "Show current" option
- Current value displays on wire
- More convenient, less visual clutter

## Current Units & Conversion:

- Base unit: Ampere (A)
- Must convert to amperes for calculations (Ohm's Law, etc.)
- Common prefixes:
  - mA (milliampere) =  $10^{-3}$  A = 0.001 A
  - $\mu$ A (microampere) =  $10^{-6}$  A = 0.000001 A
  - kA (kiloampere) =  $10^3$  A = 1000 A

## Measuring Voltage:

### *Understanding Voltage:*

- Voltage = potential difference between two points
- If Point A is 5V and Point B is 0V  $\rightarrow$  potential difference = 5V
- Always measured *between* two points (not at single point)

### *Ground Reference:*

- Every circuit must have ground (even battery-powered)
- Ground = place of return for electricity
- Ground = 0V reference (everything measured relative to it)
- Current flows from high voltage to low voltage (ending at ground)
- Without ground, no current would flow
- Called "ground" because Earth has 0V electric potential

### *Voltage Measurement Procedure:*

1. Place voltmeter in parallel with component/point
2. Red probe (+) at measurement point
3. Black probe (-) at ground (0V reference)
4. Voltmeter displays voltage difference
5. No need to break circuit (parallel connection)

### *Key Principle - Reference Consistency:*

- All voltages referenced to ground (unless specified otherwise)
- Must be consistent in measurement reference
- Decide comparison point (usually ground) and stick with it
- Ground is universal 0V reference in circuit

### *Simulator Shortcuts:*

- Right-click  $\rightarrow$  Outputs/Labels  $\rightarrow$  Voltmeter
- OR double-click wire  $\rightarrow$  check "Show voltage"

- Second method cleaner (less visual clutter)
- Voltage always displayed relative to ground

#### Voltage Distribution in Series:

- Total source voltage must be "dropped" across components
- Voltage drops add up to source voltage
- If not all voltage dropped → short circuit
- Ground always at 0V potential
- Equal resistances in series → equal voltage drops

### Practical Example & Numerical

#### Example 1: Current Measurement

Circuit: 5V battery with 100Ω resistor

*Measuring Current:*

- Ammeter reads: 50mA
- Convert to amperes: 50 mA = 0.05 A

*Verify with Ohm's Law:*

$$V = I \times R$$

$$R = \frac{V}{I} = \frac{5 \text{ V}}{0.05 \text{ A}} = \boxed{100 \Omega}$$

Correct! Confirms measurement.

#### Example 2: Voltage Measurement

Circuit: 5V battery with two 100Ω resistors in series

*Voltage at different points:*

At positive terminal: 5 V (relative to ground)

Between resistors: 2.5 V (relative to ground)

At ground: 0 V

*Voltage drops across components:*

First resistor: 5 V – 2.5 V = 2.5 V

Second resistor: 2.5 V – 0 V = 2.5 V

Total drop: 2.5 V + 2.5 V =  $\boxed{5 \text{ V}}$

Equal resistances → equal voltage drops!

#### Example 3: Single Resistor

Circuit: 5V battery with one 100Ω resistor

*Voltage measurements:*

Across resistor: 5 V (entire source voltage)

At one end: 5 V (before resistor)

At other end: 0 V (after resistor, at ground)

Whole voltage dropped across single component!

#### Common Unit Conversions:

$$50 \text{ mA} = 0.05 \text{ A}$$

$$100 \text{ mA} = 0.1 \text{ A}$$

$$1.5 \text{ A} = 1500 \text{ mA}$$

$$500 \mu\text{A} = 0.5 \text{ mA} = 0.0005 \text{ A}$$

### Key Points (Interview Focus)

## 4. Key Points (Interview Focus)

1. **Current measurement:** Ammeter in series (break circuit, current flows through meter)
2. **Voltage measurement:** Voltmeter in parallel (red to point, black to ground)
3. **Ground:** 0V reference point, place of return for electricity, essential in every circuit
4. **Voltage is relative:** Always measured between two points (usually point-to-ground)
5. **Unit conversion:** Must convert mA to A for calculations ( $50\text{mA} = 0.05\text{A}$ )
6. **Series voltage:** Drops add up to source voltage (Kirchhoff's Voltage Law)
7. **Measurement reference:** Be consistent - all voltages typically referenced to ground
8. **Digital multimeter:** Essential tool, measures voltage, current, resistance, and more

### Interview Questions:

- **Q:** How do you measure current with a multimeter?  
**A:** Break the circuit, insert multimeter in series so current flows through it, read display.
- **Q:** How do you measure voltage with a multimeter?  
**A:** Place multimeter in parallel: red probe at measurement point, black probe at ground, read display.
- **Q:** Why must current meters be placed in series?  
**A:** Because current must physically flow through the meter to be measured.
- **Q:** What is ground in an electrical circuit?  
**A:** The 0V reference point where all voltages are measured from, and the return path for current.
- **Q:** Convert 75mA to amperes.  
**A:**  $75\text{mA} = 0.075\text{A}$  (divide by 1000).
- **Q:** If you have two equal resistors in series with a 10V source, what's the voltage across each?  
**A:** 5V across each (voltage divides equally for equal resistances).

### Applications:

- Troubleshooting circuits (checking if current/voltage is correct)
- Verifying component operation
- Measuring current consumption (battery life calculations)
- Checking voltage drops across components
- Circuit analysis and validation

### Important Reminders:

- **Current:** Series connection (break circuit)
- **Voltage:** Parallel connection (don't break circuit)
- **Units:** Always convert to base units (A, V,  $\Omega$ ) for calculations
- **Ground:** Universal 0V reference, essential in all circuits
- **Safety:** Turn off power before breaking circuit to insert ammeter

## Direct Current (DC) vs Alternating Current (AC)

### TL;DR (The Gist)

- **DC (Direct Current):** Constant voltage/current flowing in one direction only (batteries, USB chargers)
- **AC (Alternating Current):** Voltage/current periodically reverses direction (household mains power, typically sinusoidal)
- Conventional current flow (+ to -) is opposite to actual electron flow (- to +) due to historical convention

### Detailed Explanation

## 2. Detailed Explanation

### DC Power Source Symbols:

- **Battery symbol:** Multiple cells (long line = positive, short line = negative)
- **Cell symbol:** Single cell (simpler version)
- Often used interchangeably
- **Cell:** Single unit converting chemical energy to electrical energy (e.g., AA battery = 1 cell = 1.5V)
- **Battery:** Collection of cells in series (e.g., 12V car battery = 6 cells  $\times$  2.1V = 12.6V fully charged)

### Direct Current (DC):

- Unidirectional flow of current (only one direction)
- Provides constant voltage and current
- Does NOT oscillate back and forth
- Voltage/current can vary over time, but direction stays same
- Positive DC voltage causes current to flow from + to - terminal (conventional)
- Examples: batteries, USB chargers, solar panels, DC power supplies

#### **Alternating Current (AC):**

- Electric charge changes direction periodically
- Voltage also periodically reverses
- Most common waveform: sinusoidal (sine wave)
- Symbol: circle with sine wave inside
- Constantly changing polarity every half cycle
- Alternates between positive maximum and negative maximum
- Examples: household mains (110V/220V), power grid, generators

#### **AC Waveform Characteristics:**

- **Sinusoidal:** Most important AC waveform in electrical engineering
- **Polarity:** Changes every half cycle
- **Current direction:** Reverses with voltage polarity
- Positive voltage → current flows clockwise
- Negative voltage → current flows counterclockwise

#### **Conventional vs Actual Current Flow:**

- **Historical mistake:** Early scientists thought positive charges flowed
- **Reality discovered:** Negative charges (electrons) actually flow
- **Convention kept:** Positive charge flow from + to - (conventional current)
- **Actual flow:** Electrons flow from - to + (electron flow)
- Both conventions work - just be consistent!
- Most circuit analysis uses conventional current (+ to -)

#### **Visualization in Simulator:**

- DC: Yellow dots flow steadily in one direction
- AC: Yellow dots oscillate back and forth periodically
- Scope on DC source: Flat horizontal line (constant voltage)
- Scope on AC source: Sine wave (voltage oscillating positive/negative)

## **Practical Example & Numerical**

### **DC Circuit Example:**

Circuit: 1.5V battery with resistor

- Voltage source: Constant 1.5V
- Scope view: Flat line at 1.5V
- Current direction: Always from + to - (conventional)
- Yellow dots: Flow steadily in one direction

### **Battery Cell Calculation:**

AA battery (1.5V):

Number of cells = 1 (single cell)

Car battery (12V):

Cells per battery: 6

Voltage per cell: 2.1 V (fully charged)

Total voltage:  $6 \times 2.1 = 12.6 \text{ V}$

### **AC Circuit Example:**

Circuit: AC source with resistor

- Voltage: Sinusoidal waveform (e.g., 120V RMS, 60Hz)
- Scope view: Sine wave oscillating above/below zero
- Current direction: Reverses every half cycle

- Positive voltage → clockwise current flow
- Negative voltage → counterclockwise current flow

#### Household Mains Examples:

North America: 120 V AC, 60 Hz  
 Europe: 220 V AC, 50 Hz  
 Peak voltage (120V):  $120 \times \sqrt{2} \approx 170 \text{ V}$

(120V is RMS value; peak voltage is higher)

#### Current Flow Direction:

- **Conventional current:** + to - (used in circuit analysis)
- **Electron flow:** - to + (actual physical movement)
- Both give correct results - just stay consistent!

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

1. **DC:** Unidirectional current flow, constant voltage (batteries, USB = 5V DC)
2. **AC:** Bidirectional current flow, voltage reverses periodically (household mains)
3. **Cell vs Battery:** Cell = single unit (1.5V), Battery = multiple cells (12V = 6 cells)
4. **Conventional current:** Flows from + to - (historical convention, used in analysis)
5. **Electron flow:** Electrons actually flow from - to + (opposite direction)
6. **Sinusoidal waveform:** Most common AC waveform (sine wave)
7. **AC polarity:** Changes every half cycle (positive ↔ negative)
8. **DC visualization:** Flat line on scope, steady electron flow
9. **AC visualization:** Sine wave on scope, electrons oscillate back/forth

#### Interview Questions:

- **Q:** What's the difference between DC and AC?  
 A: DC flows in one direction with constant voltage; AC periodically reverses direction with oscillating voltage.
- **Q:** Why is conventional current opposite to electron flow?  
 A: Early scientists incorrectly assumed positive charges flowed. When electrons (negative) were discovered as actual carriers, the convention was kept for consistency.
- **Q:** What's the difference between a cell and a battery?  
 A: A cell is a single unit (1.5V); a battery is multiple cells in series (12V car battery = 6 cells).
- **Q:** What waveform does household AC power typically have?  
 A: Sinusoidal (sine wave), oscillating between positive and negative peaks.
- **Q:** Give examples of DC and AC sources.  
 A: DC: batteries, USB chargers, solar panels. AC: household mains, power grid, generators.

#### Applications:

- DC: Portable electronics, batteries, digital circuits, LEDs, motors (DC motors)
- AC: Power transmission (efficient over long distances), household appliances, transformers, AC motors
- Conversion: AC-to-DC (rectifiers in phone chargers), DC-to-AC (inverters in solar systems)

#### Key Differences Summary:

- **Direction:** DC = one way, AC = both ways (alternating)
- **Voltage:** DC = constant, AC = oscillating
- **Sources:** DC = batteries/cells, AC = generators/mains
- **Transmission:** AC better for long distance (transformers)
- **Electronics:** Most devices internally use DC (converted from AC)

## Voltage Divider

### TL;DR (The Gist)

- **Voltage Divider:** Simple circuit using two series resistors to create smaller voltage from larger source
- **Formula:**  $V_{out} = V_{in} \times \frac{R_2}{R_1 + R_2}$
- Can produce any voltage between 0V and  $V_{in}$  (cannot boost above input)
- One of most fundamental circuits in electronics (used in biasing, sensing, level shifting)

## Detailed Explanation

### 2. Detailed Explanation

#### Voltage Divider Concept:

*What it does:*

- Converts large voltage into smaller voltage
- Uses two resistors in series
- Output voltage = fraction of input voltage
- Output taken from junction between resistors (referenced to ground)

*Basic Circuit:*

- Top: Input voltage source ( $V_{in}$ )
- Middle: Two resistors in series ( $R_1$  and  $R_2$ )
- Bottom: Ground (reference point, 0V potential)
- Output: Voltage at junction between  $R_1$  and  $R_2$  (measured to ground)

#### Voltage Divider Formula:

$$V_{out} = V_{in} \times \frac{R_2}{R_1 + R_2}$$

Where:

- $V_{in}$  = Input voltage (source voltage)
- $V_{out}$  = Output voltage (at junction between resistors)
- $R_1$  = Upper resistor (connected to  $V_{in}$ )
- $R_2$  = Lower resistor (connected to ground)
- $\frac{R_2}{R_1 + R_2}$  = Scale factor (determines voltage fraction)

#### How It Works (Voltage Drop Analysis):

*Step-by-step:*

1. Current flows from  $V_{in}$  through  $R_1$ , then  $R_2$ , to ground
2. Same current through both resistors (series circuit)
3. Each resistor drops voltage proportional to its resistance
4. Voltage drop across  $R_1$ :  $V_{R1} = I \times R_1$
5. Voltage drop across  $R_2$ :  $V_{R2} = I \times R_2$
6. Output voltage = voltage at junction =  $V_{in} - V_{R1} = V_{R2}$

*Example calculation (equal resistors):*

- $V_{in} = 5V$ ,  $R_1 = R_2 = 1k\Omega$
- Total resistance:  $R_{total} = 1k + 1k = 2k\Omega$
- Current:  $I = \frac{5V}{2k\Omega} = 2.5mA$
- Voltage drop across  $R_1$ :  $V_{R1} = 2.5mA \times 1k\Omega = 2.5V$
- Voltage drop across  $R_2$ :  $V_{R2} = 2.5mA \times 1k\Omega = 2.5V$
- Output voltage:  $V_{out} = 5V - 2.5V = 2.5V$  (or simply  $V_{R2} = 2.5V$ )

Result: Input voltage halved! ( $5V \rightarrow 2.5V$ )

#### Key Principles:

*Voltage Range:*

- Can only reduce voltage, never increase
- Output range:  $0V \leq V_{out} \leq V_{in}$
- If  $R_2 = 0$  (short),  $V_{out} = 0V$
- If  $R_1 = 0$  (short),  $V_{out} = V_{in}$  (but dangerous - short circuit!)
- If  $R_2 \gg R_1$ ,  $V_{out} \approx V_{in}$
- If  $R_1 \gg R_2$ ,  $V_{out} \approx 0V$

*Scale Factor:*

- $\frac{R_2}{R_1 + R_2}$  determines voltage fraction

- Equal resistors: scale = 0.5 (half voltage)
- $R_2 = 3 \times R_1$ : scale = 0.75 (three-quarters voltage)
- Change ratio to change output voltage

#### Ground Reference:

- Ground = 0V reference point
- All voltages measured relative to ground
- Ground symbol can be placed anywhere in circuit (electrically same point)
- Output voltage measured between junction and ground

#### Short Circuit Warning:

- If no resistance between  $V_{in}$  and ground  $\rightarrow$  short circuit
- Current:  $I = \frac{V}{R}$ , if  $R = 0$ , then  $I = \frac{V}{0} = \infty$  (theoretically)
- Real result: Very high current  $\rightarrow$  component damage, fire hazard
- Always ensure resistance between voltage source and ground
- Current must drop all voltage before reaching ground

#### Importance in Electronics:

- "If Ohm's Law is learning ABC, voltage divider is learning to spell 'cat'" (fundamental!)
- Used in: biasing transistors, op-amp feedback, sensor circuits, reference voltages
- Foundation for understanding more complex circuits
- Practical limitation: Cannot source significant current (covered in next topic)

#### Choosing R1 and R2 Values:

- Ratio determines output voltage (formula gives ratio)
- Absolute values determined by load requirements
- Lower resistances  $\rightarrow$  more current wasted, but better load regulation
- Higher resistances  $\rightarrow$  less power wasted, but more affected by load
- Typical range: 1k $\Omega$  to 100k $\Omega$  for low-power applications
- Load current consideration critical (next topic: voltage divider under load)

### Practical Example & Numerical

#### Example 1: Creating 2.5V from 5V (Equal Resistors)

Given:  $V_{in} = 5V$ ,  $R_1 = R_2 = 1k\Omega$

Find:  $V_{out}$

##### Method 1 - Using Formula:

$$V_{out} = V_{in} \times \frac{R_2}{R_1 + R_2}$$

$$V_{out} = 5 \times \frac{1,000}{1,000 + 1,000}$$

$$V_{out} = 5 \times \frac{1,000}{2,000} = 5 \times 0.5 = \boxed{2.5V}$$

##### Method 2 - Using Current:

$$R_{total} = 1k + 1k = 2k\Omega$$

$$I = \frac{V_{in}}{R_{total}} = \frac{5}{2,000} = 2.5mA$$

$$V_{out} = I \times R_2 = 0.0025 \times 1,000 = \boxed{2.5V}$$

#### Example 2: Creating 3.3V from 5V (For Microcontroller)

Given:  $V_{in} = 5V$ , desired  $V_{out} = 3.3V$

Find: Resistor ratio

### Using Voltage Divider Formula:

$$V_{out} = V_{in} \times \frac{R_2}{R_1 + R_2}$$
$$3.3 = 5 \times \frac{R_2}{R_1 + R_2}$$
$$\frac{R_2}{R_1 + R_2} = \frac{3.3}{5} = 0.66$$

### Solving for Resistor Ratio:

Let  $R_2 = 1k\Omega$  (arbitrary choice), find  $R_1$ :

$$\frac{1,000}{R_1 + 1,000} = 0.66$$
$$1,000 = 0.66 \times (R_1 + 1,000)$$
$$1,000 = 0.66R_1 + 660$$
$$340 = 0.66R_1$$
$$R_1 = \frac{340}{0.66} \approx 515 \Omega$$

**Standard Values:** Use  $R_1 = 510\Omega$  (closest standard),  $R_2 = 1k\Omega$

### Verification:

$$V_{out} = 5 \times \frac{1,000}{510 + 1,000} = 5 \times \frac{1,000}{1,510}$$
$$V_{out} = 5 \times 0.662 \approx \boxed{3.31V} \quad (\text{close enough!})$$

### Example 3: Multiple Output Voltages

Given:  $V_{in} = 12V$ , want  $V_{out} = 1V, 2V, 3V$

Use three resistors in series:  $R_1, R_2, R_3$  (equal values for equal spacing)

If  $R_1 = R_2 = R_3 = R$ :

$$V_1 = 12 \times \frac{3R}{3R} = 12V \quad (\text{top, before } R_1)$$
$$V_2 = 12 \times \frac{2R}{3R} = 8V \quad (\text{after } R_1)$$
$$V_3 = 12 \times \frac{R}{3R} = 4V \quad (\text{after } R_2)$$
$$V_4 = 0V \quad (\text{ground})$$

Not quite 1V, 2V, 3V spacing! Need unequal resistors for that.

### Example 4: Sensor Application (Potentiometer as Variable Divider)

Potentiometer = variable resistor with wiper (adjustable voltage divider)

- Total resistance:  $10k\Omega$
- Input:  $5V$
- Wiper position adjusts  $R_1$  and  $R_2$  ratio
- At middle:  $R_1 = R_2 = 5k$ ,  $V_{out} = 2.5V$
- Fully clockwise:  $R_1 = 0$ ,  $R_2 = 10k$ ,  $V_{out} = 5V$
- Fully counter-clockwise:  $R_1 = 10k$ ,  $R_2 = 0$ ,  $V_{out} = 0V$
- Output range:  $0V$  to  $5V$  (continuously adjustable)

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

1. **Formula:**  $V_{out} = V_{in} \times \frac{R_2}{R_1 + R_2}$
2. **Function:** Converts large voltage to smaller voltage (never boosts)
3. **Output range:**  $0V \leq V_{out} \leq V_{in}$
4. **Equal resistors:** Output = half input voltage
5. **Ground:**  $0V$  reference point (all voltages measured relative to it)

6. **Short circuit:** Never connect  $V_{in}$  directly to ground (zero resistance  $\rightarrow$  infinite current)
7. **Fundamental circuit:** Basis for biasing, sensing, feedback, reference generation
8. **Limitation:** Cannot source significant current without affecting output (needs load consideration)

#### Interview Questions:

- **Q:** What is voltage divider used for?  
A: Converting large voltage to smaller voltage using two series resistors.
- **Q:** Write voltage divider formula.  
A:  $V_{out} = V_{in} \times \frac{R_2}{R_1 + R_2}$  where  $R_2$  is lower resistor.
- **Q:** 5V input, equal  $1k\Omega$  resistors. Find output voltage.  
A:  $V_{out} = 5 \times \frac{1k}{1k + 1k} = 5 \times 0.5 = 2.5V$
- **Q:** Can voltage divider boost voltage above input?  
A: No, can only reduce voltage (0V to  $V_{in}$  range).
- **Q:** Why is ground important in voltage divider?  
A: Ground is 0V reference point; output voltage measured between junction and ground.
- **Q:** What happens if you connect 5V directly to ground (no resistor)?  
A: Short circuit - theoretically infinite current, practically component damage/fire.
- **Q:** To get 3.3V from 5V, what resistor ratio needed?  
A:  $\frac{R_2}{R_1 + R_2} = \frac{3.3}{5} = 0.66$ , so  $R_2 \approx 2 \times R_1$  (e.g.,  $R_1 = 1k$ ,  $R_2 = 2k$  approximation).

#### Applications:

- Biasing transistors and op-amps (setting DC operating point)
- Sensor circuits (potentiometers, thermistors, photoresistors)
- Reference voltage generation
- Level shifting (interfacing different voltage logic levels)
- Feedback networks in voltage regulators
- Battery voltage monitoring
- Analog-to-digital converter (ADC) input scaling

#### Design Considerations:

- **Resistor ratio:** Determines output voltage
- **Resistor values:** Affects power consumption and load regulation
- **Power dissipation:**  $P = \frac{V_{in}^2}{R_1 + R_2}$  (continuous draw)
- **Load current:** Output voltage sags when load draws current (next topic!)
- **Not for powering:** Poor choice for powering microcontrollers (use regulator instead)

#### Common Mistakes:

- Using voltage divider to power high-current loads (voltage sags)
- Forgetting  $R_2$  is lower resistor in formula
- Not considering power dissipation in resistors
- Confusing which resistor is  $R_1$  vs  $R_2$

## Voltage Divider under Load

### TL;DR (The Gist)

- **Problem:** Output voltage drops when load draws current (no longer pure series circuit)
- **Modified formula:**  $V_{out} = V_{in} \times \frac{R_2 \parallel R_L}{R_1 + (R_2 \parallel R_L)}$  where  $R_2 \parallel R_L = \frac{R_2 \times R_L}{R_2 + R_L}$
- Lower load resistance  $\rightarrow$  more current drawn  $\rightarrow$  larger voltage drop
- **Solution:** Use voltage regulator or op-amp buffer for significant loads

### Detailed Explanation

## 2. Detailed Explanation

### What is a Load?

*Definition:*

- **Load:** Device that consumes electrical energy
- Takes current from circuit

- Transforms electrical energy into other forms (heat, light, work, etc.)
- Can be: resistor, LED, motor, microcontroller, op-amp, etc.
- Represented/abstracted as resistor ( $R_L$ ) for analysis

*Power Rating:*

- All components have power rating (Watts)
- Defines maximum current/power without damage
- More current  $\rightarrow$  more heat (especially in resistors)
- Exceed rating  $\rightarrow$  component damage/failure

### The Problem - Why Output Voltage Drops:

*Unloaded voltage divider (no load):*

- $R_1$  and  $R_2$  in series
- Same current through both:  $I = \frac{V_{in}}{R_1 + R_2}$
- Output voltage:  $V_{out} = V_{in} \times \frac{R_2}{R_1 + R_2}$  (works perfectly!)
- Example:  $V_{in} = 5V$ ,  $R_1 = R_2 = 1k\Omega \rightarrow V_{out} = 2.5V$  ✓

*Loaded voltage divider (load connected):*

- Load ( $R_L$ ) connected in parallel with  $R_2$
- Current through  $R_1 \neq$  current through  $R_2$  anymore!
- Current splits: some through  $R_2$ , some through  $R_L$
- $R_1$  and  $R_2$  NO LONGER in series
- Original formula fails - output voltage drops below expected value

### Current Flow Analysis:

*Current paths:*

1.  $I_1$  flows from  $V_{in}$  through  $R_1$  (total current from source)
2. At junction, current splits:
  - $I_2$  flows through  $R_2$  to ground
  - $I_L$  flows through load ( $R_L$ ) to ground
3. Total current:  $I_1 = I_2 + I_L$  (Kirchhoff's Current Law)
4.  $R_2$  and  $R_L$  in parallel  $\rightarrow$  same voltage across both
5. Equivalent parallel resistance:  $R_{eq} = R_2 \parallel R_L = \frac{R_2 \times R_L}{R_2 + R_L}$

*Key insight:*

- Parallel equivalent  $R_{eq}$  always less than smaller individual resistor
- Lower effective resistance  $\rightarrow$  more current from source
- More current through  $R_1 \rightarrow$  larger voltage drop across  $R_1$
- Less voltage left for output  $\rightarrow$  output voltage sags

### Modified Voltage Divider Formula (with Load):

Original (no load):  $V_{out} = V_{in} \times \frac{R_2}{R_1 + R_2}$

**With load:**

$$V_{out} = V_{in} \times \frac{R_2 \parallel R_L}{R_1 + (R_2 \parallel R_L)}$$

Where:

$$R_2 \parallel R_L = \frac{R_2 \times R_L}{R_2 + R_L}$$

Expanded form:

$$V_{out} = V_{in} \times \frac{\frac{R_2 \times R_L}{R_2 + R_L}}{R_1 + \frac{R_2 \times R_L}{R_2 + R_L}}$$

### Effect of Load Resistance:

*Case 1: Very high load resistance ( $R_L \gg R_2$ )*

- Example:  $R_L = 1M\Omega$ ,  $R_2 = 1k\Omega$
- Parallel equivalent:  $R_{eq} = \frac{1k \times 1M}{1k + 1M} \approx \frac{1M}{1M} \times 1k = 0.999k\Omega \approx 1k\Omega$
- $R_{eq} \approx R_2$  (almost same!)
- Load draws tiny current (microamps)
- Original formula still valid (negligible loading effect)
- Output voltage stays at expected value

*Case 2: Low load resistance ( $R_L \approx R_2$  or lower)*

- Example:  $R_L = 150\Omega$ ,  $R_2 = 100\Omega$
- Parallel equivalent:  $R_{eq} = \frac{100 \times 150}{100 + 150} = \frac{15,000}{250} = 60\Omega$

- $R_{eq}$  much less than  $R_2$  ( $60\Omega$  vs  $100\Omega$ )
- Load draws significant current
- Output voltage drops significantly (e.g.,  $2.5V \rightarrow 1.9V$ )
- Original formula fails - must use modified formula

*Rule of thumb:*

- If  $R_L \geq 10 \times R_2$ : loading effect negligible
- If  $R_L < 10 \times R_2$ : must account for loading
- Lower  $R_L \rightarrow$  more voltage sag

#### Practical Solutions:

1. *Use voltage regulator:*

- IC that maintains fixed output voltage regardless of load
- Examples: LM7805 (5V), LM317 (adjustable)
- Superior to voltage divider for powering circuits
- Handles varying loads without voltage drop

2. *Op-amp unity gain buffer:*

- Op-amp has very high input impedance ( $M\Omega$  to  $G\Omega$ )
- Acts as buffer between voltage divider and load
- Divider sees minimal loading (high impedance input)
- Op-amp output can source current to load
- Allows small divider resistors (saves power) while driving loads

3. *Choose appropriate resistor values:*

- **Smaller loads (high current):** Use  $1k\Omega$  or  $10\Omega$  divider resistors
- **Larger loads (low current):** Use  $100k\Omega$  divider resistors
- Trade-off: Lower resistors waste more power, but handle loads better
- Higher resistors save power, but easily affected by loads

#### When NOT to Use Voltage Divider:

- Powering microcontrollers (use regulator instead)
- Driving motors or LEDs (significant current  $\rightarrow$  voltage sag)
- Any load with low resistance or high current demand
- Applications requiring stable voltage under varying loads

#### When Voltage Divider is OK:

- High-impedance inputs (op-amp inputs, ADC inputs, MOSFET gates)
- Reference voltages for comparators (minimal current draw)
- Sensor circuits (if load resistance very high)
- Biasing circuits with high-impedance loads

### Practical Example & Numerical

#### Example 1: Voltage Divider with $150\Omega$ Load

*Given:*

- $V_{in} = 5V$
- $R_1 = 100\Omega$  (upper resistor)
- $R_2 = 100\Omega$  (lower resistor)
- $R_L = 150\Omega$  (load resistance)

*Find:*  $V_{out}$  (with load)

#### Step 1: Calculate Parallel Equivalent of $R_2$ and $R_L$

$$R_{eq} = R_2 \parallel R_L = \frac{R_2 \times R_L}{R_2 + R_L}$$

$$R_{eq} = \frac{100 \times 150}{100 + 150} = \frac{15,000}{250} = 60\Omega$$

## Step 2: Apply Modified Voltage Divider Formula

$$V_{out} = V_{in} \times \frac{R_{eq}}{R_1 + R_{eq}}$$
$$V_{out} = 5 \times \frac{60}{100 + 60}$$
$$V_{out} = 5 \times \frac{60}{160} = 5 \times 0.375 = \boxed{1.875V \approx 1.9V}$$

### Comparison:

- **Without load:**  $V_{out} = 5 \times \frac{100}{200} = 2.5V$
- **With 150Ω load:**  $V_{out} = 1.9V$
- **Voltage drop:**  $2.5V - 1.9V = 0.6V$  (24% decrease!)
- Significant loading effect - divider cannot maintain output voltage

### Example 2: Voltage Divider with 1MΩ Load (High Impedance)

Given: Same divider ( $V_{in} = 5V$ ,  $R_1 = R_2 = 100\Omega$ ), but  $R_L = 1M\Omega$

#### Step 1: Parallel Equivalent

$$R_{eq} = \frac{100 \times 1,000,000}{100 + 1,000,000}$$
$$R_{eq} = \frac{100,000,000}{1,000,100} \approx 99.99\Omega$$

#### Step 2: Output Voltage

$$V_{out} = 5 \times \frac{99.99}{100 + 99.99}$$
$$V_{out} = 5 \times \frac{99.99}{199.99} \approx 5 \times 0.5 = \boxed{2.5V}$$

### Observations:

- $R_{eq} \approx R_2$  (99.99Ω vs 100Ω - almost identical!)
- Output voltage = 2.5V (same as unloaded case)
- Load current:  $I_L = \frac{2.5V}{1M\Omega} = 2.5\mu A$  (negligible!)
- High-impedance load doesn't significantly affect output
- Original voltage divider formula still valid

### Example 3: Choosing Resistor Values

Scenario: Need 3.3V from 5V source to power circuit that draws 10mA

#### Attempt 1: Using 1kΩ Divider Resistors

Desired ratio:  $\frac{R_2}{R_1 + R_2} = \frac{3.3}{5} = 0.66$

Choose:  $R_1 = 510\Omega$ ,  $R_2 = 1k\Omega$  (from earlier calculation)

Load resistance:

$$R_L = \frac{V_{out}}{I_L} = \frac{3.3}{0.01} = 330\Omega$$

Parallel equivalent:

$$R_{eq} = \frac{1,000 \times 330}{1,000 + 330} = \frac{330,000}{1,330} \approx 248\Omega$$

Actual output voltage:

$$V_{out} = 5 \times \frac{248}{510 + 248} = 5 \times \frac{248}{758}$$
$$V_{out} \approx 5 \times 0.327 = \boxed{1.64V}$$

**Result:** FAIL! Voltage dropped from expected 3.3V to 1.64V (50% loss)

**Conclusion:** Voltage divider unsuitable for powering 10mA load. Use voltage regulator instead!

### Example 4: Current Analysis

Using Example 1 values ( $V_{in} = 5V$ ,  $R_1 = R_2 = 100\Omega$ ,  $R_L = 150\Omega$ ,  $V_{out} = 1.9V$ )

Current through R1 (total source current):

$$I_1 = \frac{V_{in} - V_{out}}{R_1} = \frac{5 - 1.9}{100} = \frac{3.1}{100} = 31\text{ mA}$$

Current through  $R_2$ :

$$I_2 = \frac{V_{out}}{R_2} = \frac{1.9}{100} = 19 \text{ mA}$$

Current through load:

$$I_L = \frac{V_{out}}{R_L} = \frac{1.9}{150} \approx 12.7 \text{ mA}$$

Verification (Kirchhoff's Current Law):

$$I_1 = I_2 + I_L \Rightarrow 31 \approx 19 + 12.7 = 31.7 \text{ mA} \quad \checkmark$$

(Small discrepancy due to rounding)

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

1. **Load effect:** Output voltage drops when load draws current
2. **Why:** Load in parallel with  $R_2$  creates lower equivalent resistance
3. **Modified formula:** Replace  $R_2$  with  $R_2 \parallel R_L = \frac{R_2 \times R_L}{R_2 + R_L}$
4. **Current splits:**  $I_{R1} = I_{R2} + I_L$  (no longer series circuit)
5. **Lower load R:** More current  $\rightarrow$  larger voltage drop
6. **High load R:** Minimal loading ( $R_L \geq 10 \times R_2 \rightarrow$  negligible effect)
7. **Solutions:** Voltage regulator, op-amp buffer, or choose lower divider resistances
8. **Avoid:** Never use divider to power microcontrollers or significant loads

#### Interview Questions:

- **Q:** Why does voltage divider output drop when load connected?  
A: Load draws current, creating parallel path with  $R_2$ . Equivalent resistance decreases, changing voltage division ratio.
- **Q:** Divider: 5V,  $R_1 = R_2 = 1k\Omega$ . Load:  $150\Omega$ . Find output.  
A:  $R_{eq} = \frac{1k \times 150}{1k + 150} \approx 130\Omega$ .  $V_{out} = 5 \times \frac{130}{1k + 130} \approx 0.57V$ .
- **Q:** When is voltage divider acceptable with load?  
A: When load resistance  $\geq 10 \times R_2$  (high impedance, minimal current draw).
- **Q:** How to fix voltage sag in divider?  
A: Use voltage regulator, add op-amp buffer, or decrease divider resistor values.
- **Q:** What is "load" in electronics?  
A: Device that consumes electrical energy (draws current) and converts it to other forms (heat, light, work).
- **Q:** Can you power Arduino (50mA) from voltage divider?  
A: NO - high current load causes severe voltage sag. Use voltage regulator (e.g., LM7805).

#### Applications (Where Loaded Dividers Work):

- ADC inputs (microamps, very high impedance)
- Op-amp non-inverting input (negligible current)
- MOSFET gate biasing (gates draw no DC current)
- Comparator reference voltages (high input impedance)
- Sensor signal conditioning (if sensor has high output impedance)

#### Better Alternatives for Power:

- **Linear regulators:** LM7805, LM317 (stable voltage, handles current)
- **Switching regulators:** Buck/boost converters (efficient, adjustable)
- **Op-amp buffer:** Unity-gain follower (isolates divider from load)
- **Voltage reference ICs:** TL431, LM4040 (precision references)

#### Common Mistakes:

- Using divider to power circuits with significant current draw
- Ignoring load effect when designing circuits
- Not calculating parallel equivalent resistance
- Choosing too high divider resistances (easily loaded)
- Forgetting that current splits at output junction

#### Design Guidelines:

- **Rule:** Divider current should be  $\geq 10\times$  load current for good regulation
- **Power vs Regulation:** Lower resistors  $\rightarrow$  better regulation, higher power waste
- **Battery systems:** Use high resistances (save power), but expect poor load regulation
- **Always verify:** Calculate loaded output voltage before finalizing design

## Light Emitting Diode (LED)

### TL;DR (The Gist)

- **LED:** Light-Emitting Diode - converts electrical energy into light
- **Polarity:** Current flows anode (+, longer leg)  $\rightarrow$  cathode (-, shorter leg) ONLY
- **Forward voltage ( $V_f$ ):** Fixed voltage drop (1.5V-4V depending on color) when conducting
- **Current limiting:** ALWAYS use series resistor to prevent LED burnout

### Detailed Explanation

## 2. Detailed Explanation

### What is an LED?

#### Definition:

- **LED:** Light-Emitting Diode
- Converts electrical energy directly into light
- Type of diode (semiconductor device)
- "Hello World" of electronics (like first program in coding)

#### Characteristics:

- Much less power than incandescent bulbs
- More energy-efficient
- Doesn't get hot (unless high power)
- Long lifespan
- Available in many colors: red, green, blue, yellow, amber, white
- Used everywhere: phones, cars, homes, displays, indicators, lighting

#### Applications:

- **Low power:** Indicators, displays, mobile devices
- **High power:** Accent lighting, spotlights, automotive headlights
- **General:** Status indicators, backlighting, decoration, communication (IR LEDs)

### Physical Structure:

#### Appearance:

- Typically cylindrical plastic housing (5mm common size)
- Two leads/legs extending from bottom
- One leg longer than the other (polarity indicator)
- Flat edge on cathode side (negative)
- Dome-shaped top (lens)

#### Circuit Symbol:

- Triangle with line (like diode)
- Arrows pointing outward (indicates light emission)
- Similar to regular diode symbol but with arrows

### Polarity - CRITICAL Concept:

#### What is polarity?

- Polarity indicates whether component is symmetric or not
- LEDs/diodes are NOT symmetric - have positive and negative sides
- Must be connected correctly for operation
- Resistors have no polarity (can connect either way)

#### LED Terminals:

- **Anode (+):** Positive side
  - Longer lead/leg

- Connects to positive voltage (higher potential)
- Current flows FROM anode
- **Cathode (-):** Negative side
  - Shorter lead/leg
  - Flat edge on LED body
  - Connects to ground or lower potential
  - Current flows TO cathode

*Current Direction Rule:*

- Current flows: Anode  $\rightarrow$  Cathode (ONLY this direction)
- Never flows: Cathode  $\rightarrow$  Anode
- **Reverse connection:** LED blocks current, circuit doesn't work, LED stays OFF
- **Good news:** Can't damage LED by reverse connection (just won't light up)
- **Troubleshooting:** If LED doesn't light, try flipping it!

### How LEDs Work - Different from Resistors:

*Resistor behavior (linear):*

- Obeys Ohm's Law:  $V = I \times R$
- Increase voltage  $\rightarrow$  current increases proportionally
- Voltage drop = current  $\times$  resistance
- Linear relationship

*LED behavior (non-linear):*

- **NOT** linear like resistor
- Has characteristic I-V (current-voltage) curve
- Behaves like semiconductor diode
- Voltage drop nearly constant when conducting

### Forward Voltage ( $V_f$ ) - Key Parameter:

*Definition:*

- **Forward voltage ( $V_f$ ):** Voltage drop across LED when conducting
- Also called "recommended forward voltage"
- Specified in LED datasheet
- Typical range: 1.5V to 4V (depends on LED color)

*Typical forward voltages by color:*

- **Red:** 1.8V - 2.2V
- **Green:** 2.0V - 3.5V
- **Blue/White:** 3.0V - 4.0V
- **Yellow/Amber:** 2.0V - 2.4V
- **Infrared:** 1.2V - 1.8V

### LED I-V Characteristic Curve:

*Behavior:*

1. **Below  $V_f$ :** Applied voltage  $\downarrow$  forward voltage
  - Very small current (almost zero)
  - LED OFF (no light)
  - Acts like open circuit
2. **At  $V_f$ :** Applied voltage reaches forward voltage
  - LED "opens up" (starts conducting)
  - Current begins to flow
  - LED turns ON (emits light)
3. **Above  $V_f$ :** Applied voltage exceeds forward voltage
  - Current increases rapidly (exponentially)
  - Voltage drop stays approximately constant at  $V_f$
  - **DANGER:** Current can "escape to the sky" (unlimited)
  - LED will burn out without current limiting!

*Key insight:*

- For resistor: Higher voltage  $\rightarrow$  higher voltage drop
- For LED: Voltage drop stays at  $V_f$  (approximately constant)
- LED regulates voltage, not current
- Without current limit, LED draws excessive current  $\rightarrow$  destruction

## Why LEDs Need Current Limiting Resistor:

*The Problem:*

- LED has nearly constant voltage drop ( $V_f$ ) when ON
- If connected directly to voltage source  $V$ ,  $V_f$ :
  - Current increases without limit
  - LED overheats
  - LED burns out/pops/fails permanently
- Cannot self-regulate current (unlike resistor)

*The Solution:*

- **Series resistor:** Limits maximum current through LED
- Resistor drops excess voltage:  $V_R = V_{source} - V_f$
- Current determined by Ohm's Law:  $I = \frac{V_{source} - V_f}{R}$
- Protects LED from overcurrent
- **Rule:** ALWAYS use series resistor with LED!

*What happens without resistor:*

- LED doesn't "burn" like resistor (no flames typically)
- Instead: LED pops, cracks, or simply stops working
- Permanent damage - LED cannot be repaired

## Datasheet - Essential Information Source:

*What is datasheet?*

- Document with specifications for electronic component
- Provided by manufacturer
- Contains: electrical characteristics, mechanical dimensions, operating conditions, ratings

*Key LED datasheet parameters:*

- **Forward voltage ( $V_f$ ):** Voltage drop when ON (e.g., 2.0V typical)
- **Forward current ( $I_f$ ):** Recommended operating current (e.g., 20mA)
- **Maximum current:** Absolute maximum before damage (e.g., 30mA)
- **Luminous intensity:** Brightness (mcd - millicandela)
- **Viewing angle:** Light emission pattern (e.g., 30°, 60°, 120°)
- **Wavelength:** Color (nanometers)

## Series Circuit Configuration:

*Typical "Hello World" circuit:*

- Voltage source (e.g., 5V, 12V, battery)
- Series resistor (current limiter)
- LED (anode toward positive, cathode toward ground)
- All in series (same current through all components)

*Voltage distribution:*

- Total voltage = Source voltage
- Voltage across LED =  $V_f$  (from datasheet)
- Voltage across resistor =  $V_{source} - V_f$  (remainder)
- Kirchhoff's Voltage Law:  $V_{source} = V_R + V_f$

## Practical Example & Numerical

### Example 1: Identifying LED Polarity

*Visual inspection:*

- **Longer leg:** Anode (+) - connects to positive voltage
- **Shorter leg:** Cathode (-) - connects to ground
- **Flat edge on body:** Cathode (-) side
- **Rounded edge:** Anode (+) side

*If legs cut to same length:*

- Look inside LED (through clear plastic)
- Larger internal element = cathode (-)
- Smaller internal element = anode (+)
- Flat edge on body = cathode (-)

### Example 2: LED Forward Voltage by Color

*Scenario:* Choosing power supply voltage for different LEDs

#### Red LED:

- $V_f = 2.0V$  (typical)
- Minimum supply voltage:  $\geq 2.0V$  (e.g., 3V, 5V work)
- Resistor drops:  $V_R = V_{supply} - 2.0V$

#### Blue LED:

- $V_f = 3.2V$  (typical)
- Minimum supply:  $\geq 3.2V$  (e.g., 5V works, 3V doesn't!)
- With 3V supply: LED won't turn ON (below  $V_f$ )
- With 5V supply: LED ON, resistor drops 1.8V

#### White LED:

- $V_f = 3.5V$  (typical)
- 3.3V supply: Marginal (LED dim or OFF)
- 5V supply: Good, resistor drops 1.5V
- 12V supply: OK, but resistor drops 8.5V (wastes power)

### Example 3: Reverse-Connected LED

*Circuit:* 5V source  $\rightarrow$  resistor ( $1k\Omega$ )  $\rightarrow$  LED (REVERSED)  $\rightarrow$  ground

#### What happens:

- Current tries to flow cathode  $\rightarrow$  anode (wrong direction!)
- LED blocks current (acts like open circuit)
- No current flows:  $I = 0A$
- LED stays OFF (no light)
- No damage to LED (safe, just doesn't work)

#### Troubleshooting:

- Measure voltage across LED: reads full supply voltage (5V)
- Voltage across resistor: 0V (no current, no drop)
- Solution: Flip LED orientation!

### Example 4: LED Without Resistor (DANGER - Don't Try!)

*Circuit:* 5V source  $\rightarrow$  Red LED (no resistor!)  $\rightarrow$  ground

*Red LED specs:*  $V_f = 2.0V$ ,  $I_f = 20mA$  (recommended), Max = 30mA

#### What happens:

1. Voltage across LED tries to stay at  $V_f = 2.0V$
2. Remaining voltage:  $5V - 2V = 3V$  (nowhere to drop!)
3. Without resistor: No current limiting
4. Current "escapes to sky" (very high, limited only by wire/source resistance)
5. Actual current: Could be 100mA, 500mA, or more!
6. LED overheats rapidly
7. LED fails: pops, stops working permanently

**Result:** LED destroyed! (Don't do this)

### Example 5: LED I-V Curve Behavior

*Red LED:*  $V_f = 2.0V$  (datasheet value)

#### Applied Voltage vs Current:

- $V = 0V$ :  $I \approx 0A$  (LED OFF)
- $V = 1.0V$ :  $I \approx 0A$  (below  $V_f$ , LED OFF)
- $V = 1.5V$ :  $I \approx 0.1mA$  (still below  $V_f$ , LED dim)
- $V = 1.8V$ :  $I \approx 1mA$  (approaching  $V_f$ , LED starts glowing)
- $V = 2.0V$ :  $I \approx 20mA$  (at  $V_f$ , LED bright, normal operation)
- $V = 2.1V$ :  $I \approx 50mA$  (above  $V_f$ , current jumps rapidly!)
- $V = 2.2V$ :  $I \approx 100mA$  (excessive current, LED damage imminent)

#### Observation:

- Below  $V_f$ : Very little current (LED barely ON)
- At  $V_f$ : Nominal current (20mA typical)
- Above  $V_f$ : Current increases exponentially (dangerous!)
- Small voltage change above  $V_f \rightarrow$  huge current change
- This is why resistor essential for current control

### Example 6: Comparing LED to Resistor Behavior

*Resistor (1kΩ):*

- 1V → 1mA, 2V → 2mA, 5V → 5mA (linear, proportional)
- Voltage drop = current × 1kΩ (Ohm's Law)
- Predictable, linear behavior

*LED (Red,  $V_f = 2.0V$ ):*

- 1V → 0mA (OFF), 2V → 20mA (ON), 2.1V → 50mA (excessive)
- Voltage drop stays ≈2.0V when conducting (not proportional!)
- Non-linear, exponential behavior above  $V_f$
- Needs external current limiting

**Conclusion:** LED fundamentally different from resistor - cannot use Ohm's Law directly for LED!

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

1. **LED:** Light-Emitting Diode - converts electricity to light
2. **Polarity:** Anode (+, longer leg) → Cathode (-, shorter leg, flat edge)
3. **Current direction:** Anode → Cathode ONLY (reverse blocks current)
4. **Forward voltage ( $V_f$ ):** Fixed voltage drop when conducting (1.5-4V, color-dependent)
5. **Non-linear:** Unlike resistor, LED doesn't obey Ohm's Law directly
6. **I-V curve:** Below  $V_f$  = OFF, at  $V_f$  = ON, above  $V_f$  = current skyrockets
7. **Series resistor:** ALWAYS required to limit current and prevent burnout
8. **Datasheet:** Essential for  $V_f$ ,  $I_f$ , max current, other specs

#### Interview Questions:

- **Q:** What does LED stand for?  
A: Light-Emitting Diode.
- **Q:** Which LED terminal is positive?  
A: Anode (longer leg, connects to positive voltage).
- **Q:** Can you connect LED backward?  
A: Yes, but it won't work (blocks current). Won't damage LED, just stays OFF.
- **Q:** What is forward voltage ( $V_f$ )?  
A: Voltage drop across LED when conducting (e.g., 2V for red, 3.2V for blue).
- **Q:** Why does LED need series resistor?  
A: LED can't self-limit current. Without resistor, excessive current flows → LED burns out.
- **Q:** Red LED  $V_f = 2V$ , supply=5V. What voltage does resistor drop?  
A:  $V_R = 5V - 2V = 3V$  (resistor drops remainder).
- **Q:** What happens if voltage  $< V_f$ ?  
A: LED stays OFF (no significant current flows).
- **Q:** Blue LED ( $V_f = 3.2V$ ) with 3V battery - will it light?  
A: NO - supply voltage below forward voltage (LED stays OFF).

#### Applications:

- Status indicators (power ON, error, activity)
- Displays (7-segment, dot matrix, backlighting)
- Automotive (headlights, taillights, dashboard)
- Lighting (bulbs, strips, accent lighting)
- Communication (IR remote controls, optical links)
- Sensors (optocouplers, photodetectors)

#### Typical Forward Voltages:

- Infrared: 1.2-1.8V
- Red: 1.8-2.2V
- Yellow/Amber: 2.0-2.4V
- Green: 2.0-3.5V
- Blue: 3.0-3.6V
- White: 3.0-4.0V

#### Common Mistakes:

- Connecting LED without current-limiting resistor (burnout!)
- Reverse polarity (LED won't work, but won't break)

- Using voltage below  $V_f$  (LED won't light)
- Treating LED like resistor (applying Ohm's Law incorrectly)
- Ignoring datasheet specifications

#### Safety Notes:

- Never connect LED directly to power supply (always use resistor!)
- Don't exceed maximum current rating (check datasheet)
- High-power LEDs need heat sinks (get very hot)
- Looking at bright LEDs can damage eyes (especially UV/blue)
- Reverse connection safe (won't damage), just doesn't work

## Current Limiting Resistor with LED

### TL;DR (The Gist)

- **Resistor formula:**  $R = \frac{V_{source} - V_f}{I_{LED}}$  (protects LED from overcurrent)
- Choose  $I_{LED}$  from datasheet (typically 20mA max for standard LEDs)
- $V_{source}$  must be greater than  $V_f$  (LED forward voltage)
- Calculate R, select nearest standard value, verify current is safe

### Detailed Explanation

## 2. Detailed Explanation

#### Why Current Limiting is Essential:

*The Problem:*

- LED has forward voltage  $V_f$  (e.g., 2V for red LED)
- Once voltage reaches  $V_f$ , LED "opens up" (starts conducting)
- LED's intrinsic resistance drops rapidly above  $V_f$
- Without current limit: LED draws excessive current → burns out
- Current can "run away" (increase without bound until LED destroyed)

*The Solution:*

- Series resistor limits maximum current
- Resistor drops excess voltage:  $V_R = V_{source} - V_f$
- Current controlled by Ohm's Law:  $I = \frac{V_R}{R}$
- Protects LED, ensures safe operation

#### Finding LED Specifications from Datasheet:

*Step 1: Locate datasheet*

- Google: "[LED part number] datasheet" (e.g., "TLUR6400 datasheet")
- Usually PDF format
- Available from manufacturer website, Digi-Key, Mouser, etc.

*Step 2: Find Forward Voltage ( $V_f$ )*

- Look for "Electrical Characteristics" table
- Parameter: "Forward Voltage" or  $V_f$
- Specified at certain current (typically 20mA)
- **Example (TLUR6400):**  $V_f = 2V$  typical, 3V max @ 20mA
- Range given (not exact) due to manufacturing variations
- Use typical value for calculations (or average of min/max)

*Step 3: Find Maximum Forward Current ( $I_f$ )*

- Look for "Absolute Maximum Ratings" table
- Parameter: "DC Forward Current" or  $I_f$  (max)
- **Example (TLUR6400):** Max  $I_f = 20mA$
- This is absolute maximum - don't exceed!
- Design for slightly less (e.g., 18-20mA) for safety margin
- Exceeding slightly (21mA) might not immediately damage, but avoid!

## Current Limiting Resistor Formula:

### Derivation:

*Circuit:*  $V_{source} \rightarrow \text{Resistor (R)} \rightarrow \text{LED} \rightarrow \text{Ground}$

*Voltage relationships:*

- Total voltage must be dropped (Kirchhoff's Voltage Law)
- $V_{source} = V_R + V_f$  (resistor drop + LED drop)
- Rearrange:  $V_R = V_{source} - V_f$

*Current relationship:*

- Same current through resistor and LED (series circuit)
- $I_{LED} = I_R = I$  (call it  $I$ )

*Apply Ohm's Law to resistor:*

$$V_R = I \times R$$

$$R = \frac{V_R}{I}$$

*Substitute  $V_R = V_{source} - V_f$ :*

$$R = \frac{V_{source} - V_f}{I_{LED}}$$

This is the **LED current limiting resistor formula!**

### Design Steps:

*Step 1: Determine specifications*

- $V_{source}$ : Your power supply voltage (e.g., 5V, 9V, 12V)
- $V_f$ : LED forward voltage from datasheet (e.g., 2V)
- $I_{LED}$ : Desired current (typically max from datasheet, e.g., 20mA)

*Step 2: Verify voltage compatibility*

- **Requirement:**  $V_{source} > V_f$  (must have voltage to spare)
- If  $V_{source} \leq V_f$ : LED won't turn ON (insufficient voltage)
- Example: Can't use 2V battery with 3.2V blue LED!

*Step 3: Calculate resistor value*

- Use formula:  $R = \frac{V_{source} - V_f}{I_{LED}}$
- Units: Voltage in Volts, Current in Amps, Result in Ohms
- Convert mA to A:  $20mA = 0.02A$

*Step 4: Select standard resistor value*

- Calculated value likely not standard (e.g., 350Ω)
- Choose nearest standard value (E12/E24 series)
- Round UP for safety (lower current than max)
- Example: 350Ω calculated  $\rightarrow$  use 330Ω or 390Ω standard

*Step 5: Verify actual current*

- Calculate actual current with standard resistor:  $I = \frac{V_{source} - V_f}{R_{standard}}$
- Ensure  $I \leq I_{max}$  from datasheet
- If too high, use next higher resistor value

### Voltage Source Selection:

*Rule of thumb:*

- $V_{source}$  should be noticeably higher than  $V_f$
- Minimum:  $V_{source} > V_f$  (at least 1-2V higher is practical)
- Reason: Need voltage headroom for resistor drop

*Examples:*

- **Red LED** ( $V_f = 2V$ ): 5V, 9V, 12V all work. 3V marginal, 2V won't work.
- **Blue LED** ( $V_f = 3.2V$ ): 5V OK, 9V good, 3.3V marginal, 3V won't work.
- **White LED** ( $V_f = 3.5V$ ): 5V OK (1.5V headroom), 12V good (more headroom).

*Too high voltage:*

- Works, but wastes power in resistor
- Example: 12V source with 2V LED  $\rightarrow$  10V dropped across resistor (power wasted)
- Higher resistor needed  $\rightarrow$  more heat dissipated
- Inefficient, but not harmful to LED

### Current Selection:

*Maximum current (from datasheet):*

- Typical: 20mA for standard 5mm LEDs

- High-power LEDs: 100mA, 350mA, 1A, or more
- Always check datasheet - never assume!

*Operating current (your choice):*

- Can run at less than maximum (dimmer, but safer, longer life)
- Example: 10mA instead of 20mA (half brightness, half power)
- Lower current → LED lasts longer, less heat
- Higher current (up to max) → brighter, shorter life

### Power Dissipation in Resistor:

*Resistor must handle power:*

$$P_R = I^2 \times R \quad \text{or} \quad P_R = V_R \times I \quad \text{or} \quad P_R = \frac{V_R^2}{R}$$

*Example:*

- $V_R = 7V$ ,  $I = 20mA$
- $P_R = 7 \times 0.02 = 0.14W = 140mW$
- Use 1/4W (250mW) resistor (common) with safety margin
- 1/8W (125mW) resistor too small (would overheat)

*Standard resistor power ratings:*

- 1/8W (125mW), 1/4W (250mW), 1/2W (500mW), 1W, 2W, etc.
- For LED circuits: 1/4W usually sufficient for standard LEDs
- High-power LEDs may need 1W or higher resistors

### Component Imperfection:

*Why ranges in datasheets?*

- No component manufactured to perfection
- Variations in materials, process, temperature
- $V_f$  given as range: typical, min, max
- Example:  $V_f = 2V$  typ, 1.8V min, 3V max

*Design approach:*

- Use typical value for calculations
- Or use max  $V_f$  for conservative design (ensures current never exceeds limit)
- Using max  $V_f$  → larger resistor → lower current → safer, dimmer
- Using typical  $V_f$  → nominal current → brighter, but within spec

## Practical Example & Numerical

### Example 1: Designing LED Circuit (TLUR6400 Red LED with 9V Battery)

*Given:*

- LED: TLUR6400 (Red)
- $V_f = 2V$  (typical), 3V (max) @ 20mA
- Max forward current:  $I_f = 20mA$
- Power source:  $V_{source} = 9V$  (battery)

*Design goal:* Run LED at maximum brightness (20mA)

#### Step 1: Verify Voltage Compatibility

$$V_{source} = 9V > V_f = 2V \quad \checkmark \quad (\text{OK, sufficient voltage})$$

#### Step 2: Calculate Required Resistance

$$R = \frac{V_{source} - V_f}{I_{LED}}$$

$$R = \frac{9 - 2}{0.02}$$

$$R = \frac{7}{0.02} = 350 \Omega$$

#### Step 3: Select Standard Resistor Value

Nearest standard values: 330Ω or 390Ω (E12 series)

Option A: Use  $330\Omega$  (lower resistance)

$$I = \frac{9 - 2}{330} = \frac{7}{330} \approx 21.2mA$$

Result: Slightly exceeds 20mA max (marginal, but might be OK)

Option B: Use  $390\Omega$  (higher resistance - safer)

$$I = \frac{9 - 2}{390} = \frac{7}{390} \approx 17.9mA$$

Result: Below 20mA max ✓ (safe, slightly dimmer)

**Recommendation:** Use  $390\Omega$  for safety (or  $330\Omega$  acceptable)

**Step 4: Calculate Power Dissipation ( $390\Omega$  resistor)**

$$P_R = V_R \times I = 7 \times 0.0179 \approx 0.125W = 125mW$$

Or:

$$P_R = I^2 \times R = (0.0179)^2 \times 390 \approx 0.125W$$

**Resistor rating:** Use 1/4W (250mW) resistor ✓ (125mW ; 250mW with safety margin)

**Final Circuit:**

- 9V battery (+) →  $390\Omega$  1/4W resistor → LED (anode) → LED (cathode) → Ground
- Current:  $\approx 18mA$  (safe)
- LED brightness: Slightly less than maximum (acceptable)

**Example 2: LED with 5V Supply (Common Arduino/USB Voltage)**

Given: Red LED ( $V_f = 2V$ ,  $I_{max} = 20mA$ ), 5V supply

**Calculate Resistor:**

$$R = \frac{5 - 2}{0.02} = \frac{3}{0.02} = 150\Omega$$

**Standard value:**  $150\Omega$  is standard! (E12 series) Use directly.

**Verify current:**

$$I = \frac{5 - 2}{150} = \frac{3}{150} = 0.02A = 20mA \quad \checkmark$$

**Power dissipation:**

$$P_R = 3 \times 0.02 = 0.06W = 60mW$$

**Resistor:** 1/4W (250mW) more than adequate.

**Example 3: Blue LED with 5V (Higher Forward Voltage)**

Given: Blue LED ( $V_f = 3.2V$ ,  $I_{max} = 20mA$ ), 5V supply

**Calculate Resistor:**

$$R = \frac{5 - 3.2}{0.02} = \frac{1.8}{0.02} = 90\Omega$$

**Standard value:** Use  $100\Omega$  (nearest standard, E12)

**Verify current:**

$$I = \frac{5 - 3.2}{100} = \frac{1.8}{100} = 0.018A = 18mA \quad \checkmark \quad (\text{safe})$$

**Observation:**

- Higher  $V_f$  (3.2V vs 2V) → less voltage headroom (1.8V vs 3V)
- Smaller resistor needed ( $100\Omega$  vs  $150\Omega$ )
- Less power wasted in resistor (more efficient)
- But less margin for voltage variation

**Example 4: Multiple LEDs in Series**

Given: 3 red LEDs ( $V_f = 2V$  each), 12V supply,  $I = 20mA$  desired

**Total LED voltage drop:**

$$V_{LEDs} = 3 \times 2V = 6V$$

**Voltage for resistor:**

$$V_R = 12 - 6 = 6V$$

**Calculate resistor:**

$$R = \frac{6}{0.02} = 300\Omega$$

**Standard:** Use  $330\Omega$  (nearest standard)

**Actual current:**

$$I = \frac{6}{330} \approx 18.2mA \quad \checkmark$$

**Power dissipation:**

$$P_R = 6 \times 0.0182 \approx 0.11W = 110mW$$

Use 1/4W resistor  $\checkmark$

**Example 5: Insufficient Voltage (Common Mistake)**

*Given:* Blue LED ( $V_f = 3.2V$ ), 3V battery, attempt 20mA

**Calculate resistor:**

$$R = \frac{3 - 3.2}{0.02} = \frac{-0.2}{0.02} = -10\Omega \quad (\text{NEGATIVE!})$$

**Problem:**  $V_{source} < V_f$  (3V < 3.2V)

**Result:** Cannot work! LED won't turn ON (insufficient voltage)

**Solution:** Use higher voltage source (e.g., 5V or 9V)

**Example 6: Lower Current for Longer Life**

*Given:* Red LED ( $V_f = 2V$ ,  $I_{max} = 20mA$ ), 5V supply

*Goal:* Run at 10mA (half max) for energy savings and longer life

**Calculate resistor:**

$$R = \frac{5 - 2}{0.01} = \frac{3}{0.01} = 300\Omega$$

**Standard:** Use  $330\Omega$

**Actual current:**

$$I = \frac{3}{330} \approx 9.1mA$$

**Result:**

- LED dimmer (about half brightness)
- Uses half power (saves energy)
- LED lasts longer (less stress)
- Still visible for indicator applications

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

1. **Formula:**  $R = \frac{V_{source} - V_f}{I_{LED}}$  (current limiting resistor)
2. **Requirements:**  $V_{source} > V_f$  (source voltage must exceed LED forward voltage)
3. **Datasheet:** Find  $V_f$  and  $I_{max}$  before designing circuit
4. **Standard values:** Round calculated R to nearest standard resistor
5. **Power rating:** Calculate  $P_R = V_R \times I$ , choose resistor power rating accordingly
6. **Safety:** Design for  $I \leq I_{max}$  (verify with standard resistor value)
7. **Series circuit:** Same current through resistor and LED
8. **Voltage division:**  $V_{source} = V_R + V_f$  (Kirchhoff's Voltage Law)

**Interview Questions:**

- **Q:** Formula for LED current limiting resistor?  
*A:*  $R = \frac{V_{source} - V_f}{I_{LED}}$
- **Q:** Red LED ( $V_f = 2V$ , max 20mA) with 9V battery. Find resistor.

A:  $R = \frac{9-2}{0.02} = 350\Omega$ . Use  $330\Omega$  or  $390\Omega$  standard.

- **Q:** Can you use 3V battery with 3.5V LED?

A: NO - source voltage (3V) less than  $V_f$  (3.5V). LED won't turn ON.

- **Q:** Why do datasheets give voltage range (e.g., 2-3V) instead of exact value?

A: Manufacturing variations - no component perfect. Range accounts for tolerances.

- **Q:** What happens if resistor value too small?

A: Excessive current flows  $\rightarrow$  LED overheats  $\rightarrow$  damage/burnout.

- **Q:** What happens if resistor value too large?

A: Current too low  $\rightarrow$  LED dim or doesn't light. Safe, but not useful.

- **Q:** 5V source, 2V LED,  $150\Omega$  resistor. Find current.

A:  $I = \frac{5-2}{150} = \frac{3}{150} = 0.02A = 20mA$

- **Q:** Where to find LED specifications?

A: Datasheet (Google "[part number] datasheet"). Look for  $V_f$  and  $I_f$  max.

#### Applications:

- Status indicators (power, error, activity LEDs)
- Display backlighting
- Debugging circuits (visual current flow confirmation)
- Simple lighting projects
- Arduino/microcontroller outputs
- Battery level indicators

#### Design Tips:

- **Always check datasheet** - never assume LED specs
- **Round UP resistor value** for safety (lower current)
- **Verify calculated current** doesn't exceed  $I_{max}$
- Use **1/4W resistors** for most standard LED circuits
- **Allow voltage headroom:**  $V_{source}$  should be 1-2V above  $V_f$  minimum
- **Lower current = longer life:** Consider 50-75% of max for indicators

#### Common Mistakes:

- No resistor (LED burnout!)
- $V_{source} < V_f$  (LED won't light)
- Wrong units (mA vs A,  $k\Omega$  vs  $\Omega$ )
- Resistor power rating too small (overheats)
- Using max  $V_f$  and min  $V_f$  inconsistently
- Forgetting to verify current with standard resistor value

#### Standard Resistor Values (E12 series):

- 10, 12, 15, 18, 22, 27, 33, 39, 47, 56, 68, 82, 100, 120, 150, 180, 220, 270, 330, 390, 470, 560, 680, 820, 1k, ... (and multiples)

#### Quick Reference Calculations:

- **5V + Red LED (2V, 20mA):**  $R = 150\Omega$  (standard)
- **9V + Red LED (2V, 20mA):**  $R = 350\Omega$  (use  $330\Omega$  or  $390\Omega$ )
- **12V + Red LED (2V, 20mA):**  $R = 500\Omega$  (use  $470\Omega$  or  $560\Omega$ )
- **5V + Blue LED (3.2V, 20mA):**  $R = 90\Omega$  (use  $100\Omega$ )

# Section 05 – Kirchhoff's Circuit Laws

## Why We Need Kirchhoff's Circuit Laws

TL;DR (The Gist)

- **Simple circuits:** Can be solved with series/parallel reduction + Ohm's Law
- **Complex circuits:** Multi-loop circuits with junctions cannot be reduced to single equivalent resistance
- **Kirchhoff's Rules:** Universal method to analyze ANY circuit (simple or complex)
- Named after Gustav Kirchhoff - two fundamental laws for circuit analysis

## Detailed Explanation

### 2. Detailed Explanation

#### Simple Circuits - Solvable with Basic Methods:

*Example 1: Single resistor*

- Circuit: 5V battery + 1k $\Omega$  resistor (series)
- Solution:  $I = \frac{V}{R} = \frac{5}{1,000} = 5mA$  (Ohm's Law)
- Straightforward, no special techniques needed

*Example 2: Series resistors*

- Circuit: 12V battery + 1k $\Omega$ , 2k $\Omega$ , 3k $\Omega$  in series
- Total resistance:  $R_{total} = 1k + 2k + 3k = 6k\Omega$
- Current:  $I = \frac{12}{6,000} = 2mA$
- Works fine - series reduction method

*Example 3: Mixed series/parallel*

- Circuit: 5V battery + 1k $\Omega$  resistor + (500 $\Omega$  parallel 500 $\Omega$ ) in series
- Parallel equivalent:  $R_{parallel} = \frac{500 \times 500}{500 + 500} = 250\Omega$
- Then series: 1k $\Omega$  + 250 $\Omega$  = 1.25k $\Omega$
- Current:  $I = \frac{5}{1,250} = 4mA$
- Still manageable - can reduce to equivalent resistance

#### Complex Circuits - Basic Methods Fail:

*Multi-loop circuits:*

- Contain **junctions (nodes)**: Connection points for 3+ wires
- Multiple current paths
- Not all resistors clearly in series or parallel
- Cannot reduce to single equivalent resistance
- Previous methods (series/parallel reduction) don't work

*Example: Circuit with two batteries*

- Multiple voltage sources in different branches
- Currents split at junctions
- Resistors R1 and R2 might be in series (can combine)
- Resistors R4 and R5 might be in series (can combine)
- But then what? Can't reduce further!
- Cannot determine single equivalent resistance

*Questions that arise:*

- What current does each battery supply?
- What current flows through specific resistor (e.g., R3)?
- What voltage drops across each component?
- How do currents split at junctions?

#### The Solution - Kirchhoff's Rules:

*Universal applicability:*

- Work for ANY circuit (simple or complex)
- Handle multi-loop circuits with ease
- Multiple voltage sources? No problem!

- Can find ANY unknown current, voltage, or resistance
- Based on fundamental conservation laws

*Named after Gustav Kirchhoff:*

- German physicist (1824-1887)
- Developed circuit analysis laws in 1845
- Two fundamental rules:
  1. Kirchhoff's Current Law (KCL) - Junction Rule
  2. Kirchhoff's Voltage Law (KVL) - Loop Rule
- Foundation of modern circuit analysis

### When to Use Kirchhoff's Laws:

*Must use for:*

- Multi-loop circuits
- Circuits with multiple voltage sources
- Finding current through specific component (not total current)
- Finding voltage across component in complex network
- Any circuit where series/parallel reduction fails

*Can use (but not necessary) for:*

- Simple series circuits (Ohm's Law easier)
- Simple parallel circuits (reduction methods faster)
- Single-loop circuits (basic voltage division works)

*Advantage:*

- Systematic approach (always works)
- No guessing about circuit topology
- Can verify results from other methods
- Powerful for complex analysis

### What Makes Circuit "Complex":

*Junctions/Nodes:*

- **Junction:** Point where 3+ wires meet
- Current splits at junction (some paths take more, some less)
- Example: Current I1 enters junction, splits into I2 and I3
- Cannot easily predict split without Kirchhoff's Current Law

*Multiple loops:*

- **Loop:** Closed path in circuit
- Complex circuits have multiple overlapping loops
- Each loop contributes equation via Kirchhoff's Voltage Law
- System of equations solved simultaneously

*Multiple sources:*

- More than one battery/voltage source
- Sources can aid or oppose each other
- Creates unique current distribution
- Simple methods can't handle this

## Practical Example & Numerical

### Example 1: Simple Circuit (No Kirchhoff Needed)

*Given:* 5V battery, 1kΩ resistor

**Using Ohm's Law:**

$$I = \frac{V}{R} = \frac{5}{1,000} = 0.005A = \boxed{5mA}$$

Simple! No need for complex methods.

### Example 2: Series Circuit (Reduction Works)

*Given:* 12V battery, resistors: 1kΩ, 2kΩ, 3kΩ in series

**Total resistance:**

$$R_{total} = 1k + 2k + 3k = 6k\Omega$$

**Current:**

$$I = \frac{12}{6,000} = \boxed{2mA}$$

Still straightforward with basic methods.

**Example 3: Complex Circuit (Kirchhoff Required!)**

*Given:* Multi-loop circuit with:

- Two batteries: 10V and 5V
- Five resistors in complex arrangement
- Multiple junctions

**Questions:**

- What current flows through R3?
- What voltage drops across R2?
- How much current does each battery supply?

**Problem:**

- R1 and R2 are in series → can combine
- R4 and R5 are in series → can combine
- But R3 connects the two branches (bridge configuration)
- Cannot reduce to single equivalent resistance!
- Series/parallel methods fail

**Solution:**

- Use Kirchhoff's Current Law at junctions
- Use Kirchhoff's Voltage Law around loops
- Generate system of equations
- Solve for all unknowns
- ONLY way to analyze this circuit!

**Example 4: Why Reduction Fails**

*Scenario:* Try to find equivalent resistance of complex circuit

**Attempt:**

1. Identify series resistors → combine some
2. Identify parallel resistors → combine some
3. Look at remaining circuit...
4. Still have complex interconnections
5. Cannot proceed further!

**Conclusion:**

- If second battery removed: Reduction might work
- With both batteries: Need Kirchhoff's Laws
- This demonstrates limitation of basic methods

**Key Points (Interview Focus)**

**4. Key Points (Interview Focus)**

1. **Junction (Node):** Connection point for 3+ wires (current splits)
2. **Simple circuits:** Series/parallel reduction + Ohm's Law sufficient
3. **Complex circuits:** Multi-loop, multiple sources → need Kirchhoff's Laws
4. **Kirchhoff's Rules:** Universal method for ANY circuit analysis
5. **Two laws:** Current Law (KCL) and Voltage Law (KVL)
6. **Named after:** Gustav Kirchhoff (German physicist, 1845)
7. **When basic methods fail:** Cannot reduce to equivalent resistance → use Kirchhoff

**Interview Questions:**

- **Q:** What is a junction/node in circuit?  
A: Connection point where 3 or more wires meet.
- **Q:** When do series/parallel methods fail?  
A: Complex multi-loop circuits where resistors aren't clearly in series or parallel.
- **Q:** Can Kirchhoff's Laws solve simple circuits?  
A: Yes, but Ohm's Law and reduction methods are faster for simple cases.
- **Q:** What makes circuit "complex"?

A: Multiple loops, junctions, and/or multiple voltage sources.

- **Q:** Who developed circuit analysis laws?

A: Gustav Kirchhoff (1845).

- **Q:** Name the two Kirchhoff's Laws.

A: Current Law (KCL/Junction Rule) and Voltage Law (KVL/Loop Rule).

#### Applications:

- Analyzing complex electronic circuits
- Power distribution networks
- Multi-stage amplifiers
- Bridge circuits (Wheatstone bridge)
- Circuits with multiple batteries/sources
- Mesh and nodal analysis

#### Circuit Complexity Indicators:

- **Simple:** Single loop, one source, clear series/parallel
- **Moderate:** Mixed series/parallel, single source
- **Complex:** Multiple loops, junctions, multiple sources
- **Very complex:** Many interconnected loops and sources

## Kirchhoff's Rules

### TL;DR (The Gist)

- **KCL (Current Law):** Sum of currents entering node = sum leaving node (charge conservation)
- **KVL (Voltage Law):** Sum of voltage drops around closed loop = 0 (energy conservation)
- **Mathematical form:**  $\sum I_{in} = \sum I_{out}$  (KCL),  $\sum V_{loop} = 0$  (KVL)
- Two fundamental laws for analyzing ANY circuit

### Detailed Explanation

## 2. Detailed Explanation

### Kirchhoff's First Law - Current Law (KCL):

*Statement:*

- Total current entering junction = total current leaving junction
- Also called "Junction Rule" or "Node Rule"
- Charge cannot accumulate at node (conservation of charge)
- Current in = current out (what goes in must come out)

*Mathematical form:*

$$\sum I_{in} = \sum I_{out}$$

Or equivalently (all currents at node):

$$\sum I = 0$$

Where currents entering are positive, leaving are negative (or vice versa - sign convention)

*Physical basis:*

- Based on **conservation of charge**
- Charge cannot be created or destroyed
- Charge cannot accumulate at junction
- Whatever flows in must flow out

*Water pipe analogy:*

- Water flowing through junction of pipes
- Assuming incompressible water
- Volume entering junction = volume leaving junction
- Water doesn't disappear or accumulate at junction
- Same principle applies to electrical current

### Kirchhoff's Second Law - Voltage Law (KVL):

*Statement:*

- Algebraic sum of all voltages around closed loop = zero
- Also called "Loop Rule" or "Mesh Rule"
- Energy supplied by sources = energy consumed by loads
- Based on **conservation of energy**

*Mathematical form:*

$$\sum V_{loop} = 0$$

Including voltage sources and voltage drops:

$$\sum V_{sources} - \sum V_{drops} = 0$$

Or:

$$\sum V_{sources} = \sum V_{drops}$$

*Physical basis:*

- Based on **conservation of energy**
- Energy per charge (voltage) cannot be created/destroyed
- Energy supplied = energy consumed
- Potential increases (sources) = potential decreases (loads)
- Loop back to starting point → net voltage change = 0

*Gustav Kirchhoff's insight:*

- Realized energy supplied by sources must equal energy consumed
- No other ways for energy to enter or leave circuit
- In closed loop, total voltage must sum to zero
- Formalized this as Voltage Law

### **Why These Laws Work:**

*KCL - Charge conservation:*

- Fundamental law of physics
- Charge is conserved quantity (cannot vanish)
- Node is just connection point (no charge storage)
- All charge entering must leave
- No exceptions in DC or AC circuits

*KVL - Energy conservation:*

- Fundamental law of physics
- Energy is conserved in closed system
- Voltage = energy per unit charge
- Complete loop returns to starting potential
- Net change in potential = 0

### **Relationship Between the Laws:**

*Complementary nature:*

- KCL deals with current (flow of charge)
- KVL deals with voltage (energy per charge)
- Together provide complete circuit description
- KCL at nodes, KVL around loops
- Both needed for full circuit analysis

*Generate equations:*

- Each junction → one KCL equation
- Each independent loop → one KVL equation
- Total equations  $\geq$  number of unknowns → solvable!
- System of linear equations
- Solve simultaneously for currents/voltages

### **Sigma ( $\Sigma$ ) Notation:**

*Mathematical symbol:*

- $\Sigma$  = Greek letter sigma (capital)
- Means "sum of" or "summation"
- $\sum I$  = sum of all currents
- $\sum V$  = sum of all voltages
- Compact way to write "add up all terms"

*Example:*

- $\sum I = I_1 + I_2 + I_3 + \dots$
- $\sum V = V_1 + V_2 + V_3 + \dots$
- Sign matters (positive or negative)

## Practical Example & Numerical

### Example 1: KCL at Simple Junction

*Given:* Junction with 3 wires

- Current entering:  $I_1 = 10mA$
- Current leaving:  $I_2 = 6mA$ ,  $I_3 = ?$

**Apply KCL:**

$$\begin{aligned}\sum I_{in} &= \sum I_{out} \\ I_1 &= I_2 + I_3 \\ 10 &= 6 + I_3 \\ I_3 &= 10 - 6 = \boxed{4mA}\end{aligned}$$

### Example 2: KCL with Multiple Currents

*Given:* Junction with 5 wires

- Entering:  $I_1 = 15mA$
- Leaving:  $I_2 = 5mA$ ,  $I_3 = 3mA$ ,  $I_4 = 7mA$

**Apply KCL:**

$$\begin{aligned}I_1 &= I_2 + I_3 + I_4 \\ 15 &= 5 + 3 + 7 \\ 15 &= 15 \quad \checkmark \quad (\text{Verified!})\end{aligned}$$

Conservation of charge satisfied.

### Example 3: KVL in Simple Loop

*Given:* Single loop with 12V battery and three resistors

- Battery:  $V_s = 12V$
- Resistors:  $R_1 = 2k\Omega$ ,  $R_2 = 3k\Omega$ ,  $R_3 = 1k\Omega$

**Apply KVL:**

$$V_s - V_{R1} - V_{R2} - V_{R3} = 0$$

Or:

$$V_s = V_{R1} + V_{R2} + V_{R3}$$

**Interpretation:**

- Battery supplies 12V
- This 12V divided among three resistors
- Sum of voltage drops = 12V
- Energy conservation satisfied

### Example 4: KVL with Numbers

*Continuing Example 3:*

**Find current:**

$$\begin{aligned}R_{total} &= 2k + 3k + 1k = 6k\Omega \\ I &= \frac{V_s}{R_{total}} = \frac{12}{6,000} = 2mA\end{aligned}$$

**Voltage drops:**

$$\begin{aligned}V_{R1} &= I \times R_1 = 2 \times 2k = 4V \\ V_{R2} &= I \times R_2 = 2 \times 3k = 6V \\ V_{R3} &= I \times R_3 = 2 \times 1k = 2V\end{aligned}$$

### Verify KVL:

$$V_s = V_{R1} + V_{R2} + V_{R3}$$

$$12 = 4 + 6 + 2$$

$$12 = 12 \quad \checkmark$$

Energy conservation confirmed!

### Example 5: Combined KCL and KVL

*Given:* Circuit with junction splitting current

#### At junction (KCL):

- $I_1 = 10mA$  enters
- Splits into  $I_2$  and  $I_3$
- $I_1 = I_2 + I_3$  (KCL)

#### Around each loop (KVL):

- Loop 1:  $V_s - I_1 R_1 - I_2 R_2 = 0$
- Loop 2:  $I_2 R_2 - I_3 R_3 = 0$

#### Result:

- Three equations, three unknowns
- Can solve for  $I_1$ ,  $I_2$ ,  $I_3$
- Demonstrates power of Kirchhoff's Laws

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

1. **KCL:**  $\sum I_{in} = \sum I_{out}$  (current entering = current leaving)
2. **KVL:**  $\sum V_{loop} = 0$  (voltage around closed loop sums to zero)
3. **KCL basis:** Conservation of charge
4. **KVL basis:** Conservation of energy
5. **Junction:** 3+ wire connection (apply KCL)
6. **Loop:** Closed path in circuit (apply KVL)
7. **Together:** Generate system of equations to solve circuit
8.  **$\Sigma$  notation:** Summation symbol (add all terms)

#### Interview Questions:

- **Q:** State Kirchhoff's Current Law.  
A: Sum of currents entering junction equals sum leaving junction.
- **Q:** State Kirchhoff's Voltage Law.  
A: Algebraic sum of voltages around closed loop equals zero.
- **Q:** What conservation law is KCL based on?  
A: Conservation of charge.
- **Q:** What conservation law is KVL based on?  
A: Conservation of energy.
- **Q:** Junction has 8mA in, 3mA out, 2mA out. Find third current.  
A:  $I_3 = 8 - 3 - 2 = 3mA$  out.
- **Q:** Loop has 10V battery, two resistors drop 6V and 3V. Third resistor drop?  
A:  $V_{R3} = 10 - 6 - 3 = 1V$
- **Q:** Why can't charge accumulate at junction?  
A: Junction is just connection point with no charge storage capacity.

#### Applications:

- Mesh analysis (loop currents using KVL)
- Nodal analysis (node voltages using KCL)
- Multi-loop circuit solving
- Bridge circuit analysis
- Power distribution networks
- Complex electronic circuit design

#### Common Mistakes:

- Wrong current direction assumption (results negative - still valid!)
- Forgetting voltage drop signs in KVL

- Missing currents at junction in KCL
- Not including all voltage sources in KVL
- Confusing which currents enter vs leave

**Remember:**

- KCL: "What goes in must come out" (charge)
- KVL: "Energy supplied = energy consumed" (voltage)
- Both are consequences of fundamental conservation laws
- Always true (DC or AC circuits)
- Foundation of all circuit analysis

## Kirchhoff's Current Law (KCL)

### TL;DR (The Gist)

- **KCL:** Current in = current out at every junction/node
- **Formula:**  $I_1 = I_2 + I_3 + \dots$  (one in, multiple out) or  $\sum I = 0$
- Based on charge conservation (charge cannot accumulate at node)
- Water pipe analogy: Volume in = volume out at junction

### Detailed Explanation

## 2. Detailed Explanation

### Kirchhoff's Current Law - Complete Statement:

*Definition:*

- Current flowing INTO node = current flowing OUT of node
- Also known as: Junction Rule, Node Rule, KCL, Kirchhoff's First Law
- Consequence of **charge conservation**
- Mathematically:  $\sum I_{in} = \sum I_{out}$  or  $\sum I = 0$

*Physical principle:*

- Current = flow of electric charge
- Charge is conserved (fundamental law of physics)
- Charge cannot be created or destroyed
- Charge cannot accumulate at junction/node
- Whatever charge flows in MUST flow out
- No exceptions - always true

### What is a Node/Junction?

*Definition:*

- Connection point for THREE or more wires/components
- Current can split or merge at junction
- Examples: T-junction, Y-junction, star point

*NOT a junction:*

- Two wires connected (just continuation of same path)
- Component between two wires (e.g., resistor)
- Points A-C-D-F (only 2 connections each - not junctions)

*IS a junction:*

- Point where 3+ wires meet
- Current splits into multiple paths
- Example: Point B (3 wires), Point E (3 wires)

### Water Pipe Analogy:

*Visualization:*

- Replace wires with water pipes
- Current = volume flow rate of water
- Junction = pipe junction (T or Y shape)
- Assume water incompressible (cannot compress/expand)

*Principle:*

- Volume entering junction = volume leaving junction
- Water doesn't disappear at junction
- Water doesn't accumulate at junction (no storage)
- Flow in = flow out (conservation of mass)
- Same principle applies to electrical current!

### Applying KCL - Step by Step:

*Step 1: Identify junctions*

- Find all points where 3+ wires connect
- Mark each junction (label as A, B, C, etc.)
- Not all circuits have junctions (single loop doesn't)

*Step 2: Label currents*

- Assign current label to each wire ( $I_1, I_2, I_3$ , etc.)
- Draw arrows showing assumed direction
- Don't worry if direction wrong (result will be negative)
- Make sure at least one current enters, one leaves

*Step 3: Write KCL equation*

- Sum of currents entering = sum of currents leaving
- $I_{in} = I_{out}$
- Example:  $I_1 = I_2 + I_3$  (one in, two out)
- Or use sign convention:  $\sum I = 0$  (in positive, out negative)

### Important Concepts:

*Current same on both sides of component:*

- Current BEFORE resistor = current AFTER resistor
- Common beginner mistake: thinking current decreases across resistor
- Resistor affects voltage (drops voltage), NOT current amount
- Current is same throughout series path
- This is crucial mindset shift for beginners!

*Example misconception:*

- WRONG: "Current is 5mA before resistor, 3mA after"
- RIGHT: "Current is 5mA before AND after resistor"
- Resistor drops voltage (e.g.,  $5V \rightarrow 2V$ )
- But current unchanged (5mA throughout series path)

*Direction doesn't matter initially:*

- Can assume any current direction
- If assumption wrong  $\rightarrow$  result negative
- Negative result means actual direction opposite
- Magnitude still correct!
- Don't be afraid to guess direction

### Multiple Junctions - Which to Use?

*Not all junctions needed:*

- Some junction equations are redundant (linearly dependent)
- Example: Two junctions with same currents  $\rightarrow$  same equation
- Only need enough equations to include every current once
- Extra junctions provide same information (no new insight)

*Strategy:*

- Write KCL for each junction initially
- Check if equations identical or redundant
- Keep independent equations only
- Usually: (number of junctions - 1) equations sufficient

## Practical Example & Numerical

### Example 1: Simple 3-Current Junction

*Given:* Junction with labeled currents

- $I_1 = 4.1mA$  entering junction
- $I_2 = 2.6mA$  leaving junction
- $I_3 = 1.5mA$  leaving junction

**Apply KCL:**

$$I_1 = I_2 + I_3$$

**Verify:**

$$4.1 = 2.6 + 1.5$$

$$4.1 = 4.1 \quad \checkmark$$

Charge conservation verified!

### Example 2: Junction with 4 Currents

*Given:* Junction configuration

- $I_1$  entering
- $I_2, I_3, I_4$  leaving

**KCL Equation:**

$$I_1 = I_2 + I_3 + I_4$$

*If values:*  $I_1 = 20mA$ ,  $I_2 = 8mA$ ,  $I_3 = 5mA$

**Find  $I_4$ :**

$$20 = 8 + 5 + I_4$$

$$I_4 = 20 - 8 - 5 = \boxed{7mA}$$

### Example 3: Two Junctions (Redundant Equations)

*Circuit:* Two junctions (B and E) with same currents

**Junction B:**

- $I_1$  enters
- $I_2, I_3$  leave
- Equation:  $I_1 = I_2 + I_3$

**Junction E:**

- $I_2, I_3$  enter
- $I_1$  leaves
- Equation:  $I_2 + I_3 = I_1$

**Observation:**

- Both equations identical (just rearranged)!
- Linearly dependent - same information
- Only need ONE equation
- Second junction doesn't add new information

### Example 4: Complex Junction (Multiple Paths)

*Given:* Junction with 4 currents

- $I_1 = 12mA$  enters
- Splits into:  $I_2, I_3, I_4$  (all leaving)

**KCL:**

$$I_1 = I_2 + I_3 + I_4$$

*Additional info:* Circuit also has another junction where:

- $I_2, I_3$  enter
- $I_5, I_6$  leave

**Second junction KCL:**

$$I_2 + I_3 = I_5 + I_6$$

**Result:**

- Two independent equations
- Can solve for unknown currents
- Demonstrates KCL at multiple junctions

### Example 5: Current Conservation Through Resistor

*Scenario:* Resistor in series path

**Beginner mistake:**

- "Current is 10mA before resistor"
- "Resistor 'uses up' some current"

- "Current after resistor is less (maybe 7mA)"
- WRONG!

**Correct understanding:**

- Current before resistor: 10mA
- Current after resistor: 10mA (SAME!)
- Resistor doesn't "consume" current
- Resistor drops voltage, not current
- Current conserved through component

**What resistor does:**

- Voltage drops across it ( $V = IR$ )
- Example: 10V before, 3V after (7V drop)
- But current unchanged (10mA throughout)

**Example 6: Finding Unknown Current**

*Given:* Junction with 5 paths

- Entering:  $I_1 = 25mA$
- Leaving:  $I_2 = 8mA$ ,  $I_3 = 5mA$ ,  $I_4 = 9mA$ ,  $I_5 = ?$

**Apply KCL:**

$$I_1 = I_2 + I_3 + I_4 + I_5$$

$$25 = 8 + 5 + 9 + I_5$$

$$25 = 22 + I_5$$

$$I_5 = 25 - 22 = \boxed{3mA}$$

**Verification:**

$$8 + 5 + 9 + 3 = 25mA \quad \checkmark$$

**Key Points (Interview Focus)**

**4. Key Points (Interview Focus)**

1. **KCL:** Current in = current out at junction
2. **Junction/Node:** Connection of 3+ wires
3. **Formula:**  $\sum I_{in} = \sum I_{out}$  or  $I_1 = I_2 + I_3 + \dots$
4. **Basis:** Conservation of charge
5. **Current through component:** Same before and after (doesn't change across resistor!)
6. **Direction guess:** If wrong, result negative (magnitude still correct)
7. **Water analogy:** Volume in = volume out at pipe junction
8. **Redundant junctions:** Some equations linearly dependent (same info)

**Interview Questions:**

- **Q:** State Kirchhoff's Current Law.  
A: Current entering junction equals current leaving junction.
- **Q:** What is junction/node?  
A: Connection point of 3 or more wires.
- **Q:** 10mA enters junction, 4mA and 3mA leave. Third current?  
A:  $I_3 = 10 - 4 - 3 = 3mA$  leaving.
- **Q:** Does current change across resistor?  
A: NO - same current before and after (voltage changes, not current).
- **Q:** What happens if you assume wrong current direction?  
A: Result comes out negative (actual direction opposite), but magnitude correct.
- **Q:** Water pipe analogy for KCL?  
A: Water volume entering pipe junction = volume leaving (incompressible fluid).
- **Q:** Why can't charge accumulate at junction?  
A: Junction has no charge storage - just connection point. Charge must flow through.

**Applications:**

- Nodal analysis (node voltage method)
- Current distribution in parallel circuits
- Finding unknown branch currents
- Verifying circuit measurements

- Power distribution analysis
- Multi-branch circuit solving

#### Common Mistakes:

- Thinking current decreases across resistor (WRONG!)
- Forgetting to include all currents at junction
- Confusing current direction (in vs out)
- Applying KCL to 2-wire connections (not junctions)
- Not recognizing redundant junction equations

#### Mindset Shifts for Beginners:

- Current same throughout series path (doesn't "get used up")
- Resistor drops voltage, NOT current
- Current splits at junction, but total conserved
- Negative result OK (just means wrong direction guess)
- Always think: "Where does current come from and where does it go?"

## Kirchhoff's Voltage Law (KVL)

### TL;DR (The Gist)

- **KVL:** Sum of all voltages around closed loop = 0
- **Formula:**  $\sum V_{loop} = 0$  or  $V_{source} = V_{R1} + V_{R2} + \dots$
- Based on energy conservation: Energy supplied = energy consumed
- Ground = 0V reference point (all voltage drops must return to ground level)

### Detailed Explanation

## 2. Detailed Explanation

#### Kirchhoff's Voltage Law - Complete Statement:

*Definition:*

- Algebraic sum of all voltages around closed loop equals zero
- Also known as: Loop Rule, Mesh Rule, KVL, Kirchhoff's Second Law
- Consequence of **energy conservation**
- Mathematically:  $\sum V_{loop} = 0$

*Alternative form:*

$$V_{sources} = V_{drops}$$

- Voltage supplied by sources = voltage dropped across loads
- Energy per charge supplied = energy per charge consumed

#### Physical Principle - Energy Conservation:

*Kirchhoff's insight:*

- Energy supplied by voltage source must be transferred to components
- No other way for energy to enter or leave closed loop
- Voltage = energy per unit charge (Joules per Coulomb)
- Complete loop returns to starting point  $\rightarrow$  net voltage change = 0

*Conservation of energy:*

- Voltage source supplies energy (raises potential)
- Resistive elements consume energy (lower potential)
- Total energy supplied = total energy consumed
- Loop sum must be zero (back to starting potential)

#### Voltage Behavior Around Loop:

*Starting at point A, traveling around loop:*

1. Cross voltage source (A $\rightarrow$ B): Voltage INCREASES (+ sign)
2. Cross resistor R1 (B $\rightarrow$ C): Voltage DECREASES (- sign, voltage drop)
3. Cross resistor R2 (C $\rightarrow$ D): Voltage DECREASES (- sign)
4. Cross resistor R3 (D $\rightarrow$ E): Voltage DECREASES (- sign)

5. Wire back to A (E→A): No change (wire has negligible resistance)
6. Total: Net voltage change = 0 (back to starting point)

*Graphically:*

- Voltage vs position plot shows voltage profile
- Sharp increase at battery (voltage source)
- Gradual decreases at resistors (voltage drops)
- Flat sections on wires (low resistance)
- Returns to ground level (0V) completing loop

### **Ground - The 0V Reference:**

*What is ground?*

- 0V potential reference point
- All voltages measured relative to ground
- Ground symbol can be placed anywhere (same electrical point)
- Usually at negative terminal of battery
- Voltmeter black probe connects to ground

*Why ground at 0V?*

- After looping through circuit, all voltage dropped
- Voltage source raises potential (e.g., to +12V)
- Resistors drop voltage progressively
- By last resistor, entire voltage consumed
- Returns to ground at 0V
- Ground always at 0V potential (by definition)

### **Writing KVL Equation:**

*General form:*

$$V_{battery} - V_{R1} - V_{R2} - V_{R3} = 0$$

Or rearranged:

$$V_{battery} = V_{R1} + V_{R2} + V_{R3}$$

*Using Ohm's Law:*

$$V_{R1} = I \times R_1$$

$$V_{R2} = I \times R_2$$

$$V_{R3} = I \times R_3$$

*Substituting:*

$$V_{battery} = I(R_1 + R_2 + R_3)$$

*Solve for current:*

$$I = \frac{V_{battery}}{R_1 + R_2 + R_3}$$

This is series circuit formula derived from KVL!

### **Sign Convention - Critical for KVL:**

*Voltage source signs:*

- Moving from (-) to (+) terminal: ADD voltage (+ sign)
- Moving from (+) to (-) terminal: SUBTRACT voltage (- sign)
- Direction of travel matters!

*Resistor voltage drop signs:*

- Travel WITH current direction: SUBTRACT drop (- sign)
- Travel AGAINST current direction: ADD drop (+ sign)
- "Fall" in potential (with current) = minus
- "Rise" in potential (against current) = plus

### **Direction of Travel - Can Be Arbitrary:**

*Clockwise vs counterclockwise:*

- Can choose either direction to travel loop
- Equations will look different BUT are equivalent
- End result identical (same current values)
- Proof: Reversing direction just reverses all signs

*Example - Same loop, two directions:*

**Clockwise (same as current):**

$$V_s - IR_1 - IR_2 - IR_3 = 0$$

**Counterclockwise (opposite to current):**

$$-V_s + IR_3 + IR_2 + IR_1 = 0$$

Multiply second by (-1):

$$V_s - IR_3 - IR_2 - IR_1 = 0$$

Same equation! (just terms reordered)

**Wires vs Components:**

*Ideal wires:*

- Negligible resistance (assume  $R \approx 0$ )
- Voltage drop  $\approx 0$  ( $V = IR \approx 0$ )
- Voltage remains constant across wire
- Can ignore wire voltage drops in most circuits

*Components (resistors):*

- Significant resistance
- Voltage drops across them ( $V = IR$ )
- Must include in KVL equation

**KVL Demonstrates Series Circuit Principles:**

*From KVL, we derive:*

- Total resistance:  $R_{total} = R_1 + R_2 + R_3$  (series)
- Voltage division: Each resistor drops fraction of total voltage
- Same current through all components
- Sum of drops equals source voltage

*This explains:*

- Why voltage drops add in series
- How voltage divider works
- Where series formulas come from
- Foundation of circuit analysis

## Practical Example & Numerical

### Example 1: Simple Loop (Verify KVL)

*Given:*

- Battery: 12V
- Resistors:  $R_1 = 2k\Omega$ ,  $R_2 = 3k\Omega$ ,  $R_3 = 1k\Omega$  (series)

**Find current:**

$$R_{total} = 2k + 3k + 1k = 6k\Omega$$

$$I = \frac{12}{6,000} = 2mA$$

**Voltage drops:**

$$V_{R1} = 2 \times 2k = 4V$$

$$V_{R2} = 2 \times 3k = 6V$$

$$V_{R3} = 2 \times 1k = 2V$$

**Apply KVL:**

$$V_s - V_{R1} - V_{R2} - V_{R3} = 0$$

$$12 - 4 - 6 - 2 = 0$$

$$0 = 0 \quad \checkmark$$

Or:

$$V_s = V_{R1} + V_{R2} + V_{R3}$$

$$12 = 4 + 6 + 2$$

$$12 = 12 \quad \checkmark$$

Energy conservation verified!

### Example 2: Clockwise vs Counterclockwise

*Same circuit, traveling clockwise (with current):*

Loop:  $A \rightarrow B \rightarrow C \rightarrow D \rightarrow E \rightarrow A$

**KVL clockwise:**

$$+V_s - IR_1 - IR_2 - IR_3 = 0$$

*Same circuit, traveling counterclockwise (against current):*

Loop:  $A \rightarrow E \rightarrow D \rightarrow C \rightarrow B \rightarrow A$

**KVL counterclockwise:**

$$-V_s + IR_3 + IR_2 + IR_1 = 0$$

**Multiply by (-1):**

$$V_s - IR_3 - IR_2 - IR_1 = 0$$

**Result:** Same equation! Direction doesn't matter.

### Example 3: Ground as 0V Reference

*Circuit with labeled points:*

- Point A (battery +): 12V above ground
- Point B (after R1):  $12V - 4V = 8V$
- Point C (after R2):  $8V - 6V = 2V$
- Point D (after R3):  $2V - 2V = 0V$
- Point E (ground): 0V (reference)

**Observation:**

- Voltage decreases progressively
- Returns to 0V at ground
- Complete loop:  $0V \rightarrow 12V \rightarrow 8V \rightarrow 2V \rightarrow 0V$
- Net change = 0 (KVL satisfied)

### Example 4: Finding Unknown Voltage Drop

*Given:* Loop with 10V battery

- $V_{R1} = 3V$  (measured)
- $V_{R2} = 5V$  (measured)
- $V_{R3} = ?$  (unknown)

**Apply KVL:**

$$V_s = V_{R1} + V_{R2} + V_{R3}$$

$$10 = 3 + 5 + V_{R3}$$

$$V_{R3} = 10 - 3 - 5 = \boxed{2V}$$

No need to know current or resistance - KVL alone solves it!

### Example 5: Sign Convention Practice

*Given:* Loop traveled clockwise, current flows clockwise

**Battery (- to + travel):**

- Moving with potential rise
- Sign:  $+V_s$

**Resistor R1 (travel with current):**

- Moving with potential drop
- Sign:  $-IR_1$

**Resistor R2 (travel with current):**

- Moving with potential drop
- Sign:  $-IR_2$

**KVL Equation:**

$$+V_s - IR_1 - IR_2 = 0$$

### Example 6: Deriving Voltage Divider

Using KVL to derive voltage divider formula:

**Circuit:**  $V_s$  with  $R_1$  (top) and  $R_2$  (bottom) in series

**Output voltage:**  $V_{out}$  at junction between  $R_1$  and  $R_2$

**KVL around loop:**

$$V_s - IR_1 - IR_2 = 0$$

**Voltage across  $R_2$ :**

$$V_{out} = IR_2$$
$$I = \frac{V_s}{R_1 + R_2}$$

**Substitute:**

$$V_{out} = \frac{V_s}{R_1 + R_2} \times R_2 = V_s \times \frac{R_2}{R_1 + R_2}$$

Voltage divider formula derived from KVL!

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

1. **KVL:**  $\sum V_{loop} = 0$  (voltage around closed loop sums to zero)
2. **Alternative:**  $V_{sources} = \sum V_{drops}$  (energy supplied = consumed)
3. **Basis:** Conservation of energy
4. **Ground:** 0V reference point (all voltages measured relative to it)
5. **Sign convention:**  $(-) \rightarrow (+)$  battery = add;  $(+) \rightarrow (-)$  = subtract; with current = subtract drop
6. **Direction arbitrary:** Clockwise or counterclockwise gives same result
7. **Wire drops:** Negligible ( $\approx 0V$ ) - ignore in most circuits
8. **Loop returns:** Complete loop returns to starting voltage (net = 0)

#### Interview Questions:

- **Q:** State Kirchhoff's Voltage Law.  
A: Sum of all voltages around closed loop equals zero.
- **Q:** What conservation law is KVL based on?  
A: Conservation of energy.
- **Q:** Loop has 15V battery, resistors drop 6V and 4V. Third resistor drop?  
A:  $V_{R3} = 15 - 6 - 4 = 5V$
- **Q:** What is ground in circuit?  
A: 0V reference point - all voltages measured relative to it.
- **Q:** Sign for traveling  $(-)$  to  $(+)$  across battery?  
A: Positive (voltage increases, add to equation).
- **Q:** Sign for traveling with current through resistor?  
A: Negative (voltage decreases, subtract from equation).
- **Q:** Does loop direction (CW vs CCW) matter?  
A: No - different equations but same final result.
- **Q:** Why is ground at 0V?  
A: All voltage from source dropped across components, returning to 0V reference.

#### Applications:

- Mesh analysis (loop current method)
- Voltage drop calculations
- Deriving series circuit formulas
- Voltage divider analysis
- Multi-loop circuit solving
- Verifying circuit measurements

#### Sign Convention Summary:

- **Battery  $(-) \rightarrow (+)$ :**  $+V_s$  (voltage rise)
- **Battery  $(+) \rightarrow (-)$ :**  $-V_s$  (voltage drop)
- **Resistor (with current):**  $-IR$  (potential falls)
- **Resistor (against current):**  $+IR$  (potential rises)

#### Common Mistakes:

- Wrong signs for voltage sources or drops

- Forgetting components in loop
- Not accounting for travel direction
- Confusing ground with negative terminal (not always same)
- Including wire voltage drops (usually negligible)

#### KVL Proves:

- Series resistors: Total voltage = sum of drops
- Voltage divider formula validity
- Why components in series share source voltage
- Energy conservation in electrical circuits

## Problem-Solving Strategy - Kirchhoff's Rules

### TL;DR (The Gist)

- **5-Step Strategy:** Label points → Find nodes → Choose loops → Apply KCL → Apply KVL
- Sign convention critical:  $(-)\rightarrow(+)$  battery =  $+V$ ; travel with current =  $-IR$
- Direction of travel arbitrary (CW or CCW gives same result)
- Number of equations = number of unknowns (system solvable)

### Detailed Explanation

## 2. Detailed Explanation

### 5-Step Systematic Approach:

#### STEP 1: Label All Points

*Purpose:*

- Identify every electrical point in circuit
- Points where components connect
- Makes writing equations easier
- Use letters: A, B, C, D, E, F, etc.

*How to label:*

- Start at one point (usually battery terminal)
- Label clockwise or counterclockwise around circuit
- Each connection point gets unique label
- Same wire = same point (same label)
- Junction = point where 3+ components meet

#### STEP 2: Locate Nodes (KCL Points)

*What is a node?*

- Junction where 3 or more components meet
- Point where current splits or combines
- Apply KCL at nodes
- 2 component junction NOT a node (just connection)

*How to find nodes:*

- Count wires meeting at point
- 3+ wires = node (apply KCL here)
- 2 wires = not a node (simple connection)
- Mark nodes with special symbol or color

*Number of KCL equations:*

- Write KCL for each node
- If  $N$  nodes, typically  $N - 1$  independent equations
- One equation redundant (all currents already accounted)

#### STEP 3: Choose Loops (KVL Paths)

*What is a loop?*

- Closed path through circuit
- Start and end at same point

- Apply KVL around loops
- Can choose any loops (some more useful than others)

*How many loops?*

- Need enough equations to solve for all unknowns
- Typically choose "inner loops" or "meshes"
- Mesh = smallest loop (doesn't contain other loops)
- Number of loops = number of unknown currents minus equations from KCL

*Best practice:*

- Choose independent loops (don't just repeat information)
- Inner loops usually most efficient
- Avoid outer loops if inner loops suffice
- Each loop should introduce new information

#### STEP 4: Apply KCL at Nodes

*Current Law - Junction Rule:*

$$\sum I_{in} = \sum I_{out}$$

*Sign convention:*

- Currents INTO node: positive (+)
- Currents OUT OF node: negative (-)
- Or: Sum = 0 (all currents with proper signs)

*Example at node:*

- $I_1$  flowing IN
- $I_2$  flowing OUT
- $I_3$  flowing OUT
- Equation:  $I_1 - I_2 - I_3 = 0$  or  $I_1 = I_2 + I_3$

#### STEP 5: Apply KVL Around Loops

*Voltage Law - Loop Rule:*

$$\sum V_{loop} = 0$$

*Sign convention for batteries:*

- Travel (-) to (+): ADD voltage ( $+V_s$ )
- Travel (+) to (-): SUBTRACT voltage ( $-V_s$ )
- Direction relative to battery polarity

*Sign convention for resistors:*

- Travel WITH current: SUBTRACT drop ( $-IR$ )
- Travel AGAINST current: ADD drop ( $+IR$ )
- Direction relative to assumed current flow

*Important:*

- Choose travel direction for loop (CW or CCW)
- Stick with that direction around entire loop
- Sign depends on travel vs current/polarity
- Different travel direction OK (same final answer)

#### Sign Map Summary:

Component	Condition	Sign
Battery	(-) to (+) travel	$+V_s$
Battery	(+) to (-) travel	$-V_s$
Resistor	Travel with current	$-IR$
Resistor	Travel against current	$+IR$

#### Direction of Travel - Key Insight:

*Freedom of choice:*

- Can choose clockwise OR counterclockwise
- Equations look different but are equivalent
- Final numerical results identical
- Proves: Loop direction arbitrary!

*Why it works:*

- Reversing direction reverses ALL signs
- Multiply equation by (-1) gives same equation
- Physics doesn't care about arbitrary choice

- Energy conservation independent of travel direction

*Example comparison:*

**Clockwise travel (with current):**

$$+V_s - I_1 R_1 - I_1 R_2 = 0$$

**Counterclockwise travel (against current):**

$$-V_s + I_1 R_2 + I_1 R_1 = 0$$

Multiply second by (-1):

$$+V_s - I_1 R_2 - I_1 R_1 = 0$$

Same equation! (terms reordered)

**Current Direction - Also Arbitrary:**

*Assumption vs reality:*

- Assume current direction (draw arrows)
- If assumption wrong, answer will be negative
- Negative current = flows opposite to assumed direction
- No problem! Just means you guessed wrong
- Magnitude correct, sign tells true direction

*What if I assume wrong?*

- Solve equations normally
- Get negative value (e.g.,  $I = -2mA$ )
- Interpretation: 2mA flows opposite to arrow
- Can redraw with corrected direction if desired
- Math handles it automatically!

**System of Equations:**

*How many equations needed?*

- Number of equations = number of unknowns
- Unknowns = unknown currents
- Use combination of KCL and KVL
- Solve simultaneously (substitution, elimination, matrices)

*Example:*

- 3 unknown currents → need 3 equations
- 2 nodes → 1 KCL equation (N-1 rule)
- Need 2 more equations → choose 2 loops for KVL
- Solve 3 equations, 3 unknowns

**Problem-Solving Workflow:**

1. **Label:** All points (A, B, C, ...)
2. **Nodes:** Mark junctions (3+ wires)
3. **Loops:** Choose independent loops (inner loops best)
4. **Assume:** Current directions (draw arrows)
5. **KCL:** Write equations at nodes
6. **KVL:** Write equations around loops (watch signs!)
7. **Solve:** System of equations
8. **Check:** Negative current = wrong assumption, flip direction
9. **Verify:** Substitute back, check KCL/KVL satisfied

## Practical Example & Numerical

### Example 1: Sign Convention Practice

*Loop with battery and two resistors (travel clockwise):*

**Given:**

- Battery: 10V (- on left, + on right)
- Current flows clockwise (assumed)
- Resistors:  $R_1 = 2k\Omega$ ,  $R_2 = 3k\Omega$
- Travel clockwise (WITH current)

**KVL Equation:**

Starting at point A (ground), traveling clockwise:

- Cross battery (- to +):  $+V_s$  (voltage rises)
- Cross  $R_1$  (with current):  $-IR_1$  (voltage drops)
- Cross  $R_2$  (with current):  $-IR_2$  (voltage drops)
- Return to A (complete loop)

$$+V_s - IR_1 - IR_2 = 0$$

**Solve:**

$$10 - I(2000) - I(3000) = 0$$

$$10 = I(5000)$$

$$I = \frac{10}{5000} = \boxed{2mA}$$

**Example 2: Opposite Travel Direction**

Same circuit, travel counterclockwise (AGAINST current):

**KVL Equation:**

Starting at A, traveling counterclockwise:

- Cross  $R_2$  (against current):  $+IR_2$  (voltage rises against drop)
- Cross  $R_1$  (against current):  $+IR_1$  (voltage rises against drop)
- Cross battery (+ to -):  $-V_s$  (voltage drops)
- Return to A

$$+IR_2 + IR_1 - V_s = 0$$

**Rearrange:**

$$V_s = I(R_1 + R_2)$$

**Solve:**

$$10 = I(5000)$$

$$I = \boxed{2mA}$$

Same result! Direction doesn't matter.

**Example 3: Wrong Current Assumption**

Circuit with current assumed incorrectly:

**Given:**

- Battery: 12V
- $R = 6k\Omega$
- Assume current flows counterclockwise (WRONG guess)
- Reality: Flows clockwise

**KVL (with wrong assumption):**

Travel clockwise, current assumed counterclockwise:

$$+V_s + IR = 0$$

(Resistor has + sign because we travel against assumed current)

**Solve:**

$$12 + I(6000) = 0$$

$$I = -\frac{12}{6000} = \boxed{-2mA}$$

**Interpretation:**

- Negative current means assumption wrong
- Current actually 2mA in opposite direction (clockwise)
- Magnitude correct: 2mA
- Direction: Opposite to arrow (i.e., clockwise)

Math automatically corrects wrong guess!

**Example 4: Node with Three Currents**

Junction where three wires meet:

**Given:**

- $I_1 = 5mA$  flows INTO node
- $I_2 = 3mA$  flows OUT of node
- $I_3 = ?$  (unknown, flows OUT)

Apply **KCL**:

$$\begin{aligned} I_{in} &= I_{out} \\ I_1 &= I_2 + I_3 \\ 5 &= 3 + I_3 \\ I_3 &= \boxed{2mA} \end{aligned}$$

Or using sum = 0:

$$\begin{aligned} I_1 - I_2 - I_3 &= 0 \\ 5 - 3 - I_3 &= 0 \\ I_3 &= \boxed{2mA} \end{aligned}$$

### Example 5: Simple Two-Loop Circuit

*Circuit with one node and two loops:*

**Given:**

- Battery:  $V_s = 15V$
- Loop 1 resistors:  $R_1 = 1k\Omega$ ,  $R_2 = 2k\Omega$
- Loop 2 resistors:  $R_2 = 2k\Omega$  (shared),  $R_3 = 3k\Omega$
- Currents:  $I_1$  (loop 1),  $I_2$  (loop 2),  $I_3$  (through  $R_2$ )
- Node B: Junction where  $I_1$  and  $I_2$  meet

**STEP 1 - KCL at node B:**

$$I_1 = I_2 + I_3$$

**STEP 2 - KVL around loop 1 (clockwise):**

$$+V_s - I_1 R_1 - I_3 R_2 = 0$$

**STEP 3 - KVL around loop 2 (clockwise):**

$$+I_3 R_2 - I_2 R_3 = 0$$

**Solve system:**

- 3 equations, 3 unknowns ( $I_1$ ,  $I_2$ ,  $I_3$ )
- Substitution or matrices
- (Detailed solve in Circuit Analysis examples)

### Example 6: Checking Your Work

*After solving, verify:*

**1. Check KCL at all nodes:**

- Sum currents IN = sum currents OUT
- Should equal to within rounding error

**2. Check KVL around all loops:**

- Sum voltages should = 0
- Substitute solved currents into voltage drops

**3. Check sign consistency:**

- Positive currents flow with arrows
- Negative currents flow against arrows

**4. Check units:**

- Current in amps (or mA,  $\mu A$ )
- Voltage in volts
- Resistance in ohms

## Key Points (Interview Focus)

## 4. Key Points (Interview Focus)

1. **5 Steps:** Label points  $\rightarrow$  Locate nodes  $\rightarrow$  Choose loops  $\rightarrow$  KCL  $\rightarrow$  KVL
2. **Sign map:**  $(-)\rightarrow(+)=+V$ ;  $(+)\rightarrow(-)=-V$ ; with current  $=-IR$ ; against  $=+IR$
3. **Travel direction:** Arbitrary (CW or CCW gives same result)
4. **Current direction:** Can assume any; negative result = opposite flow
5. **Node:** 3+ wires meeting (apply KCL)
6. **Loop:** Closed path (apply KVL)
7. **Equations:** Number needed = number of unknowns
8. **Verification:** Substitute back, check KCL and KVL satisfied

### Interview Questions:

- **Q:** What are the 5 steps for Kirchhoff analysis?  
A: Label points, locate nodes, choose loops, apply KCL, apply KVL.
- **Q:** Sign for traveling  $(-)$  to  $(+)$  across battery?  
A: Positive  $(+V_s)$  - voltage increases.
- **Q:** Sign for traveling with current through resistor?  
A: Negative  $(-IR)$  - voltage decreases.
- **Q:** Does loop direction (CW vs CCW) affect final answer?  
A: No - equations differ but result identical.
- **Q:** What if you assume wrong current direction?  
A: Answer will be negative - means current flows opposite to assumption.
- **Q:** What is a node?  
A: Junction where 3+ wires meet (apply KCL).
- **Q:** How many KCL equations for N nodes?  
A: N-1 independent equations (one redundant).
- **Q:** How do you verify your solution?  
A: Substitute values back into KCL and KVL - should equal 0.

### Sign Convention Quick Reference:

Situation	Sign
Battery $(- \text{ to } +)$ travel	$+V_s$
Battery $(+ \text{ to } -)$ travel	$-V_s$
Resistor (with current)	$-IR$
Resistor (against current)	$+IR$

### Common Mistakes:

- Wrong signs (most common error!)
- Forgetting components in loop
- Not distinguishing nodes from simple connections
- Using outer loop when inner loops sufficient
- Panicking when current is negative (it's OK!)
- Inconsistent travel direction within loop

### Pro Tips:

- Draw clear current arrows before writing equations
- Mark travel direction on circuit diagram
- Double-check signs before solving
- Use inner loops (meshes) - usually easier
- Label everything clearly
- Verify solution by substituting back

## Circuit Analysis using Kirchhoff's Rules - Part I

### TL;DR (The Gist)

- Single loop circuits: One KVL equation solves it
- Multi-resistor series:  $R_{eq} = R_1 + R_2 + R_3$  derived from KVL
- Voltage divider:  $V_{out} = V_s \times \frac{R_2}{R_1 + R_2}$  derived from KVL

- KVL foundation for all series circuit analysis

## Detailed Explanation

### 2. Detailed Explanation

#### Single Loop Circuit Analysis:

*Simplest case:*

- One voltage source
- Multiple resistors in series
- Single current path
- Apply KVL around loop
- One equation, one unknown (current)

#### Example: Three Resistors in Series

*Circuit:*

- Battery:  $V_s$
- Resistors:  $R_1, R_2, R_3$  (series)
- Current:  $I$  (same through all)
- Points: A, B, C, D, E

**Apply KVL (clockwise):**

$$V_s - IR_1 - IR_2 - IR_3 = 0$$

**Factor out current:**

$$V_s = I(R_1 + R_2 + R_3)$$

**Solve for current:**

$$I = \frac{V_s}{R_1 + R_2 + R_3}$$

**Define equivalent resistance:**

$$R_{eq} = R_1 + R_2 + R_3$$

**Then:**

$$I = \frac{V_s}{R_{eq}}$$

This is Ohm's Law for series circuit!

#### Key Insight:

- KVL proves series resistors ADD
- Total resistance = sum of individual resistances
- Same current through all (series property)
- Voltage drops add to source voltage

#### Deriving Voltage Divider from KVL:

*Voltage divider circuit:*

- Input voltage:  $V_s$
- Top resistor:  $R_1$
- Bottom resistor:  $R_2$
- Output: Voltage at junction between  $R_1$  and  $R_2$
- Want:  $V_{out}$  in terms of  $V_s, R_1, R_2$

**Step 1 - Find current using KVL:**

$$\begin{aligned} V_s - IR_1 - IR_2 &= 0 \\ V_s &= I(R_1 + R_2) \\ I &= \frac{V_s}{R_1 + R_2} \end{aligned}$$

**Step 2 - Find output voltage:**

- $V_{out}$  measured at junction (between  $R_1$  and  $R_2$ )
- $V_{out}$  = voltage across  $R_2$  (from junction to ground)
- Using Ohm's Law:  $V_{out} = I \times R_2$

**Step 3 - Substitute current:**

$$V_{out} = \frac{V_s}{R_1 + R_2} \times R_2$$

**Rearrange:**

$$V_{out} = V_s \times \frac{R_2}{R_1 + R_2}$$

This is the voltage divider formula!

### Voltage Divider Insights:

*From the formula:*

- Output voltage = fraction of input
- Fraction =  $\frac{R_2}{R_{total}}$
- If  $R_2 = R_1$ :  $V_{out} = \frac{V_s}{2}$  (half voltage)
- If  $R_2 \gg R_1$ :  $V_{out} \approx V_s$  (most voltage)
- If  $R_2 \ll R_1$ :  $V_{out} \approx 0$  (little voltage)

*Physical interpretation:*

- Larger resistor drops more voltage
- Resistors "divide" source voltage proportionally
- Ratio of resistances determines voltage split
- Output taken at junction between resistors

### General Voltage Divider for N Resistors:

*For any resistor  $R_k$  in series string:*

$$V_{R_k} = V_s \times \frac{R_k}{R_1 + R_2 + \dots + R_N}$$

*Each resistor drops:*

- Fraction of total voltage
- Fraction = its resistance / total resistance
- Sum of all drops = source voltage
- Validates KVL:  $V_s = V_{R1} + V_{R2} + \dots$

### KVL as Foundation:

*All series formulas come from KVL:*

- Equivalent resistance formula
- Voltage divider formula
- Current same through series components
- Voltage drops add to source voltage

*Why KVL works:*

- Energy conservation
- Voltage = energy per charge
- Energy supplied by source = energy dissipated by resistors
- Complete loop  $\rightarrow$  net energy change = 0

## Practical Example & Numerical

### Example 1: Three Resistors in Series

*Given:*

- Battery:  $V_s = 12V$
- Resistors:  $R_1 = 1k\Omega$ ,  $R_2 = 2k\Omega$ ,  $R_3 = 3k\Omega$

**Find current:**

**Apply KVL:**

$$V_s - IR_1 - IR_2 - IR_3 = 0$$

**Solve:**

$$12 - I(1000) - I(2000) - I(3000) = 0$$

$$12 = I(6000)$$

$$I = \frac{12}{6000} = \boxed{2mA}$$

Verify using equivalent resistance:

$$R_{eq} = 1k + 2k + 3k = 6k\Omega$$

$$I = \frac{12V}{6k\Omega} = 2mA \quad \checkmark$$

Find voltage drops:

$$V_{R1} = 2mA \times 1k = 2V$$

$$V_{R2} = 2mA \times 2k = 4V$$

$$V_{R3} = 2mA \times 3k = 6V$$

Verify KVL:

$$V_s = V_{R1} + V_{R2} + V_{R3}$$

$$12V = 2V + 4V + 6V$$

$$12V = 12V \quad \checkmark$$

### Example 2: Voltage Divider Calculation

Given:

- Input:  $V_s = 10V$
- $R_1 = 3k\Omega$  (top)
- $R_2 = 7k\Omega$  (bottom)
- Find:  $V_{out}$  at junction

Method 1 - Using voltage divider formula:

$$\begin{aligned} V_{out} &= V_s \times \frac{R_2}{R_1 + R_2} \\ &= 10 \times \frac{7000}{3000 + 7000} \\ &= 10 \times \frac{7000}{10000} \\ &= 10 \times 0.7 \\ &= \boxed{7V} \end{aligned}$$

Method 2 - Using KVL and Ohm's Law:

Find current:

$$I = \frac{V_s}{R_1 + R_2} = \frac{10}{10,000} = 1mA$$

Find  $V_{out}$ :

$$V_{out} = I \times R_2 = 1mA \times 7k = \boxed{7V}$$

Same result!

### Example 3: Half Voltage Divider

Goal: Create 6V from 12V source

Requirement:

$$V_{out} = \frac{V_s}{2} = 6V$$

Voltage divider formula:

$$V_{out} = V_s \times \frac{R_2}{R_1 + R_2}$$

For half voltage:

$$\frac{1}{2} = \frac{R_2}{R_1 + R_2}$$

Solve:

$$R_1 + R_2 = 2R_2$$

$$R_1 = R_2$$

Conclusion: Equal resistors give half voltage

Example values:

- $R_1 = R_2 = 10k\Omega \rightarrow V_{out} = 6V$
- Or  $R_1 = R_2 = 1k\Omega \rightarrow V_{out} = 6V$
- Ratio matters, not absolute values (for unloaded divider)

#### Example 4: Four Resistors - Finding One Voltage

Given:

- Battery: 20V
- $R_1 = 1k, R_2 = 2k, R_3 = 3k, R_4 = 4k$
- Find: Voltage across  $R_3$  only

Method - Voltage divider:

Total resistance:

$$R_{total} = 1k + 2k + 3k + 4k = 10k\Omega$$

Voltage across  $R_3$ :

$$\begin{aligned} V_{R3} &= V_s \times \frac{R_3}{R_{total}} \\ &= 20 \times \frac{3000}{10000} \\ &= 20 \times 0.3 \\ &= \boxed{6V} \end{aligned}$$

No need to find current first!

#### Example 5: Deriving Voltage at Each Point

Circuit: 15V battery, three  $1k\Omega$  resistors

Ground at negative terminal (0V):

Current:

$$I = \frac{15V}{3k\Omega} = 5mA$$

Voltage at each point (from ground):

Point A (battery + terminal):

$$V_A = 15V$$

Point B (after  $R_1$ ):

$$V_B = V_A - V_{R1} = 15 - 5 = 10V$$

Point C (after  $R_2$ ):

$$V_C = V_B - V_{R2} = 10 - 5 = 5V$$

Point D (after  $R_3$ , at ground):

$$V_D = V_C - V_{R3} = 5 - 5 = 0V$$

Voltage profile:  $15V \rightarrow 10V \rightarrow 5V \rightarrow 0V$

#### Example 6: Practical Application - LED Current Limiting

Given:

- Supply: 5V
- LED forward voltage:  $V_f = 2V$
- Desired LED current: 10mA
- Find: Current limiting resistor value

Apply KVL:

$$V_s - V_{LED} - V_R = 0$$

Solve for resistor voltage:

$$V_R = V_s - V_{LED} = 5 - 2 = 3V$$

Find resistor value:

$$\begin{aligned} R &= \frac{V_R}{I} = \frac{3V}{10mA} \\ &= \frac{3}{0.01} = \boxed{300\Omega} \end{aligned}$$

Use standard value:  $330\Omega$

Verify with KVL:

$$\begin{aligned} V_s &= V_{LED} + V_R \\ 5V &= 2V + 3V \\ 5V &= 5V \quad \checkmark \end{aligned}$$

#### 4. Key Points (Interview Focus)

1. **Series  $R_{eq}$ :**  $R_1 + R_2 + R_3$  (derived from KVL)
2. **Voltage divider:**  $V_{out} = V_s \times \frac{R_2}{R_1 + R_2}$
3. **Single loop:** One KVL equation solves for current
4. **Each resistor drop:**  $V_{R_k} = V_s \times \frac{R_k}{R_{total}}$
5. **KVL foundation:** All series formulas come from energy conservation
6. **Equal resistors:** Each drops equal voltage (simple divider)
7. **Voltage profile:** Decreases progressively from source to ground
8. **Practical use:** LED current limiting, sensor interfacing, level shifting

##### Interview Questions:

- **Q:** Derive series equivalent resistance from KVL.  
A:  $V_s = IR_1 + IR_2 + IR_3 = I(R_1 + R_2 + R_3)$ , so  $R_{eq} = R_1 + R_2 + R_3$ .
- **Q:** Derive voltage divider formula.  
A:  $I = V_s / (R_1 + R_2)$ ,  $V_{out} = IR_2$ , substitute:  $V_{out} = V_s \times R_2 / (R_1 + R_2)$ .
- **Q:** Two equal resistors in series across 10V. Voltage across each?  
A: 5V each (voltage divides equally).
- **Q:** How to get 3.3V from 5V using resistors?  
A: Voltage divider:  $\frac{R_2}{R_1 + R_2} = \frac{3.3}{5}$ , e.g.,  $R_1 = 1.7k$ ,  $R_2 = 3.3k$ .
- **Q:** Why do series resistances add?  
A: KVL: Total voltage = sum of drops,  $V_s = I(R_1 + R_2 + \dots)$ , so  $R_{eq} = R_1 + R_2 + \dots$
- **Q:** Three resistors (1k, 2k, 3k) in series. Which drops most voltage?  
A: 3k $\Omega$  (largest resistance drops most voltage).

##### Applications:

- Voltage dividers (sensor interfacing, level shifting)
- LED current limiting
- Biasing circuits
- Reference voltage generation
- Analog-to-digital converter (ADC) input scaling

##### Voltage Divider Design Rules:

- Ratio determines output (not absolute values)
- Lower total resistance = more current draw
- Higher total resistance = less loading effect
- Trade-off: Current consumption vs output impedance
- Account for load if output drives something

##### Common Mistakes:

- Forgetting KVL sum includes ALL components
- Wrong resistor in voltage divider fraction
- Ignoring load effect on divider output
- Using voltage divider formula for parallel circuits

## Circuit Analysis using Kirchhoff's Rules - Part II

### TL;DR (The Gist)

- Multi-loop circuits: Need KCL at nodes + KVL around loops
- System of equations: Solve simultaneously for all currents
- Example: 2 nodes, 3 loops  $\rightarrow$  4 equations (1 KCL + 3 KVL)
- Matrix methods or substitution to solve

### Detailed Explanation

## 2. Detailed Explanation

### Multi-Loop Circuit Analysis - Complete Example:

#### Circuit Description:

Given complex circuit with:

- One voltage source:  $V_s = 20V$
- Five resistors:  $R_1 = 10\Omega$ ,  $R_2 = 20\Omega$ ,  $R_3 = 30\Omega$ ,  $R_4 = 40\Omega$ ,  $R_5 = 50\Omega$
- Two nodes (junctions): Node A and Node B
- Three loops: Loop 1 (left), Loop 2 (right), Loop 3 (outer)
- Four unknown currents:  $I_1$ ,  $I_2$ ,  $I_3$ ,  $I_4$

Circuit topology:

- Battery connects to  $R_1$  (top left)
- Node A: Junction after  $R_1$  (3 branches)
- Branch 1:  $R_2$  down from A to ground (left side)
- Branch 2:  $R_3$  right from A to Node B
- Branch 3:  $R_4$  and  $R_5$  in series down from B to ground (right side)
- Node B: Junction where  $R_3$  meets  $R_4$

#### STEP 1: Label Points and Currents

Points:

- Point 1: Battery + terminal
- Point A: Junction after  $R_1$  (Node A)
- Point B: Junction between  $R_3$  and  $R_4$  (Node B)
- Ground: 0V reference (battery - terminal)

Current labels:

- $I_1$ : Through  $R_1$  (from battery)
- $I_2$ : Through  $R_2$  (left branch, downward)
- $I_3$ : Through  $R_3$  (middle, A to B)
- $I_4$ : Through  $R_4$  and  $R_5$  (right branch, downward)

#### STEP 2: Identify Nodes

Node A:

- Three currents meet:  $I_1$  (in),  $I_2$  (out),  $I_3$  (out)
- Apply KCL:  $I_1 = I_2 + I_3$

Node B:

- Two currents:  $I_3$  (in),  $I_4$  (out)
- Apply KCL:  $I_3 = I_4$
- This tells us  $I_3$  and  $I_4$  are equal!

#### STEP 3: Choose Loops

Loop 1 (Left loop):

- Path: Battery  $\rightarrow R_1 \rightarrow$  Node A  $\rightarrow R_2 \rightarrow$  Ground  $\rightarrow$  Battery
- Components:  $V_s$ ,  $R_1$ ,  $R_2$
- Currents:  $I_1$  through  $R_1$ ,  $I_2$  through  $R_2$

Loop 2 (Right loop):

- Path: Node A  $\rightarrow R_3 \rightarrow$  Node B  $\rightarrow R_4 \rightarrow R_5 \rightarrow$  Ground  $\rightarrow R_2 \rightarrow$  Node A
- Components:  $R_3$ ,  $R_4$ ,  $R_5$ ,  $R_2$
- Currents:  $I_3$  through  $R_3$ ,  $I_4$  through  $R_4$  and  $R_5$ ,  $I_2$  through  $R_2$

Loop 3 (Outer loop - optional):

- Path: Battery  $\rightarrow R_1 \rightarrow R_3 \rightarrow R_4 \rightarrow R_5 \rightarrow$  Ground  $\rightarrow$  Battery
- Not independent (combination of Loops 1 and 2)
- Can use for verification

#### STEP 4: Apply KCL at Nodes

At Node A:

$$I_1 = I_2 + I_3 \quad (\text{Equation 1})$$

At Node B:

$$I_3 = I_4 \quad (\text{Equation 2})$$

#### STEP 5: Apply KVL Around Loops

Loop 1 (clockwise, starting at ground):

Travel: Ground  $\rightarrow$  Battery (+)  $\rightarrow R_1$  (down with  $I_1$ )  $\rightarrow$  Node A  $\rightarrow R_2$  (down with  $I_2$ )  $\rightarrow$  Ground

**Signs:**

- Battery (- to +):  $+V_s$
- $R_1$  (with  $I_1$ ):  $-I_1R_1$
- $R_2$  (with  $I_2$ ):  $-I_2R_2$

**Equation:**

$$+V_s - I_1R_1 - I_2R_2 = 0 \quad (\text{Equation 3})$$

**Loop 2 (clockwise, starting at Node A):**

Travel: A  $\rightarrow R_3$  (right with  $I_3$ )  $\rightarrow$  B  $\rightarrow R_4$  (down with  $I_4$ )  $\rightarrow R_5$  (down with  $I_4$ )  $\rightarrow$  Ground  $\rightarrow R_2$  (up against  $I_2$ )  $\rightarrow$  A

**Signs:**

- $R_3$  (with  $I_3$ ):  $-I_3R_3$
- $R_4$  (with  $I_4$ ):  $-I_4R_4$
- $R_5$  (with  $I_4$ ):  $-I_4R_5$
- $R_2$  (against  $I_2$ ):  $+I_2R_2$

**Equation:**

$$-I_3R_3 - I_4R_4 - I_4R_5 + I_2R_2 = 0 \quad (\text{Equation 4})$$

**System of Equations:**

$$I_1 = I_2 + I_3 \quad (\text{Eq 1 - KCL at A})$$

$$I_3 = I_4 \quad (\text{Eq 2 - KCL at B})$$

$$V_s - I_1R_1 - I_2R_2 = 0 \quad (\text{Eq 3 - KVL Loop 1})$$

$$-I_3R_3 - I_4R_4 - I_4R_5 + I_2R_2 = 0 \quad (\text{Eq 4 - KVL Loop 2})$$

**Simplification Using Equation 2:**

Since  $I_3 = I_4$ , substitute in Equation 4:

$$-I_3R_3 - I_3R_4 - I_3R_5 + I_2R_2 = 0$$

$$-I_3(R_3 + R_4 + R_5) + I_2R_2 = 0$$

$$I_2R_2 = I_3(R_3 + R_4 + R_5)$$

**Equation 4 simplified:**

$$I_2R_2 = I_3(R_3 + R_4 + R_5) \quad (\text{Eq 4'})$$

**Solving the System (Substitution Method):****From Equation 1:**

$$I_1 = I_2 + I_3$$

**Substitute into Equation 3:**

$$V_s - (I_2 + I_3)R_1 - I_2R_2 = 0$$

$$V_s - I_2R_1 - I_3R_1 - I_2R_2 = 0$$

$$V_s = I_2(R_1 + R_2) + I_3R_1$$

**From Equation 4':**

$$I_2 = I_3 \times \frac{R_3 + R_4 + R_5}{R_2}$$

**Substitute into  $V_s$  equation:**

$$V_s = I_3 \frac{R_3 + R_4 + R_5}{R_2} \times (R_1 + R_2) + I_3R_1$$

$$V_s = I_3 \left[ \frac{(R_3 + R_4 + R_5)(R_1 + R_2)}{R_2} + R_1 \right]$$

**Solve for  $I_3$ :**

$$I_3 = \frac{V_s}{\frac{(R_3 + R_4 + R_5)(R_1 + R_2)}{R_2} + R_1}$$

**Numerical Calculation:**

Given values:

- $V_s = 20V$

- $R_1 = 10\Omega$ ,  $R_2 = 20\Omega$ ,  $R_3 = 30\Omega$ ,  $R_4 = 40\Omega$ ,  $R_5 = 50\Omega$

Calculate  $I_3$ :

Step 1 - Sum of right resistors:

$$R_3 + R_4 + R_5 = 30 + 40 + 50 = 120\Omega$$

Step 2 - Sum of  $R_1$  and  $R_2$ :

$$R_1 + R_2 = 10 + 20 = 30\Omega$$

Step 3 - Calculate denominator:

$$\begin{aligned}\text{Denominator} &= \frac{120 \times 30}{20} + 10 \\ &= \frac{3600}{20} + 10 \\ &= 180 + 10 \\ &= 190\Omega\end{aligned}$$

Step 4 - Solve for  $I_3$ :

$$I_3 = \frac{20}{190} = 0.1053A = \boxed{105.3mA}$$

But let's verify with simpler approach using actual example from source material...

**Actual Example from Material (Simplified):**

*Circuit with:*

- $V_s = 20V$
- $R_1 = 20\Omega$  (from battery)
- $R_2 = 20\Omega$  (left branch)
- $R_3 = 30\Omega$  (middle branch)
- $R_4 = 50\Omega$  (right branch, combines with  $R_5$ )

**Final Results from Source Material:**

- $I_3 = 117mA$  (middle branch current)
- $I_2 = 294mA$  (left branch current)
- $V_{R2} = I_2 \times R_2 = 0.294 \times 20 = 5.88V$

**Key Insights from Multi-Loop Analysis:**

*System solving:*

- 4 unknowns  $\rightarrow$  need 4 equations
- Got 4 equations: 2 from KCL, 2 from KVL
- Solve using substitution, elimination, or matrices
- Negative current OK (means opposite direction)

*Current distribution:*

- Source current splits at junctions
- Lower resistance branch carries more current
- Total current conserved (KCL)
- Voltages consistent around loops (KVL)

*Verification methods:*

- Check KCL at all nodes (currents in = currents out)
- Check KVL around all loops (sum = 0)
- Check power:  $P_{source} = P_{R1} + P_{R2} + \dots$
- Use outer loop (Loop 3) as additional check

## Practical Example & Numerical

### Example 1: Complete Two-Loop Circuit (From Source Material)

*Given circuit:*

- Battery:  $V_s = 20V$
- Resistors:  $R_1 = 20\Omega$ ,  $R_2 = 20\Omega$ ,  $R_3 = 30\Omega$ ,  $R_4 = 50\Omega$
- 2 nodes, 3 possible loops
- 3 unknown currents:  $I_1$  (source),  $I_2$  (left),  $I_3$  (right)

**STEP 1: KCL at Node A (after  $R_1$ ):**

$$I_1 = I_2 + I_3 \quad (\text{Eq 1})$$

**STEP 2: KVL Loop 1 (Battery  $\rightarrow R_1 \rightarrow R_2 \rightarrow$  Ground):**

$$V_s - I_1 R_1 - I_2 R_2 = 0 \quad (\text{Eq 2})$$

**STEP 3: KVL Loop 2 ( $R_2 \rightarrow$  Node A  $\rightarrow R_3 \rightarrow R_4 \rightarrow$  Ground):**

$$I_2 R_2 - I_3 R_3 - I_3 R_4 = 0 \quad (\text{Eq 3})$$

**Simplify Equation 3:**

$$I_2 R_2 = I_3 (R_3 + R_4)$$

$$I_2 \times 20 = I_3 (30 + 50)$$

$$20 I_2 = 80 I_3$$

$$I_2 = 4 I_3 \quad (\text{Eq 3'})$$

**Substitute Eq 3' into Eq 1:**

$$I_1 = 4 I_3 + I_3 = 5 I_3$$

**Substitute both into Eq 2:**

$$20 - (5 I_3)(20) - (4 I_3)(20) = 0$$

$$20 - 100 I_3 - 80 I_3 = 0$$

$$20 = 180 I_3$$

$$I_3 = \frac{20}{180} = 0.111 A = \boxed{111 mA}$$

(Source material shows 117mA - small difference due to rounding or exact resistor values)

**Find other currents:**

$$I_2 = 4 \times 0.111 = \boxed{444 mA} \quad (\text{or } 294 mA \text{ from source})$$

$$I_1 = I_2 + I_3 = 444 + 111 = \boxed{555 mA}$$

**Find voltage across  $R_2$ :**

$$V_{R2} = I_2 \times R_2 = 0.444 \times 20 = 8.88 V \quad (\text{or } 5.88 V \text{ from source})$$

**Example 2: Verification Using KCL**

**At Node A:**

$$I_1 = I_2 + I_3$$

$$555 mA = 444 mA + 111 mA$$

$$555 mA = 555 mA \quad \checkmark$$

**Example 3: Verification Using KVL (Loop 1)**

**Loop 1: Battery  $\rightarrow R_1 \rightarrow R_2 \rightarrow$  Ground**

$$V_s = I_1 R_1 + I_2 R_2$$

$$20 = 0.555 \times 20 + 0.444 \times 20$$

$$20 = 11.1 + 8.88$$

$$20 \approx 20 \quad \checkmark$$

**Example 4: Verification Using KVL (Loop 2)**

**Loop 2: Around right mesh**

$$I_2 R_2 = I_3 (R_3 + R_4)$$

$$0.444 \times 20 = 0.111 \times (30 + 50)$$

$$8.88 = 0.111 \times 80$$

$$8.88 = 8.88 \quad \checkmark$$

### Example 5: Power Balance Check

Power supplied by source:

$$P_s = V_s \times I_1 = 20 \times 0.555 = 11.1W$$

Power dissipated by resistors:

$$P_{R1} = I_1^2 R_1 = (0.555)^2 \times 20 = 6.16W$$

$$P_{R2} = I_2^2 R_2 = (0.444)^2 \times 20 = 3.95W$$

$$P_{R3} = I_3^2 R_3 = (0.111)^2 \times 30 = 0.37W$$

$$P_{R4} = I_3^2 R_4 = (0.111)^2 \times 50 = 0.62W$$

$$P_{total} = 6.16 + 3.95 + 0.37 + 0.62 = 11.1W \quad \checkmark$$

Energy conservation verified!

### Example 6: Finding Unknown Resistor

Given:

- Circuit with known currents (measured)
- $I_2 = 300mA$ ,  $I_3 = 120mA$
- Voltage across  $R_2 = 6V$  (measured)
- $R_3 = 30\Omega$ ,  $R_4 = ?$  (unknown)

Find  $R_2$  first:

$$R_2 = \frac{V_{R2}}{I_2} = \frac{6}{0.3} = 20\Omega$$

Use KVL Loop 2:

$$I_2 R_2 = I_3 (R_3 + R_4)$$

$$0.3 \times 20 = 0.12(30 + R_4)$$

$$6 = 3.6 + 0.12R_4$$

$$2.4 = 0.12R_4$$

$$R_4 = \frac{2.4}{0.12} = \boxed{20\Omega}$$

### Example 7: Three-Loop Circuit (More Complex)

Given:

- Two batteries:  $V_1 = 12V$ ,  $V_2 = 6V$
- Five resistors in complex network
- 3 nodes, 4 unknown currents

Strategy:

1. KCL at 2 nodes (3 nodes  $\rightarrow$  2 independent equations)
2. KVL around 2 inner loops
3. Total: 4 equations, 4 unknowns
4. Solve using matrix method or substitution

Matrix form:

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix}$$

Solve using Gaussian elimination, Cramer's rule, or calculator/software.

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

1. **Multi-loop:** Requires KCL + KVL system of equations
2. **Equation count:** Number of equations = number of unknowns
3. **KCL equations:** N nodes  $\rightarrow$  N-1 independent equations
4. **KVL equations:** Choose independent loops (inner meshes best)
5. **Solving:** Substitution, elimination, or matrix methods
6. **Verification:** Check KCL at nodes, KVL around loops, power balance

7. **Current splits:** Lower resistance path carries more current
8. **System approach:** Label, identify, write equations, solve, verify

#### Interview Questions:

- **Q:** How many equations needed for 3 unknown currents?  
A: 3 equations (combination of KCL and KVL).
- **Q:** Circuit has 4 nodes. How many independent KCL equations?  
A:  $N-1 = 3$  independent KCL equations.
- **Q:** Two loops in circuit, 2 nodes. How many equations total?  
A: 3 unknowns: 1 KCL + 2 KVL = 3 equations.
- **Q:** How to verify multi-loop solution?  
A: Check KCL at all nodes, KVL around all loops, power balance.
- **Q:** What if calculated current is negative?  
A: Flows opposite to assumed direction - magnitude correct.
- **Q:** Which loop gives more current - higher or lower resistance?  
A: Lower resistance path carries more current.

#### Applications:

- Power distribution networks
- Bridge circuits (Wheatstone bridge)
- Multi-stage amplifier analysis
- Complex filter networks
- Battery management systems
- Load-sharing circuits

#### Solution Methods:

- **Substitution:** Solve one equation for variable, substitute into others
- **Elimination:** Add/subtract equations to eliminate variables
- **Matrix:** Use Cramer's rule or Gaussian elimination
- **Software:** MATLAB, Python (NumPy), calculator matrix mode

#### Common Mistakes:

- Wrong sign in KVL (most common!)
- Not enough independent equations
- Using dependent loop (outer loop when have inner loops)
- Arithmetic errors in complex calculations
- Forgetting to verify solution

#### Verification Checklist:

- KCL at every node (within rounding error)
- KVL around every loop (sum = 0)
- Power supplied = power consumed
- Current directions make physical sense
- Magnitudes reasonable for given voltages/resistances

#### Pro Tips:

- Choose inner loops (meshes) for KVL - usually simplest
- Draw current arrows clearly before equations
- Mark loop travel direction on diagram
- Double-check signs before solving system
- Use symmetry to simplify when possible
- Verify with outer loop as final check

# Section 06 – Electric Power P[W] Fundamentals

## Electric Power - Introduction

TL;DR (The Gist)

- **Power:** Rate of energy transfer over time
- **Electric Power:** How fast electrical energy is converted to other forms
- Energy cannot be created/destroyed - only transformed
- Producers supply power (batteries), consumers use power (LEDs, motors)

## Detailed Explanation

### 2. Detailed Explanation

#### Why Power Matters:

*Two fundamental reasons:*

- **Cost:** Energy costs money - batteries and electricity aren't free
- **Safety:** Energy can be harmful (heat, radiation, sound, nuclear)

*Power measures:*

- How fast pennies drain from your wallet
- How fast energy is being used or produced
- Potential for component damage (overheating, smoking resistors)

#### What is Electric Power?

*General definition:*

- Power = rate at which energy is transferred or transformed
- "Rate" means per unit time
- More power = faster energy transfer

*Energy basics:*

- Energy = ability to move something or make change happen
- Energy cannot be created or destroyed (conservation law)
- Energy can only be **transformed** from one form to another

#### Forms of Energy:

*Many types exist:*

- **Mechanical:** Motion, kinetic energy
- **Electrical:** Moving electrons, current flow
- **Chemical:** Batteries, fuel
- **Electromagnetic:** Light, radio waves
- **Thermal:** Heat energy
- **Nuclear:** Atomic reactions
- **Sound:** Acoustic energy

#### Energy Transformations in Electronics:

*Electronics converts energy to/from electrical form:*

##### Electric to Light (LED):

- Electrical energy → Electromagnetic energy
- LED consumes electric power, produces light
- Some energy lost as heat (byproduct)

##### Electric to Motion (Motor):

- Electrical energy → Mechanical energy
- Motor consumes electric power, produces rotation
- Also produces heat and sound (losses)

##### Electric to Sound (Buzzer):

- Electrical energy → Acoustic energy

- Buzzer consumes electric power, produces sound waves

#### Chemical to Electric (Battery):

- Chemical energy → Electrical energy
- Battery produces electric power from chemical reactions
- 9V alkaline battery converts chemical potential to voltage

#### Electric Energy Flow:

*How electric energy works:*

1. Starts as **electric potential energy** (voltage)
2. Electrons flow through potential difference
3. Potential energy converts to **electric energy** (current × voltage)
4. Electric energy transforms to other useful forms (light, heat, motion)

#### Power Consumers vs Producers:

*Consumers:*

- Transform electric energy INTO another form
- Examples: Resistors (heat), LEDs (light), motors (motion)
- **Consume** or **dissipate** power
- Power is positive (energy leaving electrical form)

*Producers:*

- Transform energy FROM another form into electric
- Examples: Batteries (chemical→electric), solar cells (light→electric)
- **Supply** or **generate** power
- Power is supplied to circuit

#### Power Measures Two Things:

*Electric power combines:*

1. **How much:** Amount of electric energy transferred (Joules)
2. **How fast:** Rate of transfer (per second)

*Result:*

- Power = Energy / Time
- Units: Joules per second
- Standard name: Watt (W)

#### Conservation in Circuits:

*Energy conservation law:*

- Power supplied = Power consumed (in steady state)
- Battery power out = Sum of all component powers
- No energy created or destroyed
- All supplied energy eventually becomes heat (usually)

*Example circuit:*

- Battery supplies 10W
- LED consumes 2W (1.8W light + 0.2W heat)
- Resistor consumes 8W (all becomes heat)
- Total consumed: 2W + 8W = 10W ✓

### Practical Example & Numerical

#### Example 1: Energy Transformations

*LED circuit:*

- 5V battery powers LED through resistor
- Battery: Chemical → Electric (produces power)
- LED: Electric → Light + Heat (consumes power)
- Resistor: Electric → Heat (consumes power)

**Energy flow:**

Chemical  $\xrightarrow{\text{Battery}}$  Electric  $\xrightarrow{\text{LED+Resistor}}$  Light + Heat

#### Example 2: Power Scale Examples

*Different power levels in real devices:*

**Arduino (Microcontroller):**

- Operating power: 100-500 mW (milliwatts)
- Low power sleep mode: 1-10 mW
- Range: Microwatts to milliwatts

#### LED Lighting:

- Small indicator LED: 20-100 mW
- Standard LED bulb: 5-15 W
- High-power LED: 1-10 W

#### Laptop Computer:

- Typical operation: 30-65 W
- Heavy load: 100-150 W
- Range: Standard watts

#### Household:

- Average house: 1-5 kW (kilowatts)
- Air conditioner: 2-5 kW
- Electric stove: 2-3 kW

#### Large Stadium:

- Lighting and facilities: 1-10 MW (megawatts)
- Major sporting event: 5-20 MW

#### Power Station:

- Large coal plant: 500-2000 MW
- Nuclear plant: 1-2 GW (gigawatts)
- Hydroelectric dam: 1-10 GW

#### Example 3: Motor Energy Conversion

*DC motor powered by 12V battery:*

#### Energy transformations:

- Input:  $12V \times 500mA = 6W$  electrical
- Output: Mechanical rotation (shaft work)
- Losses: Heat (70%), Sound (5%)
- Useful mechanical:  $25\% = 1.5W$

#### Energy accounting:

- 6W supplied (chemical→electric in battery)
- 1.5W useful mechanical work
- 4.2W lost as heat
- 0.3W lost as sound
- Total: 6W consumed = 6W supplied ✓

#### Example 4: Battery Lifetime Estimation

*Given:*

- 9V battery capacity: 500 mAh (milliamp-hours)
- Circuit draws: 50 mA constant

#### Battery life:

$$\text{Time} = \frac{\text{Capacity}}{\text{Current}} = \frac{500 \text{ mAh}}{50 \text{ mA}} = 10 \text{ hours}$$

#### Energy used:

- Power:  $P = 9V \times 50mA = 450mW = 0.45W$
- Time: 10 hours = 36,000 seconds
- Energy:  $E = P \times t = 0.45 \times 36000 = 16,200 \text{ J}$

#### Cost (if from wall outlet):

- Energy:  $0.45W \times 10h = 4.5 \text{ Wh} = 0.0045 \text{ kWh}$
- At \$0.12/kWh:  $0.0045 \times 0.12 = \$0.00054$  (~0.05 cents)

#### Example 5: Power Prefix Practice

*Convert between units:*

#### Microwatts to watts:

$$500 \mu W = 500 \times 10^{-6} W = 0.0005 W$$

#### Milliwatts to watts:

$$250 mW = 250 \times 10^{-3} W = 0.25 W$$

#### Kilowatts to watts:

$$3.5 kW = 3.5 \times 10^3 W = 3500 W$$

**Megawatts to watts:**

$$2 \text{ MW} = 2 \times 10^6 \text{ W} = 2,000,000 \text{ W}$$

**Gigawatts to watts:**

$$1.21 \text{ GW} = 1.21 \times 10^9 \text{ W} = 1,210,000,000 \text{ W}$$

(Yes, that's a Back to the Future reference - DeLorean time machine!)

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

1. **Power:** Rate of energy transfer (Energy/Time)
2. **Conservation:** Energy cannot be created/destroyed, only transformed
3. **Consumers:** Convert electric→other (LEDs, motors, resistors)
4. **Producers:** Convert other→electric (batteries, solar cells)
5. **Forms:** Electrical, mechanical, chemical, electromagnetic, thermal, sound
6. **Why care:** Cost (money) and safety (heat, damage)
7. **Circuit balance:** Power supplied = Power consumed
8. **Transformations:** Always involve some loss (usually heat)

#### Interview Questions:

- **Q:** What is electric power?  
A: Rate at which electrical energy is transferred or transformed.
- **Q:** Can energy be created or destroyed?  
A: No - only transformed from one form to another (conservation law).
- **Q:** What energy transformation happens in an LED?  
A: Electrical energy → Electromagnetic (light) + Heat.
- **Q:** Is a battery a power consumer or producer?  
A: Producer - converts chemical energy to electrical.
- **Q:** Is a resistor a power consumer or producer?  
A: Consumer - converts electrical energy to heat.
- **Q:** Why do we care about power in circuits?  
A: Cost (energy costs money) and safety (too much power causes heat/damage).
- **Q:** What happens to energy supplied by battery?  
A: Consumed by components and transformed to other forms (light, heat, motion).

#### Energy Transformation Examples:

- LED: Electric → Light + Heat
- Motor: Electric → Mechanical + Heat + Sound
- Buzzer: Electric → Sound + Heat
- Resistor: Electric → Heat (100%)
- Battery: Chemical → Electric
- Solar cell: Light → Electric

#### Power Scale Reference:

- $\mu\text{W}$  (microwatt):  $10^{-6} \text{ W}$  - Low-power sensors
- mW (milliwatt):  $10^{-3} \text{ W}$  - Arduino, small LEDs
- W (watt):  $10^0 \text{ W}$  - Laptops, light bulbs
- kW (kilowatt):  $10^3 \text{ W}$  - Household appliances
- MW (megawatt):  $10^6 \text{ W}$  - Large buildings, stadiums
- GW (gigawatt):  $10^9 \text{ W}$  - Power stations

#### Common Misconceptions:

- Power is NOT voltage (voltage is potential)
- Power is NOT current (current is flow rate)
- Current doesn't "get used up" (energy does)
- More voltage doesn't always mean more power (depends on current too)

## Wattage

### TL;DR (The Gist)

- **Watt (W):** Unit of power = Joules per second
- Energy measured in Joules; Power = Energy/Time
- Symbol: W (uppercase, not to confuse with "w" for work)
- Prefixes:  $\mu$ W, mW, W, kW, MW, GW (depends on application)

## Detailed Explanation

### 2. Detailed Explanation

#### The Watt - Official Unit of Power:

##### Definition:

*Power measures energy transfer rate:*

- Energy measured in **Joules (J)**
- Time measured in **seconds (s)**
- Power = Energy / Time = Joules/second

*International System of Units (SI):*

- Official name: **Watt**
- Symbol: **W**
- Equivalence: 1 W = 1 J/s
- Named after James Watt (Scottish inventor)

#### Mathematical Expression:

$$P = \frac{E}{t}$$

Where:

- $P$  = Power (Watts)
- $E$  = Energy (Joules)
- $t$  = Time (seconds)

*Rearranging:*

$$E = P \times t \quad (\text{Energy from power and time})$$

$$t = \frac{E}{P} \quad (\text{Time from energy and power})$$

#### Prefixes for Different Scales:

*Very common in electronics and power systems:*

##### Microwatt ( $\mu$ W):

- $1 \mu W = 10^{-6} \text{ W} = 0.000001 \text{ W}$
- Ultra-low power devices
- Examples: Watches, pacemakers, wireless sensors

##### Milliwatt (mW):

- $1 mW = 10^{-3} \text{ W} = 0.001 \text{ W}$
- Low power electronics
- Examples: Arduino, LEDs, small circuits

##### Watt (W):

- Base unit = 1 W
- Common consumer electronics
- Examples: Laptops, light bulbs, phone chargers

##### Kilowatt (kW):

- $1 kW = 10^3 \text{ W} = 1,000 \text{ W}$
- Household and automotive power
- Examples: Appliances, electric vehicles, HVAC

##### Megawatt (MW):

- $1 MW = 10^6 \text{ W} = 1,000,000 \text{ W}$
- Industrial and large facilities
- Examples: Factories, data centers, large buildings

##### Gigawatt (GW):

- $1 GW = 10^9 \text{ W} = 1,000,000,000 \text{ W}$

- Power generation and distribution
- Examples: Power plants, electrical grids, time machines

### Application-Specific Ranges:

#### Microcontrollers ( $\mu\text{W}$ to $\text{mW}$ ):

- Arduino Uno: 200-500 mW (active)
- Arduino sleep mode: 1-10 mW
- ESP32 WiFi: 100-300 mW
- ATtiny sleep: 1-100  $\mu\text{W}$

#### Consumer Electronics ( $\text{W}$ range):

- LED bulb: 5-15 W
- Laptop: 30-100 W
- Desktop PC: 100-500 W
- Phone charger: 5-20 W

#### Household ( $\text{kW}$ range):

- Refrigerator: 100-800 W (0.1-0.8 kW)
- Microwave: 600-1200 W (0.6-1.2 kW)
- Air conditioner: 2-5 kW
- Electric water heater: 3-5 kW
- Whole house: 1-5 kW average

#### Large Scale ( $\text{MW}$ to $\text{GW}$ ):

- Sports stadium: 5-20 MW
- Small town: 10-50 MW
- Large city: 1-10 GW
- Coal power plant: 500-2000 MW
- Nuclear plant: 1-2 GW

### Energy vs Power - Critical Distinction:

#### Energy (Joules):

- **Amount** of work that can be done
- Total capacity
- Stored in batteries, capacitors, fuel
- Example: "Battery stores 10,000 J"

#### Power (Watts):

- **Rate** at which work is done
- How fast energy is used/produced
- Example: "Circuit consumes 5 W"

#### Analogy:

- Energy = Water in bucket (amount)
- Power = Flow rate from bucket (how fast)
- 10 liters flowing at 1 L/s  $\rightarrow$  10 seconds to empty
- 10,000 J at 5 W  $\rightarrow$  2,000 seconds to deplete

### Watt-Hour (Wh) - Energy Unit:

#### Common in batteries and utilities:

- Watt-hour (Wh) = Power  $\times$  Time
- 1 Wh = 1 W for 1 hour = 3,600 J
- Kilowatt-hour (kWh) = 1,000 Wh

#### Why use Wh instead of J?

- More convenient for everyday use
- Easier to understand (watts  $\times$  hours)
- Standard on electricity bills (kWh)
- Battery capacity often in mAh or Wh

#### Example:

- 100W bulb for 10 hours = 1,000 Wh = 1 kWh
- At \$0.12/kWh  $\rightarrow$  costs \$0.12

## Practical Example & Numerical

### Example 1: Energy to Power Conversion

Given:

- Device uses 5,000 J of energy
- Runs for 50 seconds

Calculate power:

$$P = \frac{E}{t} = \frac{5000 J}{50 s} = \boxed{100 W}$$

Device operates at 100 watts.

### Example 2: Power to Energy Conversion

Given:

- LED consumes 50 mW
- Operates for 2 hours

Calculate energy:

$$\begin{aligned} P &= 50 mW = 0.05 W \\ t &= 2 hours = 2 \times 3600 = 7200 s \\ E &= P \times t = 0.05 \times 7200 = \boxed{360 J} \end{aligned}$$

Also in watt-hours:

$$E = 0.05 W \times 2 h = 0.1 Wh$$

### Example 3: Unit Conversion Practice

Convert 2,500 mW to watts:

$$2500 mW = 2500 \times 10^{-3} = 2.5 W$$

Convert 0.003 W to microwatts:

$$0.003 W = 3 \times 10^{-3} = 3 mW = 3000 \mu W$$

Convert 5 kW to watts:

$$5 kW = 5 \times 10^3 = 5000 W$$

Convert 1.5 MW to kW:

$$1.5 MW = 1.5 \times 10^6 W = 1500 kW$$

### Example 4: Electricity Bill Calculation

Given:

- 2 kW air conditioner runs 6 hours/day for 30 days
- Electricity rate: \$0.12 per kWh

Energy consumed:

$$\begin{aligned} E &= P \times t \\ &= 2 kW \times (6 h/day \times 30 days) \\ &= 2 \times 180 = 360 kWh \end{aligned}$$

Cost:

$$\text{Cost} = 360 kWh \times \$0.12/kWh = \boxed{\$43.20}$$

### Example 5: Battery Runtime Calculation

Given:

- Battery capacity: 2,000 mAh at 3.7V
- Device power consumption: 500 mW

Battery energy:

$$\begin{aligned} E &= V \times Q \\ Q &= 2000 mAh = 2 Ah = 2 \times 3600 = 7200 C \\ E &= 3.7 \times 7200 = 26,640 J \end{aligned}$$

Or in watt-hours:

$$E = 3.7 V \times 2 Ah = 7.4 Wh$$

Runtime:

$$t = \frac{E}{P} = \frac{7.4 Wh}{0.5 W} = 14.8 hours$$

Or in Joules:

$$t = \frac{26640 \text{ J}}{0.5 \text{ W}} = 53,280 \text{ s} = \boxed{14.8 \text{ hours}}$$

#### Example 6: Comparing Power Levels

Which uses more power?

**Option A:** 500 mW for 10 hours

$$E_A = 0.5 \text{ W} \times 10 \text{ h} = 5 \text{ Wh}$$

**Option B:** 2 W for 2 hours

$$E_B = 2 \text{ W} \times 2 \text{ h} = 4 \text{ Wh}$$

**Result:** Option A uses more *energy* (5 Wh vs 4 Wh), but Option B has higher *power* (2 W vs 0.5 W).

Key distinction: Power is rate, energy is total amount!

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

1. **Watt (W):** Unit of power = 1 Joule/second
2. **Formula:**  $P = E/t$  (Power = Energy / Time)
3. **Common prefixes:**  $\mu\text{W}$ , mW, W, kW, MW, GW
4. **Energy vs Power:** Energy = amount; Power = rate
5. **Watt-hour (Wh):** Energy unit = Power  $\times$  Time
6. **Electricity billing:** kWh (kilowatt-hours)
7. **Named after:** James Watt (Scottish inventor)
8. **Symbol:** W (uppercase)

#### Interview Questions:

- **Q:** What is a watt?  
A: Unit of power equal to one joule per second.
- **Q:** What's the difference between Joules and Watts?  
A: Joules measure energy (amount), Watts measure power (rate of energy transfer).
- **Q:** How many watts in 1 kilowatt?  
A: 1,000 watts.
- **Q:** What is a kilowatt-hour?  
A: Energy used by 1 kW device for 1 hour = 3.6 million Joules.
- **Q:** Device uses 200 mW for 5 hours. Energy consumed?  
A:  $E = 0.2 \text{ W} \times 5 \text{ h} = 1 \text{ Wh} = 3,600 \text{ J}$ .
- **Q:** Typical power range for Arduino?  
A: 100-500 mW (milliwatt range).

#### Power Range Guide:

- $\mu\text{W}$ : Ultra-low power (watches, sensors)
- mW: Low power electronics (Arduino, LEDs)
- W: Consumer devices (laptops, bulbs)
- kW: Appliances, vehicles
- MW: Industrial, large buildings
- GW: Power plants, grids

#### Unit Conversion Quick Reference:

- $1 \text{ W} = 1,000 \text{ mW} = 1,000,000 \mu\text{W}$
- $1 \text{ kW} = 1,000 \text{ W}$
- $1 \text{ MW} = 1,000 \text{ kW} = 1,000,000 \text{ W}$
- $1 \text{ GW} = 1,000 \text{ MW} = 1,000,000,000 \text{ W}$

#### Common Calculations:

- Power from energy and time:  $P = E/t$
- Energy from power and time:  $E = P \times t$
- Time from energy and power:  $t = E/P$
- Watt-hours to Joules:  $\text{Wh} \times 3,600 = \text{J}$
- Joules to Watt-hours:  $\text{J} / 3,600 = \text{Wh}$

# Calculating Power

## TL;DR (The Gist)

- **Basic formula:**  $P = V \times I$  (Power = Voltage  $\times$  Current)
- **With resistance:**  $P = I^2 R$  or  $P = V^2 / R$  (using Ohm's Law)
- Need any 2 of 3 values (V, I, R) to calculate power
- Power in component = voltage drop  $\times$  current through it

## Detailed Explanation

### 2. Detailed Explanation

#### Fundamental Power Equation:

#### Deriving Power from Basic Definitions:

*What we know:*

- **Voltage (V):** Potential energy per unit charge = Joules/Coulomb
- **Current (I):** Charge flow per unit time = Coulombs/second
- **Power (P):** Energy transfer per unit time = Joules/second

*Combining voltage and current:*

$$\begin{aligned} P &= \frac{\text{Energy}}{\text{Time}} \\ &= \frac{\text{Joules}}{\text{second}} \\ &= \frac{\text{Joules}}{\text{Coulomb}} \times \frac{\text{Coulombs}}{\text{second}} \\ &= V \times I \end{aligned}$$

#### Result - Primary Power Formula:

$$P = V \times I$$

Where:

- $P$  = Power (Watts)
- $V$  = Voltage (Volts)
- $I$  = Current (Amperes)

#### Using Ohm's Law to Create Alternative Formulas:

*Ohm's Law reminder:*

$$V = I \times R \quad \text{or} \quad I = \frac{V}{R}$$

#### Power Formula 1: Using Voltage and Resistance

*Start with:*  $P = V \times I$

*Substitute:*  $I = V/R$

$$\begin{aligned} P &= V \times \frac{V}{R} \\ P &= \frac{V^2}{R} \end{aligned}$$

#### Result:

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

*Use when:*

- Know voltage across component
- Know resistance of component
- Don't know current (don't need to calculate it)

#### Power Formula 2: Using Current and Resistance

*Start with:*  $P = V \times I$

*Substitute:*  $V = I \times R$

$$P = (I \times R) \times I$$

$$P = I^2 \times R$$

**Result:**

$$P = I^2 R$$

*Use when:*

- Know current through component
- Know resistance of component
- Don't know voltage (don't need to calculate it)

**Three Power Formulas - Summary:**

Formula	When to Use	Known Values
$P = V \times I$	V and I known	Voltage, Current
$P = \frac{V^2}{R}$	V and R known	Voltage, Resistance
$P = I^2 R$	I and R known	Current, Resistance

*Key insight:*

- Need ANY TWO of three values (V, I, R)
- Can always calculate power
- Choose formula based on what you know

**Step-by-Step Power Calculation:**

**Example approach:**

1. Identify the component (resistor, LED, etc.)
2. Find voltage drop ACROSS component
3. Find current THROUGH component
4. Multiply:  $P = V \times I$

*Alternative if resistance known:*

1. Know any two: V, I, or R
2. Choose appropriate power formula
3. Calculate power
4. Check if within component rating

**Practical Circuit Example:**

*Given:*

- 9V battery
- 10Ω resistor
- Series circuit

**Step 1 - Find current (Ohm's Law):**

$$I = \frac{V}{R} = \frac{9}{10} = 0.9 \text{ A} = 900 \text{ mA}$$

**Step 2 - Calculate power (Method 1: V and I):**

$$P = V \times I = 9 \times 0.9 = 8.1 \text{ W}$$

**Or Step 2 - Calculate power (Method 2:  $V^2/R$ ):**

$$P = \frac{V^2}{R} = \frac{9^2}{10} = \frac{81}{10} = 8.1 \text{ W}$$

**Or Step 2 - Calculate power (Method 3:  $I^2 R$ ):**

$$P = I^2 R = (0.9)^2 \times 10 = 0.81 \times 10 = 8.1 \text{ W}$$

All three methods give same answer!

**Physical Interpretation:**

*What does 8.1W mean?*

- Resistor dissipates 8.1 Joules per second
- Electrical energy → Heat energy
- 8.1W of heat produced continuously

- After 1 minute:  $8.1 \times 60 = 486$  Joules as heat
- After 10 minutes:  $8.1 \times 600 = 4,860$  Joules

#### When Each Formula is Most Useful:

$P = V \times I$  (Traditional):

- Most direct and intuitive
- Use when both V and I are known/measured
- Works for any component (not just resistors)
- Best for components with varying resistance

$P = V^2/R$  (Voltage-based):

- Use when voltage is fixed/known
- Don't need to calculate current first
- Common for components across power supply
- Shows: Double voltage =  $4\times$  power (quadratic relationship)

$P = I^2 R$  (Current-based):

- Use when current is fixed/known
- Common in series circuits (same current everywhere)
- Don't need to calculate voltage first
- Shows: Double current =  $4\times$  power (quadratic relationship)

#### Power in Complete Circuit:

*Conservation principle:*

- Power supplied = Power consumed (steady state)
- Battery/source power = Sum of all component powers
- $P_{source} = P_{R1} + P_{R2} + P_{R3} + \dots$

*Example verification:*

- 12V battery, 1A current  $\rightarrow P_{source} = 12 \times 1 = 12W$
- Three resistors in series: 4W, 5W, 3W
- Total consumed:  $4 + 5 + 3 = 12W$  ✓

### Practical Example & Numerical

#### Example 1: All Three Methods

*Given:*  $R = 100\Omega$ ,  $V = 10V$  across resistor

**Method 1 - Find I, then P:**

$$I = \frac{V}{R} = \frac{10}{100} = 0.1 A$$

$$P = V \times I = 10 \times 0.1 = \boxed{1 W}$$

**Method 2 - Use  $V^2/R$ :**

$$P = \frac{V^2}{R} = \frac{10^2}{100} = \frac{100}{100} = \boxed{1 W}$$

**Method 3 - Use  $I^2 R$ :**

$$I = 0.1 A \text{ (from Method 1)}$$

$$P = I^2 R = (0.1)^2 \times 100 = 0.01 \times 100 = \boxed{1 W}$$

All methods confirm: 1W dissipated!

#### Example 2: Series Circuit Power Distribution

*Given:*

- 12V battery
- Three resistors in series:  $R_1 = 10\Omega$ ,  $R_2 = 20\Omega$ ,  $R_3 = 30\Omega$

**Total resistance:**

$$R_{total} = 10 + 20 + 30 = 60\Omega$$

**Circuit current:**

$$I = \frac{12}{60} = 0.2 A$$

**Power in each resistor (using  $P = I^2 R$ ):**

$$P_{R1} = I^2 R_1 = (0.2)^2 \times 10 = 0.04 \times 10 = 0.4 \text{ W}$$

$$P_{R2} = I^2 R_2 = (0.2)^2 \times 20 = 0.04 \times 20 = 0.8 \text{ W}$$

$$P_{R3} = I^2 R_3 = (0.2)^2 \times 30 = 0.04 \times 30 = 1.2 \text{ W}$$

**Total power:**

$$P_{total} = 0.4 + 0.8 + 1.2 = 2.4 \text{ W}$$

**Verify with source power:**

$$P_{source} = V \times I = 12 \times 0.2 = 2.4 \text{ W} \quad \checkmark$$

*Observation:* Larger resistor dissipates more power in series!

### Example 3: LED Current Limiting Resistor Power

*Given:*

- 5V supply
- LED:  $V_f = 2\text{V}$ ,  $I_f = 20\text{mA}$
- Current limiting resistor:  $R = ?$

**Find resistor value:**

$$V_R = V_{supply} - V_{LED} = 5 - 2 = 3\text{V}$$

$$R = \frac{V_R}{I} = \frac{3}{0.02} = 150\Omega$$

**Power in resistor:**

$$P_R = V_R \times I = 3 \times 0.02 = \boxed{0.06 \text{ W} = 60 \text{ mW}}$$

Or using  $I^2 R$ :

$$P_R = (0.02)^2 \times 150 = 0.0004 \times 150 = 0.06 \text{ W}$$

**Resistor rating needed:** Standard 1/8W (125mW) is sufficient.

### Example 4: Voltage Doubling Effect on Power

*Given:*  $R = 50\Omega$  resistor

**At 5V:**

$$P_1 = \frac{V^2}{R} = \frac{5^2}{50} = \frac{25}{50} = 0.5 \text{ W}$$

**At 10V (doubled):**

$$P_2 = \frac{V^2}{R} = \frac{10^2}{50} = \frac{100}{50} = 2 \text{ W}$$

**Ratio:**

$$\frac{P_2}{P_1} = \frac{2}{0.5} = 4$$

*Conclusion:* Doubling voltage quadruples power! (Quadratic relationship)

### Example 5: Multi-Component Circuit

*Circuit:*

- 15V battery
- $R_1 = 100\Omega$  in series with parallel combination
- $R_2 = 200\Omega$  and  $R_3 = 200\Omega$  in parallel

**Parallel combination:**

$$R_{23} = \frac{R_2 \times R_3}{R_2 + R_3} = \frac{200 \times 200}{200 + 200} = 100\Omega$$

**Total resistance:**

$$R_{total} = R_1 + R_{23} = 100 + 100 = 200\Omega$$

**Main current:**

$$I_1 = \frac{15}{200} = 0.075 \text{ A} = 75 \text{ mA}$$

**Power in  $R_1$ :**

$$P_1 = I_1^2 R_1 = (0.075)^2 \times 100 = 0.5625 \text{ W}$$

**Voltage across parallel resistors:**

$$V_{23} = I_1 \times R_{23} = 0.075 \times 100 = 7.5\text{V}$$

Current through each parallel resistor:

$$I_2 = I_3 = \frac{7.5}{200} = 0.0375 \text{ A} = 37.5 \text{ mA}$$

Power in  $R_2$  and  $R_3$ :

$$P_2 = P_3 = V \times I = 7.5 \times 0.0375 = 0.28125 \text{ W}$$

Total power:

$$P_{total} = 0.5625 + 0.28125 + 0.28125 = 1.125 \text{ W}$$

Verify:

$$P_{source} = 15 \times 0.075 = 1.125 \text{ W} \quad \checkmark$$

#### Example 6: Finding Unknown Resistance from Power

Given:

- Resistor dissipates 2W
- Current through it: 100mA

Find resistance:

From  $P = I^2 R$ :

$$R = \frac{P}{I^2} = \frac{2}{(0.1)^2} = \frac{2}{0.01} = \boxed{200\Omega}$$

Verify with voltage:

$$V = I \times R = 0.1 \times 200 = 20\text{V}$$

$$P = V \times I = 20 \times 0.1 = 2\text{W} \quad \checkmark$$

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

1. **Basic formula:**  $P = V \times I$  (most fundamental)
2. **With resistance:**  $P = V^2/R$  or  $P = I^2 R$
3. **Need 2 of 3:** Knowing any two (V, I, R) allows power calculation
4. **Quadratic relationship:** Double V or I  $\rightarrow 4\times$  power
5. **Conservation:**  $P_{source} = \sum P_{components}$
6. **All formulas equivalent:** Choose based on known values
7. **Units:** V in volts, I in amps, R in ohms  $\rightarrow$  P in watts
8. **Energy over time:**  $E = P \times t$  (power  $\times$  duration)

#### Interview Questions:

- **Q:** State the three power formulas.  
A:  $P = VI$ ,  $P = V^2/R$ ,  $P = I^2 R$ .
- **Q:** 10V across 100 $\Omega$  resistor. Power dissipated?  
A:  $P = V^2/R = 100/100 = 1\text{W}$ .
- **Q:** If voltage doubles, how does power change?  
A: Quadruples ( $4\times$  power), since  $P \propto V^2$ .
- **Q:** Which resistor dissipates more power in series - larger or smaller?  
A: Larger resistance (same current,  $P = I^2 R$ , so larger R  $\rightarrow$  larger P).
- **Q:** 12V, 2A through circuit. Total power?  
A:  $P = VI = 12 \times 2 = 24\text{W}$ .
- **Q:** Derive  $P = V^2/R$  from  $P = VI$ .  
A: Substitute  $I = V/R$  into  $P = VI$ :  $P = V(V/R) = V^2/R$ .

#### Power Formula Selection Guide:

- Known V and I  $\rightarrow$  Use  $P = VI$
- Known V and R  $\rightarrow$  Use  $P = V^2/R$
- Known I and R  $\rightarrow$  Use  $P = I^2 R$
- Any two values sufficient!

#### Applications:

- Resistor power rating selection
- LED current limiting resistor sizing

- Circuit power consumption calculation
- Battery life estimation
- Thermal management (heat dissipation)
- Energy cost calculation

#### Common Mistakes:

- Using total voltage instead of voltage drop across component
- Forgetting to square V or I in formulas
- Wrong units (must use Volts, Amps, Ohms)
- Confusing power (rate) with energy (total)

#### Key Relationships:

- $P \propto V^2$  (at constant R)
- $P \propto I^2$  (at constant R)
- $P \propto 1/R$  (at constant V)
- $P \propto R$  (at constant I)

## Resistor Power Ratings

### TL;DR (The Gist)

- **Power rating:** Maximum power component can safely dissipate
- Common resistor ratings: 1/8W, 1/4W, 1/2W, 1W, 2W
- Exceeding rating → overheating → "magic smoke" (component failure)
- Always select resistor with rating  $\geq$  calculated power (safety margin)

### Detailed Explanation

## 2. Detailed Explanation

#### Why Power Ratings Matter:

#### Energy Transformation and Heat:

*What happens in components:*

- All components transform energy from one type to another
- **Desired transformations:** LEDs→light, motors→motion, batteries→charging
- **Undesired transformations:** Energy losses, usually as heat
- Heat is unavoidable byproduct in most circuits

*Even "useful" components produce heat:*

- LEDs: Mostly light, but some heat
- Motors: Mostly motion, but winding resistance creates heat
- Batteries: Charging creates heat
- All have internal resistance → power loss

#### Heat and Component Damage:

*Too much heat is dangerous:*

- Components have maximum temperature limits
- Exceeding limits causes:
  - Physical damage (melting, burning)
  - Performance degradation
  - Parameter drift
  - Complete failure ("letting the magic smoke out")

*Power rating definition:*

- Maximum power component can dissipate safely
- Usually specified at room temperature (25°C)
- Higher ambient temperature → must derate (use less power)
- Exceeding rating → overheating → damage

#### Resistors - Notorious Power Consumers:

*Why resistors are special concern:*

- 100% of electrical energy  $\rightarrow$  heat (no useful output)
- Drop voltage AND pass current  $\rightarrow P = VI$
- More voltage = more current = MORE power (quadratic)
- Easy to exceed rating if not careful

*Example of dangerous scenario:*

- 9V across  $10\Omega$  resistor
- Current:  $I = 9/10 = 0.9A$
- Power:  $P = 9 \times 0.9 = 8.1W$
- Standard  $1/2W$  (0.5W) resistor rated for only 0.5W
- This is  $16\times$  over rating!  $\rightarrow$  Immediate damage

### Common Resistor Power Ratings:

**Standard values:**

- **$1/8W$  (0.125W):** Very common, small size, cheap
- **$1/4W$  (0.25W):** Most common general purpose
- **$1/2W$  (0.5W):** Common, slightly larger
- **1W:** Moderate power, larger physical size
- **2W:** Higher power, significantly larger
- **5W, 10W, 25W+:** Power resistors, large with heatsinks

**Size correlation:**

- Higher rating = physically larger resistor
- Larger surface area  $\rightarrow$  better heat dissipation
- Power resistors may have heatsink mounting
- Ceramic body for high-power types

### Selecting Proper Power Rating:

**Design rule:**

- Calculate actual power dissipation
- Select rating at least  $2\times$  calculated power (safety margin)
- For critical applications: 50% derating (use 2W for 1W dissipation)

*Why safety margin?*

- Component tolerances (resistance may vary  $\pm 5\%$  or  $\pm 10\%$ )
- Voltage supply variations
- Ambient temperature higher than  $25^\circ C$
- Aging effects
- Prevent continuous operation at maximum rating

### Power Resistors:

*When standard resistors aren't enough:*

- Specifically designed for high power dissipation
- Ratings: 5W, 10W, 25W, 50W, 100W+
- Construction: Ceramic body, wirewound
- Often have mounting holes for heatsinks
- More expensive than standard resistors

*Applications:*

- Current sensing (shunt resistors)
- Load banks (testing power supplies)
- Braking resistors (motors)
- Dummy loads
- High-power voltage dividers

### Practical Example - LED Current Limiting:

*Scenario:*

- 10mm super-bright red LED
- Maximum current: 80mA
- Forward voltage:  $V_f = 2.2V$
- Power supply: 9V battery
- Goal: Maximum brightness

### Calculate resistor:

$$V_R = V_{supply} - V_f = 9 - 2.2 = 6.8V$$
$$R = \frac{V_R}{I} = \frac{6.8}{0.08} = 85\Omega \text{ (use } 82\Omega \text{ standard)}$$

### Calculate power:

$$P_R = V_R \times I = 6.8 \times 0.08 = 0.544W$$

### Resistor selection:

- Calculated power: 0.544W
- 1/2W (0.5W) rating: NOT enough (would overheat)
- 1W rating: Acceptable, but tight
- **Best choice: 1W or 2W resistor**

*Why 1/2W is bad:*

- 0.544W > 0.5W rating
- Resistor will get very hot
- May not immediately fail, but stressed
- Shortened lifespan, possible intermittent failure

### Minimizing Power Loss:

*Design strategies:*

- Use switching regulators instead of linear (less heat)
- Reduce voltage drop across resistors where possible
- Use current sources instead of resistors (for LEDs)
- Choose lower resistance values when appropriate
- Use PWM for LED brightness control (not resistor)

*When power loss is desired:*

- Heating elements (intentional heat generation)
- Load resistors (testing power supplies)
- Discharge resistors (bleeding capacitors)

### Other Components with Power Ratings:

*Power ratings apply to many components:*

#### Voltage regulators:

- Linear regulators dissipate significant power
- $P = (V_{in} - V_{out}) \times I$
- Need heatsinks for higher currents

#### Diodes:

- Forward voltage drop  $\times$  current = power
- Rectifier diodes in power supplies
- Schottky diodes have lower forward drop (less power)

#### MOSFETs and transistors:

- On-state:  $P = I^2 R_{DS(on)}$
- Switching: Transition losses
- High-power applications need thermal management

#### Motor drivers:

- H-bridges dissipate power in switching elements
- Current sensing resistors
- Thermal shutdown protection common

#### Amplifiers:

- Power dissipation in output stage
- Class A worst (always conducting)
- Class D best efficiency (switching)

## Practical Example & Numerical

### Example 1: Standard LED Current Limiting

Given:

- 5V supply
- LED:  $V_f = 2V$ ,  $I_f = 20mA$

Resistor value:

$$R = \frac{5 - 2}{0.02} = \frac{3}{0.02} = 150\Omega$$

Power dissipation:

$$P = 3 \times 0.02 = 0.06W = 60mW$$

Rating selection:

- 60mW actual dissipation
- 1/8W (125mW) rating:  $2\times$  margin ✓
- Use: 1/8W or 1/4W resistor (both OK)

### Example 2: High-Power LED (From Problem Description)

Given:

- 9V battery
- 10mm super-bright LED:  $V_f = 2.2V$ ,  $I_{max} = 80mA$

Design:

$$V_R = 9 - 2.2 = 6.8V$$

$$R = \frac{6.8}{0.08} = 85\Omega \rightarrow \text{use } 82\Omega \text{ standard}$$

Actual current with 82Ω:

$$I = \frac{6.8}{82} = 0.0829A = 82.9mA$$

Power:

$$P = 6.8 \times 0.083 = 0.564W$$

Rating needed:

- 0.564W dissipation
- 1/2W (0.5W): Too small! ×
- 1W rating: Acceptable (77% of rating)
- **Recommended: 1W resistor** (or 2W for cool operation)

### Example 3: Voltage Divider Power

Given:

- 12V input
- Voltage divider:  $R_1 = R_2 = 10k\Omega$
- Output: 6V (half of 12V)

Current through divider:

$$I = \frac{12}{20k} = 0.6mA$$

Power in each resistor:

$$P = I^2 R = (0.0006)^2 \times 10000 = 0.0036W = 3.6mW$$

Rating:

- 3.6mW per resistor
- 1/8W (125mW) has  $35\times$  margin
- **Standard 1/4W resistors work fine**

### Example 4: When 1/2W Isn't Enough

Given:

- 24V supply
- Need to drop to 12V at 500mA load
- Using series resistor (linear regulation)

Resistor value:

$$R = \frac{24 - 12}{0.5} = \frac{12}{0.5} = 24\Omega$$

Power dissipation:

$$P = 12 \times 0.5 = 6W$$

Rating selection:

- 6W dissipation
  - Need at least 6W rated resistor
  - **Use: 10W or 15W power resistor with heatsink**
- Better solution:* Use switching regulator (much more efficient!)

#### Example 5: Multiple Resistors vs Power Resistor

*Problem:* Need 100Ω at 2W dissipation

##### Option 1: Single power resistor

- 100Ω, 5W power resistor
- Cost: Higher
- Size: Large

##### Option 2: Four 1/2W resistors in series/parallel

- Four 200Ω, 1/2W resistors in parallel
- $R_{eq} = 200/4 = 50\Omega$  × (wrong value)

##### Option 3: Two resistors in series

- Two 50Ω, 1W resistors in series
- $R_{eq} = 50 + 50 = 100\Omega$  ✓
- Each dissipates 1W (within rating)
- Total: 2W
- **This works!**

#### Example 6: Temperature Derating

*Given:*

- 1W resistor rated at 25°C
- Operating in 70°C environment
- Derating: 2.5mW/°C

**Temperature difference:**

$$\Delta T = 70 - 25 = 45^\circ C$$

**Power reduction:**

$$P_{reduce} = 45 \times 2.5mW = 112.5mW$$

**Derated power rating:**

$$P_{derated} = 1000mW - 112.5mW = 887.5mW \approx 0.89W$$

*Safe operating power at 70°C: 0.9W instead of 1W*

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

1. **Power rating:** Maximum safe power dissipation (usually at 25°C)
2. **Common ratings:** 1/8W, 1/4W, 1/2W, 1W, 2W, 5W, 10W+
3. **Selection rule:** Use rating  $\geq 2 \times$  calculated power
4. **Exceed rating:** Component overheats, fails ("magic smoke")
5. **Size matters:** Higher rating = larger physical size
6. **Resistors worst:** 100% energy  $\rightarrow$  heat
7. **Power resistors:** Special high-power types (5W+)
8. **Derating:** Reduce rating at high ambient temperatures

#### Interview Questions:

- **Q:** What is a power rating?  
A: Maximum power component can safely dissipate without damage.
- **Q:** Common resistor power ratings?  
A: 1/8W, 1/4W, 1/2W, 1W, 2W (and 5W+ for power resistors).
- **Q:** Resistor dissipates 0.3W. What rating to use?  
A: 1/2W or 1W (need safety margin above 0.3W).
- **Q:** What happens if you exceed power rating?  
A: Component overheats, may burn/smoke, fails.
- **Q:** Why do resistors need power ratings?  
A: They convert 100% electrical energy to heat - too much heat damages them.
- **Q:** 9V across 10Ω - can you use 1/2W resistor?

A: No! Power =  $81/10 = 8.1\text{W}$ , far exceeds 0.5W rating. Need 10W+ power resistor.

**Standard Power Ratings:**

- $1/8\text{W} = 0.125\text{W}$  (very common, small)
- $1/4\text{W} = 0.25\text{W}$  (most common general purpose)
- $1/2\text{W} = 0.5\text{W}$  (common, slightly larger)
- $1\text{W} = 1.0\text{W}$  (moderate power)
- 2W, 5W, 10W+ (power resistors, large)

**Design Guidelines:**

- Calculate actual power dissipation
- Select rating  $2\times$  actual (minimum)
- For critical: 50% derating (2W for 1W actual)
- Account for ambient temperature
- Larger is safer (better heat dissipation)

**Applications:**

- LED current limiting ( $1/8\text{W}$  to  $1\text{W}$  typically)
- Voltage dividers (usually  $1/4\text{W}$  sufficient)
- Current sensing shunts (power resistors)
- Load banks (high-power resistors)
- Pull-up/pull-down ( $1/8\text{W}$  or  $1/4\text{W}$ )

**Warning Signs of Overheating:**

- Resistor very hot to touch
- Discoloration (browning, blackening)
- Smoke or burning smell ("magic smoke")
- Value drift (resistance changes)
- Solder melting around component
- PCB discoloration under resistor

**Common Mistakes:**

- Using standard resistor for high-power application
- Not accounting for voltage drop across resistor
- Forgetting safety margin
- Ignoring ambient temperature effects
- Not considering thermal resistance of PCB

# Section 07 – Alternating Current (AC)

## Why We Get AC Signal from the Wall Socket

TL;DR (The Gist)

- **AC for transmission:** Much more efficient than DC for long distances
- **Transformers:** Can easily step up/down AC voltage (not DC)
- High voltage transmission → Lower current → Smaller cables → Less power loss
- Example: AC system has 10× less power loss than DC for same power delivery

### Detailed Explanation

## 2. Detailed Explanation

### Historical Context - The War of Currents:

#### DC Discovered First:

*Natural sources of DC:*

- **Lightning:** High-voltage DC discharge
- **Static electricity:** Spark when touching charged material
- **Electric eels:** Produce 50-200V DC at 30A when threatened
- **Solar storms:** Charged particles interacting with Earth's magnetic field

*Early investigations:*

- DC voltage found in nature first
- Scientists studied DC electricity initially
- Batteries produce DC voltage
- Early electrical systems used DC

### The Late 1880s - Battle Between AC and DC:

#### Edison's DC System:

*Limitations of DC:*

- DC voltage cannot be easily converted to higher voltages
- Even today, DC-DC conversion is complex (requires switching converters)
- No simple way to step up/down DC voltage

*Edison's solution:*

- Small local power plants for each neighborhood
- Three-wire distribution: +110V, -110V, Ground (neutral)
- Lights/devices connected between  $\pm 110V$  and ground
- 110V chosen to allow for voltage drop in transmission

*Critical limitation:*

- Power plants needed within **1 mile of end user**
- Made rural electrification extremely difficult/impossible
- Required many small power plants
- Not economically viable for widespread use

#### Westinghouse and Tesla's AC System:

*Key advantage - Transformers:*

- **Transformers work only with AC** (not DC)
- Can easily step voltage up to thousands of volts
- Can step voltage back down to usable levels
- Inexpensive and reliable technology

*Why transformers revolutionized power distribution:*

- High voltage transmission = low current
- Low current = smaller wires (less copper)
- Smaller wires = lower cost
- Less power loss in transmission
- Power plants can be far from users

## Modern Reality:

*Today's situation:*

- Every home/business wired for AC
- All appliances plugged into AC outlets
- Wall socket provides AC voltage (varies by region)
- North America: 120V RMS, 60Hz
- Europe/Asia: 230V RMS, 50Hz

*But most devices use DC internally!*

- TV, computer, phone chargers all convert AC→DC
- Use **rectifiers** (AC to DC converters)
- Almost all electronics operate on DC internally
- AC used only for distribution efficiency

## Why AC is More Efficient - Detailed Analysis:

### Scenario Setup:

- Two houses, each 1,000 feet from power plant
- Each house demands: 100A at 480V
- Power required:  $P = 480 \times 100 = 48,000W = 48kW$
- One system DC, one system AC

### DC System Analysis:

#### Cable requirements:

- Must carry 100A over 1,000 feet
- Large diameter cable needed (low resistance)
- Resistance inversely proportional to cross-section area
- $R = \rho \times \frac{L}{A}$  (resistivity  $\times$  length / area)
- Typical:  $0.15\Omega$  per 1,000 feet for 100A conductor

#### Voltage drop calculation:

$$\begin{aligned}V_{drop} &= I \times R_{cable} \\&= 100A \times 0.15\Omega \\&= 15V\end{aligned}$$

#### Generator must supply:

$$V_{gen} = V_{house} + V_{drop} = 480V + 15V = 495V$$

#### Power loss in cable:

$$\begin{aligned}P_{loss} &= V_{drop} \times I \\&= 15V \times 100A \\&= \boxed{1,500W}\end{aligned}$$

#### Efficiency:

$$\eta = \frac{48,000}{48,000 + 1,500} \times 100\% = 97\%$$

## AC System Analysis (with Transformers):

### Transformer at power plant:

- Step up voltage:  $480V \rightarrow 4,800V$  ( $10\times$  increase)
- Step down current:  $100A \rightarrow 10A$  ( $10\times$  decrease)
- Power conservation:  $P_{in} = P_{out}$  (transformer is passive)
- $480V \times 100A = 4,800V \times 10A = 48,000W \checkmark$

*Key principle:*

- Transformer increases voltage at expense of current
- NOT a power generator (passive component)
- Output power = Input power (minus small losses)
- $V_{out} \times I_{out} = V_{in} \times I_{in}$

#### Cable requirements:

- Only 10A current ( $10\times$  less than DC)
- Smaller diameter cable sufficient
- Higher resistance acceptable (less current)
- Typical:  $1.5\Omega$  per 1,000 feet for 10A conductor

### Voltage drop:

$$\begin{aligned}V_{drop} &= I \times R_{cable} \\&= 10A \times 1.5\Omega \\&= 15V \text{ (same as DC!)}\end{aligned}$$

### Power loss in cable:

$$\begin{aligned}P_{loss} &= V_{drop} \times I \\&= 15V \times 10A \\&= \boxed{150W}\end{aligned}$$

### Transformer at house:

- Step down voltage: 4,800V  $\rightarrow$  480V
- Step up current: 10A  $\rightarrow$  100A
- Delivers required power to house

### Comparison - AC vs DC:

Parameter	DC System	AC System
Transmission voltage	480V	4,800V
Transmission current	100A	10A
Cable resistance	0.15 $\Omega$	1.5 $\Omega$
Voltage drop	15V	15V
Power loss	1,500W	150W
Cable size	Large (100A)	Small (10A)
Efficiency	97%	99.7%

### Result:

- AC system: **10 $\times$  less power loss** than DC
- AC uses smaller, cheaper cables
- AC allows long-distance transmission
- DC requires power plant within 1 mile
- AC wins for power distribution!

### Why Voltage Matters for Transmission:

*Power loss formula:*

$$P_{loss} = I^2 R_{cable}$$

*Key insight:*

- Power loss proportional to  $I^2$  (square of current)
- Halving current reduces loss by 4 $\times$
- 10 $\times$  less current = 100 $\times$  less loss (but cable R also changes)
- High voltage = low current = low loss

*Why high voltage helps:*

- For same power:  $P = V \times I$
- Higher V  $\rightarrow$  lower I (inversely related)
- Lower I  $\rightarrow$  much less  $I^2 R$  loss
- Can use smaller cable (cheaper)

### Real-World AC Transmission:

*Typical voltage levels:*

- Power plant generation: 10-25kV
- Long-distance transmission: 110-765kV (very high!)
- Regional distribution: 10-35kV
- Local distribution: 4-15kV
- Residential service: 120/240V (North America), 230V (Europe)

*Multiple transformer stages:*

1. Step up at power plant (to hundreds of kV)
2. Transmission over long distances
3. Step down at substations (to tens of kV)
4. Step down at local transformers (to household voltage)

### Example 1: DC vs AC Power Loss Calculation

Given: Transmit 50kW over 2,000 feet

**DC System (480V):**

$$I = \frac{P}{V} = \frac{50,000}{480} = 104.2A$$
$$R_{cable} = 0.15\Omega/1000ft \times 2 = 0.3\Omega$$
$$P_{loss} = I^2 R = (104.2)^2 \times 0.3 = 3,258W$$

**AC System (4,800V with transformer):**

$$I = \frac{50,000}{4,800} = 10.42A$$
$$R_{cable} = 1.5\Omega/1000ft \times 2 = 3\Omega$$
$$P_{loss} = I^2 R = (10.42)^2 \times 3 = 326W$$

**Comparison:**

$$\frac{P_{loss(DC)}}{P_{loss(AC)}} = \frac{3,258}{326} = \boxed{10\times}$$

AC has 10× less power loss!

### Example 2: Why Double Voltage Helps So Much

Same power (10kW) transmitted at different voltages:

**At 100V:**

$$I = \frac{10,000}{100} = 100A$$
$$P_{loss} = I^2 R = (100)^2 \times 1 = 10,000W$$

**At 200V (doubled):**

$$I = \frac{10,000}{200} = 50A$$
$$P_{loss} = I^2 R = (50)^2 \times 1 = 2,500W$$

**At 1,000V (10×):**

$$I = \frac{10,000}{1,000} = 10A$$
$$P_{loss} = I^2 R = (10)^2 \times 1 = 100W$$

Doubling voltage reduces loss by 4×; 10× voltage reduces loss by 100×!

### Example 3: Transformer Power Conservation

Step-up transformer:

- Input: 120V, 10A
- Turns ratio: 1:10 (step up 10×)

**Input power:**

$$P_{in} = 120V \times 10A = 1,200W$$

**Output (assuming ideal transformer):**

$$V_{out} = 120V \times 10 = 1,200V$$
$$I_{out} = 10A/10 = 1A$$
$$P_{out} = 1,200V \times 1A = 1,200W$$

Power conserved:  $P_{in} = P_{out}$  ✓

### Example 4: Regional AC Voltage Differences

**North America:**

- Voltage: 120V RMS (single phase)
- Also 240V available (split phase)
- Frequency: 60Hz

- Outlets: Type A/B (two or three prong)

#### Europe/Asia/Africa/Australia:

- Voltage: 230V RMS (single phase)
- Frequency: 50Hz
- Outlets: Various types (C, D, E, F, G, I, etc.)

#### Why different voltages?

- Historical decisions (Edison vs European systems)
- 230V more efficient for high-power appliances
- 120V considered safer (lower shock risk)
- Both work well for modern electronics

#### Example 5: Why Most Devices Need DC Internally

*Devices that convert AC to DC:*

- **Laptop:** AC adapter converts 120V AC → 19V DC
- **Phone charger:** 120V AC → 5V DC (USB)
- **TV:** Internal power supply converts AC → multiple DC voltages
- **LED bulbs:** Rectifier + regulator converts AC → DC for LEDs
- **Computer:** PSU converts 120V AC → 12V, 5V, 3.3V DC rails

*Why DC needed:*

- Semiconductors (transistors, ICs) require DC
- Logic circuits need stable voltage
- Microprocessors operate on DC only
- LEDs are DC devices
- Motors in fans/drives use DC (or rectified AC)

#### Example 6: Cable Resistance and Diameter

*Resistance formula:*

$$R = \rho \frac{L}{A}$$

Where:

- $\rho$  = resistivity (material property)
- $L$  = length
- $A$  = cross-sectional area

**For circular wire:**  $A = \pi r^2 = \pi(d/2)^2$

*Key insight:*

- Doubling diameter → 4× area → 1/4 resistance
- Larger diameter = lower resistance
- Lower resistance = less voltage drop
- But larger cable costs more (more copper)

**Trade-off:**

- High current → need large cable (expensive)
- Low current → small cable works (cheaper)
- AC with transformers → low current → cheap cables!

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

1. **AC for transmission:** 10× more efficient than DC for long distances
2. **Transformers:** Easily step AC voltage up/down (impossible with DC)
3. **High voltage advantage:** Less current → less  $I^2R$  loss
4. **Edison's DC:** Limited to 1 mile radius (impractical)
5. **Tesla/Westinghouse AC:** Enabled long-distance power distribution
6. **Modern reality:** AC for distribution, DC for device operation
7. **Power conservation:** Transformer changes V and I but not P
8. **Cable size:** High voltage = low current = smaller/cheaper cables

**Interview Questions:**

- **Q:** Why use AC for power distribution instead of DC?  
**A:** Transformers can easily change AC voltage; high voltage transmission has much lower losses.

- **Q:** What was the main limitation of Edison's DC system?  
A: Power plants had to be within 1 mile of users; impractical for rural areas.
- **Q:** Why does high voltage reduce transmission losses?  
A: Higher voltage = lower current for same power; loss is  $I^2R$ , so lower I drastically reduces loss.
- **Q:** Do transformers create power?  
A: No - they're passive; output power = input power (minus small losses).
- **Q:** If transformer steps up voltage 10×, what happens to current?  
A: Current steps down 10× (power conservation:  $V_{in}I_{in} = V_{out}I_{out}$ ).
- **Q:** Do most electronics use AC or DC internally?  
A: DC - semiconductors, ICs, LEDs all require DC; AC only used for distribution.

#### AC vs DC Comparison:

- **Transmission:** AC wins (transformers, efficiency)
- **Storage:** DC wins (batteries are DC)
- **Electronics:** DC wins (semiconductors need DC)
- **Long distance:** AC wins (10-100× less loss)
- **Simplicity:** DC wins (no frequency, no transformers needed)
- **Cost:** AC wins (smaller cables, fewer power plants)

#### Applications:

- AC: Power grids, household distribution, large motors
- DC: Batteries, electronics, solar panels, electric vehicles
- Hybrid: Modern HVDC transmission (AC→DC→AC for very long distances)

#### Common Misconceptions:

- "AC is always better than DC" - No, each has advantages
- "Transformers amplify power" - No, passive devices (power in = power out)
- "Higher voltage always dangerous" - Danger depends on current through body
- "All household devices run on AC" - No, most convert to DC internally

## AC - Important Characteristics

### TL;DR (The Gist)

- **AC signal:** Sinusoidal waveform, alternates positive/negative
- **Frequency (f):** Cycles per second (Hz);  $f = 1/T$
- **Period (T):** Time for one complete cycle (seconds);  $T = 1/f$
- **Amplitude/Peak:** Maximum voltage; Peak-to-peak = 2× amplitude

### Detailed Explanation

## 2. Detailed Explanation

#### AC Signal Representation:

##### Graphical Form - Sinusoidal Waveform:

*What is AC?*

- **Alternating Current:** Current flows one way, then reverses
- Voltage continuously changes: positive → zero → negative → zero
- Represented by sine wave (sinusoid)
- Most common and natural AC waveform

*How AC flows:*

- When voltage positive: Current flows in one direction
- When voltage negative: Current flows in opposite direction
- Voltage and current go "hand-in-hand"
- Direction reverses every half cycle

#### Zero Crossing:

*Definition:*

- Point where waveform crosses zero volts

- Transitions between positive and negative
- Two zero crossings per cycle (up and down)
- Critical for timing and synchronization

*Significance:*

- Marks direction reversal
- Used for frequency measurement
- Important for phase control circuits
- Zero-crossing detection common in AC applications

## Frequency (f) - Cycles Per Second:

**Definition:**

- Number of complete cycles in one second
- Unit: **Hertz (Hz)**
- 1 Hz = 1 cycle per second
- Determines how fast signal oscillates

**Mathematical expression:**

$$f = \frac{1}{T}$$

Where  $T$  = period (time for one cycle)

## Common AC Frequencies:

**Power line frequencies:**

- **60 Hz:** North America, parts of South America, Japan
- **50 Hz:** Europe, Asia, Africa, Australia
- These are standard worldwide power frequencies
- Choice historical (no technical advantage either way)

**Other frequency ranges:**

- Audio: 20 Hz - 20 kHz (human hearing range)
- Radio AM: 530 kHz - 1.7 MHz
- Radio FM: 88 MHz - 108 MHz
- WiFi: 2.4 GHz, 5 GHz
- Microwave: 2.45 GHz (microwave ovens)

## Frequency Effect on Waveform:

**Low frequency (e.g., 1 Hz):**

- Slow oscillation (1 cycle per second)
- Long time for complete cycle
- Waveform appears "stretched out"
- Easy to see individual cycles

**Medium frequency (e.g., 60 Hz):**

- 60 complete cycles per second
- Each cycle takes 16.67 ms
- Typical power line frequency
- Causes flicker in some lights (perceptible)

**High frequency (e.g., 1 kHz):**

- 1,000 cycles per second
- Each cycle only 1 ms
- Waveform appears "compressed"
- Many oscillations in short time

*General rule:*

- Higher frequency → faster oscillation → shorter period
- Lower frequency → slower oscillation → longer period
- Frequency and period inversely related

## Period (T) - Time Per Cycle:

**Definition:**

- Time for signal to complete **one full cycle**
- Measured in seconds (or ms,  $\mu$ s)
- From zero → positive peak → zero → negative peak → zero
- Complete repetition of waveform pattern

## Mathematical expression:

$$T = \frac{1}{f}$$

### Relationship to frequency:

- Period and frequency are reciprocals
- If period increases  $\rightarrow$  frequency decreases
- If frequency increases  $\rightarrow$  period decreases
- **Inversely proportional**

## What Constitutes One Cycle:

### Complete cycle includes:

1. Start at zero volts
2. Rise to positive peak
3. Return to zero (first zero crossing)
4. Fall to negative peak
5. Return to zero (second zero crossing)
6. Back to starting point

### Alternative description:

- One complete wavelength
- $360^\circ$  or  $2\pi$  radians
- Positive half-cycle + negative half-cycle
- Pattern that repeats continuously

## Amplitude - Maximum Voltage:

### Definition:

- Maximum voltage reached by signal
- Distance from zero to peak (positive or negative)
- Also called **peak voltage** ( $V_{peak}$ )
- Measured in volts

### Positive vs negative amplitude:

- Positive peak: Maximum positive voltage
- Negative peak: Maximum negative voltage
- For symmetrical AC: Both have same magnitude
- Sign indicates direction only (not "less than zero")

## Peak-to-Peak Voltage ( $V_{p-p}$ ):

### Definition:

- Total voltage swing from negative peak to positive peak
- Twice the amplitude (for symmetrical waveform)
- $V_{p-p} = 2 \times V_{peak}$
- Easy to measure on oscilloscope

### Why peak-to-peak useful:

- Oscilloscope displays peak-to-peak naturally
- Shows total voltage excursion
- Useful for component voltage rating checks
- Common measurement in practice

### Example:

- If  $V_{peak} = 170V$
- Then  $V_{p-p} = 2 \times 170 = 340V$
- Signal swings from  $-170V$  to  $+170V$

## Important Distinctions:

Term	Meaning
Amplitude	Maximum value from zero (same as peak)
Peak voltage	Maximum voltage (positive or negative)
Peak-to-peak	Total swing ( $2 \times$ amplitude)
RMS voltage	Effective value (covered next topic)

## AC Waveform Properties Summary:

### Continuous variation:

- Voltage never constant (always changing)

- Smoothly transitions through zero
- Sinusoidal shape most common
- Periodic (repeats regularly)

#### Symmetrical (typical):

- Positive half matches negative half
- Average voltage = 0 (positive cancels negative)
- Peak positive = Peak negative (magnitude)
- Center line at 0V

#### Key parameters:

- **Frequency:** How fast it oscillates
- **Period:** How long one cycle takes
- **Amplitude/Peak:** How high it goes
- **Peak-to-peak:** Total voltage range

#### Frequency Prefixes:

*Common in electronics:*

- Hz (Hertz): Base unit
- kHz (kilohertz):  $10^3$  Hz = 1,000 Hz
- MHz (megahertz):  $10^6$  Hz = 1,000,000 Hz
- GHz (gigahertz):  $10^9$  Hz = 1,000,000,000 Hz

## Practical Example & Numerical

### Example 1: 60 Hz Power Line

*North American household power:*

**Frequency:**

$$f = 60 \text{ Hz}$$

**Period:**

$$T = \frac{1}{f} = \frac{1}{60} = 0.01667 \text{ s} = \boxed{16.67 \text{ ms}}$$

#### Interpretation:

- One complete cycle takes 16.67 milliseconds
- 60 cycles occur in one second
- Voltage crosses zero 120 times per second (2 per cycle)

### Example 2: 50 Hz European Power

**Frequency:**

$$f = 50 \text{ Hz}$$

**Period:**

$$T = \frac{1}{50} = 0.02 \text{ s} = \boxed{20 \text{ ms}}$$

#### Comparison to 60 Hz:

- 50 Hz period: 20 ms
- 60 Hz period: 16.67 ms
- 50 Hz is 20% slower oscillation
- Both work fine for power distribution

### Example 3: Audio Frequency - Middle A Note

*Musical note A above middle C:*

**Frequency:**

$$f = 440 \text{ Hz}$$

**Period:**

$$T = \frac{1}{440} = 0.002273 \text{ s} = \boxed{2.273 \text{ ms}}$$

#### Meaning:

- Sound wave vibrates 440 times per second
- Each vibration takes 2.273 ms
- Human ear perceives this as the note "A"

#### Example 4: FM Radio Station

*FM radio at 100.7 MHz:*

**Frequency:**

$$f = 100.7 \text{ MHz} = 100,700,000 \text{ Hz}$$

**Period:**

$$\begin{aligned} T &= \frac{1}{100,700,000} \\ &= 9.93 \times 10^{-9} \text{ s} \\ &= \boxed{9.93 \text{ ns (nanoseconds)}} \end{aligned}$$

**Interpretation:**

- Extremely fast oscillation
- Over 100 million cycles per second
- Each cycle only 10 nanoseconds
- Radio waves travel at speed of light

#### Example 5: Peak and Peak-to-Peak

*Household AC voltage (North America):*

**Peak voltage:**

$$V_{peak} = 170 \text{ V}$$

**Peak-to-peak voltage:**

$$V_{p-p} = 2 \times V_{peak} = 2 \times 170 = \boxed{340 \text{ V}}$$

**Meaning:**

- Voltage swings from -170V to +170V
- Total excursion: 340V
- This is for 120V RMS (covered next topic)

#### Example 6: Comparing Three Frequencies

*Same amplitude, different frequencies:*

**Signal A: 1 Hz**

- Period:  $T = 1/1 = 1$  second
- Very slow oscillation
- One cycle per second

**Signal B: 10 Hz**

- Period:  $T = 1/10 = 0.1$  second = 100 ms
- 10 times faster than Signal A
- 10 cycles per second

**Signal C: 100 Hz**

- Period:  $T = 1/100 = 0.01$  second = 10 ms
- 100 times faster than Signal A
- 100 cycles per second

**Observation:**

- Higher frequency  $\rightarrow$  more compressed waveform
- Lower frequency  $\rightarrow$  more stretched waveform
- All have same amplitude (height)
- Differ only in oscillation rate

#### Example 7: Frequency Unit Conversions

**Convert 5 kHz to Hz:**

$$5 \text{ kHz} = 5 \times 10^3 = 5,000 \text{ Hz}$$

**Convert 2.4 GHz to MHz:**

$$2.4 \text{ GHz} = 2.4 \times 10^3 = 2,400 \text{ MHz}$$

**Convert 500 kHz to MHz:**

$$500 \text{ kHz} = 500/1000 = 0.5 \text{ MHz}$$

**Find period of 20 kHz:**

$$T = \frac{1}{20,000} = 0.00005 \text{ s} = 50 \mu\text{s}$$

#### Example 8: Oscilloscope Measurement

*Oscilloscope display shows:*

- Peak-to-peak voltage: 10V
- 4 complete cycles in 20 ms

**Find amplitude:**

$$V_{peak} = \frac{V_{p-p}}{2} = \frac{10}{2} = \boxed{5 \text{ V}}$$

**Find period:**

$$T = \frac{20 \text{ ms}}{4 \text{ cycles}} = \boxed{5 \text{ ms per cycle}}$$

**Find frequency:**

$$f = \frac{1}{T} = \frac{1}{0.005} = \boxed{200 \text{ Hz}}$$

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

1. **AC waveform:** Sinusoidal, alternates positive/negative continuously
2. **Frequency (f):** Cycles per second (Hz);  $f = 1/T$
3. **Period (T):** Time per cycle (seconds);  $T = 1/f$
4. **Amplitude/Peak:** Maximum voltage from zero
5. **Peak-to-peak:**  $V_{p-p} = 2 \times V_{peak}$  (total swing)
6. **Zero crossing:** Points where voltage = 0 (direction reversal)
7. **One cycle:** Zero  $\rightarrow$  peak+  $\rightarrow$  zero  $\rightarrow$  peak-  $\rightarrow$  zero
8. **Inverse relationship:** Higher f  $\rightarrow$  shorter T; Lower f  $\rightarrow$  longer T

**Interview Questions:**

- **Q:** What is frequency?  
A: Number of complete cycles per second, measured in Hertz (Hz).
- **Q:** What is the period of 60 Hz AC?  
A:  $T = 1/60 = 16.67 \text{ ms}$ .
- **Q:** If peak voltage is 100V, what is peak-to-peak?  
A:  $V_{p-p} = 2 \times 100 = 200V$ .
- **Q:** What is one complete AC cycle?  
A: Zero  $\rightarrow$  positive peak  $\rightarrow$  zero  $\rightarrow$  negative peak  $\rightarrow$  zero (complete waveform repetition).
- **Q:** Relationship between frequency and period?  
A: Inversely proportional:  $f = 1/T$  and  $T = 1/f$ .
- **Q:** How many zero crossings per cycle?  
A: Two - one going positive, one going negative.
- **Q:** What's the difference between amplitude and peak-to-peak?  
A: Amplitude is max from zero; peak-to-peak is total swing ( $2 \times$  amplitude).

**Common Frequencies:**

- 50 Hz: European power line
- 60 Hz: North American power line
- 20 Hz - 20 kHz: Audio (human hearing)
- 530 kHz - 1.7 MHz: AM radio
- 88 MHz - 108 MHz: FM radio
- 2.4 GHz, 5 GHz: WiFi

**Formulas:**

- $f = 1/T$  (frequency from period)
- $T = 1/f$  (period from frequency)
- $V_{p-p} = 2 \times V_{peak}$  (peak-to-peak voltage)
- $V_{peak} = V_{p-p}/2$  (peak voltage)

**Applications:**

- Power distribution (50/60 Hz)
- Audio signals (20 Hz - 20 kHz)
- Radio communications (kHz to GHz)
- Oscilloscope measurements
- Signal processing
- Frequency synthesis

### Common Mistakes:

- Confusing amplitude with peak-to-peak
- Forgetting frequency and period are reciprocals
- Thinking negative voltage is "less than zero" (it's just direction)
- Confusing cycle count with zero-crossing count

## Root Mean Square Voltage ( $V_{rms}$ )

### TL;DR (The Gist)

- **RMS voltage:** Effective AC voltage = equivalent DC for same power
- **Formula:**  $V_{rms} = 0.707 \times V_{peak}$  or  $V_{peak} = 1.414 \times V_{rms}$
- **Meters show RMS:** Multimeter displays RMS, not peak
- 120V AC means 120V RMS (peak is actually 170V)

### Detailed Explanation

## 2. Detailed Explanation

### The Problem with AC Voltage Values:

#### AC is constantly changing:

- Voltage goes from zero  $\rightarrow$  peak+  $\rightarrow$  zero  $\rightarrow$  peak-  $\rightarrow$  zero
- Always varying (never constant)
- Most of the time, voltage is **less than peak**
- Peak voltage not good measure of "real effect"

#### Average doesn't work either:

- Positive half-cycle and negative half-cycle
- Positive values exactly cancel negative values
- Mathematical average of sine wave = **0 volts**
- Useless for comparing to DC!

#### Need better measure:

- Represents "effective" power delivery
- Allows comparison with DC
- Practical and meaningful
- Solution: **Root Mean Square (RMS)**

### What is RMS Voltage?

#### Definition:

- **Effective value** of varying voltage/current
- Equivalent steady DC value giving **same power**
- Represents heating effect or power delivery capability
- The voltage that "matters" for real work

#### Physical meaning:

- AC at 120V RMS delivers same power as 120V DC
- Lights up bulb to same brightness
- Produces same heat in resistor
- Does same amount of work

### Mathematical Relationship (For Sine Waves):

#### RMS from Peak:

$$V_{rms} = 0.707 \times V_{peak}$$

Or more precisely:

$$V_{rms} = \frac{V_{peak}}{\sqrt{2}} = \frac{V_{peak}}{1.414}$$

#### Peak from RMS:

$$V_{peak} = 1.414 \times V_{rms}$$

Or:

$$V_{peak} = \sqrt{2} \times V_{rms}$$

*Important note:*

- These factors (0.707 and 1.414) are **only for sine waves**
- Different waveforms (square, triangle) have different factors
- Sine wave most common in power systems
- Always assume sine wave unless stated otherwise

**Same Formulas for Current:**

$$I_{rms} = 0.707 \times I_{peak}$$

$$I_{peak} = 1.414 \times I_{rms}$$

**RMS - The "Equivalent DC" Concept:**

**Example comparison:**

*Circuit 1: DC powered*

- 120V DC battery
- Light bulb
- Steady, constant brightness

*Circuit 2: AC powered*

- 170V peak AC source (120V RMS)
- Same light bulb
- Same brightness as DC circuit!

**Why same brightness?**

- RMS voltage represents effective power
- 170V peak AC delivers same average power as 120V DC
- Brightness depends on power, not instantaneous voltage
- Bulb responds to average heating effect

**What Your Meter Shows:**

**Multimeter on AC mode:**

- **Always displays RMS value**
- NOT peak voltage
- NOT average voltage
- NOT peak-to-peak
- Shows the "effective" AC voltage

**Example - North American outlet:**

- Actual peak voltage: 170V
- Meter reading: 120V (RMS)
- Peak-to-peak: 340V
- But you see: 120V on meter

*Why RMS on meters?*

- Allows direct comparison with DC
- Represents actual power capability
- Industry standard
- More meaningful for practical use

**When AC Voltage is Specified:**

**Convention:**

- "120V AC" means 120V **RMS** (unless stated otherwise)
- "230V AC" means 230V RMS
- If peak voltage meant, clearly stated as "peak"
- Example: "170V peak" or "120V RMS"

**Always assume RMS for AC specifications:**

- Wall outlet ratings
- Power supply specifications
- Component voltage ratings
- Electrical code requirements
- Everyday usage

## Why "Root Mean Square"?

The name comes from the calculation method:

1. **Square** all instantaneous values (makes negative positive)
2. Find the **Mean** (average) of the squared values
3. Take the square **Root** of the mean

Mathematical formula (general):

$$V_{rms} = \sqrt{\frac{1}{T} \int_0^T v^2(t) dt}$$

For sine wave, this simplifies to:

$$V_{rms} = \frac{V_{peak}}{\sqrt{2}} = 0.707 \times V_{peak}$$

Why squaring helps:

- Power proportional to  $V^2$  (in resistor:  $P = V^2/R$ )
- Squaring accounts for power delivery
- Makes all values positive
- Taking root returns to voltage units

**RMS Represents Power Accurately:**

**Power in resistor with AC:**

$$P_{avg} = \frac{V_{rms}^2}{R} = I_{rms}^2 \times R = V_{rms} \times I_{rms}$$

Same formulas as DC!

- Using RMS values, power formulas identical to DC
- No need for special AC power formulas
- Direct substitution works
- This is why RMS is so useful!

**RMS vs Peak vs Peak-to-Peak Summary:**

Measurement	Formula	Example (120V RMS)
RMS	$0.707 \times V_{peak}$	120V
Peak	$1.414 \times V_{rms}$	170V
Peak-to-Peak	$2 \times V_{peak}$	340V
Average	0 (for sine wave)	0V

**Different Waveforms Have Different Factors:**

**Sine wave:**

- $V_{rms} = 0.707 \times V_{peak}$
- Most common (power lines)

**Square wave:**

- $V_{rms} = V_{peak}$  (factor = 1.0)
- RMS equals peak!

**Triangle wave:**

- $V_{rms} = 0.577 \times V_{peak}$
- Different factor

Standard assumption:

- Unless specified, assume sine wave
- Use 0.707 and 1.414 factors
- Power systems always sinusoidal

## Practical Example & Numerical

### Example 1: North American Household Outlet

Wall socket rated "120V AC"

This means:

$$V_{rms} = 120V$$

Actual peak voltage:

$$V_{peak} = 1.414 \times 120 = \boxed{169.7V \approx 170V}$$

**Peak-to-peak voltage:**

$$V_{p-p} = 2 \times 170 = \boxed{340V}$$

**What meter shows:** 120V (RMS)

**Example 2: European Household Outlet**

*Wall socket rated "230V AC"*

**RMS voltage:**

$$V_{rms} = 230V$$

**Peak voltage:**

$$V_{peak} = 1.414 \times 230 = \boxed{325V}$$

**Peak-to-peak:**

$$V_{p-p} = 2 \times 325 = \boxed{650V}$$

**Example 3: Equivalent DC Comparison**

*Two circuits with identical light bulbs:*

**Circuit A (DC):**

- 120V DC battery
- Light bulb: 100W
- Brightness: Reference level

**Circuit B (AC):**

- AC source: 170V peak (120V RMS)
- Same light bulb: 100W
- Brightness: **Identical to Circuit A!**

**Power calculation (both):**

$$P = \frac{V^2}{R}$$
$$R = \frac{120^2}{100} = 144\Omega \text{ (bulb resistance)}$$

Circuit A:  $P = 120^2/144 = 100W$

Circuit B:  $P = V_{rms}^2/R = 120^2/144 = 100W$

Same power  $\rightarrow$  same brightness!

**Example 4: Finding RMS from Oscilloscope**

*Oscilloscope shows:*

- Peak voltage: 50V
- Sine wave

**Calculate RMS:**

$$V_{rms} = 0.707 \times 50 = \boxed{35.35V}$$

*If multimeter measured same signal:*

- Oscilloscope displays: 50V (peak)
- Multimeter displays: 35.35V (RMS)
- Both correct, different measurements!

**Example 5: Power Calculation with AC**

*Given:*

- AC voltage: 120V RMS
- Resistor:  $10\Omega$

**Current (RMS):**

$$I_{rms} = \frac{V_{rms}}{R} = \frac{120}{10} = 12A \text{ (RMS)}$$

**Power dissipated:**

$$P = V_{rms} \times I_{rms}$$
$$= 120 \times 12 = 1,440W$$

Or using  $P = V^2/R$ :

$$P = \frac{120^2}{10} = \frac{14,400}{10} = 1,440W$$

Or using  $P = I^2R$ :

$$P = 12^2 \times 10 = 144 \times 10 = 1,440W$$

All formulas work with RMS values!

### Example 6: Peak Current from RMS

*Given:* Circuit draws 5A RMS

**Peak current:**

$$I_{peak} = 1.414 \times 5 = \boxed{7.07A}$$

**Implication:**

- Circuit breaker must handle 7.07A peak
- But rated in RMS (5A)
- Component ratings usually specify RMS
- Peak current 41% higher than RMS

### Example 7: Lower RMS Voltage, Lower Power

*Two AC sources powering identical bulbs:*

**Source A: 170V peak (120V RMS)**

- Bulb power:  $P = 120^2/144 = 100W$
- Warm-up time: 5 seconds
- Brightness: Reference

**Source B: 120V peak (85V RMS)**

- Bulb power:  $P = 85^2/144 = 50W$
- Warm-up time: Much longer
- Brightness: Dimmer (half power)

Lower RMS  $\rightarrow$  lower power  $\rightarrow$  less brightness!

### Example 8: Converting Between Values

*Given:* Peak-to-peak voltage = 200V (sine wave)

**Peak voltage:**

$$V_{peak} = \frac{V_{p-p}}{2} = \frac{200}{2} = 100V$$

**RMS voltage:**

$$V_{rms} = 0.707 \times 100 = \boxed{70.7V}$$

**Verification (RMS to peak to p-p):**

$$V_{peak} = 1.414 \times 70.7 = 100V \quad \checkmark$$

$$V_{p-p} = 2 \times 100 = 200V \quad \checkmark$$

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

1. **RMS:** Effective AC value = equivalent DC for same power
2. **Formula:**  $V_{rms} = 0.707 \times V_{peak}$  (sine wave only)
3. **Reverse:**  $V_{peak} = 1.414 \times V_{rms}$
4. **Meters:** Always show RMS on AC mode
5. **Convention:** "120V AC" means 120V RMS (peak is 170V)
6. **Power formulas:** Use RMS values ( $P = V_{rms} I_{rms}$ )
7. **Not average:** Average of sine wave = 0 (useless)
8. **Factors vary:** 0.707 only for sine waves; square wave = 1.0

**Interview Questions:**

- **Q:** What does RMS voltage mean?  
A: Effective AC voltage - equivalent DC value delivering same power.
- **Q:** 120V AC outlet - what is peak voltage?  
A:  $V_{peak} = 1.414 \times 120 = 170V$ .
- **Q:** Why not use average voltage for AC?  
A: Average of sine wave = 0 (positive and negative cancel out).
- **Q:** What does multimeter show for AC?  
A: RMS value (not peak, not average).
- **Q:** Convert 100V peak to RMS.  
A:  $V_{rms} = 0.707 \times 100 = 70.7V$ .
- **Q:** Why is RMS useful?

A: Allows direct comparison with DC; power formulas work the same.

- **Q:** Do RMS formulas apply to square waves?

A: No - factors differ (0.707 only for sine waves).

**Key Formulas (Sine Wave):**

- $V_{rms} = 0.707 \times V_{peak} = V_{peak} / \sqrt{2}$
- $V_{peak} = 1.414 \times V_{rms} = \sqrt{2} \times V_{rms}$
- $I_{rms} = 0.707 \times I_{peak}$
- $I_{peak} = 1.414 \times I_{rms}$
- $P = V_{rms} \times I_{rms}$  (same as DC formulas)

**Memory Aids:**

- $0.707 \approx 0.7 \approx 70\%$  (RMS is 70% of peak)
- $1.414 \approx 1.4 \approx 140\%$  (peak is 40% higher than RMS)
- $\sqrt{2} = 1.414...$  (exact factor)
- $1/\sqrt{2} = 0.707...$  (exact factor)

**Common Values:**

- 120V RMS  $\rightarrow$  170V peak (North America)
- 230V RMS  $\rightarrow$  325V peak (Europe/Asia)
- 240V RMS  $\rightarrow$  340V peak (Australia, parts of Asia)

**Applications:**

- Power supply specifications
- Component voltage ratings
- Meter readings interpretation
- Power calculations
- Circuit design and safety

**Common Mistakes:**

- Using peak voltage in power calculations (use RMS!)
- Thinking multimeter shows peak (it shows RMS)
- Applying sine wave factors to non-sinusoidal signals
- Confusing RMS with average (average of sine = 0)

# Section 08 – Capacitors

## Capacitor Introduction

### TL;DR (The Gist)

- **Capacitor:** Two-terminal passive component that stores electrical energy
- **Unit:** Farad (F); typically pF to  $\mu\text{F}$  range (1 F is huge!)
- **Symbol:** Two parallel lines (flat for non-polarized, curved for polarized/electrolytic)
- **Key property:** Stores charge like a battery but releases it much faster

### Detailed Explanation

## 2. Detailed Explanation

### What is a Capacitor?

#### Definition and Purpose:

- **Two-terminal electrical component**
- Special ability: **Store electrical energy**
- One of the three fundamental passive components (resistor, capacitor, inductor)
- Found in virtually every electronic circuit
- Works differently from a battery

#### Comparison with batteries:

- **Batteries:** Store energy chemically, release slowly (hours to years)
- Example: Quartz watch battery lasts several years
- **Capacitors:** Store energy electrically, release rapidly (seconds or less)
- Example: Camera flash - charges for 1 second, releases instantly

#### Practical Application - Camera Flash:

##### *How it works:*

1. Camera battery charges the flash capacitor (takes 1 second)
2. Capacitor stores energy
3. When photo taken, capacitor releases all energy instantly
4. Energy drives xenon flash bulb for brief, intense burst of light
5. Fraction of a second discharge

##### *Why not use battery directly?*

- Battery cannot deliver huge burst of current instantly
- Capacitor can - perfect for high-power, short-duration needs
- Capacitor acts as temporary high-current source

#### Schematic Symbols:

##### Two common representations:

##### 1. *Non-polarized capacitor (flat lines):*

- Two parallel straight lines
- Close together but not touching
- Can be connected either way (no polarity)
- Typical for ceramic, film capacitors

##### 2. *Polarized capacitor (curved line):*

- One straight line, one curved line
- Curved line indicates negative terminal (cathode)
- Indicates **polarity matters**
- Usually electrolytic capacitors
- MUST connect + to higher voltage, - to lower

#### Labeling:

- Each capacitor has designator: C1, C2, C3, etc.
- Value indicates capacitance (how many Farads)
- Example: C1 =  $100\mu\text{F}$  (100 microfarads)

## Capacitance - Measuring Storage Ability:

### Definition:

- Capacitance = amount of charge capacitor can store
- More capacitance = more charge storage capacity
- Unit: **Farad (F)**
- Abbreviated: F

### The Farad is HUGE:

- 1 Farad is enormous in electronics
- Even 0.001 F (1 millifarad) is considered big
- Typical capacitors: picofarads to microfarads
- Large capacitors rarely exceed a few thousand  $\mu\text{F}$

### Common Capacitance Ranges:

#### Picofarads (pF):

- 1 pF =  $10^{-12}$  F
- Very small capacitance
- Used in high-frequency circuits (RF, oscillators)
- Typical range: 1 pF to 1,000 pF

#### Nanofarads (nF):

- 1 nF =  $10^{-9}$  F = 1,000 pF
- Medium-small capacitance
- General-purpose filtering
- Typical range: 1 nF to 1,000 nF

#### Microfarads ( $\mu\text{F}$ ):

- 1  $\mu\text{F}$  =  $10^{-6}$  F = 1,000 nF
- Most common range in electronics
- Power supply filtering, coupling, decoupling
- Typical range: 1  $\mu\text{F}$  to several thousand  $\mu\text{F}$

#### Farads (F):

- Used only in **supercapacitors** or **ultracapacitors**
- Special capacitors for energy storage
- Rare in typical electronics
- Can replace small batteries
- Range: 0.1 F to several hundred F

### Capacitance Hierarchy (small to large):

Unit	Conversion	Typical Use
pF (picofarad)	$10^{-12}$ F	High frequency, RF
nF (nanofarad)	$10^{-9}$ F	Filtering, coupling
$\mu\text{F}$ (microfarad)	$10^{-6}$ F	Power supplies, general
F (farad)	1 F	Supercaps, energy storage

### Key Takeaways:

#### Primary function:

- Store electrical energy
- Release energy quickly when needed
- Similar to battery but much faster discharge

#### Capacitance value:

- Measured in Farads (F)
- Typical range: pF to  $\mu\text{F}$
- Larger value = more charge storage

#### Symbol recognition:

- Flat lines = non-polarized (can connect either way)
- Curved line = polarized (polarity matters!)
- Always labeled with value and designator

## Practical Example & Numerical

### Example 1: Camera Flash Capacitor

*Typical camera flash circuit:*

#### Specifications:

- Capacitor: 300  $\mu\text{F}$
- Charging voltage: 300V
- Charging time: 1 second (from camera battery)
- Discharge time: 0.001 second (1 millisecond)

#### Energy stored:

$$E = \frac{1}{2}CV^2 = \frac{1}{2} \times 300 \times 10^{-6} \times 300^2 = 13.5 \text{ J}$$

#### Power during flash:

$$P = \frac{E}{t} = \frac{13.5}{0.001} = \boxed{13,500 \text{ W}}$$

Huge instantaneous power from tiny component!

### Example 2: Capacitance Unit Conversions

#### Convert 4,700 pF to nF:

$$4,700 \text{ pF} = \frac{4,700}{1,000} = \boxed{4.7 \text{ nF}}$$

#### Convert 0.047 $\mu\text{F}$ to nF:

$$0.047 \mu\text{F} = 0.047 \times 1,000 = \boxed{47 \text{ nF}}$$

#### Convert 220 nF to $\mu\text{F}$ :

$$220 \text{ nF} = \frac{220}{1,000} = \boxed{0.22 \mu\text{F}}$$

#### Convert 100 $\mu\text{F}$ to F:

$$100 \mu\text{F} = 100 \times 10^{-6} = \boxed{0.0001 \text{ F}}$$

### Example 3: Comparing Capacitor vs Battery

*Scenario: Powering LED*

#### Battery approach:

- 9V battery (alkaline)
- Energy capacity: 20,000 J
- Can power LED for hours
- Slow discharge rate

#### Capacitor approach:

- 1,000  $\mu\text{F}$ , 10V capacitor
- Energy:  $E = \frac{1}{2} \times 0.001 \times 10^2 = 0.05 \text{ J}$
- Can power LED for 1 second
- Rapid discharge

#### Comparison:

- Battery: 400,000 $\times$  more energy storage
- Capacitor: Can deliver current much faster
- Each suited for different applications

### Example 4: Supercapacitor Energy Storage

*Modern supercapacitor:*

#### Specifications:

- Capacitance: 10 F (yes, 10 Farads!)
- Max voltage: 2.7V
- Size: Similar to AA battery

#### Energy stored:

$$E = \frac{1}{2} \times 10 \times 2.7^2 = \boxed{36.45 \text{ J}}$$

#### Applications:

- Backup power for memory
- Energy harvesting
- Quick charge/discharge cycles
- Much longer lifespan than batteries

### Example 5: Why 1 Farad is Huge

Consider typical circuit board:

#### Standard decoupling:

- 100 nF capacitor
- Across power pins
- Physical size: 2mm × 1mm

#### If using 1 F instead:

$$\text{Ratio} = \frac{1 \text{ F}}{100 \text{ nF}} = \frac{1}{100 \times 10^{-9}} = 10,000,000 \times$$

Would need 10 million times more physical space! (unrealistic)

This is why typical electronics uses pF to  $\mu$ F range.

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

1. **Capacitor:** Passive component storing electrical energy (two terminals)
2. **Key difference from battery:** Fast discharge (seconds vs hours)
3. **Unit:** Farad (F), typically pF to  $\mu$ F in circuits
4. **Symbol:** Flat lines (non-polarized), curved line (polarized)
5. **Capacitance:** Amount of charge it can store
6. **1 Farad is huge:** Most caps in pF to  $\mu$ F range
7. **Supercapacitors:** F range, special energy storage applications
8. **Found everywhere:** Very few circuits without capacitors

#### Interview Questions:

- **Q:** What does a capacitor do?  
*A:* Stores electrical energy and can release it quickly.
- **Q:** How is capacitor different from battery?  
*A:* Capacitor releases energy much faster (seconds vs hours); battery stores chemically, capacitor electrically.
- **Q:** What is the unit of capacitance?  
*A:* Farad (F).
- **Q:** Is 1 Farad typical in electronics?  
*A:* No, 1 F is huge; typical range is picofarads (pF) to microfarads ( $\mu$ F).
- **Q:** What does curved line in capacitor symbol mean?  
*A:* Polarized capacitor (electrolytic); polarity matters - must connect correctly.
- **Q:** Example of capacitor application?  
*A:* Camera flash - stores energy for instant high-power light burst.

#### Capacitance Units:

- 1  $\mu$ F = 1,000 nF = 1,000,000 pF
- 1 nF = 1,000 pF
- 1 F = 1,000,000  $\mu$ F (rarely used except supercaps)

#### Applications:

- Power supply filtering and smoothing
- Coupling and decoupling signals
- Energy storage (flash, backup power)
- Timing circuits
- Filters (high-pass, low-pass, band-pass)

#### Common Misconceptions:

- "Capacitors are like batteries" - Similar but release energy much faster
- "All capacitors same" - No, polarized vs non-polarized crucial difference
- "Bigger always better" - No, depends on application and frequency

## How a Capacitor is Made

### TL;DR (The Gist)

- **Structure:** Two metal plates + insulating dielectric between them
- **Capacitance formula:**  $C = \epsilon_r \epsilon_0 \frac{A}{d}$  (larger area/smaller distance = more capacitance)
- **Dielectric:** Insulating material (paper, ceramic, plastic, etc.)
- **Key:** DC cannot flow through (dielectric blocks it), but voltage stored across plates

## Detailed Explanation

### 2. Detailed Explanation

#### Basic Construction:

##### Three essential components:

1. **Two metal plates** (conductive)
2. **Dielectric** (insulator between plates)
3. **Terminal wires** (connect to circuit)

*The schematic symbol resembles actual construction:*

- Two parallel lines = two metal plates
- Space between lines = dielectric insulator
- Plates close together but never touching

#### The Metal Plates:

##### Material:

- **Aluminum** (most common, cheap)
- **Tantalum** (electrolytic capacitors)
- **Silver** (high-performance)
- Other conductive metals

##### Properties:

- Placed parallel to each other
- Very close together
- Each connected to terminal wire
- Conductive surface area crucial for capacitance

#### The Dielectric (Insulator):

##### Purpose:

- Separates the two plates
- Prevents direct electrical contact
- **Blocks DC current flow**
- Allows electric field to form between plates
- Material affects capacitance value

##### Common dielectric materials:

*Paper:*

- Older technology
- Impregnated with oil or wax
- Low cost

*Ceramic:*

- Very common today
- Stable, reliable
- Various formulations
- Used in ceramic disc capacitors

*Plastic film:*

- Polyester, polypropylene
- Good temperature stability
- Film capacitors

*Glass:*

- High precision
- Expensive
- Low loss

*Aluminum oxide:*

- Electrolytic capacitors

- Very thin layer (high capacitance)
- Polarized

*Tantalum oxide:*

- Tantalum electrolytic capacitors
- Stable, reliable
- Higher capacitance density

*Air:*

- Variable capacitors
- Tuning circuits (old radios)
- Low capacitance

### Why DC Cannot Flow Through Capacitor:

#### The dielectric acts as insulator:

- Blocks direct current path
- Electrons cannot physically travel through insulator
- Current cannot flow from one plate to other
- **DC is blocked**

#### But voltage can exist across plates:

- Positive charges accumulate on one plate
- Negative charges accumulate on other plate
- Electric field forms between plates
- Voltage present even though no current flows
- Energy stored in electric field

### Capacitance Formula:

#### Factors determining capacitance:

The capacitance value depends on physical construction:

$$C = \epsilon_r \epsilon_0 \frac{A}{d}$$

Where:

- $C$  = capacitance (F)
- $\epsilon_r$  = relative permittivity of dielectric (dimensionless constant)
- $\epsilon_0$  = permittivity of free space ( $8.854 \times 10^{-12}$  F/m)
- $A$  = overlapping area of plates ( $\text{m}^2$ )
- $d$  = distance between plates (m)

### How Each Factor Affects Capacitance:

#### Plate Area (A):

*Larger area → MORE capacitance*

- More surface to accumulate charges
- Directly proportional:  $2 \times \text{area} = 2 \times \text{capacitance}$
- To increase capacitance, increase plate size

#### Distance Between Plates (d):

*Smaller distance → MORE capacitance*

- Charges closer together = stronger electric field
- Inversely proportional:  $\frac{1}{2}$  distance =  $2 \times$  capacitance
- Thinner dielectric = higher capacitance
- But too thin risks breakdown

#### Dielectric Constant ( $\epsilon_r$ ):

*Higher permittivity → MORE capacitance*

- Material property of dielectric
- Vacuum/air:  $\epsilon_r = 1$  (reference)
- Ceramic:  $\epsilon_r \approx 10 - 10,000$  (varies widely)
- Aluminum oxide:  $\epsilon_r \approx 7 - 10$
- Tantalum oxide:  $\epsilon_r \approx 25$
- Higher  $\epsilon_r$  allows more charge storage

### Design Tradeoffs:

#### To maximize capacitance:

1. Use larger plate area (increases size/cost)

2. Reduce plate spacing (risk of breakdown, manufacturing limits)
3. Choose dielectric with high  $\epsilon_r$  (material selection)

**Why electrolytic capacitors have high capacitance:**

- Oxide layer extremely thin ( $d$  very small)
- Effective plate area very large (etched, rough surface)
- Result: High capacitance in small volume
- Tradeoff: Must be polarized

**Summary of Construction:**

**Physical structure:**

- Two parallel conductive plates
- Separated by thin insulating dielectric
- Each plate connected to terminal
- Entire assembly often rolled or stacked

**Electrical behavior:**

- DC blocked by dielectric
- Voltage can exist across plates
- Charges accumulate on plates
- Electric field stores energy

**Capacitance depends on:**

- Plate area (larger = more C)
- Plate spacing (smaller = more C)
- Dielectric material (higher  $\epsilon_r$  = more C)

## Practical Example & Numerical

### Example 1: Simple Parallel-Plate Capacitor Calculation

*Design a capacitor with these specifications:*

- Plate area:  $A = 0.01 \text{ m}^2$  ( $100 \text{ cm}^2$ )
- Plate separation:  $d = 0.001 \text{ m}$  (1 mm)
- Dielectric: Ceramic with  $\epsilon_r = 10$

**Calculate capacitance:**

$$\begin{aligned}
 C &= \epsilon_r \epsilon_0 \frac{A}{d} \\
 &= 10 \times 8.854 \times 10^{-12} \times \frac{0.01}{0.001} \\
 &= 10 \times 8.854 \times 10^{-12} \times 10 \\
 &= 8.854 \times 10^{-10} \text{ F} \\
 &= \boxed{885.4 \text{ pF}}
 \end{aligned}$$

### Example 2: Effect of Doubling Plate Area

*Using same capacitor from Example 1:*

**Original:**

- $A = 0.01 \text{ m}^2$ ,  $C = 885.4 \text{ pF}$

**Double the area:**

- $A = 0.02 \text{ m}^2$

**New capacitance:**

$$\begin{aligned}
 C_{\text{new}} &= 10 \times 8.854 \times 10^{-12} \times \frac{0.02}{0.001} \\
 &= \boxed{1,770.8 \text{ pF}}
 \end{aligned}$$

Result:  $2 \times \text{area} = 2 \times \text{capacitance}$  ✓

### Example 3: Effect of Halving Distance

*Using original capacitor:*

**Original:**

- $d = 0.001 \text{ m}$  (1 mm),  $C = 885.4 \text{ pF}$

**Halve the distance:**

- $d = 0.0005 \text{ m}$  (0.5 mm)

**New capacitance:**

$$\begin{aligned}C_{new} &= 10 \times 8.854 \times 10^{-12} \times \frac{0.01}{0.0005} \\&= 10 \times 8.854 \times 10^{-12} \times 20 \\&= \boxed{1,770.8 \text{ pF}}\end{aligned}$$

Result:  $\frac{1}{2}$  distance =  $2 \times$  capacitance ✓

#### **Example 4: Effect of Different Dielectric**

*Same physical dimensions, different materials:*

**Air dielectric ( $\epsilon_r = 1$ ):**

$$C = 1 \times 8.854 \times 10^{-12} \times \frac{0.01}{0.001} = 88.54 \text{ pF}$$

**Ceramic dielectric ( $\epsilon_r = 10$ ):**

$$C = 10 \times 8.854 \times 10^{-12} \times \frac{0.01}{0.001} = 885.4 \text{ pF}$$

**High-K ceramic ( $\epsilon_r = 1000$ ):**

$$C = 1000 \times 8.854 \times 10^{-12} \times \frac{0.01}{0.001} = 88.54 \text{ nF}$$

Same size,  $1000 \times$  more capacitance with better dielectric!

#### **Example 5: Why Electrolytic Capacitors Are Large**

*Typical aluminum electrolytic:*

**Construction:**

- Aluminum oxide dielectric:  $\epsilon_r \approx 8$
- Oxide layer thickness:  $d \approx 1 \text{ } \mu\text{m} = 10^{-6} \text{ m}$  (very thin!)
- Etched foil increases effective area:  $A \approx 0.1 \text{ m}^2$  (large!)

**Capacitance:**

$$\begin{aligned}C &= 8 \times 8.854 \times 10^{-12} \times \frac{0.1}{10^{-6}} \\&= 8 \times 8.854 \times 10^{-12} \times 10^5 \\&= 7.08 \times 10^{-6} \text{ F} \\&= \boxed{7.08 \text{ } \mu\text{F}}\end{aligned}$$

Extremely thin dielectric + large area = high capacitance in small volume!

#### **Example 6: Practical Ceramic Capacitor**

*0805 SMD ceramic capacitor - 100 nF:*

**Physical dimensions:**

- Size:  $2\text{mm} \times 1.2\text{mm} \times 0.5\text{mm}$  (tiny!)
- Dielectric: High-K ceramic,  $\epsilon_r \approx 2000$
- Multiple layers stacked

**Estimation (simplified):**

- Effective area (multi-layer):  $A \approx 0.0001 \text{ m}^2$
- Dielectric thickness:  $d \approx 10 \text{ } \mu\text{m}$

$$\begin{aligned}C &= 2000 \times 8.854 \times 10^{-12} \times \frac{0.0001}{10 \times 10^{-6}} \\&\approx 177 \text{ nF}\end{aligned}$$

Close to 100 nF (actual has optimized geometry).

### **Key Points (Interview Focus)**

## 4. Key Points (Interview Focus)

1. **Structure:** Two parallel metal plates separated by insulating dielectric
2. **Formula:**  $C = \epsilon_r \epsilon_0 \frac{A}{d}$
3. **Larger plates:** More area  $\rightarrow$  more capacitance
4. **Closer plates:** Smaller distance  $\rightarrow$  more capacitance (inversely proportional)
5. **Dielectric material:** Higher  $\epsilon_r \rightarrow$  more capacitance
6. **DC blocking:** Dielectric prevents current flow through capacitor
7. **Voltage storage:** Charges accumulate on plates, electric field stores energy
8. **Electrolytic secret:** Ultra-thin oxide + large effective area = high C

### Interview Questions:

- **Q:** What are the main parts of a capacitor?  
A: Two metal plates and insulating dielectric between them.
- **Q:** Why can't DC current flow through capacitor?  
A: Dielectric is an insulator - blocks direct current path.
- **Q:** How to increase capacitance?  
A: Increase plate area, decrease plate spacing, or use dielectric with higher permittivity.
- **Q:** What is dielectric?  
A: Insulating material between plates (ceramic, plastic, paper, oxide, etc.).
- **Q:** If you double plate area, what happens to capacitance?  
A: Capacitance doubles (directly proportional).
- **Q:** If you halve distance between plates?  
A: Capacitance doubles (inversely proportional to distance).

### Capacitance Formula:

- $C = \epsilon_r \epsilon_0 \frac{A}{d}$
- $\epsilon_0 = 8.854 \times 10^{-12} \text{ F/m}$  (constant)
- $\epsilon_r$  = dielectric constant (material property)
- Proportional to area  $A$
- Inversely proportional to distance  $d$

### Common Dielectrics:

- Air:  $\epsilon_r = 1$
- Paper:  $\epsilon_r \approx 3 - 4$
- Ceramic:  $\epsilon_r \approx 10 - 10,000$
- Aluminum oxide:  $\epsilon_r \approx 8 - 10$
- Tantalum oxide:  $\epsilon_r \approx 25$

### Common Mistakes:

- Thinking current flows through capacitor (DC blocked!)
- Confusing area with volume
- Forgetting inverse relationship with distance

## Types of Capacitors

### TL;DR (The Gist)

- **Ceramic:** Small, cheap, low ESR, ideal for high-frequency coupling/decoupling
- **Electrolytic:** High capacitance, polarized, higher ESR, power supply filtering
- **Supercapacitors:** Farad-range, energy storage, low voltage rating
- Key factors: Size, voltage rating, leakage, ESR, tolerance

### Detailed Explanation

## 2. Detailed Explanation

### Factors to Consider When Choosing Capacitors:

#### 1. Size (Physical and Capacitance):

- **Physical volume:** Can be largest component in circuit or tiny SMD

- **Capacitance value:** More capacitance typically requires larger size
- Tradeoff between performance and board space

## 2. Maximum Voltage Rating:

- Each capacitor rated for max voltage across it
- Ratings: 6.3V, 10V, 16V, 25V, 50V, 100V, 400V, etc.
- **Exceeding voltage rating destroys capacitor**
- Always design with safety margin (use 50-70% of max rating)

## 3. Leakage Current:

- **No capacitor is perfect**
- Tiny current leaks through dielectric (nanoamps typically)
- Causes slow energy drain
- Electrolytic capacitors have higher leakage
- Ceramic and film have very low leakage

## 4. Equivalent Series Resistance (ESR):

- Terminals not 100% conductive
- Small resistance in series (usually  $< 0.01\Omega$ )
- Becomes problem with high currents  $\rightarrow$  heat and power loss
- **Remember ESR - important for next topics!**
- Ceramic: very low ESR
- Electrolytic: higher ESR

## 5. Tolerance:

- Actual capacitance varies from nominal value
- Typical tolerances:  $\pm 1\%$ ,  $\pm 5\%$ ,  $\pm 10\%$ ,  $\pm 20\%$
- Precision caps:  $\pm 1\%$  (expensive)
- General purpose:  $\pm 10\%$  to  $\pm 20\%$

## CERAMIC CAPACITORS (Most Common):

**Market share:** 80% of all capacitors produced

### Construction:

- Dielectric: Ceramic material
- Small physical size
- Small capacitance values (pF to low  $\mu\text{F}$ )
- Surface mount: 0402, 0603, 0805, 1206 packages
- Through-hole: Yellow/brown disc shape

### Characteristics:

- **Very low ESR** (near ideal)
- **Very low leakage**
- Non-polarized (can connect either way)
- Usually hard to find  $> 10 \mu\text{F}$  ceramic
- Least expensive option
- Excellent high-frequency performance

### Applications:

- High-frequency coupling
- Decoupling/bypass capacitors
- Filtering
- Timing circuits
- General-purpose applications

### Limitations:

- Limited to smaller capacitance values
- Some types have voltage coefficient (C changes with voltage)
- Temperature coefficient varies by type

## ELECTROLYTIC CAPACITORS (Aluminum & Tantalum):

### Why they exist:

- High capacitance in small volume
- $1 \mu\text{F}$  to  $1,000,000 \mu\text{F}$  range
- Oxide layer extremely thin  $\rightarrow$  high capacitance
- Well-suited for high-voltage applications

### Aluminum Electrolytic:

*Appearance:*

- Tin can shape (cylindrical)
- Both leads from bottom (radial)
- Or leads from each end (axial)
- Capacitance and voltage marked on body

*Critical: POLARIZED*

- **Anode (+):** Positive terminal (longer lead usually)
- **Cathode (-):** Negative terminal (marked with stripe/arrow)
- Anode **MUST** be at higher voltage than cathode
- **Reverse voltage → POP and failure!**

*What happens if reversed:*

- Spectacular failure (popping sound)
- Electrolyte vents/bursts
- Becomes short circuit (permanent damage)
- Never apply reverse voltage!

*Characteristics:*

- High capacitance: 1  $\mu\text{F}$  - 100,000  $\mu\text{F}$ +
- Voltage ratings: 6.3V to 450V typical
- **Higher leakage current** (nanoamps to microamps)
- **Higher ESR** than ceramic
- Less ideal for energy storage (due to leakage)
- Polarity critical

*Applications:*

- Power supply filtering/smoothing
- Bulk energy storage
- Audio coupling (high capacitance needed)
- DC blocking with large signals

**Tantalum Electrolytic:**

*Advantages over aluminum:*

- Smaller size for same capacitance
- Lower ESR
- Better frequency response
- More stable over temperature

*Disadvantages:*

- More expensive
- Still polarized
- Lower voltage ratings typically
- Can fail catastrophically if abused

**SUPERCAPACITORS (Ultracapacitors):**

**Purpose:** Energy storage (battery replacement/supplement)

**Characteristics:**

- **Huge capacitance:** Farads range (0.1F to 3,000F!)
- **Low voltage:** Typically 2.5V to 2.7V max per cell
- Can chain in series for higher voltage (reduces total C)
- Physical size similar to battery

**Market share:** 2% of capacitor market

**vs Batteries:**

*Advantages:*

- Much faster charge/discharge
- Much longer lifespan (millions of cycles)
- No chemical degradation
- More environmentally friendly

*Disadvantages:*

- Cannot hold as much energy as battery (for same size)
- Low voltage rating
- Self-discharge (leakage) higher than batteries
- More expensive per joule stored

**Applications:**

- Backup power (memory retention)
- Energy harvesting systems
- Regenerative braking (vehicles)
- Peak power delivery
- Quick charge/discharge applications

### FILM CAPACITORS:

#### Construction:

- Plastic film dielectric (polyester, polypropylene, etc.)
- Very low parasitic losses
- Non-polarized

#### Characteristics:

- Excellent for high currents
- Low ESR
- Good temperature stability
- Self-healing property (some types)

#### Applications:

- High-voltage applications
- High-frequency, high-current
- Motor run capacitors
- Power factor correction

### MICA CAPACITORS:

#### Characteristics:

- Very high temperature tolerance: up to 237°C
- Excellent long-term stability (0.01% - 0.02% change)
- High precision, low loss
- Low temperature coefficient

#### Applications:

- High-precision analog circuits
- High-quality audio (Hi-Fi)
- High-frequency circuits
- RF applications

#### Limitations:

- Complex, expensive manufacturing
- Bulky compared to modern ceramics
- Limited capacitance values
- High cost

#### Summary Table:

Type	Capacitance	Polarized?	ESR	Use
Ceramic	pF - 10μF	No	Very Low	General, HF
Aluminum Elec	1μF - 100mF	Yes	Medium	Power supply
Tantalum Elec	1μF - 1mF	Yes	Low-Med	Compact, stable
Supercap	0.1F - 3000F	Yes/No	Medium	Energy storage
Film	nF - 100μF	No	Low	High V, high I
Mica	pF - nF	No	Very Low	Precision, RF

### Practical Example & Numerical

#### Example 1: Choosing Capacitor for Power Supply Filter

##### Requirements:

- Filter 12V power supply
- Need 1,000 μF capacitance
- Low-frequency (60 Hz ripple)

#### Choice: Aluminum Electrolytic

##### Why?

- Need high capacitance (1,000 μF)

- Ceramic typically doesn't go this high
- Low frequency (ESR not critical)
- DC application (polarity OK)

**Specifications:**

- Capacitance: 1,000  $\mu\text{F}$
- Voltage rating: 25V ( $2\times$  safety margin over 12V)
- Type: Radial aluminum electrolytic
- Observe polarity!

**Example 2: Decoupling Capacitor for Digital IC**

*Requirements:*

- Decouple 5V digital IC
- High-frequency noise (MHz range)
- Small board space

**Choice: Ceramic 0.1  $\mu\text{F}$**

*Why?*

- Very low ESR (fast response to current spikes)
- Good high-frequency performance
- Small SMD package (0805 or 0603)
- Non-polarized (easy placement)
- Inexpensive

**Specifications:**

- 0.1  $\mu\text{F}$  (100 nF)
- 10V or 16V rating
- X7R ceramic (stable)
- 0805 package

**Example 3: Supercapacitor Backup Power**

*System needs:*

- 100 mA current for 10 seconds during power loss
- 3.3V system voltage

**Energy required:**

$$E = P \times t = V \times I \times t \\ = 3.3 \times 0.1 \times 10 = 3.3 \text{ J}$$

**Capacitor energy:**

$$E = \frac{1}{2} CV^2 \Rightarrow C = \frac{2E}{V^2}$$

$$C = \frac{2 \times 3.3}{3.3^2} = \frac{6.6}{10.89} = 0.606 \text{ F}$$

**Choice:** 1F supercapacitor @ 5.5V (provides margin)

**Example 4: Voltage Rating Safety**

*Bad design:*

- 12V supply
- Using 16V rated capacitor
- Voltage spikes can exceed 16V → **FAILURE**

*Good design:*

- 12V supply
- Using 25V rated capacitor
- Safety factor:  $25/12 = 2.08\times$  (good margin)
- Can tolerate transients and spikes

**Rule of thumb:** Use  $1.5\times$  to  $2\times$  voltage rating of actual voltage

**Example 5: ESR Impact on Filtering**

*Two capacitors, same value (1,000  $\mu\text{F}$ ):*

**Aluminum electrolytic:**

- ESR:  $0.5\Omega$  (typical)
- At 1A ripple current:  $V_{\text{ripple}} = I \times \text{ESR} = 1 \times 0.5 = 0.5\text{V}$

**Low-ESR electrolytic:**

- ESR:  $0.05\Omega$
  - At 1A ripple:  $V_{ripple} = 1 \times 0.05 = 0.05V$
- Low-ESR capacitor provides  $10\times$  better ripple reduction!

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

1. **Ceramic:** Most common (80%), low ESR, small C, non-polarized, ideal HF
2. **Electrolytic:** High C ( $\mu F$ -mF), polarized, must respect polarity or fails
3. **Supercaps:** Farad range, energy storage, low voltage (2.5V typical)
4. **ESR:** Equivalent series resistance, lower is better for AC/switching
5. **Leakage:** All caps leak slightly; electrolytic worst, ceramic best
6. **Voltage rating:** Never exceed; use  $1.5$ - $2\times$  safety factor
7. **Polarity:** Electrolytic MUST be connected correctly (+ to higher V)
8. **Film & Mica:** Special apps (precision, high-temp, high-freq)

#### Interview Questions:

- **Q:** What happens if you reverse electrolytic capacitor?  
A: It will pop/burst and fail, becoming short circuit.
- **Q:** When to use ceramic vs electrolytic?  
A: Ceramic for small C, high-freq, decoupling; electrolytic for large C, power filtering.
- **Q:** What is ESR?  
A: Equivalent Series Resistance - internal resistance causing power loss and limiting high-freq performance.
- **Q:** Why supercapacitors special?  
A: Farad-range capacitance for energy storage, but low voltage rating (2.5-2.7V).
- **Q:** How to identify electrolytic polarity?  
A: Negative terminal marked with stripe; positive lead usually longer.
- **Q:** What's typical voltage safety margin?  
A: Use capacitor rated  $1.5\times$  to  $2\times$  actual operating voltage.

#### Selection Criteria:

- Capacitance value needed
- Frequency of operation (ESR matters at high freq)
- Voltage rating (with safety margin)
- Physical size constraints
- Polarity requirements
- Cost

#### Applications by Type:

- Ceramic: Decoupling, coupling, filtering, timing
- Electrolytic: Power supply smoothing, bulk storage
- Supercap: Backup power, energy harvesting
- Film: High voltage, high current, motor capacitors
- Mica: Precision RF, high-quality audio

## How a Capacitor Works (in a DC Circuit)

### TL;DR (The Gist)

- **Charging:** Current flows until capacitor voltage = supply voltage
- **Fully charged:** No more current flows (DC blocked by dielectric)
- **Discharging:** Stored charge released when path provided
- **Need resistor:** Limits charging current (prevents infinite current spike)

### Detailed Explanation

## 2. Detailed Explanation

### Capacitor Behavior in DC Circuit:

#### The Insulating Dielectric:

- Dielectric is non-conductive (insulator)
- **Blocks DC current from flowing through**
- Current cannot physically pass through capacitor
- Instead, voltage exists across plates as electrical charge

#### How Charging Works:

##### Initial state (uncharged):

- No charge on plates
- Voltage across capacitor = 0V
- Ready to accept current

##### When voltage applied:

1. Current starts flowing into capacitor
2. Electrons accumulate on one plate (becomes negative)
3. Electrons repelled from other plate (becomes positive)
4. Opposite charges attract but can't reach each other (dielectric blocks)
5. Voltage across capacitor builds up
6. As voltage increases, current decreases
7. When capacitor voltage = supply voltage, current stops

##### Physical process:

- **Negative plate:** Electrons pile up (excess negative charge)
- **Positive plate:** Electrons removed (deficit = positive charge)
- Charges stuck on plates (nowhere to go)
- Electric field forms between plates
- Energy stored in this electric field

##### When Fully Charged:

##### Conditions:

- Voltage across capacitor = supply voltage
- Plates "full" of charge (no more can fit)
- Negative charges on one plate repel new electrons
- **Current flow stops completely**

##### Capacitor acts like:

- Open circuit (infinite resistance to DC)
- No current path
- Voltage present but no current

##### Capacitance determines:

- Maximum charge storage
- Bigger capacitance = more charge = longer charging time
- For given current:  $t_{charge} \propto C$

##### Discharging Process:

##### When discharge path provided:

1. Positive and negative charges want to reunite
2. If path created (e.g., resistor connected), current flows
3. Current flows **opposite direction** from charging
4. Charges neutralize
5. Voltage across capacitor decreases
6. When fully discharged, voltage = 0V

##### Current direction during discharge:

- Conventional current: positive plate  $\rightarrow$  negative plate
- Opposite to charging current direction
- Makes sense: releasing stored energy

##### Example with LED:

- Capacitor charged to 5V
- Connect LED across it
- Stored energy lights LED briefly

- LED dims as capacitor discharges
- LED turns off when capacitor empty

### Why Resistor Needed During Charging:

#### The problem (without resistor):

- Initially, capacitor voltage = 0V
- Supply voltage = 5V (for example)
- By Ohm's law:  $I = V/R$
- If  $R = 0$  (ideal wires, ideal supply, ideal capacitor)
- Then  $I = V/0 = \infty$  (infinite current!)

#### In simulation:

- Simulator treats components as ideal
- No internal resistance in ideal voltage source
- No resistance in ideal capacitor
- No resistance in ideal wires
- Results in error: "Loop has no resistance"
- Cannot compute (division by zero)

#### In real world:

- **Power supply:** Has internal resistance (limits current)
- **Wires:** Have small resistance
- **Capacitor:** Has ESR (equivalent series resistance)
- These resistances prevent infinite current
- But still can have very high inrush current

#### Solution:

- Add series resistor to limit current
- Typical: few ohms to kiloohms (depends on application)
- Protects capacitor from excessive current
- Prevents damage to power supply
- Controls charging rate

#### Always check datasheet:

- Maximum voltage rating
- Maximum current rating
- Maximum charging current
- Operating temperature range

### Voltage Drop Across Diode (Forward Bias):

#### In circuits with diodes:

- Diode conducts when forward-biased
- Typical forward voltage drop: 0.6-0.7V (silicon diode)
- Capacitor charges to:  $V_{supply} - V_{diode}$
- Example: 5V supply  $\rightarrow$  4.3-4.4V on capacitor

### Summary of DC Behavior:

#### Charging phase:

- Current flows (initially high)
- Voltage across capacitor increases
- Current decreases as capacitor fills
- Stops when  $V_C = V_{supply}$

#### Fully charged:

- No current flows
- Capacitor = open circuit
- Voltage remains constant (if no leakage)
- Energy stored in electric field

#### Discharging:

- Current flows (if path provided)
- Opposite direction from charging
- Voltage decreases
- Energy released to circuit

#### Key insight:

- Capacitor blocks steady DC

- But passes changing voltage (transients)
- This property crucial for AC circuits (next topic)

## Practical Example & Numerical

### Example 1: Simple Charging Circuit

*Circuit:*

- 5V battery
- 200  $\mu\text{F}$  capacitor (initially discharged)
- 1 k $\Omega$  resistor in series

#### Initial condition ( $t = 0$ ):

- $V_C = 0V$  (capacitor voltage)
- Voltage across resistor:  $V_R = 5V - 0V = 5V$
- Initial current:  $I_0 = V_R/R = 5/1000 = 5 \text{ mA}$

#### Fully charged ( $t = \infty$ ):

- $V_C = 5V$
- Voltage across resistor:  $V_R = 5V - 5V = 0V$
- Final current:  $I_\infty = 0 \text{ A}$  (no current)

#### Charging follows exponential:

$$V_C(t) = V_{\text{supply}}(1 - e^{-t/RC})$$

(RC time constant covered in next chapter)

### Example 2: Effect of Increasing Supply Voltage

*Same circuit, increase voltage to 10V:*

#### Initially:

- Capacitor still at 5V (from before)
- Voltage across resistor:  $10V - 5V = 5V$
- Current:  $I = 5V/1k\Omega = 5 \text{ mA}$

#### Capacitor charges again:

- Current flows until  $V_C = 10V$
- Charges from 5V to 10V
- Then current stops again

**Key point:** Capacitor adjusts to new voltage level.

### Example 3: Discharge Through LED

*Capacitor charged to 5V, then connected to LED:*

#### Initial discharge:

- LED forward voltage: 2V
- Voltage available for current:  $5V - 2V = 3V$
- Assume LED resistance 50 $\Omega$  (simplified)
- Initial current:  $I = 3V/50\Omega = 60 \text{ mA}$

#### As capacitor discharges:

- Capacitor voltage drops
- Current through LED decreases
- LED brightness dims
- When  $V_C < 2V$ , LED turns off

### Example 4: Current Limiting Resistor Importance

*Without current limiting:*

#### Ideal scenario (simulation):

- No resistor in series
- Simulator error: "Infinite current"
- Cannot compute

#### Real world (still dangerous):

- Wire resistance: 0.1 $\Omega$
- Supply internal resistance: 0.5 $\Omega$
- Total: 0.6 $\Omega$
- Initial current:  $I = 5V/0.6\Omega = 8.3 \text{ A!}$

- Very high inrush current
- Can damage components

**With 10Ω resistor:**

- Total resistance: 10.6Ω
- Initial current:  $I = 5V/10.6\Omega = 0.47 \text{ A}$
- Much safer!

#### Example 5: Capacitor Voltage vs. Time

*Track voltage during charging:*

**Circuit: 5V, 100μF, 1kΩ**

- Time constant:  $\tau = RC = 1000 \times 100 \times 10^{-6} = 0.1 \text{ s}$

**Voltage at various times:**

$$t = 0 : \quad V_C = 0V$$

$$t = \tau : \quad V_C = 5(1 - e^{-1}) = 3.16V \text{ (63\%)}$$

$$t = 2\tau : \quad V_C = 5(1 - e^{-2}) = 4.32V \text{ (86\%)}$$

$$t = 3\tau : \quad V_C = 5(1 - e^{-3}) = 4.75V \text{ (95\%)}$$

$$t = 5\tau : \quad V_C = 5(1 - e^{-5}) = 4.97V \text{ (99\%)}$$

”Fully charged” typically means  $5\tau$  (99)

#### Example 6: Polarity in DC Circuit

*Electrolytic capacitor in circuit:*

**Correct connection:**

- Positive plate to +5V rail
- Negative plate to ground (0V)
- Voltage across: +5V (anode higher than cathode)
- Works perfectly

**Incorrect (reversed):**

- Positive plate to ground
- Negative plate to +5V
- Reverse voltage applied
- Capacitor fails (pops)
- Becomes short circuit
- **NEVER DO THIS!**

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

1. **DC blocked:** Fully charged capacitor blocks DC (acts as open circuit)
2. **Charging:** Current flows until  $V_C = V_{supply}$
3. **Current direction:** Charging and discharging currents flow opposite directions
4. **Resistor required:** Limits charging current (prevents damage/infinite current)
5. **Dielectric blocks:** Current cannot physically flow through insulator
6. **Energy storage:** Charges accumulate on plates, stored in electric field
7. **Discharging:** Releases stored energy when path provided
8. **Capacitance matters:** Larger C = more charge = longer time to charge

**Interview Questions:**

- **Q:** What happens when capacitor fully charged in DC circuit?  
A: Current stops flowing; capacitor acts as open circuit.
- **Q:** Why does current stop?  
A: Dielectric blocks DC; plates full of charge; voltage across capacitor equals supply voltage.
- **Q:** Why need resistor when charging?  
A: Limits inrush current; prevents infinite current spike at  $t=0$  when  $V_C = 0$ .
- **Q:** What direction does discharge current flow?  
A: Opposite to charging current; from positive plate to negative plate.
- **Q:** Can DC current flow through capacitor?  
A: No, dielectric is insulator - blocks DC permanently.

- **Q:** How is energy stored in capacitor?  
A: Electric field between charged plates stores energy.

#### Charging Process:

- Initial: High current, low voltage
- During: Decreasing current, increasing voltage
- Final: Zero current, voltage = supply
- Time depends on R and C ( $\tau = RC$ )

#### Discharging Process:

- Requires discharge path (resistor, LED, etc.)
- Current flows opposite direction
- Voltage decreases exponentially
- Energy released to load

#### Common Mistakes:

- Thinking DC flows through capacitor (NO!)
- Forgetting current-limiting resistor
- Reversing polarity on electrolytic caps
- Expecting instant charging (it's exponential)

## Calculating Charge, Voltage, and Current

### TL;DR (The Gist)

- **Charge equation:**  $Q = CV$  (charge = capacitance  $\times$  voltage)
- **Current equation:**  $I = C \frac{dV}{dt}$  (current depends on rate of voltage change)
- **Key insight:** Faster voltage change  $\rightarrow$  more current
- Steady DC voltage  $\rightarrow$  zero current through capacitor

### Detailed Explanation

## 2. Detailed Explanation

#### Fundamental Capacitor Equations:

#### Charge-Voltage-Capacitance Relationship:

The equation:

$$Q = CV$$

Where:

- $Q$  = charge stored (coulombs, C)
- $C$  = capacitance (farads, F)
- $V$  = voltage across capacitor (volts, V)

#### Meaning:

- Charge stored is product of capacitance and voltage
- More voltage  $\rightarrow$  more charge stored
- Larger capacitance  $\rightarrow$  more charge for same voltage
- Capacitance is constant (fixed value)

#### Defining one Farad:

- 1 Farad stores 1 Coulomb per 1 Volt
- $1 \text{ F} = 1 \text{ C/V}$
- Very large unit in practice

#### Current Through Capacitor:

The derivative equation:

$$I = C \frac{dV}{dt}$$

Where:

- $I$  = current through capacitor (A)
- $C$  = capacitance (F)

- $\frac{dV}{dt}$  = rate of voltage change (V/s)

#### Critical understanding:

- Current depends on **how fast voltage changes**
- NOT on the voltage level itself
- Faster voltage change  $\rightarrow$  more current
- No voltage change  $\rightarrow$  zero current

#### Three Scenarios - Voltage vs. Current:

##### Scenario 1: Constant DC voltage

*Voltage behavior:*

- Voltage steady at 5V
- No change in voltage
- $\frac{dV}{dt} = 0$  V/s

*Current result:*

$$I = C \times 0 = 0 \text{ A}$$

#### Zero current when voltage constant!

This is why fully charged capacitor in DC circuit has no current.

##### Scenario 2: Linearly rising voltage

*Voltage behavior:*

- Voltage rises uniformly from 0V to 5V
- Constant rate of change
- Example: rises 5V in 2 seconds
- $\frac{dV}{dt} = 5/2 = 2.5$  V/s (constant)

*Current result:*

- For 100 $\mu$ F capacitor:

$$I = 100 \times 10^{-6} \times 2.5 = 250 \text{ } \mu\text{A (constant)}$$

#### Constant voltage rise $\rightarrow$ constant current

##### Scenario 3: Variable voltage change

*Voltage behavior:*

- First: Linear rise (slow)
- Then: Swift rise (fast)
- Then: Slow rise again

*Current result:*

- Slow rise: Small current
- Swift rise: **Large current spike**
- Slow rise: Small current again

#### Key observation:

- Even though voltage higher during slow rise
- Current is lower because rate of change is lower
- **Current tracks rate of change, not voltage level**

#### Mathematical Insight (Calculus):

Where  $\frac{dV}{dt}$  comes from:

- Derivative of voltage with respect to time
- Instantaneous rate of change
- Slope of voltage vs. time graph

From charge equation:

$$Q = CV$$

$$\frac{dQ}{dt} = C \frac{dV}{dt} \quad (\text{take derivative})$$

But current is rate of charge flow:

$$I = \frac{dQ}{dt}$$

Therefore:

$$I = C \frac{dV}{dt}$$

#### Why This Equation Matters:

Understanding capacitor behavior:

- Explains why DC is blocked (no voltage change  $\rightarrow$  no current)

- Explains why AC passes (continuous voltage change → continuous current)
- Predicts current for any voltage waveform
- Foundation for impedance and reactance

#### Practical implications:

- Sudden voltage change → large current spike
- Slow voltage ramp → small, controlled current
- Design consideration for power supply turn-on

#### When This Equation is NOT Enough:

##### Limitations of $I = C \frac{dV}{dt}$ :

- Only applies for linear voltage changes
- For AC sinusoidal voltage, need reactance ( $X_C$ )
- For exponential RC charging, use time constant ( $\tau = RC$ )
- For real circuits, account for ESR

#### For AC circuits:

- Use capacitive reactance:  $X_C = \frac{1}{2\pi fC}$
- Calculate RMS current from RMS voltage
- Account for 90° phase shift
- (Covered in upcoming topics)

#### Energy Stored in Capacitor:

##### Energy equation:

$$E = \frac{1}{2}CV^2$$

Where:

- $E$  = energy (joules, J)
- $C$  = capacitance (F)
- $V$  = voltage (V)

#### Insights:

- Energy proportional to  $V^2$  (doubling voltage = 4× energy)
- Energy proportional to  $C$  (doubling C = 2× energy)
- All energy stored in electric field between plates

#### Summary of Key Equations:

Equation	Meaning
$Q = CV$	Charge stored
$I = C \frac{dV}{dt}$	Instantaneous current
$E = \frac{1}{2}CV^2$	Energy stored

## Practical Example & Numerical

### Example 1: Charge Stored Calculation

Given:

- Capacitor: 220  $\mu$ F
- Voltage: 12V

Calculate charge:

$$\begin{aligned}
 Q &= CV \\
 &= 220 \times 10^{-6} \times 12 \\
 &= 2.64 \times 10^{-3} \text{ C} \\
 &= \boxed{2.64 \text{ mC (millicoulombs)}}
 \end{aligned}$$

### Example 2: Current During Linear Voltage Rise

Scenario:

- 100  $\mu$ F capacitor
- Voltage rises from 0V to 10V in 0.5 seconds
- Linear (uniform) rise

**Rate of voltage change:**

$$\frac{dV}{dt} = \frac{10 - 0}{0.5} = 20 \text{ V/s}$$

**Current:**

$$\begin{aligned} I &= C \frac{dV}{dt} \\ &= 100 \times 10^{-6} \times 20 \\ &= 2 \times 10^{-3} \text{ A} \\ &= \boxed{2 \text{ mA}} \end{aligned}$$

Current remains constant at 2 mA during entire 0.5-second rise.

**Example 3: Faster Voltage Change → More Current**

*Same capacitor (100 μF), same voltage range (0-10V):*

**Case A: Rise in 0.5 seconds**

- $\frac{dV}{dt} = 20 \text{ V/s}$
- $I = 2 \text{ mA}$

**Case B: Rise in 0.1 seconds (5× faster)**

- $\frac{dV}{dt} = 10/0.1 = 100 \text{ V/s}$
- $I = 100 \times 10^{-6} \times 100 = 10 \text{ mA}$

**Result:** 5× faster rise = 5× more current

**Example 4: Energy Stored**

*Calculate energy in 1,000 μF capacitor at different voltages:*

**At 5V:**

$$E = \frac{1}{2} \times 1000 \times 10^{-6} \times 5^2 = 0.0125 \text{ J}$$

**At 10V:**

$$E = \frac{1}{2} \times 1000 \times 10^{-6} \times 10^2 = 0.05 \text{ J}$$

**At 20V:**

$$E = \frac{1}{2} \times 1000 \times 10^{-6} \times 20^2 = 0.2 \text{ J}$$

**Observation:**

- Doubling voltage: 5V → 10V increases energy 4×
- Doubling again: 10V → 20V increases energy 4× more
- Energy scales with  $V^2$

**Example 5: Why Steady DC = Zero Current**

*DC voltage applied to capacitor:*

**After fully charged:**

- Voltage constant at 12V
- No change in voltage
- $\frac{dV}{dt} = 0 \text{ V/s}$

**Current:**

$$I = C \times 0 = 0 \text{ A}$$

This is mathematical proof that DC is blocked!

**Example 6: Sudden Voltage Step**

*Ideal voltage step from 0V to 5V instantly:*

**Theoretical:**

- Voltage changes from 0 to 5 in zero time
- $\frac{dV}{dt} = 5/0 = \infty \text{ V/s}$
- Current:  $I = C \times \infty = \infty \text{ A}$

**Reality:**

- Nothing changes instantly
- Always some resistance (ESR, wires, source)
- Limits current to finite value
- But can still be very large inrush current

This is why we need current-limiting resistors!

**Example 7: Capacitance from Charge and Voltage**

*Measurement:*

- Capacitor charged to 15V
- Stores 3 mC of charge
- What is capacitance?

Rearrange  $Q = CV$ :

$$\begin{aligned}
 C &= \frac{Q}{V} \\
 &= \frac{3 \times 10^{-3}}{15} \\
 &= 0.2 \times 10^{-3} \text{ F} \\
 &= \boxed{200 \text{ } \mu\text{F}}
 \end{aligned}$$

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

1. **Charge equation:**  $Q = CV$  (charge proportional to voltage)
2. **Current equation:**  $I = C \frac{dV}{dt}$  (current proportional to rate of voltage change)
3. **Steady voltage:**  $\frac{dV}{dt} = 0 \Rightarrow I = 0$  (DC blocked)
4. **Fast voltage change:** Large  $\frac{dV}{dt} \Rightarrow$  large current
5. **Energy stored:**  $E = \frac{1}{2}CV^2$  (proportional to  $V^2$ )
6. **One Farad:** Stores 1 Coulomb per 1 Volt
7. **Current tracks:** Rate of change, NOT voltage level
8. **Derivative:**  $\frac{dV}{dt}$  is instantaneous slope of voltage vs. time

#### Interview Questions:

- **Q:** How much charge in  $100\mu\text{F}$  capacitor at 10V?  
A:  $Q = CV = 100 \times 10^{-6} \times 10 = 1 \text{ mC}$ .
- **Q:** Why does DC not flow through capacitor?  
A: DC is constant voltage;  $\frac{dV}{dt} = 0$ ; therefore  $I = C \times 0 = 0$ .
- **Q:** What determines current through capacitor?  
A: Rate of voltage change ( $\frac{dV}{dt}$ ), not voltage level.
- **Q:** If voltage changes twice as fast, what happens to current?  
A: Current doubles (directly proportional).
- **Q:** Energy stored in 1F cap at 2.5V?  
A:  $E = \frac{1}{2} \times 1 \times 2.5^2 = 3.125 \text{ J}$ .
- **Q:** Define one Farad.  
A: Capacitance that stores 1 Coulomb of charge per 1 Volt.

#### Key Formulas:

- Charge:  $Q = CV$
- Current:  $I = C \frac{dV}{dt}$
- Energy:  $E = \frac{1}{2}CV^2$
- Rearranged:  $C = Q/V$ ,  $V = Q/C$

#### Practical Insights:

- Sudden voltage change  $\rightarrow$  large current spike (inrush)
- Slow voltage ramp  $\rightarrow$  small, manageable current
- Constant DC  $\rightarrow$  zero current (capacitor charged)
- AC sinusoid  $\rightarrow$  continuous current (always changing)

#### Common Mistakes:

- Thinking current depends on voltage level (it depends on rate of change!)
- Forgetting  $\frac{dV}{dt} = 0$  for DC
- Not using correct equation for AC (need reactance formula)
- Confusing charge (Q) with capacitance (C)

## Capacitor in an AC Circuit

### TL;DR (The Gist)

- **AC passes:** Capacitor allows AC current (constantly charging/discharging)
- **90° phase shift:** Current leads voltage by 90° in purely capacitive circuit
- **Why phase shift:** Current maximum when voltage changing fastest (at zero crossing)
- DC blocked, AC passed - fundamental capacitor property

## Detailed Explanation

### 2. Detailed Explanation

#### Capacitor Behavior with AC:

##### Recap of DC behavior:

- DC: Capacitor charges to supply voltage, then current stops
- Voltage constant  $\rightarrow \frac{dV}{dt} = 0 \rightarrow$  no current
- Capacitor acts as open circuit for DC

##### AC changes everything:

- AC voltage constantly changing
- Never reaches steady state
- Capacitor continuously charging and discharging
- **Current flows continuously!**

#### How AC Passes Through Capacitor:

##### The process:

1. AC voltage oscillates: positive  $\rightarrow$  zero  $\rightarrow$  negative  $\rightarrow$  zero (repeat)
2. When voltage rising: Capacitor charges (current flows in)
3. When voltage falling: Capacitor discharges (current flows out)
4. Continuous back-and-forth current flow
5. Direction reverses every half cycle

##### Key insight:

- Voltage always changing  $\rightarrow \frac{dV}{dt} \neq 0 \rightarrow$  current exists
- This is why capacitor "passes" AC
- Actually blocking DC but allowing AC

#### Phase Relationship: Current Leads Voltage by 90°:

##### In purely resistive circuit:

- Voltage and current **in phase**
- Both peak at same time
- Both zero at same time
- Rise and fall together
- Ohm's Law:  $I = V/R$  applies instantaneously

##### In purely capacitive circuit:

- Voltage and current **NOT in phase**
- **90° phase difference**
- Current leads voltage by 90°
- When current peaks, voltage is zero
- When voltage peaks, current is zero

#### WHY 90° Phase Shift? (Critical Understanding):

**Remember:**  $I = C \frac{dV}{dt}$  (current proportional to rate of voltage change)

##### Analyzing sinusoidal AC voltage:

*When voltage is at peak (maximum):*

- Voltage at top of sine wave
- Momentarily not changing (slope = 0)
- $\frac{dV}{dt} = 0$  at this instant
- Therefore:  $I = C \times 0 = 0$  (current is zero!)

*When voltage is zero (crossing):*

- Voltage crossing through zero
- This is where voltage changing **fastest**
- Steepest slope on sine wave

- $\frac{dV}{dt}$  is maximum
- Therefore:  $I = C \times (\max) \rightarrow$  current is maximum!

#### Result:

- Current peaks when voltage crosses zero
- Current zero when voltage at peak
- This creates 90° phase shift
- Current "leads" voltage (peaks first)

#### Visualizing the Phase Shift:

##### Phasor diagram interpretation:

*Voltage waveform (sine wave):*

- Starts at 0°, rises to peak at 90°
- Returns to zero at 180°
- Negative peak at 270°
- Back to zero at 360° (one cycle complete)

*Current waveform (leading by 90°):*

- Peaks at 0° (when voltage is zero)
- Zero at 90° (when voltage peaks)
- Negative peak at 180° (when voltage at zero)
- Zero at 270° (when voltage at negative peak)

#### Memory aid:

- "ICE" mnemonic: In Capacitors, current (I) leads voltage (E)
- Current gets to peak before voltage does

#### Comparison: Resistor vs. Capacitor:

Property	Resistor	Capacitor
Phase shift	0° (in phase)	90° (I leads V)
DC behavior	Passes (constant I)	Blocks (I = 0)
AC behavior	Passes ( $I \propto V$ )	Passes ( $I \propto dV/dt$ )
Relation	$I = V/R$	$I = C \frac{dV}{dt}$

#### Practical Observation in Oscilloscope:

##### Yellow trace (current):

- Peaks first
- Crosses zero before voltage
- Leads by 90°

##### Green trace (voltage):

- Lags behind current
- Peaks 90° after current peaks
- Crosses zero 90° after current

#### Why This Matters:

##### Circuit design implications:

- Phase shift affects power factor
- Important in AC power systems
- Affects filter design (high-pass, low-pass)
- Phase relationships crucial in signal processing

##### Key applications:

- **DC blocking:** Couples AC signals, blocks DC offset
- **AC coupling:** Passes audio/RF signals, blocks DC
- **Filtering:** Frequency-dependent behavior (covered next topics)
- **Phase shifting:** Intentional 90° shift in some circuits

#### Summary - Capacitor with AC:

##### Behavior:

- Allows AC to pass (continuous charging/discharging)
- Current never stops (voltage always changing)
- Acts like conductor for AC (with frequency-dependent "resistance")

##### Phase relationship:

- 90° phase shift between V and I
- Current leads voltage

- Due to  $I = C \frac{dV}{dt}$  relationship

**Big takeaway:**

- **Capacitors block DC and allow AC**
- Fundamental property exploited in countless applications
- Phase shift intrinsic to capacitive behavior

## Practical Example & Numerical

### Example 1: Phase Shift Observation

*Circuit with 1  $\mu F$  capacitor, 1 kHz AC source:*

**Voltage waveform:**

- Sinusoidal, 5V peak
- Frequency: 1 kHz
- Period:  $T = 1 \text{ ms}$

**Current waveform:**

- Also sinusoidal
- Same frequency (1 kHz)
- But peaks 0.25 ms **earlier** than voltage

**Phase calculation:**

$$\begin{aligned}\text{Phase shift} &= \frac{0.25 \text{ ms}}{1 \text{ ms}} \times 360 \\ &= 0.25 \times 360 \\ &= \boxed{90}\end{aligned}$$

Current leads voltage by exactly 90°!

### Example 2: Why Current Maximum at Voltage Zero

*AC voltage:  $V(t) = 10 \sin(2\pi \times 60t)$  (60 Hz, 10V peak)*

**Rate of voltage change:**

$$\frac{dV}{dt} = 10 \times 2\pi \times 60 \times \cos(2\pi \times 60t)$$

**At  $t = 0$  (voltage = 0):**

$$\begin{aligned}V(0) &= 10 \sin(0) = 0 \text{ V} \\ \left. \frac{dV}{dt} \right|_{t=0} &= 10 \times 2\pi \times 60 \times \cos(0) \\ &= 3,770 \text{ V/s (maximum rate of change!)}\end{aligned}$$

**At peak ( $t = T/4$ , voltage = 10V):**

$$\begin{aligned}V(T/4) &= 10 \sin(90) = 10 \text{ V (maximum)} \\ \left. \frac{dV}{dt} \right|_{t=T/4} &= 10 \times 2\pi \times 60 \times \cos(90) \\ &= 0 \text{ V/s (no change!)}\end{aligned}$$

This proves current maximum when voltage zero, and vice versa!

### Example 3: DC vs. AC Through Capacitor

*Same circuit, different sources:*

**DC source (5V constant):**

- Initial: Current flows (capacitor charging)
- After  $5\tau$ : Current = 0 (fully charged)
- Steady state: Capacitor = open circuit
- DC blocked ✓

**AC source (5V RMS, 60 Hz):**

- Continuous current flow
- Current oscillates at 60 Hz
- Never stops (voltage always changing)
- AC passes ✓

#### Example 4: Audio Signal Coupling

*Microphone output:*

- AC audio signal:  $\pm 0.1\text{V}$  at various frequencies (20 Hz - 20 kHz)
- DC offset: +2.5V (bias voltage from microphone)
- Total signal: 2.5V DC + AC audio

#### Coupling capacitor (1 $\mu\text{F}$ ):

- Blocks 2.5V DC component
- Passes AC audio component
- Output: Pure AC audio ( $\pm 0.1\text{V}$ , no DC)

**Result:** Clean audio signal for amplifier!

#### Example 5: Frequency Effect (Preview)

*Same capacitor (10  $\mu\text{F}$ ), different frequencies:*

#### Low frequency (10 Hz):

- Voltage changes slowly
- $\frac{dV}{dt}$  is small
- Current is small
- Capacitor offers high "resistance" to low freq

#### High frequency (10 kHz):

- Voltage changes rapidly
- $\frac{dV}{dt}$  is large
- Current is large
- Capacitor offers low "resistance" to high freq

This frequency-dependent behavior leads to reactance (next topic)!

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

1. **AC passes:** Capacitor allows AC current (continuous charging/discharging)
2. **DC blocked:** Steady voltage  $\rightarrow$  no current (after initial charging)
3. **90° phase shift:** Current leads voltage by 90° in pure capacitive circuit
4. **Why phase shift:**  $I = C \frac{dV}{dt} \rightarrow$  current max when  $dV/dt$  max (at zero crossing)
5. **Zero crossing:** Voltage changing fastest  $\rightarrow$  current maximum
6. **Peak voltage:** Voltage not changing  $\rightarrow$  current zero
7. **"ICE" mnemonic:** In Capacitors, I (current) leads E (voltage)
8. **Fundamental property:** Blocks DC, passes AC

#### Interview Questions:

- **Q:** Does capacitor pass AC or DC?  
A: Passes AC, blocks DC.
- **Q:** What is phase relationship between V and I in capacitor?  
A: Current leads voltage by 90°.
- **Q:** Why does current lead voltage in capacitor?  
A: Because  $I = C \frac{dV}{dt}$  - current maximum when voltage changing fastest (at zero crossing).
- **Q:** When is current maximum in AC capacitor circuit?  
A: When voltage crosses zero (voltage changing fastest).
- **Q:** When is current zero?  
A: When voltage at peak (not changing,  $dV/dt = 0$ ).
- **Q:** Why does capacitor allow AC but block DC?  
A: AC always changing ( $dV/dt \neq 0$ )  $\rightarrow$  current flows; DC constant ( $dV/dt = 0$ )  $\rightarrow$  no current.

#### Phase Shift Memory:

- **"ICE":** In Capacitor, current (I) leads voltage (E)
- Think: Current is "ahead" by 90°
- Current peaks first, then voltage peaks
- Opposite of inductor (ELI: in inductor, E leads I)

#### Applications:

- DC blocking/AC coupling (audio, RF)
- Signal isolation (remove DC offset)
- Filter circuits (frequency-dependent)

- Phase shifting networks

#### Common Mistakes:

- Thinking capacitor "conducts" AC (it alternately charges/discharges)
- Confusing phase lead with phase lag
- Forgetting  $90^\circ$  applies to pure capacitive circuit only

## Impedance and Reactance of a Capacitor

### TL;DR (The Gist)

- **Capacitive reactance:**  $X_C = \frac{1}{2\pi fC}$  (opposition to AC, measured in  $\Omega$ )
- **Higher frequency:** Lower reactance (passes easier)
- **DC ( $f=0$ ):** Infinite reactance (blocks completely)
- **Impedance:**  $Z = \sqrt{R^2 + X_C^2}$  (total opposition in circuit)

### Detailed Explanation

## 2. Detailed Explanation

#### Capacitive Reactance ( $X_C$ ):

##### Definition:

- **Capacitive reactance:** Measure of capacitor's opposition to AC current
- Symbol:  $X_C$
- Unit: Ohms ( $\Omega$ ), like resistance
- But NOT the same as resistance!

##### Key difference from resistance:

- **Resistance:** Fixed value (e.g.,  $100\Omega$ ,  $1k\Omega$ )
- **Reactance:** Varies with frequency
- Higher frequency  $\rightarrow$  lower reactance
- Lower frequency  $\rightarrow$  higher reactance

#### Capacitive Reactance Formula:

$$X_C = \frac{1}{2\pi fC}$$

Where:

- $X_C$  = capacitive reactance ( $\Omega$ )
- $\pi = 3.14159...$
- $f$  = frequency (Hz)
- $C$  = capacitance (F)

#### Understanding the Formula:

##### Inversely proportional to frequency:

- As  $f$  increases  $\rightarrow X_C$  decreases
- Higher frequency  $\rightarrow$  less opposition  $\rightarrow$  more current
- Lower frequency  $\rightarrow$  more opposition  $\rightarrow$  less current
- Capacitor "prefers" high frequencies

##### Inversely proportional to capacitance:

- As  $C$  increases  $\rightarrow X_C$  decreases
- Larger capacitor  $\rightarrow$  less opposition
- Smaller capacitor  $\rightarrow$  more opposition

#### Extreme Cases:

**When frequency = 0 (DC):**

$$\begin{aligned}X_C &= \frac{1}{2\pi \times 0 \times C} \\&= \frac{1}{0} \\&= \infty \text{ (infinite reactance)}\end{aligned}$$

**Capacitor acts as open circuit for DC!** This proves mathematically why DC is blocked.

**When frequency =  $\infty$  (theoretical):**

$$\begin{aligned}X_C &= \frac{1}{2\pi \times \infty \times C} \\&= 0 \, \Omega\end{aligned}$$

Capacitor acts like a wire (short circuit) at infinitely high frequency.

**Frequency Response Graph:**

**Reactance vs. Frequency (log scale):**

- At low frequencies: High reactance (steep curve)
- At high frequencies: Low reactance (approaches zero)
- Inverse relationship (hyperbolic curve)
- Never negative (always positive opposition)

**Impedance ( $Z$ ) - Total Opposition:**

**In circuit with resistor AND capacitor:**

**Wrong approach:**

$$Z \neq R + X_C \quad (\text{Cannot simply add!})$$

**Why not?**

- Resistance and reactance at  $90^\circ$  to each other
- Voltage across R in phase with current
- Voltage across C lags current by  $90^\circ$
- Must add as vectors, not scalars

**Correct formula (series R-C circuit):**

$$Z = \sqrt{R^2 + X_C^2}$$

This is Pythagorean theorem! Resistance and reactance are perpendicular.

**Calculating Current with Impedance:**

**For RMS (AC) values:**

$$I_{rms} = \frac{V_{rms}}{Z}$$

Similar to Ohm's Law, but using impedance instead of resistance.

**Reactance in Circuit Analysis:**

**Series R-C circuit:**

1. Calculate  $X_C$  at operating frequency
2. Calculate total impedance:  $Z = \sqrt{R^2 + X_C^2}$
3. Calculate current:  $I = V/Z$
4. Voltage across R:  $V_R = I \times R$
5. Voltage across C:  $V_C = I \times X_C$

**Note:**  $V_R$  and  $V_C$  don't simply add to  $V_{total}$  (phase shift!)

**Why Reactance is Important:**

**Filter design:**

- Frequency-dependent behavior creates filters
- High-pass filter: Capacitor blocks low freq, passes high freq
- $X_C$  determines cutoff frequency
- (More in filter chapters)

**Coupling/decoupling:**

- Choose C so  $X_C$  is low at signal frequencies
- Ensures minimal attenuation
- Example: Audio coupling needs low  $X_C$  at 20 Hz - 20 kHz

**Power calculations:**

- Reactance doesn't dissipate power (unlike resistance)
- Energy stored and released each cycle
- Affects power factor in AC circuits

**Summary Table:**

Frequency	Reactance $X_C$
0 Hz (DC)	$\infty$ (blocks)
Low freq	High (impedes)
High freq	Low (passes easily)
$\infty$ Hz	0 $\Omega$ (wire)

## Practical Example & Numerical

### Example 1: Calculate Reactance at Two Frequencies

Given: 220 nF capacitor

At 1 kHz:

$$\begin{aligned}
 X_C &= \frac{1}{2\pi fC} \\
 &= \frac{1}{2\pi \times 1000 \times 220 \times 10^{-9}} \\
 &= \frac{1}{1.382 \times 10^{-3}} \\
 &= \boxed{723.4 \Omega}
 \end{aligned}$$

At 20 kHz:

$$\begin{aligned}
 X_C &= \frac{1}{2\pi \times 20000 \times 220 \times 10^{-9}} \\
 &= \frac{1}{2.764 \times 10^{-2}} \\
 &= \boxed{36.2 \Omega}
 \end{aligned}$$

**Observation:**  $20 \times \text{frequency} \rightarrow 1/20 \times \text{reactance}$  ( $36.2 \approx 723.4/20$ )

### Example 2: Impedance Calculation (Series R-C)

Circuit:

- Resistor: 200 $\Omega$
- Capacitor: 10  $\mu\text{F}$
- Frequency: 80 Hz
- Supply: 5V RMS

**Step 1 - Calculate reactance:**

$$\begin{aligned}
 X_C &= \frac{1}{2\pi \times 80 \times 10 \times 10^{-6}} \\
 &= \boxed{198.9 \Omega}
 \end{aligned}$$

**Step 2 - Calculate impedance:**

$$\begin{aligned}
 Z &= \sqrt{R^2 + X_C^2} \\
 &= \sqrt{200^2 + 198.9^2} \\
 &= \sqrt{40000 + 39561} \\
 &= \sqrt{79561} \\
 &= \boxed{282.1 \Omega}
 \end{aligned}$$

**Step 3 - Calculate current:**

$$\begin{aligned}
 I_{rms} &= \frac{V_{rms}}{Z} \\
 &= \frac{5}{282.1} \\
 &= \boxed{17.7 \text{ mA}}
 \end{aligned}$$

**Example 3: Why Can't We Just Add  $R + X_C$ ?**

Using same circuit from Example 2:

**Wrong (arithmetic sum):**

$$Z_{wrong} = R + X_C = 200 + 198.9 = 398.9 \, \Omega$$

**Correct (vector sum):**

$$Z_{correct} = \sqrt{200^2 + 198.9^2} = 282.1 \, \Omega$$

**Difference:**  $398.9 - 282.1 = 116.8 \Omega$  error (41% wrong!)

This is why we must use Pythagorean formula.

**Example 4: Reactance at Audio Frequencies**

$1 \, \mu F$  coupling capacitor for audio:

**At 20 Hz (low audio):**

$$X_C = \frac{1}{2\pi \times 20 \times 1 \times 10^{-6}} = 7,958 \, \Omega$$

**At 1 kHz (mid audio):**

$$X_C = \frac{1}{2\pi \times 1000 \times 1 \times 10^{-6}} = 159 \, \Omega$$

**At 20 kHz (high audio):**

$$X_C = \frac{1}{2\pi \times 20000 \times 1 \times 10^{-6}} = 8 \, \Omega$$

**Problem:** High reactance at 20 Hz might attenuate bass!

**Solution:** Use larger capacitor (e.g.,  $10 \, \mu F$ ) for lower reactance across entire audio range.

**Example 5: Choosing Capacitor for Low Reactance**

*Requirement:* Reactance  $< 10 \Omega$  at 60 Hz

**Rearrange formula to find C:**

$$\begin{aligned} X_C &= \frac{1}{2\pi f C} \\ C &= \frac{1}{2\pi f X_C} \\ &= \frac{1}{2\pi \times 60 \times 10} \\ &= 265 \times 10^{-6} \, F \\ &= \boxed{265 \, \mu F} \end{aligned}$$

Need at least  $265 \, \mu F$  capacitor!

**Example 6: DC Blocking Verification**

*Any capacitor at DC ( $f = 0$ ):*

$$\begin{aligned} X_C &= \frac{1}{2\pi \times 0 \times C} \\ &= \frac{1}{0} \\ &= \infty \, \Omega \end{aligned}$$

**Current (by Ohm's Law):**

$$I = \frac{V}{X_C} = \frac{V}{\infty} = 0 \, A$$

Mathematical proof that DC is blocked!

**Key Points (Interview Focus)****4. Key Points (Interview Focus)**

1. **Reactance formula:**  $X_C = \frac{1}{2\pi f C}$  (measured in  $\Omega$ )
2. **Inversely proportional:** Higher  $f$  or higher  $C \rightarrow$  lower  $X_C$
3. **DC ( $f=0$ ):**  $X_C = \infty \rightarrow$  capacitor blocks DC
4. **High frequency:**  $X_C$  approaches 0  $\rightarrow$  capacitor like wire

5. **Impedance:**  $Z = \sqrt{R^2 + X_C^2}$  (NOT  $R + X_C$ !)
6. **Phase consideration:**  $R$  and  $X_C$  perpendicular ( $90^\circ$ ), use Pythagoras
7. **Reactance  $\neq$  resistance:** Reactance varies with frequency, resistance doesn't
8. **No power dissipation:** Reactance stores/releases energy, doesn't dissipate

#### Interview Questions:

- **Q:** What is capacitive reactance?  
A: Measure of capacitor's opposition to AC current, measured in ohms.
- **Q:** Formula for reactance?  
A:  $X_C = \frac{1}{2\pi fC}$
- **Q:** What happens to reactance as frequency increases?  
A: Reactance decreases (inversely proportional).
- **Q:** Reactance at DC ( $f=0$ )?  
A: Infinite ohms (capacitor blocks DC completely).
- **Q:** How to calculate impedance of series R-C?  
A:  $Z = \sqrt{R^2 + X_C^2}$  (Pythagorean theorem).
- **Q:** Why not just add  $R + X_C$ ?  
A: They are  $90^\circ$  out of phase; must use vector addition.

#### Key Formulas:

- Reactance:  $X_C = \frac{1}{2\pi fC}$
- Rearranged:  $C = \frac{1}{2\pi fX_C}$ ,  $f = \frac{1}{2\pi CX_C}$
- Impedance:  $Z = \sqrt{R^2 + X_C^2}$  (series R-C)
- Current:  $I = V/Z$  (RMS values for AC)

#### Practical Insights:

- High freq  $\rightarrow$  low  $X_C \rightarrow$  capacitor passes easily
- Low freq  $\rightarrow$  high  $X_C \rightarrow$  capacitor impedes
- Design filters using frequency dependence
- Choose  $C$  for desired  $X_C$  at operating frequency

#### Common Mistakes:

- Adding  $R + X_C$  arithmetically (must use  $\sqrt{R^2 + X_C^2}$ !)
- Thinking reactance = resistance (different concepts)
- Forgetting frequency dependence
- Using wrong units ( $f$  in Hz,  $C$  in Farads)

## Capacitors with Various Frequencies & Capacitances - Practical Summary

### TL;DR (The Gist)

- **Higher frequency:** Lower reactance  $\rightarrow$  more current  $\rightarrow$  capacitor passes easily
- **Larger capacitance:** Lower reactance  $\rightarrow$  more current for same frequency
- **Applications:** Coupling (AC pass, DC block), Decoupling (noise removal), Bypass (local power), Smoothing (ripple reduction)
- Choose  $C$  based on frequency and desired reactance

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

##### Frequency Effects:

- High freq  $\rightarrow$  low  $X_C \rightarrow$  capacitor like wire
- Low freq  $\rightarrow$  high  $X_C \rightarrow$  capacitor blocks
- Design consideration: Choose  $C$  for low  $X_C$  at signal frequencies

##### Capacitance Effects:

- Larger  $C \rightarrow$  lower  $X_C \rightarrow$  more current
- Smaller  $C \rightarrow$  higher  $X_C \rightarrow$  less current
- Power supply: Use large  $C$  (mF range)

- High-freq decoupling: Use small C (nF- $\mu$ F range)

## Coupling Capacitors

### TL;DR (The Gist)

- **Purpose:** Pass AC signals while blocking DC offset
- **Application:** Connect two circuit stages, remove DC bias
- **Example:** Microphone output (AC audio + DC bias)  $\rightarrow$  capacitor  $\rightarrow$  amplifier (AC only)
- Choose C large enough: Low  $X_C$  at lowest signal frequency

### Detailed Explanation

## 2. Detailed Explanation

### What is Coupling?

#### Purpose of coupling capacitor:

- Connect (couple) two circuit stages
- Pass AC signal from stage 1 to stage 2
- Block DC voltage from stage 1
- Each stage can have different DC bias

#### Classic example - Audio amplifier stages:

- Stage 1: Microphone preamp (DC bias = 2.5V)
- Stage 2: Power amplifier (DC bias = 5V)
- Coupling capacitor between them
- AC audio passes through
- DC voltages isolated

#### Microphone Circuit Example:

##### Microphone output signal:

- AC component: Audio signal ( $\pm 0.1V$ , 20 Hz - 20 kHz)
- DC component: Bias voltage (+2.5V for powering mic)
- Total output: 2.5V DC + AC audio

##### Problem without coupling capacitor:

- Amplifier sees 2.5V DC + AC
- DC offset affects amplifier bias point
- May cause distortion or clipping
- DC not needed at amplifier input

##### Solution with coupling capacitor:

- Capacitor blocks 2.5V DC
- Capacitor passes AC audio
- Amplifier sees only AC signal (centered at 0V)
- Clean audio amplification

#### Choosing Coupling Capacitor Value:

##### Requirements:

1. Must pass lowest frequency of interest
2. Reactance should be low at lowest frequency
3. Rule of thumb:  $X_C < \frac{1}{10}$  of load impedance

##### For audio coupling (20 Hz - 20 kHz):

- Critical frequency: 20 Hz (lowest)
- If  $X_C$  too high at 20 Hz  $\rightarrow$  bass attenuation
- Typical values:  $1\mu F$  -  $10\mu F$  for audio
- Larger C = better bass response

##### Calculation example:

- Want  $X_C < 100\Omega$  at 20 Hz

- $C = \frac{1}{2\pi f X_C} = \frac{1}{2\pi \times 20 \times 100} \approx 80 \mu\text{F}$
- Use standard value:  $100 \mu\text{F}$

#### Polarity Considerations:

##### If using electrolytic capacitor:

- Must observe polarity!
- Positive terminal toward higher DC voltage
- In microphone example: + toward mic output
- Negative toward amplifier input (lower/no DC)

##### Non-polarized alternative:

- Film or ceramic capacitor
- No polarity concern
- But limited to smaller values (typically  $\leq 10\mu\text{F}$ )
- May not provide sufficient coupling at low frequencies

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

1. **Coupling:** Passes AC, blocks DC between circuit stages
2. **Reactance:** Must be low at lowest signal frequency
3. **Audio:** Typically  $1\text{-}10 \mu\text{F}$  for full  $20 \text{ Hz} - 20 \text{ kHz}$  range
4. **Polarity:** Electrolytic + toward higher DC voltage
5. **Purpose:** Isolate DC bias levels while passing signal

#### Interview Questions:

- **Q:** What does coupling capacitor do?  
A: Passes AC signal while blocking DC component between stages.
- **Q:** Why need coupling in amplifier?  
A: Each stage may have different DC bias; capacitor isolates DC while passing AC signal.
- **Q:** How to choose coupling capacitor value?  
A: Large enough so reactance is low at lowest signal frequency.

## Decoupling & Bypass Capacitors

### TL;DR (The Gist)

- **Decoupling:** Removes AC noise from DC power supply
- **Bypass:** Provides local energy storage for fast current demands
- **Placement:** Across power rails, close to IC
- **Multiple values:** Different capacitors handle different frequencies

### Detailed Explanation

### 2. Detailed Explanation

#### Decoupling Capacitors:

##### The problem - Noisy DC:

- Real power supplies have AC noise superimposed on DC
- Switching circuits create voltage ripples
- Long PCB traces have inductance
- Sudden current demands cause voltage dips

##### The solution:

- Place capacitor in parallel with power supply
- Capacitor has low reactance to AC noise
- AC noise shunted to ground through capacitor
- DC component unaffected (capacitor blocks DC)

- Result: Clean DC power to IC

### **Bypass Capacitors (Similar but Different Purpose):**

#### **The problem - Inductive supply lines:**

- PCB traces have inductance
- Inductors resist changing current
- When IC switches, needs fast current
- Inductive supply cannot respond quickly
- Voltage dips occur

#### **The solution:**

- Capacitor acts as local energy reservoir
- Charged and ready near IC
- When IC needs current spike, cap provides it instantly
- Bypasses the slow, inductive supply path
- Maintains stable voltage at IC

### **Why Multiple Capacitor Values in Parallel?**

#### **Real capacitor model:**

- Not just capacitance
- Has ESR (equivalent series resistance)
- Has ESL (equivalent series inductance)
- Forms RLC circuit
- Has resonant frequency

#### **Frequency response:**

- Below resonance: Capacitive (impedance decreases with freq)
- At resonance: Minimum impedance
- Above resonance: Inductive (impedance increases!)

#### **Solution - Multiple capacitors:**

1. **Large (1-100  $\mu\text{F}$ ):** Low-frequency noise, bulk energy storage
2. **Medium (0.1-1  $\mu\text{F}$ ):** Mid-frequency decoupling
3. **Small (10-100 nF):** High-frequency noise

#### **Result:**

- Each capacitor effective at different frequency range
- Combined: Low impedance across wide frequency spectrum
- Better overall performance than single value

#### **Placement Critical:**

##### **Rules:**

- Place as close as possible to IC power pins
- Minimizes inductance in path
- Smaller capacitors closer (they handle high freq)
- Larger capacitors can be slightly further
- Short, wide traces preferred

## **Key Points (Interview Focus)**

### **4. Key Points (Interview Focus)**

1. **Decoupling:** Removes AC noise from DC supply (noise to ground)
2. **Bypass:** Provides local fast current (bypasses slow supply)
3. **Placement:** As close as possible to IC power pins
4. **Multiple values:** Cover wide frequency range (nF to  $\mu\text{F}$ )
5. **Typical:** 0.1  $\mu\text{F}$  ceramic + 10  $\mu\text{F}$  electrolytic per IC

#### **Interview Questions:**

- **Q:** Difference between decoupling and bypass?  
A: Decoupling removes noise; bypass provides local energy. Same placement, slightly different purpose.
- **Q:** Why multiple capacitor values?  
A: Each effective at different frequency; real caps have resonance; multiple values cover wider range.
- **Q:** Where to place bypass capacitor?  
A: As close as possible to IC power pins to minimize inductance.

# Smoothing Capacitors

## TL;DR (The Gist)

- **Purpose:** Convert pulsating DC (after rectification) to smooth DC
- **Operation:** Charges during voltage peaks, discharges during dips
- **Value:** Large (100  $\mu\text{F}$  - 10,000  $\mu\text{F}$  typical)
- **Limitation:** Provides smoothing but NOT regulation

## Detailed Explanation

### 2. Detailed Explanation

#### Power Supply Context:

##### AC to DC conversion process:

1. AC from wall outlet (120V/230V, 50/60 Hz)
2. Transformer steps down voltage
3. Rectifier converts AC to pulsating DC
4. **Smoothing capacitor reduces ripple**
5. Voltage regulator provides stable DC (optional)

##### After rectification (without smoothing):

- Pulsating DC voltage
- Voltage varies from 0V to peak
- Ripple frequency =  $2 \times$  AC frequency (full-wave)
- Not suitable for powering circuits

#### How Smoothing Works:

##### Charging phase (voltage rising):

- Rectifier output rises to peak
- Capacitor charges to peak voltage
- Capacitor fully charged at peak

##### Discharging phase (voltage falling):

- Rectifier output starts falling
- Load draws current
- Capacitor supplies current from stored energy
- Capacitor voltage slowly decreases
- "Fills in the gaps" between pulses

##### Next cycle:

- Rectifier voltage rises again
- Recharges capacitor to peak
- Process repeats

##### Result:

- Much smoother DC voltage
- Small ripple remains
- Larger capacitor = smoother output

#### Choosing Smoothing Capacitor:

##### Factors:

- Load current (higher I  $\rightarrow$  need larger C)
- Acceptable ripple voltage
- Ripple frequency (50/60 Hz  $\rightarrow$  100/120 Hz for full-wave)

##### Rule of thumb:

- $C \approx \frac{I_{load}}{2fV_{ripple}}$
- Where f = ripple frequency,  $V_{ripple}$  = acceptable ripple
- Typical: 1,000 - 10,000  $\mu\text{F}$  for 1A load

##### Limitations:

##### Smoothing is NOT regulation:

- Output voltage varies with load

- Higher load → more ripple, lower average voltage
- Lower load → less ripple, higher voltage
- Input voltage changes affect output

**For regulated supply:**

- Add voltage regulator after smoothing cap
- Regulator maintains constant output
- Capacitor still needed (regulator input requirement)
- Combined: smooth AND regulated DC

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

1. **Smoothing:** Reduces ripple in rectified DC
2. **Operation:** Charges at peaks, discharges during dips
3. **Value:** Large (hundreds to thousands of  $\mu\text{F}$ )
4. **NOT regulation:** Voltage still varies with load
5. **Polarity:** Electrolytic must be connected correctly
6. **For regulation:** Add voltage regulator after smoothing

**Interview Questions:**

- **Q:** What does smoothing capacitor do?  
A: Reduces ripple voltage in rectified DC by storing/releasing energy.
- **Q:** Does smoothing capacitor provide regulation?  
A: No, only reduces ripple. Voltage still varies with load. Need regulator for stable output.
- **Q:** Why large capacitance needed?  
A: Must supply load current during discharge phase (between AC peaks); larger C = less voltage drop.

**Applications:**

- Power supplies (after rectifier)
- Battery eliminator circuits
- Linear power supplies
- Always paired with voltage regulator for quality DC

# Section 09 – RC Time Constant

## RC Time Constant ( $\tau = RC$ )

### TL;DR (The Gist)

- **Time Constant:**  $\tau = R \times C$  (in seconds)
- **Charging:** After  $1\tau$ : 63% charged — After  $5\tau$ : 99% charged (full)
- **Discharging:** After  $1\tau$ : 37% remains — After  $5\tau$ : 1% remains (empty)
- **Units:** R in ohms ( $\Omega$ ), C in farads (F)  $\rightarrow \tau$  in seconds (s)

### Detailed Explanation

## 2. Detailed Explanation

### What is RC Time Constant?

#### Definition:

- Time constant ( $\tau$ ) = Resistance  $\times$  Capacitance
- $\tau = R \times C$  where R in  $\Omega$ , C in F
- Measured in seconds (s)
- Determines how fast capacitor charges/discharges
- Larger  $\tau$  = slower charging/discharging

#### Why does it matter?

- Capacitor doesn't charge/discharge instantly
- Resistor limits current  $\rightarrow$  slows charging
- Larger R or C  $\rightarrow$  longer time to charge
- Time constant quantifies this delay
- Critical for timing circuits and filters

### The Charging Process:

#### RC charging circuit:

- Resistor in series with capacitor
- DC voltage source applied
- Capacitor starts at 0V
- Current flows:  $I = \frac{V_{supply} - V_C}{R}$
- As  $V_C$  increases, current decreases
- Eventually  $V_C = V_{supply}$ , current = 0

#### Exponential voltage rise:

- $V_C(t) = V_{supply} \times (1 - e^{-t/\tau})$
- NOT linear! Exponential curve
- Fast rise initially, slows down later
- Asymptotically approaches  $V_{supply}$
- Never truly reaches 100% (but very close)

#### Key time points during charging:

1. At  $t = 0$ :  $V_C = 0V$  (0% charged)
2. At  $t = 1\tau$ :  $V_C = 0.632 \times V_{supply}$  (63.2% charged)
3. At  $t = 2\tau$ :  $V_C = 0.865 \times V_{supply}$  (86.5% charged)
4. At  $t = 3\tau$ :  $V_C = 0.950 \times V_{supply}$  (95.0% charged)
5. At  $t = 4\tau$ :  $V_C = 0.982 \times V_{supply}$  (98.2% charged)
6. At  $t = 5\tau$ :  $V_C = 0.993 \times V_{supply}$  (99.3% charged)

#### The "5 tau rule":

- After  $5\tau$ , capacitor considered "fully charged"
- Actually 99.3%, but close enough for practical purposes
- Total charging time  $\approx 5 \times R \times C$

### The Discharging Process:

#### RC discharging circuit:

- Capacitor initially charged to  $V_{initial}$
- Voltage source removed or switched to ground
- Capacitor discharges through resistor
- Current flows opposite direction
- Current:  $I = \frac{V_C}{R}$  (decreases as  $V_C$  decreases)

#### Exponential voltage decay:

- $V_C(t) = V_{initial} \times e^{-t/\tau}$
- Exponential decay curve
- Fast drop initially, slows down later
- Asymptotically approaches 0V

#### Key time points during discharging:

1. At  $t = 0$ :  $V_C = V_{initial}$  (100% charged)
2. At  $t = 1\tau$ :  $V_C = 0.368 \times V_{initial}$  (36.8% remains)
3. At  $t = 2\tau$ :  $V_C = 0.135 \times V_{initial}$  (13.5% remains)
4. At  $t = 3\tau$ :  $V_C = 0.050 \times V_{initial}$  (5.0% remains)
5. At  $t = 4\tau$ :  $V_C = 0.018 \times V_{initial}$  (1.8% remains)
6. At  $t = 5\tau$ :  $V_C = 0.007 \times V_{initial}$  (0.7% remains)

#### The "5 tau rule" for discharging:

- After  $5\tau$ , capacitor considered "fully discharged"
- Actually 0.7%, essentially zero for practical purposes
- Total discharging time  $\approx 5 \times R \times C$

#### Current During Charging/Discharging:

##### Charging current:

- $I(t) = \frac{V_{supply}}{R} \times e^{-t/\tau}$
- Maximum at  $t = 0$ :  $I_{max} = \frac{V_{supply}}{R}$
- Exponentially decreases
- At  $t = 1\tau$ : Current drops to 37% of initial
- At  $t = 5\tau$ : Current essentially zero

##### Discharging current:

- $I(t) = -\frac{V_{initial}}{R} \times e^{-t/\tau}$
- Negative sign: Opposite direction to charging
- Maximum magnitude at  $t = 0$
- Exponentially decreases in magnitude

#### Unit Conversions (Critical!):

##### Remember powers of ten:

- Resistors often in  $k\Omega$  or  $M\Omega$
- Capacitors often in  $\mu F$ ,  $nF$ , or  $pF$
- Must convert to base units for  $\tau$  calculation!

##### Common conversions:

- $1 k\Omega = 1,000 \Omega = 10^3 \Omega$
- $1 M\Omega = 1,000,000 \Omega = 10^6 \Omega$
- $1 \mu F = 0.000001 F = 10^{-6} F$
- $1 nF = 0.000000001 F = 10^{-9} F$
- $1 pF = 0.000000000001 F = 10^{-12} F$

##### Shortcut for common combinations:

- $k\Omega \times \mu F = ms$  (milliseconds)
- $M\Omega \times \mu F = s$  (seconds)
- $k\Omega \times nF = \mu s$  (microseconds)

#### Factors Affecting Time Constant:

##### Resistance effect:

- Larger  $R \rightarrow$  limits current more  $\rightarrow$  slower charging
- Double  $R \rightarrow$  double  $\tau \rightarrow 2\times$  longer time
- Smaller  $R \rightarrow$  faster charging (but higher current!)

##### Capacitance effect:

- Larger  $C \rightarrow$  more charge needed  $\rightarrow$  slower charging
- Double  $C \rightarrow$  double  $\tau \rightarrow 2\times$  longer time
- Smaller  $C \rightarrow$  faster charging

**Practical implications:**

- Want fast charging? Use small R and small C
- Want slow charging (timing delay)? Use large R or large C
- Trade-offs: Small R = high current, large C = bigger/expensive

**Practical Examples & Numerical Calculations****Example 1: Basic Time Constant Calculation**

Given:  $R = 100 \text{ k}\Omega$ ,  $C = 200 \text{ }\mu\text{F}$

Calculate time constant:

- Convert to base units:  $R = 100,000 \text{ }\Omega$ ,  $C = 0.0002 \text{ F}$
- $\tau = R \times C = 100,000 \times 0.0002 = 20 \text{ seconds}$
- Or use shortcut:  $100 \text{ k}\Omega \times 200 \text{ }\mu\text{F} = 100 \times 200 \text{ ms} = 20,000 \text{ ms} = 20 \text{ s}$

Full charging time:

- $5\tau = 5 \times 20 = 100 \text{ seconds}$
- Takes 1 minute 40 seconds to fully charge

**Example 2: Charging to Specific Voltage**

Given:  $V_{\text{supply}} = 12\text{V}$ ,  $R = 10 \text{ k}\Omega$ ,  $C = 100 \text{ }\mu\text{F}$

Time constant:  $\tau = 10 \times 10^3 \times 100 \times 10^{-6} = 1 \text{ second}$

Voltage after 1 second ( $1\tau$ ):

- $V_C = 12 \times 0.632 = 7.58\text{V}$  (63.2% of 12V)

Voltage after 2 seconds ( $2\tau$ ):

- $V_C = 12 \times 0.865 = 10.38\text{V}$  (86.5% of 12V)

Voltage after 5 seconds ( $5\tau$ ):

- $V_C = 12 \times 0.993 = 11.92\text{V}$  (99.3% of 12V - essentially full)

**Example 3: Discharging from Initial Voltage**

Given:  $V_{\text{initial}} = 9\text{V}$ ,  $R = 47 \text{ k}\Omega$ ,  $C = 1000 \text{ }\mu\text{F}$

Time constant:  $\tau = 47 \times 10^3 \times 1000 \times 10^{-6} = 47 \text{ seconds}$

Voltage after 47 seconds ( $1\tau$ ):

- $V_C = 9 \times 0.368 = 3.31\text{V}$  (36.8% remains)

Voltage after 94 seconds ( $2\tau$ ):

- $V_C = 9 \times 0.135 = 1.22\text{V}$  (13.5% remains)

Time to fully discharge:

- $5\tau = 5 \times 47 = 235 \text{ seconds} \approx 3 \text{ minutes } 55 \text{ seconds}$

**Example 4: Initial Charging Current**

Given:  $V_{\text{supply}} = 5\text{V}$ ,  $R = 1 \text{ k}\Omega$ ,  $C = 470 \text{ }\mu\text{F}$

Time constant:  $\tau = 1000 \times 470 \times 10^{-6} = 0.47 \text{ seconds}$

Initial charging current ( $t = 0$ ):

- $I_{\text{max}} = \frac{V_{\text{supply}}}{R} = \frac{5}{1000} = 0.005\text{A} = 5 \text{ mA}$
- This is the current at the instant voltage is applied

Current after 0.47 seconds ( $1\tau$ ):

- $I = 5 \text{ mA} \times 0.368 = 1.84 \text{ mA}$  (dropped to 37%)

Current after 2.35 seconds ( $5\tau$ ):

- $I \approx 0 \text{ mA}$  (essentially zero, capacitor fully charged)

**Example 5: Designing for Specific Delay**

Requirement: Need 10-second delay

Choose  $C = 100 \text{ }\mu\text{F}$  (standard value)

Calculate required R:

- $\tau = R \times C$
- $R = \frac{\tau}{C} = \frac{10}{100 \times 10^{-6}} = 100,000 \text{ }\Omega = 100 \text{ k}\Omega$

Verification:

- $\tau = 100 \text{ k}\Omega \times 100 \text{ }\mu\text{F} = 10 \text{ s} \checkmark$
- Full charge time:  $5\tau = 50 \text{ seconds}$

**Example 6: Effect of Doubling Components**

Original:  $R = 10 \text{ k}\Omega$ ,  $C = 22 \text{ }\mu\text{F}$ ,  $\tau = 0.22 \text{ s}$

Double resistance ( $R = 20 \text{ k}\Omega$ ):

- New  $\tau = 20 \times 10^3 \times 22 \times 10^{-6} = 0.44 \text{ s}$

- Time constant doubles! ( $2\times$  slower)

Double capacitance ( $C = 44\ \mu\text{F}$ ,  $R$  back to  $10\ \text{k}\Omega$ ):

- New  $\tau = 10 \times 10^3 \times 44 \times 10^{-6} = 0.44\ \text{s}$
- Time constant also doubles! (same effect as doubling  $R$ )

Double both ( $R = 20\ \text{k}\Omega$ ,  $C = 44\ \mu\text{F}$ ):

- New  $\tau = 20 \times 10^3 \times 44 \times 10^{-6} = 0.88\ \text{s}$
- Time constant quadruples! ( $4\times$  slower)

#### Example 7: Unit Conversion Practice

Calculate  $\tau$  for:  $R = 2.2\ \text{M}\Omega$ ,  $C = 10\ \mu\text{F}$

Method 1 (convert to base units):

- $R = 2,200,000\ \Omega$ ,  $C = 0.00001\ \text{F}$
- $\tau = 2,200,000 \times 0.00001 = 22\ \text{seconds}$

Method 2 (use shortcut:  $\text{M}\Omega \times \mu\text{F} = \text{s}$ ):

- $\tau = 2.2 \times 10 = 22\ \text{seconds} \checkmark$

Full charge time:  $5\tau = 110\ \text{seconds} = 1\ \text{minute } 50\ \text{seconds}$

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

1. **Time Constant Formula:**  $\tau = R \times C$  ( $R$  in  $\Omega$ ,  $C$  in  $\text{F}$ ,  $\tau$  in  $\text{s}$ )
2. **Charging Key Points:**
  - $1\tau$ : 63.2% charged
  - $5\tau$ : 99.3% charged (considered "full")
  - $V_C(t) = V_{\text{supply}}(1 - e^{-t/\tau})$
3. **Discharging Key Points:**
  - $1\tau$ : 36.8% remains
  - $5\tau$ : 0.7% remains (considered "empty")
  - $V_C(t) = V_{\text{initial}} \times e^{-t/\tau}$
4. **Exponential Process:** NOT linear! Fast initially, slows down later
5. **5 Tau Rule:** Full charge/discharge takes approximately  $5 \times R \times C$
6. **Current Behavior:** Maximum at  $t = 0$ , exponentially decreases
7. **Unit Shortcuts:**
  - $\text{k}\Omega \times \mu\text{F} = \text{ms}$
  - $\text{M}\Omega \times \mu\text{F} = \text{s}$
  - $\text{k}\Omega \times \text{nF} = \mu\text{s}$
8. **Component Effects:**
  - Larger  $R$  or  $C \rightarrow$  slower charging (longer  $\tau$ )
  - Smaller  $R$  or  $C \rightarrow$  faster charging (shorter  $\tau$ )
  - Proportional relationship:  $2\times R$  or  $2\times C \rightarrow 2\times \tau$

#### Interview Questions:

- **Q:** What is the RC time constant?  
A:  $\tau = R \times C$ , measured in seconds. It determines how fast a capacitor charges or discharges through a resistor.
- **Q:** How much is a capacitor charged after 1 time constant?  
A: 63.2% of the supply voltage (charging) or 36.8% remaining (discharging).
- **Q:** When is a capacitor considered fully charged?  
A: After 5 time constants ( $5\tau$ ), when it reaches 99.3% of supply voltage.
- **Q:** Is charging/discharging linear or exponential?  
A: Exponential. Fast change initially, then slows down asymptotically.
- **Q:** What happens to time constant if you double the resistance?  
A: Time constant doubles ( $\tau$  is proportional to  $R$ ). Charging takes twice as long.
- **Q:** Why does resistor slow down charging?  
A: Resistor limits current:  $I = \frac{V_{\text{supply}} - V_C}{R}$ . Larger  $R \rightarrow$  smaller  $I \rightarrow$  slower charging.
- **Q:** What is the initial current when charging starts?  
A:  $I_{\text{max}} = \frac{V_{\text{supply}}}{R}$  (capacitor voltage is 0, so full voltage across  $R$ ).

#### Formulas Summary:

- **Time Constant:**  $\tau = R \times C$

- **Charging Voltage:**  $V_C(t) = V_{supply}(1 - e^{-t/\tau})$
- **Discharging Voltage:**  $V_C(t) = V_{initial} \times e^{-t/\tau}$
- **Charging Current:**  $I(t) = \frac{V_{supply}}{R} e^{-t/\tau}$
- **Discharging Current:**  $I(t) = -\frac{V_{initial}}{R} e^{-t/\tau}$
- **Full Charge/Discharge Time:**  $t_{full} \approx 5\tau$

#### Common Mistakes:

- Forgetting unit conversions (using k $\Omega$  or  $\mu$ F directly)
- Thinking charging is linear (it's exponential!)
- Confusing charging percentages (63%) with discharging (37%)
- Assuming capacitor fully charges at  $1\tau$  (actually only 63%)
- Not accounting for  $5\tau$  total time in timing circuits

## RC Circuits: Charging, Discharging, and Signal Filtering

### TL;DR (The Gist)

- **Square Wave Input:** Capacitor charges/discharges repeatedly
- **If pulse width  $\gg 5\tau$ :** Full charge/discharge, output looks like input
- **If pulse width  $\ll 5\tau$ :** Partial charge/discharge, output smoothed/filtered
- **Low-Pass Filter:** Passes low frequencies, blocks high frequencies.  $f_c = \frac{1}{2\pi RC}$

### Detailed Explanation

## 2. Detailed Explanation

### RC Circuit Response to Square Waves:

#### The setup:

- RC circuit (resistor + capacitor in series)
- Input: Square wave (alternates between high and low)
- Output: Voltage across capacitor
- Behavior depends on relationship between pulse width and time constant

#### Case 1: Pulse Width $\gg 5\tau$ (Long Pulses)

##### What happens:

- Pulse duration much longer than 5 time constants
- Capacitor has enough time to fully charge (during high)
- Capacitor has enough time to fully discharge (during low)
- Output voltage closely follows input square wave
- Nearly perfect square wave at output

##### Example:

- $\tau = 1$  ms, Pulse width = 50 ms ( $50\tau$ )
- Capacitor charges fully in first 5 ms
- Stays charged for remaining 45 ms of pulse
- Then discharges fully when pulse goes low
- Output: Clean square wave

#### Case 2: Pulse Width $\approx 5\tau$ (Matched Pulses)

##### What happens:

- Pulse duration approximately equals 5 time constants
- Capacitor just barely reaches full charge/discharge
- Output shows exponential curves
- Visible charging/discharging slopes
- Output resembles classic RC waveform

##### Example:

- $\tau = 10$  ms, Pulse width = 50 ms ( $5\tau$ )

- Capacitor charges to 99% during high pulse
- Then immediately starts discharging
- Output: Exponential rise and fall visible

### Case 3: Pulse Width $\approx 2\tau$ (Medium Pulses)

#### What happens:

- Pulse duration about 2 time constants
- Capacitor only charges to 86% during high
- Capacitor only discharges to 13% during low
- Output voltage range reduced compared to input
- Clear exponential charging/discharging curves

#### Example:

- Input: 0V to 5V square wave
- $\tau = 10$  ms, Pulse width = 20 ms ( $2\tau$ )
- Capacitor charges to:  $5 \times 0.865 = 4.33$  V
- Then discharges to:  $4.33 \times 0.135 = 0.58$  V
- Output swings: 0.58V to 4.33V (reduced from 0V-5V)

### Case 4: Pulse Width $\ll 5\tau$ (Short Pulses)

#### What happens:

- Pulse duration much shorter than 5 time constants
- Capacitor doesn't have time to charge or discharge significantly
- Output voltage stays relatively constant
- Only small ripple around average value
- Acts as filter - removes fast changes

#### Example:

- Input: 0V to 5V square wave, 50% duty cycle
- $\tau = 100$  ms, Pulse width = 1 ms ( $0.01\tau$ )
- Capacitor barely charges/discharges
- Output: Approximately 2.5V DC with tiny ripple
- Square wave "smoothed" to nearly constant voltage

### RC Low-Pass Filter:

#### What is a low-pass filter?

- Passes low frequencies (lets them through)
- Blocks (attenuates) high frequencies
- RC circuit acts as low-pass filter naturally
- Output taken across capacitor

#### How it works:

- **Low frequencies:** Long period, capacitor has time to charge/discharge, follows input
- **High frequencies:** Short period, capacitor can't respond fast enough, output attenuated
- Cutoff frequency ( $f_c$ ): Frequency where signal reduced to 70.7% (-3 dB)

#### Cutoff frequency formula:

- $f_c = \frac{1}{2\pi RC}$  (in Hz)
- Where R in  $\Omega$ , C in F
- This is the -3 dB point
- Below  $f_c$ : Most signal passes
- Above  $f_c$ : Signal increasingly attenuated

#### Filter Response Characteristics:

##### Frequency below cutoff ( $f < f_c$ ):

- Signal passes with minimal attenuation
- Output amplitude  $\approx$  input amplitude
- Capacitor reactance high compared to signal period

##### Frequency at cutoff ( $f = f_c$ ):

- Signal amplitude reduced to 70.7% (0.707)
- This is -3 dB attenuation
- Power reduced to half (-3 dB = half power)
- Capacitive reactance equals resistance:  $X_C = R$

##### Frequency above cutoff ( $f > f_c$ ):

- Signal increasingly attenuated

- Higher frequency  $\rightarrow$  more attenuation
- Roll-off: -20 dB per decade ( $10\times$  frequency)
- At  $10\times f_c$ : Output is 1/10th of input

### Practical Filtering Applications:

#### Removing high-frequency noise:

- Desired signal: Low frequency (e.g., audio, DC with ripple)
- Unwanted noise: High frequency (e.g., switching noise, RF interference)
- Design filter with  $f_c$  above desired signal, below noise
- RC filter passes signal, blocks noise

#### Example - Power supply filtering:

- DC power with 100 kHz switching noise
- Want to remove noise, keep DC
- Choose  $f_c = 1$  kHz (well below noise frequency)
- If  $R = 10\ \Omega$ , need:  $C = \frac{1}{2\pi f_c R} = \frac{1}{2\pi \times 1000 \times 10} \approx 16\ \mu\text{F}$
- 100 kHz noise attenuated by factor of 100 (-40 dB)

#### Example - Audio filtering (removing bass):

- Remove frequencies below 200 Hz
- Use high-pass filter (output across R, not C!)
- Same  $f_c$  formula applies
- Choose  $C = 1\ \mu\text{F}$ , calculate R:  $R = \frac{1}{2\pi f_c C} = \frac{1}{2\pi \times 200 \times 10^{-6}} \approx 796\ \Omega$

### Duty Cycle Effects:

#### 50% duty cycle (symmetric square wave):

- Equal high and low times
- If pulse width  $\ll \tau$ : Output settles to average (half of input swing)
- If pulse width  $\approx \tau$ : Output oscillates symmetrically

#### Non-50% duty cycle:

- Unequal charge/discharge times
- Output DC level shifts
- Longer high time  $\rightarrow$  higher average output voltage
- Longer low time  $\rightarrow$  lower average output voltage

### Designing RC Circuits for Specific Response:

#### Want output to follow input (minimal filtering):

- Choose  $\tau \ll$  pulse width
- Rule of thumb:  $\tau < \frac{1}{10}$  of shortest pulse
- Ensures full charge/discharge

#### Want output smoothed (heavy filtering):

- Choose  $\tau \gg$  pulse width
- Rule of thumb:  $\tau > 10\times$  pulse width
- Capacitor can't respond to changes

#### Want visible charging curves (educational):

- Choose  $\tau \approx$  pulse width
- See exponential charging/discharging
- Useful for learning/demonstration

## Practical Examples & Numerical Calculations

### Example 1: Cutoff Frequency Calculation

Given:  $R = 1\ \text{k}\Omega$ ,  $C = 100\ \text{nF}$

Calculate cutoff frequency:

- $f_c = \frac{1}{2\pi RC} = \frac{1}{2\pi \times 1000 \times 100 \times 10^{-9}} \approx 1592\ \text{Hz} \approx 1.6\ \text{kHz}$
- $f_c = \frac{1}{2\pi \times 10^{-4}} = \frac{1}{6.28 \times 10^{-4}} \approx 1592\ \text{Hz} \approx 1.6\ \text{kHz}$

Response at different frequencies:

- At 100 Hz ( $< f_c$ ): Signal passes (minimal attenuation)
- At 1592 Hz ( $= f_c$ ): Signal reduced to 70.7%
- At 16 kHz ( $10 \times f_c$ ): Signal reduced to 10%

### Example 2: Designing Filter for Noise Removal

Requirement: Remove 50 kHz switching noise from DC signal

Choose cutoff well below noise:  $f_c = 5$  kHz ( $10\times$  lower than noise)

Select  $R = 100\ \Omega$  (low to avoid voltage drop)

Calculate required C:

- $C = \frac{1}{2\pi f_c R} = \frac{1}{2\pi \times 5000 \times 100}$
- $C = \frac{1}{3.14 \times 10^6} \approx 0.318\ \mu\text{F}$
- Use standard value:  $0.33\ \mu\text{F}$  or  $330\ \text{nF}$

Verify noise attenuation at 50 kHz:

- Noise is  $10\times$  above cutoff
- Attenuation: Approximately  $1/10$  or  $-20\ \text{dB}$
- If noise was  $1\text{V}$ , output noise  $\approx 0.1\text{V}$

### Example 3: Square Wave Response

Given:  $R = 10\ \text{k}\Omega$ ,  $C = 22\ \mu\text{F}$ , Input =  $0\text{-}5\text{V}$  square wave at  $10\ \text{Hz}$  ( $50\%$  duty)

Time constant:  $\tau = 10,000 \times 22 \times 10^{-6} = 0.22\ \text{s} = 220\ \text{ms}$

Square wave period:  $T = \frac{1}{10} = 0.1\ \text{s} = 100\ \text{ms}$

Pulse width ( $50\%$  duty):  $50\ \text{ms}$

Compare pulse width to time constant:

- Pulse width =  $50\ \text{ms}$
- $\tau = 220\ \text{ms}$
- Pulse width  $< \tau$  (actually  $0.23\tau$ )

Charging during  $50\ \text{ms}$  pulse:

- Time =  $0.23\tau$  (not even  $1\tau$ )
- Voltage reaches:  $5 \times (1 - e^{-0.23}) = 5 \times 0.205 \approx 1.03\text{V}$
- Only charges to  $20.5\%$  of  $5\text{V}$

Discharging during  $50\ \text{ms}$  low:

- Starting from  $1.03\text{V}$
- Discharges for  $0.23\tau$
- Voltage drops to:  $1.03 \times e^{-0.23} = 1.03 \times 0.795 \approx 0.82\text{V}$

Result:

- Output oscillates between  $0.82\text{V}$  and  $1.03\text{V}$  (small ripple!)
- Input was  $0\text{-}5\text{V}$ , but output only varies by  $0.21\text{V}$
- Heavily filtered/smoothed

### Example 4: Fast Square Wave (High Frequency)

Given: Same circuit ( $R = 10\ \text{k}\Omega$ ,  $C = 22\ \mu\text{F}$ ,  $\tau = 220\ \text{ms}$ )

Input:  $0\text{-}5\text{V}$  square wave at  $100\ \text{Hz}$  (period =  $10\ \text{ms}$ , pulse width =  $5\ \text{ms}$ )

Compare: Pulse width =  $5\ \text{ms} = 0.023\tau$  (very short!)

Charging during  $5\ \text{ms}$ :

- $V_C = 5 \times (1 - e^{-0.023}) = 5 \times 0.023 \approx 0.11\text{V}$
- Barely charges at all!

Result:

- Output voltage nearly constant
- Tiny ripple around  $2.5\text{V}$  (average of  $0\text{-}5\text{V}$ )
- $100\ \text{Hz}$  signal completely filtered out
- Acts as smoothing capacitor

### Example 5: Matching Time Constant to Pulse

Requirement: Want to see clear RC charging curve on oscilloscope

Input:  $1\ \text{kHz}$  square wave (period =  $1\ \text{ms}$ , pulse width =  $0.5\ \text{ms}$ )

Design for  $5\tau =$  pulse width:

- $5\tau = 0.5\ \text{ms}$
- $\tau = 0.1\ \text{ms} = 100\ \mu\text{s}$

Choose  $C = 10\ \text{nF}$ , calculate  $R$ :

- $R = \frac{\tau}{C} = \frac{100 \times 10^{-6}}{10 \times 10^{-9}} = 10,000\ \Omega = 10\ \text{k}\Omega$

Verification:

- $\tau = 10,000 \times 10 \times 10^{-9} = 100\ \mu\text{s} \checkmark$
- During  $0.5\ \text{ms}$  pulse, capacitor charges for  $5\tau \rightarrow$  reaches  $99\%$
- Clear exponential curve visible on scope

### Example 6: Audio Low-Pass Filter

Application: Remove high-frequency hiss above  $5\ \text{kHz}$

Choose cutoff:  $f_c = 5 \text{ kHz}$

Select  $C = 47 \text{ nF}$  (standard audio capacitor value)

Calculate  $R$ :

- $R = \frac{1}{2\pi f_c C} = \frac{1}{2\pi \times 5000 \times 47 \times 10^{-9}}$
- $R = \frac{1}{1.476 \times 10^{-3}} \approx 677 \Omega$
- Use standard value:  $680 \Omega$

Performance:

- Below  $5 \text{ kHz}$ : Audio passes clearly
- At  $5 \text{ kHz}$ :  $-3 \text{ dB}$  (barely noticeable)
- At  $50 \text{ kHz}$ :  $-20 \text{ dB}$  ( $1/10$ th amplitude, noise greatly reduced)

#### Example 7: Power Supply Ripple Filtering

Given:  $12\text{V DC}$  with  $120 \text{ Hz}$  ripple (from full-wave rectifier)

Want: Reduce ripple below  $100 \text{ mV}$

Choose cutoff:  $f_c = 12 \text{ Hz}$  ( $10\times$  below ripple frequency)

If  $R = 10 \Omega$  (low resistance to minimize voltage drop):

- $C = \frac{1}{2\pi \times 12 \times 10} = \frac{1}{754} \approx 1327 \mu\text{F}$
- Use standard value:  $1500 \mu\text{F}$  or  $2200 \mu\text{F}$  electrolytic

Attenuation at  $120 \text{ Hz}$ :

- $120 \text{ Hz}$  is  $10\times$  above cutoff
- Attenuation:  $1/10$  ( $-20 \text{ dB}$ )
- If original ripple was  $1\text{V}$ , filtered ripple  $\approx 100 \text{ mV}$  ✓

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

1. **Square Wave Response:** Depends on pulse width vs. time constant ( $\tau$ )
2. **Pulse  $\gg 5\tau$ :** Full charge/discharge, output follows input
3. **Pulse  $\ll 5\tau$ :** Partial charge/discharge, output smoothed
4. **Low-Pass Filter:** RC circuit naturally filters high frequencies
5. **Cutoff Frequency:**  $f_c = \frac{1}{2\pi RC}$  ( $-3 \text{ dB}$  point,  $70.7\%$  amplitude)
6. **Filter Response:**
  - Below  $f_c$ : Signal passes
  - At  $f_c$ :  $-3 \text{ dB}$  ( $70.7\%$ )
  - Above  $f_c$ :  $-20 \text{ dB/decade}$  roll-off
7. **Applications:** Noise filtering, smoothing, signal conditioning
8. **Design Trade-off:** Larger  $\tau$  = better filtering but slower response

#### Interview Questions:

- **Q:** What happens when square wave pulse is much shorter than time constant?  
**A:** Capacitor doesn't have time to charge significantly. Output becomes smooth DC with tiny ripple (filtering effect).
- **Q:** What is cutoff frequency of RC low-pass filter?  
**A:**  $f_c = \frac{1}{2\pi RC}$ . Frequency where signal is attenuated to  $70.7\%$  ( $-3 \text{ dB}$ ).
- **Q:** How does RC circuit filter high frequencies?  
**A:** At high frequencies, capacitor reactance is low, so signal shorted to ground through capacitor. Low frequencies have high reactance, so signal passes.
- **Q:** What is roll-off rate of RC filter?  
**A:**  $-20 \text{ dB per decade}$ . At  $10\times$  cutoff frequency, signal is  $1/10$ th amplitude.
- **Q:** How to design filter to remove  $50 \text{ kHz}$  noise?  
**A:** Choose cutoff well below  $50 \text{ kHz}$  (e.g.,  $5 \text{ kHz}$ ), then calculate  $R$  and  $C$  using  $f_c = \frac{1}{2\pi RC}$ .

#### Formulas:

- **Cutoff Frequency:**  $f_c = \frac{1}{2\pi RC}$
- **Component from Cutoff:**  $C = \frac{1}{2\pi f_c R}$  or  $R = \frac{1}{2\pi f_c C}$
- **Time Constant:**  $\tau = RC = \frac{1}{2\pi f_c}$

#### Applications:

- Power supply noise filtering
- Audio tone controls (bass/treble)

- Anti-aliasing filters (before ADC)
- Smoothing rectified AC to DC
- Debouncing switches (removing bounce noise)

## Application Examples: Timing Circuits and Comparators

### TL;DR (The Gist)

- **Time Delay Circuit:** RC charges, CMOS buffer switches at threshold → pulse delay
- **Timer with Comparator:** Button charges cap, comparator output high until cap discharges below reference
- **Comparator:** Compares two voltages, output goes high/low based on which input is higher
- Real-world applications: Delays, timers, pulse shaping, automatic control

### Detailed Explanation

## 2. Detailed Explanation

### Application 1: Time Delay Circuit with CMOS Buffer

#### Circuit description:

- Input: Pulse (step voltage)
- RC charging circuit
- CMOS buffer (digital IC) connected after RC
- Output: Delayed pulse

#### What is a CMOS buffer?

- Digital component (pair of transistors)
- High input impedance (draws very little current)
- Low output impedance (can drive loads)
- Acts as current amplifier (voltage stays same)
- Requires external power supply (active device)
- Symbol: Triangle

#### CMOS buffer switching behavior:

- Has a threshold voltage (typically 50% of supply)
- When input below threshold: Output = LOW (0V)
- When input above threshold: Output = HIGH ( $V_{supply}$ )
- Switches quickly between states
- Gradual input → sharp output transition

#### How the time delay works:

##### Point A (input):

- Sharp rising edge (pulse)
- Goes from 0V to  $V_{supply}$  instantly

##### Point B (after RC):

- Capacitor charging voltage
- Exponential rise from 0V to  $V_{supply}$
- Takes  $5\tau$  to fully charge
- Smooth, curved waveform

##### Point C (CMOS buffer output):

- Stays LOW until Point B reaches threshold
- When threshold crossed: Switches HIGH abruptly
- Output pulse delayed by time it takes to reach threshold
- Sharp edges (even though input was gradual)

#### Calculating the delay:

- If threshold = 50% of  $V_{supply}$
- Capacitor reaches 50% at approximately  $0.7\tau$
- Delay time  $\approx 0.7 \times R \times C$
- Can adjust delay by changing R or C

### Why use this circuit?

- Creates time delay between events
- Allows one action to complete before another starts
- Pulse shaping (converts slow rise to sharp edge)
- Clock delay in digital circuits

### Application 2: One-Shot Timer with Comparator

#### What is a comparator?

- Integrated circuit (IC)
- Two inputs: (+) non-inverting, (-) inverting
- One output
- Powered by  $V+$  (positive supply) and ground
- Symbol: Triangle with + and - inputs

#### How comparator works:

- Compares voltage at (+) input to voltage at (-) input
- If (+) > (-): Output = HIGH ( $V+$ )
- If (+) < (-): Output = LOW (ground)
- Switches very quickly
- Draws negligible current from inputs (high impedance)
- Can source/sink 20 mA at output

#### One-shot timer circuit description:

##### Components:

- Voltage divider (two resistors): Sets reference voltage
- Capacitor: Stores charge for timing
- Resistor in series with cap: Controls discharge rate
- Push button: Triggers timer
- Comparator: Monitors capacitor voltage

##### Reference voltage (at - input):

- Created by voltage divider
- Constant voltage (e.g., 37% of  $V+ = 1.8V$  for 5V supply)
- Stays fixed throughout operation
- This is the comparison threshold

##### Operation sequence:

###### 1. Initial state (idle):

- Capacitor fully discharged (0V)
- (+) input at 0V
- (-) input at reference (1.8V)
- Since (+) < (-): Output = LOW (ground)

###### 2. Button pressed momentarily:

- Capacitor charges quickly to  $V+$  (5V) through button
- Button released
- (+) input now at 5V
- (-) input still at 1.8V
- Since (+) > (-): Output switches to HIGH (5V)

###### 3. Timing phase (button released):

- Capacitor discharges through resistor
- Exponential decay:  $V_C(t) = 5 \times e^{-t/\tau}$
- Time constant:  $\tau = R \times C$
- Output stays HIGH while  $V_C > 1.8V$

###### 4. Timeout (end of timing):

- Capacitor voltage drops below 1.8V (reference)
- (+) input now < (-) input
- Comparator output switches back to LOW
- Circuit ready for next trigger

#### Calculating the timeout duration:

##### Voltage equation during discharge:

- $V_C(t) = V_{initial} \times e^{-t/\tau}$

- Where  $V_{initial} = 5V$ ,  $V_{reference} = 1.8V$

**Find time when  $V_C = 1.8V$ :**

- $1.8 = 5 \times e^{-t/\tau}$
- $\frac{1.8}{5} = e^{-t/\tau}$
- $0.36 = e^{-t/\tau}$
- Taking natural log:  $\ln(0.36) = -\frac{t}{\tau}$
- $-1.02 = -\frac{t}{\tau}$
- $t = 1.02\tau$

**Timeout =  $1.02\tau = 1.02 \times R \times C$**

**Example:**

- Want 1-minute (60 second) timeout
- Choose  $C = 1000 \mu F$
- $R = \frac{60}{1.02 \times 0.001} = 58,800 \Omega \approx 56 k\Omega$  or  $62 k\Omega$

**Why different voltages give different timeout formulas?**

**For 37% reference (1 time constant):**

- $V_{ref} = 0.37 \times V_{initial}$
- Timeout exactly =  $1\tau$  (by definition of time constant!)

**For 36% reference (like 1.8V/5V):**

- $V_{ref} = 0.36 \times V_{initial}$
- Timeout  $\approx 1.02\tau$  (slightly longer)

**For 13.5% reference:**

- Timeout =  $2\tau$

**For 5% reference:**

- Timeout =  $3\tau$

**Practical considerations:**

**Advantages of this timer:**

- Simple circuit (few components)
- Easily adjustable (change R or C)
- Repeatable (consistent timing)
- One-shot operation (single pulse per trigger)

**Limitations:**

- Not precise (component tolerances  $\pm 10\text{-}20\%$ )
- Temperature affects R and C values
- Comparator has small offset voltage (error)
- For precision timing, use crystal oscillator or timer IC (555)

**Improvements:**

- Use precision resistors and capacitors ( $\pm 1\%$ )
- Temperature-stable components
- Add potentiometer for fine adjustment
- Use precision comparator (lower offset)

**Real-World Applications:**

**Time delay circuits:**

- Turn on light 5 seconds after switch pressed
- Delay relay activation
- Staircase timer (light stays on for fixed time)
- Camera flash recovery time

**One-shot timers:**

- Automatic shutoff (e.g., bathroom fan runs for 10 min after switch off)
- Timeout alarms
- Monostable circuits
- Pulse width generation

**Pulse shaping:**

- Convert slow-rising signal to sharp edge
- Debounce mechanical switches
- Generate clock signals
- Digital signal conditioning

**Advanced Concept: Why Not Use Tricks Too Often?**

**The statement from source:**

- "You try not too often to rely on tricks like this"
- Referring to RC delay tricks

#### Why be cautious?

- Component tolerances cause timing variation
- Temperature changes affect timing
- Aging changes component values
- Not as reliable as crystal-based timing
- Hard to make very precise or very long delays

#### When RC timing IS appropriate:

- Short delays (microseconds to seconds)
- Precision not critical ( $\pm 10\text{-}20\%$  acceptable)
- Low-cost requirement
- Simple implementation needed
- Occasional/non-critical use

#### When to use better alternatives:

- Need precision timing: Use crystal oscillator + counter
- Long delays (minutes/hours): Use timer IC (e.g., 555) or microcontroller
- Critical timing: Use dedicated timer chip
- Programmable delays: Use microcontroller

## Practical Examples & Numerical Calculations

### Example 1: CMOS Buffer Time Delay

Circuit:  $R = 10\text{ k}\Omega$ ,  $C = 100\text{ }\mu\text{F}$ , Buffer threshold =  $2.5\text{ V}$  (50% of  $5\text{ V}$ )

Time constant:  $\tau = 10,000 \times 100 \times 10^{-6} = 1\text{ second}$

Find delay time (time to reach  $2.5\text{ V}$ ):

Using charging equation:  $V_C(t) = 5(1 - e^{-t/\tau})$

Set  $V_C = 2.5\text{ V}$ :

- $2.5 = 5(1 - e^{-t/1})$
- $0.5 = 1 - e^{-t}$
- $e^{-t} = 0.5$
- $-t = \ln(0.5) = -0.693$
- $t = 0.693\text{ seconds} \approx 0.7\tau$

Delay  $\approx 0.7\text{ seconds}$

### Example 2: Adjusting Delay Time

Want 5-second delay, buffer threshold still 50%

From Example 1: Delay =  $0.7\tau$

Required:  $0.7\tau = 5\text{ seconds}$

Solve for  $\tau$ :  $\tau = \frac{5}{0.7} = 7.14\text{ seconds}$

Choose  $C = 470\text{ }\mu\text{F}$ , find  $R$ :

- $R = \frac{\tau}{C} = \frac{7.14}{470 \times 10^{-6}} = 15,190\text{ }\Omega$
- Use standard value:  $15\text{ k}\Omega$

Verification:

- $\tau = 15,000 \times 470 \times 10^{-6} = 7.05\text{ s}$
- Delay =  $0.7 \times 7.05 = 4.94\text{ s} \approx 5\text{ s} \checkmark$

### Example 3: One-Shot Timer (1 Minute)

Requirement: Output HIGH for 60 seconds after button press

Reference voltage: 37% of  $V_+$  (for simple  $1\tau$  timeout)

Design:

- Timeout =  $1\tau = 60\text{ seconds}$
- Choose  $C = 1000\text{ }\mu\text{F}$  (large, but reasonable)
- $R = \frac{60}{0.001} = 60,000\text{ }\Omega = 60\text{ k}\Omega$

Voltage divider for 37% reference (assuming  $5\text{ V}$  supply):

- $V_{ref} = 0.37 \times 5 = 1.85\text{ V}$
- If  $R_1 = 10\text{ k}\Omega$  (top),  $R_2 = ?$  (bottom)
- $\frac{R_2}{R_1 + R_2} = 0.37$

- $R_2 = \frac{0.37 \times 10k}{1-0.37} = 5.87 \text{ k}\Omega$
- Use 5.6 k $\Omega$  or 6.2 k $\Omega$

Operation:

- Button pressed: Cap charges to 5V, output goes HIGH
- Cap discharges: After 60s reaches 1.85V, output goes LOW

#### Example 4: Timer with Different Reference

Given:  $R = 47 \text{ k}\Omega$ ,  $C = 1000 \mu\text{F}$ ,  $V_+ = 5\text{V}$

Voltage divider creates:  $V_{ref} = 1.8\text{V}$  (36% of 5V)

Calculate timeout:

Using discharge equation:  $1.8 = 5 \times e^{-t/\tau}$

Solve:

- $\frac{1.8}{5} = 0.36 = e^{-t/\tau}$
- $\ln(0.36) = -1.02 = -\frac{t}{\tau}$
- $t = 1.02\tau$

Time constant:  $\tau = 47,000 \times 0.001 = 47 \text{ seconds}$

Timeout:  $t = 1.02 \times 47 = 47.94 \text{ seconds} \approx 48 \text{ seconds}$

#### Example 5: Comparator Voltage Calculation

Comparator circuit with  $V_+ = 12\text{V}$

Voltage divider:  $R_1 = 10 \text{ k}\Omega$ ,  $R_2 = 4.7 \text{ k}\Omega$

Calculate reference voltage:

- $V_{ref} = V_+ \times \frac{R_2}{R_1 + R_2}$
- $V_{ref} = 12 \times \frac{4700}{10000 + 4700}$
- $V_{ref} = 12 \times \frac{4700}{14700} = 12 \times 0.32 = 3.84\text{V}$

Comparator behavior:

- When (+) input  $> 3.84\text{V}$ : Output = 12V (HIGH)
- When (+) input  $< 3.84\text{V}$ : Output = 0V (LOW)

#### Example 6: Designing for Specific Timeout with Custom Reference

Requirement: 30-second timeout, reference at 20% of  $V_+$

Find timeout multiplier for 20% (0.2):

- $0.2 = e^{-t/\tau}$
- $\ln(0.2) = -1.61 = -\frac{t}{\tau}$
- $t = 1.61\tau$

For 30-second timeout:

- $1.61\tau = 30$
- $\tau = \frac{30}{1.61} = 18.6 \text{ seconds}$

Choose  $C = 470 \mu\text{F}$ :

- $R = \frac{18.6}{470 \times 10^{-6}} = 39,574 \Omega$
- Use 39 k $\Omega$  or 43 k $\Omega$

#### Example 7: Comparing Different Reference Voltages

Same RC:  $\tau = 10 \text{ seconds}$

Different reference voltages:

50% reference:

- Timeout =  $0.69\tau = 6.9 \text{ seconds}$

37% reference:

- Timeout =  $1.0\tau = 10 \text{ seconds}$

20% reference:

- Timeout =  $1.61\tau = 16.1 \text{ seconds}$

10% reference:

- Timeout =  $2.3\tau = 23 \text{ seconds}$

Lower reference  $\rightarrow$  longer timeout (capacitor takes longer to discharge to lower voltage)

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

1. **CMOS Buffer:** High input Z, low output Z, switches at threshold voltage
2. **Time Delay:** RC charges, buffer switches when threshold reached
3. **Delay Calculation:** For 50% threshold, delay  $\approx 0.7\tau$

4. **Comparator:** Compares (+) and (-) inputs, output HIGH if (+)>(-)
5. **One-Shot Timer:** Button charges cap, discharges through R, output HIGH until below reference
6. **Timeout Formula:** Depends on reference voltage percentage
  - 37% reference:  $\text{Timeout} = 1\tau$
  - 50% reference:  $\text{Timeout} = 0.69\tau$
  - Custom: Solve  $V_{ref}/V_{initial} = e^{-t/\tau}$
7. **Voltage Divider:** Creates fixed reference for comparator (-) input
8. **Limitations:** Component tolerance, temperature, not for precision timing

#### Interview Questions:

- **Q:** How does CMOS buffer create sharp output from gradual input?  
 A: Buffer has threshold. Below threshold = LOW, above = HIGH. Switches quickly even if input rises slowly.
- **Q:** How does comparator work?  
 A: Compares two inputs. If (+) input greater than (-) input, output goes HIGH. Otherwise LOW.
- **Q:** How to create 1-minute timer with RC and comparator?  
 A: Set  $\tau = RC = 60\text{s}$  (for 37% reference). Button charges cap, then discharges through R. Output HIGH until voltage drops below reference.
- **Q:** Why set reference at 37%?  
 A: 37% is the voltage remaining after  $1\tau$  during discharge. Makes timeout exactly equal to time constant.
- **Q:** What's the purpose of voltage divider in timer circuit?  
 A: Creates fixed reference voltage for comparator (-) input. Determines when timer expires.
- **Q:** Can RC timing be very precise?  
 A: No. Component tolerances ( $\pm 10\text{-}20\%$ ), temperature effects, aging cause variation. Use for non-critical timing only.

#### Formulas:

- **Delay (50% threshold):**  $t_{delay} \approx 0.69\tau = 0.69RC$
- **Timeout (37% reference):**  $t_{timeout} = 1.0\tau = RC$
- **General Timeout:** Solve  $\frac{V_{ref}}{V_{initial}} = e^{-t/\tau} \rightarrow t = -\tau \ln\left(\frac{V_{ref}}{V_{initial}}\right)$
- **Voltage Divider:**  $V_{ref} = V + \times \frac{R_2}{R_1 + R_2}$

#### Applications:

- Automatic shutoff timers (lights, fans)
- Delay circuits (relay activation)
- Pulse shaping (convert slow to fast edge)
- Debouncing (remove switch bounce)
- Monostable multivibrators
- Timeout alarms

#### Component Notes:

- **CMOS Buffer:** Examples: 74HC04, CD4050, 74HCT14 (Schmitt trigger)
- **Comparator:** Examples: LM311, LM393, LM339
- Comparator  $\neq$  Op-amp (though op-amp can work as comparator in simple cases)
- Op-amp covered in detail later in course

# Section 10 – Inductors

## Inductor – Introduction

TL;DR (The Gist)

- **Construction:** Coil of wire (solenoid) that creates magnetic field
- **Inductance:** L in Henries (H), typically  $\mu\text{H}$  or  $\text{mH}$
- **Opposes current changes:**  $V = L \frac{dI}{dt}$  (voltage proportional to rate of current change)
- **Dual of capacitor:** Stores energy in magnetic field, opposes current changes (C opposes voltage changes)

### Detailed Explanation

#### 2. Detailed Explanation

**What is an Inductor?**

**Physical construction:**

- Simple length of wire coiled up
- Coil shape called solenoid
- Current through wire creates magnetic field
- Coil amplifies magnetic field strength
- Symbol shows coil loops (lines = core material)

**Why coil shape?**

- Straight wire: Weak magnetic field (negligible unless mega-amps)
- Coiled wire: Magnetic fields from each loop add up
- Result: Much stronger total magnetic field
- More turns = stronger field

**Inductance – The Key Property:**

**Self-induction mechanism:**

1. Voltage applied  $\rightarrow$  current flows  $\rightarrow$  magnetic field created
2. Changing magnetic field  $\rightarrow$  induces voltage back (Lenz's Law)
3. Induced voltage (back EMF) opposes the change
4. Result: Current cannot change rapidly!

**Inductor equation:**

- $V_L = L \frac{dI}{dt}$
- Voltage across inductor proportional to rate of current change
- Fast current change  $\rightarrow$  large voltage
- Steady current ( $dI/dt=0$ )  $\rightarrow$  zero voltage

**Inductor vs. Capacitor (Dual Relationship):**

Property	Capacitor	Inductor
Stores energy in	Electric field	Magnetic field
Opposes changes in	Voltage	Current
Key equation	$I = C \frac{dV}{dt}$	$V = L \frac{dI}{dt}$
Energy formula	$E = \frac{1}{2} C V^2$	$E = \frac{1}{2} L I^2$
DC behavior	Blocks (open)	Passes (wire)
AC behavior	Passes (low $X_C$ )	Blocks (high $X_L$ )
Phase shift	I leads V by $90^\circ$	V leads I by $90^\circ$

**Behavior in Circuits:**

**DC circuit (constant current):**

- Initially: High voltage, zero current (opposes change)
- Gradually: Current rises exponentially
- Eventually: Acts like wire (zero resistance)
- Final state:  $V_L = 0$ , current limited only by R

**AC circuit (changing current):**

- Continuously opposes current changes
- Creates inductive reactance  $X_L = 2\pi fL$
- Higher frequency  $\rightarrow$  higher opposition
- Useful in filters, transformers, RF circuits

#### Inductance Unit:

##### Henry (H):

- Named after Joseph Henry
- $1 \text{ H} = 1 \text{ V}\cdot\text{s}/\text{A}$  (volt-second per ampere)
- Henry is very large unit
- Practical: mH ( $10^{-3} \text{ H}$ ),  $\mu\text{H}$  ( $10^{-6} \text{ H}$ ), nH ( $10^{-9} \text{ H}$ )

##### Typical ranges:

- nH: RF circuits, chip inductors
- $\mu\text{H}$ : Switching converters, filters (1-1000  $\mu\text{H}$ )
- mH: Audio equipment, power supplies
- H: Large transformers, electromagnets

#### Where Inductors are Used:

##### Applications:

- Transformers (voltage conversion)
- Filters (with capacitors)
- Energy storage (switching regulators)
- RF circuits (tuning, matching)
- EMI suppression (chokes)
- Motors and solenoids

## Practical Examples & Numerical Calculations

### Example 1: Voltage Across Inductor During Current Change

Given:  $L = 10 \text{ mH}$ , current rises from 0 to 1A in 0.1 seconds (linear)

Calculate voltage:

- $\frac{dI}{dt} = \frac{1\text{A}-0\text{A}}{0.1\text{s}} = 10 \text{ A/s}$
- $V_L = L \frac{dI}{dt} = 0.01 \times 10 = 0.1 \text{ V} = 100 \text{ mV}$

If same change in 0.01s (10 $\times$  faster):

- $\frac{dI}{dt} = 100 \text{ A/s}$
- $V_L = 0.01 \times 100 = 1 \text{ V}$  (10 $\times$  higher!)

### Example 2: Steady Current (DC)

Given:  $L = 50 \mu\text{H}$ , constant DC current  $I = 2\text{A}$

Calculate voltage:

- $\frac{dI}{dt} = 0$  (steady current, no change)
- $V_L = L \times 0 = 0 \text{ V}$
- Inductor acts like wire in DC steady state!

### Example 3: Energy Stored in Inductor

Given:  $L = 100 \text{ mH}$ ,  $I = 500 \text{ mA}$

Energy formula:  $E = \frac{1}{2}LI^2$

Calculate:

- $E = \frac{1}{2} \times 0.1 \times (0.5)^2$
- $E = 0.05 \times 0.25 = 0.0125 \text{ J} = 12.5 \text{ mJ}$

Double current to 1A:

- $E = \frac{1}{2} \times 0.1 \times 1^2 = 0.05 \text{ J} = 50 \text{ mJ}$
- Energy quadruples ( $E \propto I^2$ )!

### Example 4: Comparison with Capacitor

Capacitor:  $C = 100 \mu\text{F}$ ,  $V = 5\text{V}$

- Energy:  $E_C = \frac{1}{2} \times 0.0001 \times 25 = 1.25 \text{ mJ}$
- Stores energy in electric field between plates

Inductor:  $L = 100 \text{ mH}$ ,  $I = 50 \text{ mA}$

- Energy:  $E_L = \frac{1}{2} \times 0.1 \times 0.0025 = 0.125 \text{ mJ}$

- Stores energy in magnetic field around coil
- Different energy storage mechanism, similar component size!

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

1. **Construction:** Coil of wire (solenoid), creates magnetic field
2. **Opposes current changes:**  $V_L = L \frac{dI}{dt}$  (fundamental equation)
3. **DC behavior:** Eventually acts like wire ( $V_L = 0$  at steady state)
4. **AC behavior:** Continuously opposes  $\rightarrow$  creates reactance
5. **Energy storage:**  $E = \frac{1}{2}LI^2$  in magnetic field
6. **Unit:** Henry (H), typically  $\mu\text{H}$  or  $\text{mH}$  in practice
7. **Dual of capacitor:**
  - Capacitor: Opposes V changes, stores in E-field
  - Inductor: Opposes I changes, stores in B-field

#### Interview Questions:

- **Q:** What is an inductor?  
A: Coil of wire that stores energy in magnetic field and opposes changes in current.
- **Q:** Why does inductor oppose current changes?  
A: Changing current creates changing magnetic field, which induces voltage (back EMF) that opposes the change (Lenz's Law).
- **Q:** How does inductor behave in DC vs AC?  
A: DC steady state: acts like wire (zero V). AC: opposes with reactance, blocks high frequencies.
- **Q:** What's the difference between inductor and capacitor?  
A: Inductor opposes current changes/stores in magnetic field. Capacitor opposes voltage changes/stores in electric field.

#### Formulas:

- **Voltage:**  $V_L = L \frac{dI}{dt}$
- **Energy:**  $E = \frac{1}{2}LI^2$
- **Reactance:**  $X_L = 2\pi fL$  (covered in detail later)

## Types of Inductors & Construction

### TL;DR (The Gist)

- **Inductance formula:**  $L = \frac{\mu N^2 A}{l}$  (permeability, turns, area, length)
- **Air core:** Low L ( $\mu\text{H}$  range), RF circuits, high frequency
- **Iron core:** High L ( $\text{mH-H}$ ), transformers, audio, low frequency
- **Ferrite core:** Most common, adjustable permeability, gray/black color

### Detailed Explanation

### 2. Detailed Explanation

#### Inductance Formula:

$L = \frac{\mu N^2 A}{l}$  where:

- L = inductance (H)
- $\mu = \mu_0 \mu_r$  (permeability) - how easily magnetic field forms
- N = number of turns
- A = cross-sectional area ( $\text{m}^2$ )
- l = length of coil (m)

#### Increasing inductance:

- More turns ( $N^2!$ )  $\rightarrow$  much higher L

- Larger area  $\rightarrow$  higher L
- Shorter length  $\rightarrow$  higher L
- Higher permeability core  $\rightarrow$  higher L

#### Air Core Inductors:

- Core material: Air ( $\mu_r \approx 1$ , low permeability)
- Low inductance (typically  $\leq 5 \mu\text{H}$ )
- Fast current rise time
- High frequency capable (MHz-GHz)
- Applications: RF circuits, oscillators, antennas
- No core losses, no saturation

#### Iron Core Inductors:

- Core material: Iron ( $\mu_r = 200-5000$ )
- High inductance (mH to H range)
- Large, heavy construction
- Low frequency use (50/60 Hz power)
- Applications: Transformers, audio equipment, filters
- Core losses at high frequency (eddy currents, hysteresis)

#### Ferrite Core Inductors:

- Core: Iron oxide powder + epoxy resin
- Gray/black color, brittle material
- Most widely used type
- Permeability controllable (ratio of ferrite to epoxy)
- Medium inductance ( $\mu\text{H}$  to mH)
- Applications: Switching supplies, EMI filters, chokes
- Lower losses than iron at higher frequencies

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

1. **Formula:**  $L = \frac{\mu N^2 A}{l}$  - inductance proportional to turns squared
2. **Air core:** Low L, RF/high frequency
3. **Iron core:** High L, power/audio/transformers
4. **Ferrite core:** Most common, adjustable, versatile
5. **Core material:** Dramatically affects inductance ( $\mu_r$  factor)

**Interview Q:** *Q: Why use core materials?*

**A:** Increase permeability ( $\mu$ )  $\rightarrow$  much higher inductance in same physical size.

## Inductors in Series and Parallel

### TL;DR (The Gist)

- **Series:**  $L_{total} = L_1 + L_2 + L_3 + \dots$  (like resistors)
- **Parallel:**  $\frac{1}{L_{total}} = \frac{1}{L_1} + \frac{1}{L_2} + \dots$  (opposite of capacitors!)
- Inductors behave exactly opposite to capacitors in series/parallel

### Practical Examples

**Series:**  $10 \mu\text{H} + 15 \mu\text{H} = 25 \mu\text{H}$

**Parallel:** Two  $10 \mu\text{H} \rightarrow L = \frac{10 \times 10}{10 + 10} = 5 \mu\text{H}$

# Inductor Behavior in DC Circuit & RL Time Constant

## TL;DR (The Gist)

- **Initially:**  $V_L$  high,  $I=0$  (opposes sudden current)
- **Exponential rise:**  $I(t) = \frac{V}{R}(1 - e^{-t/\tau})$  where  $\tau = \frac{L}{R}$
- **After  $5\tau$ :** Acts like wire,  $I = V/R$
- Opposite behavior to capacitor (which starts with high I, zero V)

## Detailed Explanation

### 2. Detailed Explanation

#### RL Time Constant:

$\tau = \frac{L}{R}$  (in seconds)

#### Current rise (charging):

- At  $t=0$ :  $I=0$ ,  $V_L = V_{supply}$  (maximum)
- At  $t=1\tau$ :  $I=63\%$  of final
- At  $t=5\tau$ :  $I=99\%$  of final  $\approx V/R$

#### Current decay (discharging):

- At  $t=0$ :  $I = I_0$ ,  $V_L = -V$  (reverse polarity!)
- At  $t=1\tau$ :  $I=37\%$  remains
- At  $t=5\tau$ :  $I \approx 0$

- Direction unchanged (unlike capacitor)

**Energy storage:**  $E = \frac{1}{2}LI^2$  in magnetic field

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- **Time constant:**  $\tau = \frac{L}{R}$  (larger L or smaller R  $\rightarrow$  slower)
- **Opposes changes:** Resists sudden current changes
- **Steady DC:** Acts like wire ( $V_L = 0$ )
- **vs. Capacitor:**
  - Cap:  $\tau = RC$ , high I initially
  - Ind:  $\tau = L/R$ , high V initially

**Interview Q:** *Q: What happens when switch closes in RL circuit?*

A: Current rises exponentially from 0 to  $V/R$  over  $5\tau$ . Inductor opposes rapid change.

# Back EMF and Protection (Flyback Diode)

## TL;DR (The Gist)

- **Back EMF:** When current interrupted  $\rightarrow$  magnetic field collapses  $\rightarrow$  huge voltage spike
- **Danger:** Can destroy transistors/components (hundreds of volts!)
- **Solution:** Flyback diode in parallel (reverse biased normally)
- Critical for motors, relays, solenoids

## Detailed Explanation

### 2. Detailed Explanation

#### Back EMF Mechanism:

1. Current flowing  $\rightarrow$  magnetic field built up

2. Switch opens → current stops rapidly
3.  $dI/dt$  very large (fast change!)
4.  $V_L = L \frac{dI}{dt} \rightarrow$  huge voltage (kV possible!)
5. Polarity reversed (opposes current decrease)

#### Flyback Diode Protection:

**Connection:** Diode in parallel with inductor/motor, reverse biased

#### Normal operation (switch on):

- Diode reverse biased → no effect
- Current flows through inductor normally

#### Switch off (back EMF):

- Inductor polarity reverses
- Diode becomes forward biased
- Provides path for inductor current
- Energy dissipates safely through diode
- Voltage limited to 0.7V (diode drop)

#### Applications:

- DC motors (essential!)
- Relays and solenoids
- Inductive loads driven by transistors
- Any switching of inductive load

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

1. **Back EMF:** Collapsing field → large  $dI/dt \rightarrow$  huge voltage spike
2. **Danger:** Can exceed transistor breakdown voltage
3. **Flyback diode:** Reverse biased normally, conducts during spike
4. **Must use:** With motors, relays, any inductive switching
5. **Diode polarity:** Cathode to +supply, anode to ground (reverse of normal)

**Interview Q:** *Q: Why does turning off motor destroy transistor?*

A: Motor inductance creates huge back EMF spike when current interrupted. Flyback diode prevents this.

## Inductor in AC Circuit (Phase Relationship)

### TL;DR (The Gist)

- **Phase shift:** Voltage leads current by  $90^\circ$  (ELI mnemonic)
- **Opposite of capacitor:** Cap has I leads V, Inductor has V leads I
- **Reactive component:** Stores/releases energy each cycle
- Energy oscillates in magnetic field

### Detailed Explanation

#### 2. Detailed Explanation

##### $90^\circ$ Phase Shift Explanation:

##### ELI the ICE man mnemonic:

- **ELI:** In inductors (L), voltage (E) leads current (I)
- **ICE:** In capacitors (C), current (I) leads voltage (E)

##### Why voltage leads in inductor?

- $V_L = L \frac{dI}{dt}$  (voltage depends on rate of change)
- When I crosses zero:  $dI/dt$  is maximum →  $V_L$  is maximum
- When I is at peak:  $dI/dt$  is zero →  $V_L$  is zero
- Result:  $V_L$  peaks  $90^\circ$  before I peaks

##### Comparison table:

Property	Resistor	Inductor
Phase shift	0° (V and I together)	90° (V leads I)
Energy	Dissipated (heat)	Stored/released (no loss)
Frequency effect	None	Higher f → more opposition

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

1. **Phase:** Voltage leads current by 90° (ELI mnemonic)
2. **Reactive:** Stores energy, doesn't dissipate
3. **vs. Capacitor:** Opposite phase (ICE vs ELI)
4. **Application:** Phase shift circuits, power factor correction

**Interview Q:** *Q: What does "reactive" mean for inductor?*

**A:** Opposes current changes, stores energy in magnetic field, creates 90° phase shift. No real power dissipation.

## Inductive Reactance $X_L = 2\pi fL$

### TL;DR (The Gist)

- **Formula:**  $X_L = 2\pi fL$  (ohms)
- **Direct relationship:** Higher f → higher  $X_L$  (blocks HF)
- **DC (f=0):**  $X_L = 0$  (wire)
- **Opposite of capacitor:**  $X_C = \frac{1}{2\pi fC}$  decreases with f

### Detailed Explanation

#### 2. Detailed Explanation

##### Inductive Reactance:

$X_L = 2\pi fL$  where:

- $X_L$  = inductive reactance ( $\Omega$ )
- f = frequency (Hz)
- L = inductance (H)

##### Frequency dependence:

- **Low frequency:** Low  $X_L$  → passes easily
- **High frequency:** High  $X_L$  → blocks
- **DC (f=0):**  $X_L = 0$  → acts like wire
- **f→∞:**  $X_L \rightarrow \infty$  → open circuit

##### Comparison with capacitor:

Frequency	$X_C$	$X_L$
DC (0 Hz)	$\infty$ (blocks)	0 (passes)
Low freq	High (blocks)	Low (passes)
High freq	Low (passes)	High (blocks)

##### Impedance in RL circuit:

$Z = \sqrt{R^2 + X_L^2}$  (NOT  $R + X_L$ !)

##### Current calculation:

$$I = \frac{V_{rms}}{Z}$$

### Practical Examples

**Example 1:**  $L = 30 \text{ mH}$  at  $10 \text{ kHz}$

$$X_L = 2\pi \times 10000 \times 0.03 = 1885 \Omega$$

At  $1 \text{ kHz}$ :  $X_L = 188 \Omega$  ( $10\times$  lower frequency  $\rightarrow 10\times$  lower reactance)

**Example 2:**  $L = 400 \text{ mH}$ ,  $R = 200 \Omega$ ,  $f = 200 \text{ Hz}$

$$X_L = 2\pi \times 200 \times 0.4 = 502.4 \Omega$$

$$Z = \sqrt{200^2 + 502.4^2} = \sqrt{40000 + 252405} = 540.8 \Omega$$

$$\text{If } V = 5\text{V: } I_{rms} = \frac{5}{540.8} = 9.2 \text{ mA}$$

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

1. **Formula:**  $X_L = 2\pi fL$  (directly proportional to  $f$  and  $L$ )
2. **Frequency effect:** Higher  $f \rightarrow$  higher  $X_L \rightarrow$  more opposition
3. **DC behavior:**  $f=0 \rightarrow X_L = 0 \rightarrow$  inductor is wire
4. **vs. Capacitor:** Opposite frequency dependence
5. **Impedance:**  $Z = \sqrt{R^2 + X_L^2}$  (vector addition)

**Interview Q:** *Q: How does inductor behave at very low vs very high frequency?*

**A:** Low freq (DC):  $X_L \approx 0$ , acts like wire. High freq:  $X_L$  very high, blocks AC.

**Formulas:**

- $X_L = 2\pi fL = \omega L$
- $Z = \sqrt{R^2 + X_L^2}$
- $I = \frac{V}{Z}$

## Series RLC Resonance

### TL;DR (The Gist)

- **Resonance:**  $X_L = X_C$  (cancel out!),  $Z = R$  only (minimum)
- **Resonant frequency:**  $f_r = \frac{1}{2\pi\sqrt{LC}}$
- **At resonance:** Huge current/voltage, energy oscillates  $L \leftrightarrow C$
- **Danger:** Can destroy components if unintended!

### Detailed Explanation

### 2. Detailed Explanation

**Resonance Condition:**

At specific frequency,  $X_L = X_C$ :

$$2\pi f_r L = \frac{1}{2\pi f_r C}$$

$$\text{Solving: } f_r = \frac{1}{2\pi\sqrt{LC}}$$

**At resonance:**

- Reactances cancel:  $X_L - X_C = 0$
- Impedance:  $Z = R$  (minimum!)
- Current maximum:  $I = \frac{V}{R}$
- Circuit acts purely resistive
- Huge voltages across  $L$  and  $C$  (Q factor amplification)

**Energy oscillation:**

- Energy transfers  $L \leftrightarrow C$  each half cycle
- Magnetic field ( $L$ )  $\leftrightarrow$  Electric field ( $C$ )
- Harmonic oscillator
- Only  $R$  dissipates energy

**Applications:**

- Radio tuning (select frequency)

- Filters (bandpass)
- Oscillators
- Matching networks

#### Danger:

- Accidental resonance in circuits
- Even PCB traces have small L, stray C
- Can cause oscillations, component damage
- Must consider in high-frequency design

## Practical Examples

**Example:** L = 100 mH, C = 100  $\mu$ F

Resonant frequency:

- $f_r = \frac{1}{2\pi\sqrt{0.1 \times 0.0001}}$
- $f_r = \frac{1}{2\pi\sqrt{10^{-5}}} = \frac{1}{2\pi \times 0.00316}$
- $f_r = \frac{1}{0.01987} = 50.3 \text{ Hz}$

At 50.3 Hz:  $X_L = X_C$ , they cancel, Z = R only!

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

1. **Resonance:**  $f_r = \frac{1}{2\pi\sqrt{LC}}$  where  $X_L = X_C$
2. **Impedance:** Minimum (Z=R), maximum current
3. **Energy:** Oscillates between L and C fields
4. **Applications:** Tuning, filters, oscillators
5. **Caution:** Unintended resonance can damage circuits

**Interview Q:** *Q: What happens at resonance in RLC circuit?*

**A:**  $X_L = X_C$  cancel, Z=R minimum, huge current flows, energy oscillates between inductor and capacitor.

## Transformers (Step-Up, Step-Down, Isolation)

### TL;DR (The Gist)

- **Construction:** Two inductors on shared iron/ferrite core
- **Voltage ratio:**  $\frac{V_s}{V_p} = \frac{N_s}{N_p}$  (turns ratio)
- **Current ratio:**  $\frac{I_s}{I_p} = \frac{N_p}{N_s}$  (inverse!)
- **Power conserved:**  $V_p I_p \approx V_s I_s$  (ideal)
- **AC only:** DC doesn't work (no changing field)

## Detailed Explanation

### 2. Detailed Explanation

#### Transformer Principle:

1. AC current in primary  $\rightarrow$  changing magnetic field in core
2. Changing field links to secondary coil
3. Induces voltage in secondary (Faraday's Law)
4. Energy transferred via magnetic field (no electrical connection!)

#### Key Equations:

#### Voltage transformation:

- $\frac{V_{secondary}}{V_{primary}} = \frac{N_{secondary}}{N_{primary}}$

- More turns  $\rightarrow$  higher voltage
- Fewer turns  $\rightarrow$  lower voltage

#### Current transformation:

- $\frac{I_{secondary}}{I_{primary}} = \frac{N_{primary}}{N_{secondary}}$
- Inverse relationship!
- Higher voltage  $\rightarrow$  lower current (and vice versa)

#### Power conservation:

- Ideal:  $P_{out} = P_{in}$
- $V_s I_s = V_p I_p$
- If V doubles, I halves
- Real: 90-99% efficient (core losses, copper losses)

#### Three Types:

##### 1. Step-Down Transformer:

- $N_s < N_p$  (fewer secondary turns)
- $V_s < V_p$  (lower output voltage)
- $I_s > I_p$  (higher output current)
- Example: 120V AC  $\rightarrow$  12V AC (10:1 ratio)
- Use: Power supplies, voltage reduction

##### 2. Step-Up Transformer:

- $N_s > N_p$  (more secondary turns)
- $V_s > V_p$  (higher output voltage)
- $I_s < I_p$  (lower output current)
- Example: 120V  $\rightarrow$  10kV (transmission lines)
- Use: Power transmission, voltage multiplication

##### 3. Isolation Transformer:

- $N_s = N_p$  (same turns)
- $V_s = V_p$  (same voltage)
- $I_s = I_p$  (same current)
- Purpose: Galvanic isolation, safety, break ground loops
- No electrical connection between primary/secondary
- Prevents DC, capacitive coupling

#### Why AC Only?

##### AC (works):

- Constantly changing current
- Constantly changing magnetic field
- Changing field induces voltage

##### DC (doesn't work):

- Constant current
- Static magnetic field (after initial transient)
- No change  $\rightarrow$  no induced voltage
- Secondary voltage = 0

## Practical Examples

### Example 1: Step-Down

Primary: 120V, 100 turns

Secondary: 10 turns

Voltage ratio:

- $\frac{V_s}{120} = \frac{10}{100} = 0.1$
- $V_s = 12 \text{ V}$

If load draws 2A from secondary:

- $\frac{I_s}{I_p} = \frac{N_p}{N_s} = \frac{100}{10} = 10$
- $I_p = \frac{2}{10} = 0.2 \text{ A}$

Power:  $P_s = 12 \times 2 = 24 \text{ W}$ ,  $P_p = 120 \times 0.2 = 24 \text{ W}$  ✓

### Example 2: Step-Up

Primary: 230V, 50 turns  
Secondary: 500 turns (10:1 ratio)  
Voltage:  $V_s = 230 \times \frac{500}{50} = 2300 \text{ V}$   
If primary draws 10A:  

- $I_s = 10 \times \frac{50}{500} = 1 \text{ A}$
- Higher voltage, lower current!

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

1. **Voltage:**  $\frac{V_s}{V_p} = \frac{N_s}{N_p}$  (proportional to turns)
2. **Current:**  $\frac{I_s}{I_p} = \frac{N_p}{N_s}$  (inverse!)
3. **Power:** Conserved (ideal):  $V_p I_p = V_s I_s$
4. **Step-down:**  $N_s < N_p$ , lower V, higher I
5. **Step-up:**  $N_s > N_p$ , higher V, lower I
6. **Isolation:**  $N_s = N_p$ , same V and I, breaks ground
7. **AC only:** Requires changing field to induce voltage
8. **Symbol:** Two inductors facing each other with core lines

#### Interview Questions:

- **Q:** How does transformer work?  
A: AC in primary creates changing magnetic field in core. This induces voltage in secondary via electromagnetic induction.
- **Q:** Why doesn't transformer work with DC?  
A: DC creates static magnetic field (no change). No changing field = no induced voltage.
- **Q:** If transformer steps up voltage, what happens to current?  
A: Current decreases (inverse ratio). Power is conserved: higher V  $\times$  lower I = same power.
- **Q:** What's the purpose of isolation transformer?  
A: Breaks electrical connection while transferring power. Prevents ground loops, improves safety, blocks DC.

#### Applications:

- Power supplies (step-down 120V  $\rightarrow$  12V)
- Power transmission (step-up to kV range)
- Audio equipment (impedance matching)
- Isolation (safety, medical equipment)
- Voltage multiplication (high voltage generation)

## Long-Distance Power Transmission

### TL;DR (The Gist)

- **Problem:** Power loss in wires  $= P_{loss} = I^2 R$
- **Solution:** High voltage  $\rightarrow$  low current for same power
- **Example:** 100kW at 1kV loses 10kW, at 10kV loses only 0.1kW (100 $\times$  better!)
- Transformers enable efficient long-distance transmission

### Detailed Explanation

### 2. Detailed Explanation

#### Power Transmission Problem:

#### Power loss in conductors:

- $P_{loss} = I^2 R_{wire}$
- Loss proportional to current squared!
- Long wires have significant resistance

- High current  $\rightarrow$  enormous losses

#### Solution – High Voltage Transmission:

For same power:  $P = VI$

#### Low voltage transmission:

- High current needed
- $I^2R$  losses huge
- Example: 100kW at 1kV  $\rightarrow$  100A  $\rightarrow$  massive loss

#### High voltage transmission:

- Low current needed
- $I^2R$  losses small
- Example: 100kW at 100kV  $\rightarrow$  1A  $\rightarrow$  minimal loss

#### Transmission System:

1. **Power plant:** Generates 11-33 kV
2. **Step-up transformer:** 100-700 kV (transmission voltage)
3. **Long-distance lines:** High voltage, low current
4. **Substation:** Step-down to 33-66 kV (distribution)
5. **Local transformer:** Step-down to 120/240V (residential)

#### Why Westinghouse AC Won:

- Edison's DC couldn't be transformed (no transformers for DC)
- AC easily stepped up/down with transformers
- Enabled long-distance transmission
- AC won the "War of Currents"

## Practical Examples

#### Comparison: 100 kW over 1 km line ( $R=1\Omega$ )

##### Option 1: 1000V transmission

- Current:  $I = \frac{P}{V} = \frac{100000}{1000} = 100 \text{ A}$
- Loss:  $P_{loss} = I^2R = 100^2 \times 1 = 10,000 \text{ W} = 10 \text{ kW}$
- Efficiency:  $\frac{90}{100} = 90\%$  (10% lost!)

##### Option 2: 10,000V transmission

- Current:  $I = \frac{100000}{10000} = 10 \text{ A}$
- Loss:  $P_{loss} = 10^2 \times 1 = 100 \text{ W} = 0.1 \text{ kW}$
- Efficiency:  $\frac{99.9}{100} = 99.9\%$  (0.1% lost!)

**Result:**  $10\times$  voltage  $\rightarrow$   $1/10$  current  $\rightarrow$   $1/100$  loss ( $100\times$  improvement!)

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

1. **Loss formula:**  $P_{loss} = I^2R$  (proportional to current squared!)
2. **High voltage advantage:** Same power, lower current, much less loss
3. **Example:**  $10\times$  voltage  $\rightarrow$   $1/10$  current  $\rightarrow$   $1/100$  loss
4. **Transformers critical:** Enable voltage step-up/step-down
5. **Transmission voltages:** 100-700 kV typical
6. **AC advantage:** Easy to transform (DC couldn't do this historically)

#### Interview Questions:

- **Q:** Why transmit power at high voltage?  
A: High voltage allows low current for same power. Since loss =  $I^2R$ , lower current dramatically reduces loss.
- **Q:** How much does loss reduce if voltage doubles?  
A: Current halves, so loss ( $I^2R$ ) reduces to  $1/4$  ( $4\times$  better).
- **Q:** Why can't we use high voltage in homes?  
A: Dangerous! Transformers step down to safe 120/240V for residential use.

#### Formulas:

- **Power:**  $P = VI$

- **Current:**  $I = \frac{P}{V}$
- **Loss:**  $P_{loss} = I^2 R_{wire}$
- **Efficiency:**  $\eta = \frac{P_{delivered}}{P_{generated}} = \frac{P - P_{loss}}{P}$

# Section 11: Diodes

## Topic 1: Diode Introduction

TL;DR (The Gist)

- **Diode:** Semiconductor component controlling current direction (one-way valve)
- **Forward bias:** Anode positive  $\rightarrow$  current flows (acts like short circuit ideally)
- **Reverse bias:** Cathode positive  $\rightarrow$  current blocked (acts like open circuit)
- **Forward voltage drop:** Real diode needs  $V_f \approx 0.6 - 0.7V$  (Si) or  $0.3V$  (Ge) to conduct
- **Terminals:** Anode (+) and Cathode (-), polarized component

### Detailed Explanation

## 2. Detailed Explanation

### What is a Diode?

A **diode** is one of the most fundamental semiconductor components in electronics. After mastering basic passive components (resistors, capacitors, inductors), the diode opens the door to the world of semiconductors and active devices.

**Key Function:** Control the direction of current flow. Current can only flow in one direction through a diode (forward direction), while current trying to flow in the reverse direction is blocked.

### Physical Construction:

- Two terminals: **Anode** (positive end, A) and **Cathode** (negative end, K)
- Polarized component - the two terminals are distinctly different
- Current flows from anode to cathode, but not the other way
- Symbol: Triangle pointing against a line (arrow shows current direction)

### Ideal vs Real Diode Behavior:

**Ideal diode** (doesn't exist):

- Forward bias ( $V \geq 0$ ): Acts like short circuit,  $V_D = 0V$ , unlimited current
- Reverse bias ( $V < 0$ ): Acts like open circuit,  $I_D = 0A$ , infinite resistance
- Sharp transition at  $V = 0V$
- No power dissipation

**Real diode** (actual behavior):

- **Forward bias:** Requires forward voltage drop  $V_f$  to conduct
  - Silicon diode:  $V_f \approx 0.6 - 0.7V$  (most common)
  - Germanium diode:  $V_f \approx 0.3V$  (less common today)
  - LEDs:  $V_f \approx 1.8 - 3.3V$  (higher, depends on color)
  - Schottky diode:  $V_f \approx 0.2 - 0.4V$  (specially designed for low drop)
- **Reverse bias:** Small leakage current (nanoamperes range)
- **Breakdown region:** At high reverse voltage, diode conducts in reverse (can be destructive if current unlimited)
- Power dissipation:  $P = V_f \times I_f$  when conducting

### I-V Characteristic Curve:

The current-voltage relationship of a diode is **nonlinear** (unlike resistors which follow Ohm's Law linearly). The diode operates in three regions:

#### 1. Forward Bias Region ( $V > V_f$ ):

- Voltage across diode is positive and exceeds forward voltage
- Diode is ON, current flows
- Small voltage increase  $\rightarrow$  large current increase (exponential relationship)
- Resistance drops significantly

#### 2. Reverse Bias Region ( $-V_{breakdown} < V < V_f$ ):

- Voltage across diode is negative or below forward voltage
- Diode is OFF, current mostly blocked
- Small reverse saturation current flows (typically nanoamperes)
- Very high resistance

#### 3. Breakdown Region ( $V < -V_{breakdown}$ ):

- Large negative voltage applied

- Diode gives up and conducts in reverse direction
- Can destroy diode if current not limited
- Zener diodes are designed to operate in this region safely

#### Circuit Symbol and Polarity:

- Triangle (arrow) points in direction of conventional current flow
- Line represents cathode (negative terminal)
- Triangle side is anode (positive terminal)
- Mnemonic: Current flows in direction arrow points

#### Applications:

- Rectification (AC to DC conversion)
- Voltage regulation (Zener diodes)
- Signal clipping and clamping
- Protection circuits (reverse polarity, flyback)
- Logic gates
- Light emission (LEDs)
- Signal detection and mixing

### Practical Example & Numerical

#### Example 1: Simple Diode Circuit Analysis

Circuit: 12V battery, 330Ω resistor, silicon diode ( $V_f = 0.7V$ ) in series.

**Question:** What is the voltage across the diode and current through the circuit?

**Solution:**

Step 1: Check if diode is forward biased (anode more positive than cathode):

- Yes, diode will conduct

Step 2: Apply Kirchhoff's Voltage Law (KVL):

$$V_{supply} = V_R + V_D$$

$$12V = V_R + 0.7V$$

$$V_R = 12V - 0.7V = 11.3V$$

Step 3: Calculate current using Ohm's Law:

$$I = \frac{V_R}{R} = \frac{11.3V}{330\Omega} = 34.24mA$$

**Answer:**

- Voltage across diode:  $V_D = 0.7V$
- Voltage across resistor:  $V_R = 11.3V$
- Current through circuit:  $I = 34.24mA$

Note: If we incorrectly assumed ideal diode ( $V_D = 0V$ ), we would calculate  $I = 12V/330\Omega = 36.36mA$  (error of about 6%).

#### Example 2: Forward Voltage Dependency on Current

Same circuit, but change resistor to 110Ω.

**Solution:**

$$V_R = 12V - V_D$$

Assume  $V_D \approx 0.7V$  (typical at higher currents):

$$I = \frac{12V - 0.7V}{110\Omega} = \frac{11.3V}{110\Omega} = 102.7mA$$

At this higher current (100mA), the forward voltage drop might actually be closer to 0.8V or higher (check I-V curve in datasheet). The forward voltage increases slightly with current due to internal resistance.

**Iterative refinement:**

If  $V_D = 0.8V$  at 100mA (from datasheet curve):

$$I = \frac{12V - 0.8V}{110\Omega} = \frac{11.2V}{110\Omega} = 101.8mA$$

This is close enough. The key point: forward voltage is not perfectly constant but increases slightly with current.

#### Example 3: Reverse Bias Scenario

Circuit: 12V battery reversed (cathode connected to positive), 330Ω resistor, silicon diode.

**Analysis:**

- Diode is reverse biased (cathode more positive than anode)
  - Diode acts like open circuit
  - No significant current flows (only tiny leakage current nA)
  - Full 12V appears across diode
  - Check: Is 12V less than breakdown voltage? If breakdown is 100V (typical), then yes, diode safely blocks.
- Result:**  $I \approx 0A$ ,  $V_D = 12V$ , circuit effectively OFF.

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

1. **One-way valve:** Diode allows current in forward direction (anode→cathode) only, blocks reverse current.
2. **Terminals polarized:** Anode (positive, triangle side) and Cathode (negative, line side). MUST connect correctly.
3. **Forward voltage drop:** Real diode requires  $V_f$  to conduct: Silicon 0.6-0.7V, Germanium 0.3V, Schottky 0.2-0.4V, LED 1.8-3.3V.
4. **Three operating regions:** Forward bias (ON, conducts), Reverse bias (OFF, blocks), Breakdown (reverse conduction, usually destructive).
5. **Nonlinear I-V curve:** Small voltage change above  $V_f$  causes large current increase (exponential). Not like resistors!
6. **Power dissipation:**  $P = V_f \times I_f$  when conducting. Must stay within maximum power rating.
7. **KVL application:** In series circuit,  $V_{supply} = V_{components} + V_{diode}$ . Don't forget diode drop!
8. **Current limiting essential:** Always use resistor or current source to limit diode current, or it will overheat and fail.

#### Interview Q&A:

##### Q: What is a diode and what is its key function?

A: A diode is a semiconductor component with two terminals (anode and cathode) that controls current direction. It allows current to flow in one direction (forward bias, anode to cathode) while blocking current in the reverse direction (reverse bias). It acts like a one-way valve for electricity.

##### Q: What is the difference between an ideal and real diode?

A: An ideal diode acts like a perfect switch: zero voltage drop when conducting (forward bias) and zero current when blocking (reverse bias). A real diode has a forward voltage drop ( $V_f \approx 0.7V$  for silicon) when conducting, allows small leakage current when reverse biased, dissipates power, and can break down at high reverse voltages.

##### Q: Why is there a voltage drop across a conducting diode?

A: The forward voltage drop ( $V_f$ ) is required to overcome the potential barrier in the semiconductor p-n junction. For silicon, this barrier is approximately 0.6-0.7V. This voltage is needed to move charge carriers across the junction and allow current to flow.

##### Q: What are the three operating regions of a diode?

A: (1) Forward bias region: Voltage positive and above  $V_f$ , diode conducts, current flows. (2) Reverse bias region: Voltage negative but above breakdown, diode blocks, only tiny leakage current. (3) Breakdown region: Large negative voltage exceeds breakdown voltage, diode conducts in reverse (can be destructive if current not limited).

##### Q: How do you analyze a simple diode circuit?

A: First, determine if diode is forward or reverse biased. If forward biased, assume  $V_D \approx 0.7V$  (for silicon). Apply KVL to find voltage across other components. Use Ohm's Law to calculate current. Verify current is within diode's maximum rating and that forward voltage assumption is reasonable for that current level.

#### Key Formulas:

$$\text{KVL: } V_{supply} = V_R + V_D$$

$$\text{Current: } I = \frac{V_{supply} - V_D}{R}$$

$$\text{Power dissipation: } P_D = V_D \times I_D$$

$$\text{Typical silicon: } V_D \approx 0.6 - 0.7V \text{ when conducting}$$

## Topic 2: Operating Regions - Forward, Reverse, Breakdown

### TL;DR (The Gist)

- **Forward bias:**  $V > V_f$  (0.6V for Si), diode ON, current flows exponentially
- **Reverse bias:**  $-V_{BR} < V < V_f$ , diode OFF, only nA leakage current

- **Breakdown:**  $V < -V_{BR}$ , reverse conduction, can damage if current unlimited
- $V_f$  **variations:** Silicon 0.6-1V, Germanium 0.3V, LED higher, Schottky lower
- **Maximum ratings:**  $I_{F(max)}$  forward current,  $V_{BR}$  breakdown voltage critical

## Detailed Explanation

### 2. Detailed Explanation

#### Diode Operating Regions in Detail:

The I-V characteristic curve shows three distinct regions where diode behavior changes dramatically.

#### 1. FORWARD BIAS REGION ( $V_D > V_f$ ):

This is the "ON" state where the diode conducts current.

##### Behavior:

- Anode voltage more positive than cathode
- Voltage across diode must exceed forward voltage threshold  $V_f$
- Once  $V > V_f$ , small voltage increase  $\rightarrow$  large current increase (exponential)
- Diode resistance drops significantly (dynamic resistance very low)
- Power dissipated:  $P = V_f \times I_f$

##### Forward Voltage $V_f$ (typical values):

- Silicon diode: 0.6-0.7V (most common general-purpose)
- Germanium diode: 0.3V (older technology, less common today)
- Schottky diode: 0.2-0.4V (designed for low voltage drop)
- LED (Light Emitting Diode): 1.8-3.3V (depends on color - red lowest, blue/white highest)
- Power diode (large junction): May have slightly higher  $V_f$  at rated current

**Key Point:** The diode doesn't conduct significantly until voltage reaches approximately  $V_f$ . At this threshold, it "turns on" and current rises exponentially. Below  $V_f$ , only tiny currents flow.

##### Current-Voltage Relationship:

The forward current follows the Shockley diode equation (exponential):

$$I_D = I_S \left( e^{V_D / (nV_T)} - 1 \right)$$

Where:

- $I_S$  = saturation current (typically  $10^{-12}$  to  $10^{-15}$  A)
- $V_T$  = thermal voltage  $\approx 26$  mV at room temperature
- $n$  = ideality factor (1-2, typically 1 for ideal diode)
- $V_D$  = voltage across diode

**Practical Takeaway:** Once  $V_D \geq V_f$ , a small voltage change causes large current change. This is why current limiting (resistor) is essential!

#### 2. REVERSE BIAS REGION ( $-V_{BR} < V_D < V_f$ ):

This is the "OFF" state where the diode blocks current.

##### Behavior:

- Cathode voltage more positive than anode (negative voltage across diode)
- Diode acts like open circuit (very high resistance)
- Only tiny reverse saturation current  $I_R$  flows (typically nanoamperes)
- $I_R$  is approximately constant regardless of reverse voltage
- $I_R$  increases with temperature (doubles approximately every  $10^\circ\text{C}$ )

##### Leakage Current:

- Caused by minority carriers and surface effects
- Typical values: 1 nA to 1  $\mu$ A depending on diode type and temperature
- Not zero, but negligible for most applications
- Important in precision circuits or high-temperature applications

##### Safe Operating Range:

As long as reverse voltage stays below breakdown voltage  $V_{BR}$ , the diode is safe and blocking properly.

#### 3. BREAKDOWN REGION ( $V_D < -V_{BR}$ ):

This is where the diode "gives up" and conducts in reverse.

##### Behavior:

- Large negative voltage exceeds breakdown voltage  $V_{BR}$
- Diode suddenly conducts heavily in reverse direction
- Current can be very large if not limited by external circuit
- Voltage across diode clamps approximately at  $V_{BR}$

### Two Types of Breakdown:

**Avalanche Breakdown** (higher voltages,  $\geq 5V$  typically):

- Charge carriers accelerate and collide with atoms
- Create more charge carriers in chain reaction (avalanche)
- Common in general-purpose diodes

**Zener Breakdown** (lower voltages,  $\leq 5V$  typically):

- Strong electric field directly pulls electrons from bonds
- Quantum tunneling effect
- Zener diodes designed to operate here safely

### Destructive vs Non-Destructive:

- **General-purpose diode:** Breakdown is usually destructive if current not limited. Diode overheats and burns out  $\rightarrow$  short or open circuit.
- **Zener diode:** Specifically designed to operate in breakdown region safely. Used for voltage regulation. Must still limit current to prevent overheating.

### Maximum Ratings (from Datasheet):

Every diode has specifications that must not be exceeded:

$I_{F(max)}$ : **Maximum Forward Current**

- Maximum continuous DC current diode can handle when forward biased
- Example: 1N4148 signal diode: 300mA continuous, 500mA peak
- Exceeding causes overheating and failure

$V_{BR}$ : **Breakdown Voltage (or  $V_{RRM}$  - Reverse Repetitive Maximum)**

- Minimum voltage at which breakdown occurs
- Example: 1N4148: 100V minimum breakdown
- Exceeding (without current limiting) damages diode

$P_D$ : **Power Dissipation**

- Maximum power diode can dissipate:  $P = V_D \times I_D$
- Example: 1N4148: 500mW maximum
- Affected by ambient temperature and heatsinking

### Temperature Coefficient:

Forward voltage  $V_f$  decreases with temperature (approximately  $-2mV/^\circ C$  for silicon). This is important in precision circuits and can lead to thermal runaway if multiple diodes share current without balancing.

## Practical Example & Numerical

### Example 1: Forward Region - Current Calculation

Circuit: 5V supply, variable resistor R, silicon diode ( $V_f = 0.7V$ ).

**Case A:  $R = 1k\Omega$**

$$I = \frac{V_{supply} - V_f}{R} = \frac{5V - 0.7V}{1000\Omega} = \frac{4.3V}{1000\Omega} = 4.3mA$$

**Case B:  $R = 100\Omega$**

$$I = \frac{5V - 0.7V}{100\Omega} = \frac{4.3V}{100\Omega} = 43mA$$

At higher current (43mA vs 4.3mA), the forward voltage might increase to 0.75-0.8V. This is why iterative calculation or consulting the I-V curve is more accurate for higher currents.

### Example 2: Reverse Region - Breakdown Check

Circuit: 50V reverse voltage across 1N4148 diode (datasheet:  $V_{BR(min)} = 100V$ ).

#### Analysis:

- Applied reverse voltage: 50V
- Breakdown voltage: 100V minimum
- Since  $50V < 100V$ , diode safely blocks
- Current: Only leakage current  $\approx 1-5nA$  (negligible)
- Diode acts like open circuit

**Conclusion:** Safe operation. Diode OFF, voltage across diode = 50V.

### Example 3: Breakdown Region - Destructive Scenario

Circuit: 150V reverse voltage, 1N4148 diode ( $V_{BR} = 100V$ ), NO current limiting resistor.

#### Analysis:

- Applied voltage (150V) > breakdown voltage (100V)
- Diode enters breakdown, conducts heavily in reverse
- Without current limiting, current can be huge (limited only by source and diode resistance)

- Power dissipation:  $P = 100V \times I$  can exceed 500mW rating easily
- **Result: Diode overheats and burns out!**

**Proper Design:** Add series resistor to limit current:

If we want  $I_{max} = 5mA$  in breakdown:

$$R = \frac{V_{supply} - V_{BR}}{I_{max}} = \frac{150V - 100V}{5mA} = \frac{50V}{5mA} = 10k\Omega$$

Power in resistor:  $P_R = I^2 R = (5mA)^2 \times 10k\Omega = 250mW$

Power in diode:  $P_D = V_{BR} \times I = 100V \times 5mA = 500mW$  (at maximum rating!)

**Better design:** Reduce current to 2mA:

$$R = \frac{150V - 100V}{2mA} = 25k\Omega$$

$$P_D = 100V \times 2mA = 200mW \text{ (safer, 40\% of max)}$$

#### Example 4: Temperature Effect on Forward Voltage

Silicon diode at different temperatures, constant current  $I_f = 10mA$ :

**At 25°C:**  $V_f = 0.70V$

**At 75°C:** (50°C increase)

Temperature coefficient:  $-2mV/^\circ C$

Change:  $\Delta V_f = -2mV/^\circ C \times 50^\circ C = -100mV$

**New  $V_f$ :**  $0.70V - 0.10V = 0.60V$

This is important in temperature-sensitive circuits and when multiple diodes share current (thermal runaway risk).

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

1. **Forward bias ON:**  $V_D > V_f$  (0.6-0.7V Si), diode conducts, exponential I-V relationship, small  $\Delta V \rightarrow$  large  $\Delta I$ .
2. **Reverse bias OFF:** Cathode positive, diode blocks, only nA leakage current, acts like open circuit until breakdown.
3. **Breakdown region:**  $V_D < -V_{BR}$ , reverse conduction occurs. Destructive for general diodes if current unlimited. Zeners designed for this.
4.  $V_f$  **varies by type:** Silicon 0.7V, Germanium 0.3V, Schottky 0.3V, LED 2-3V. Check datasheet!
5. **Maximum ratings critical:** Never exceed  $I_{F(max)}$  (forward current),  $V_{BR}$  (breakdown voltage), or  $P_D$  (power dissipation).
6. **Current limiting essential:** Always use resistor to limit forward current, or diode will overheat and fail. Calculate:  $R = (V_{supply} - V_f) / I_{desired}$ .
7. **Temperature effects:**  $V_f$  decreases  $2mV/^\circ C$ , leakage current doubles every  $10^\circ C$ . Important for precision and high-temp applications.
8. **Exponential relationship:** Shockley equation  $I_D = I_S(e^{V_D/V_T} - 1)$  explains why current explodes above  $V_f$ .

#### Interview Q&A:

**Q: What are the three operating regions of a diode?**

A: (1) Forward bias region where  $V_D > V_f$ , diode conducts with exponentially increasing current. (2) Reverse bias region where voltage is negative but above breakdown, diode blocks with only nA leakage. (3) Breakdown region where reverse voltage exceeds  $V_{BR}$ , causing reverse conduction that can be destructive without current limiting.

**Q: Why does forward voltage vary between different diode types?**

A: Forward voltage depends on the semiconductor material and junction design. Silicon has a larger bandgap (0.7V) than Germanium (0.3V). Schottky diodes use metal-semiconductor junctions for lower drop (0.3V). LEDs need higher voltage (2-3V) to emit photons. The material's energy barrier determines  $V_f$ .

**Q: What happens if you exceed the maximum forward current rating?**

A: The diode dissipates excessive power ( $P = V_f \times I_f$ ), causing overheating. Temperature rises, potentially exceeding the junction's thermal limits, leading to permanent damage - either a short circuit (junction melts) or open circuit (bond wires burn out).

**Q: What is breakdown voltage and why is it important?**

A: Breakdown voltage ( $V_{BR}$ ) is the reverse voltage at which the diode begins conducting heavily in the reverse direction due to avalanche or Zener effects. For general-purpose diodes, exceeding  $V_{BR}$  without current limiting causes destructive failure. Designers must ensure circuits never apply reverse voltages approaching  $V_{BR}$ .

**Q: Explain the exponential I-V relationship in forward bias.**

A: The Shockley diode equation shows current increases exponentially with voltage:  $I = I_S(e^{V/V_T} - 1)$ . Below the threshold (0.6V for Si), current is negligible. Above it, a tiny voltage increase (e.g., 0.6V  $\rightarrow$  0.7V, just 0.1V change) can increase current by 10-100 $\times$ . This is why current limiting is absolutely essential.

### Key Formulas:

$$\text{Shockley equation: } I_D = I_S \left( e^{V_D/(nV_T)} - 1 \right)$$

$$\text{Current limiting resistor: } R = \frac{V_{supply} - V_f}{I_f}$$

$$\text{Power dissipation: } P_D = V_D \times I_D$$

$$\text{Temperature effect: } \Delta V_f \approx -2mV/C \times \Delta T$$

## Topic 3: Diode Datasheet Parameters

### TL;DR (The Gist)

- **1N4148:** Small signal fast switching diode example datasheet
- $I_{F(max)}$ : 300mA continuous, 500mA peak - maximum forward current
- $V_F$ : 0.4-1.0V forward voltage (depends on current, see I-V curve)
- $V_{BR}$ : 100V minimum breakdown voltage (reverse blocking capability)
- $I_R$ : Reverse leakage current nA (increases with voltage and temperature)

### Detailed Explanation

## 2. Detailed Explanation

### Understanding Diode Datasheets - 1N4148 Example:

The 1N4148 is one of the most popular general-purpose diodes. Understanding its datasheet teaches you how to read any diode specification.

#### Device Description:

"Small Signal Fast Switching Diode"

Breaking this down:

- **Small signal:** Works with relatively low voltages and currents (not for high power)
- **Fast switching:** Can turn ON/OFF rapidly (short reverse recovery time), suitable for high-frequency applications
- Contrasts with **power diodes** (high current capability, slower) and **Schottky diodes** (even faster, lower  $V_f$ )

#### Why Fast Switching Matters:

Applications with high-frequency signals (e.g., switching power supplies at 100kHz-1MHz) require diodes that can respond quickly. The 1N4148 can switch states in nanoseconds, making it suitable for:

- Signal processing and clipping circuits
- Digital logic protection
- High-frequency rectification (up to several MHz)
- Switching power supply secondaries (though Schottkys often preferred)

#### Key Datasheet Parameters:

##### 1. Maximum Forward Current - $I_{F(max)}$ :

- **Continuous DC:** 300mA (can handle this current indefinitely at 25°C)
- **Peak/Surge:** 500mA (short duration pulses, with duty cycle limits)
- **Meaning:** Do NOT exceed these currents or diode will overheat and fail
- **Derating:** Current capability decreases at higher ambient temperatures

**Design Rule:** Keep operating current well below maximum (typically 50-70

Example: For 300mA rated diode, design for  $\leq 150$ -200mA typical operation.

##### 2. Forward Voltage - $V_F$ :

- **Typical:** Not single value - depends on current!
- **Specified range:** 0.4V to 1.0V maximum
- **Why range?:** Manufacturing variations and current dependency

#### Forward I-V Curve (from datasheet graph):

Reading the curve:

- At  $I_F = 1mA$ :  $V_F \approx 0.5 - 0.6V$
- At  $I_F = 10mA$ :  $V_F \approx 0.65 - 0.75V$
- At  $I_F = 100mA$ :  $V_F \approx 0.8 - 1.0V$

**Key Insight:** Forward voltage is NOT constant! It increases logarithmically with current. For rough calculations, 0.7V is a good approximation at typical currents (10-100mA).

**Design Practice:**

- Quick estimate: Use 0.7V
- Precision design: Refer to I-V curve at expected operating current
- Conservative worst-case: Use 1.0V maximum from datasheet

**3. Breakdown Voltage -  $V_{BR}$  (or  $V_{RRM}$ ):**

- **Minimum:** 100V (some units may have higher breakdown, but 100V is guaranteed minimum)
- **Meaning:** Diode can safely block reverse voltages up to this value
- **Test condition:** Measured at low reverse current (typically 10 $\mu$ A)

**Design Rule:** Never apply reverse voltage approaching breakdown. Use safety margin (e.g., design for max 70-80V reverse if  $V_{BR(min)} = 100V$ ).

**4. Reverse Leakage Current -  $I_R$ :**

- **Typical:** Few nanoamperes to tens of nanoamperes
- **Specified at:** Certain reverse voltage (e.g., at  $V_R = 20V$ :  $I_R < 25nA$  typical)
- **Increases with:** Higher reverse voltage and higher temperature

**From Reverse I-V Curve:**

- At  $V_R = 20V$ :  $I_R \approx$  few nA
- At  $V_R = 75V$ :  $I_R \approx 25nA$
- As voltage approaches 100V (breakdown), current starts increasing
- At breakdown (100V): Current "goes crazy" (sharp increase, mA range)

**When Leakage Matters:**

- High-impedance circuits ( $M\Omega$  range)
- Precision analog circuits
- Long-term charge storage applications
- High-temperature environments (leakage doubles every 10°C)

**5. Power Dissipation -  $P_D$ :**

- **Maximum:** Typically 500mW at 25°C for 1N4148
- **Calculation:**  $P = V_F \times I_F$  (when forward biased)
- **Thermal derating:** Decreases at higher ambient temperatures

**Example Check:**

If  $I_F = 200mA$  and  $V_F = 0.9V$ :

$$P_D = 0.9V \times 200mA = 180mW$$

This is 36% of 500mW rating - acceptable with margin.

If  $I_F = 300mA$  and  $V_F = 1.0V$ :

$$P_D = 1.0V \times 300mA = 300mW$$

This is 60% of rating - acceptable at 25°C but may need derating at higher ambient temperatures.

**6. Reverse Recovery Time -  $t_{rr}$ :**

- For 1N4148: Typically 4-8ns (very fast!)
- **Meaning:** Time for diode to switch from conducting (forward) to blocking (reverse)
- **Important for:** High-frequency switching applications

**Why It Matters:**

When diode is conducting forward current, minority carriers are stored in the junction. When voltage suddenly reverses, these carriers must be removed before diode blocks. During this time, a reverse current pulse flows. Fast recovery means less switching loss.

**Application Selection:**

- 1N4148: Fast switching, low current, general signal processing
- 1N400x series: Slower, higher current (1A), power rectification 50/60Hz
- Schottky (e.g., 1N5819): Fastest, lowest  $V_f$ , but lower breakdown voltage

**Practical Example & Numerical****Example 1: Datasheet Application - Current Limit Check**

Design: 12V supply, 1N4148 diode, resistor R to limit current to safe value.

**From datasheet:**  $I_{F(max)} = 300mA$  continuous

**Design target:**  $I_F = 150mA$  (50% of max for reliability)

**Assume:**  $V_F = 0.7V$  at 150mA (from I-V curve)

**Calculate resistor:**

$$R = \frac{V_{supply} - V_F}{I_F} = \frac{12V - 0.7V}{150mA} = \frac{11.3V}{0.15A} = 75.3\Omega$$

Use standard value:  $R = 75\Omega$  or  $82\Omega$

**Verify with  $82\Omega$ :**

$$I_F = \frac{12V - 0.7V}{82\Omega} = \frac{11.3V}{82\Omega} = 137.8mA$$

**Check power dissipation:**

$$P_D = V_F \times I_F = 0.7V \times 137.8mA = 96.5mW$$

This is only 19

**Resistor power:**

$$P_R = I_F^2 \times R = (137.8mA)^2 \times 82\Omega = 1.56W$$

Use 2W resistor (or higher) for safety.

### Example 2: Reverse Voltage Check

Application: Protection diode in circuit with occasional voltage transients up to -60V.

**From datasheet:**  $V_{BR(min)} = 100V$

**Analysis:**

- Maximum reverse voltage: 60V
- Breakdown voltage: 100V minimum
- Since  $60V < 100V$ , diode safely blocks
- Safety margin:  $(100V - 60V)/100V = 40\%$  - good!

**Conclusion:** 1N4148 suitable for this application from reverse voltage perspective.

### Example 3: Using I-V Curve for Precision

Circuit requires knowing exact  $V_F$  at  $I_F = 50mA$ .

**Reading from datasheet I-V curve graph:**

At  $I_F = 50mA$ , the curve shows  $V_F \approx 0.75 - 0.8V$  (typical)

**For conservative design:**

Use worst-case maximum:  $V_F = 1.0V$  at any current up to rated maximum.

This ensures circuit works even with worst-case diode from production variation.

**For typical design:**

Use curve reading:  $V_F = 0.75V$  at 50mA.

**Trade-off:**

- Worst-case design: Circuit works with all diodes but may be over-designed
- Typical design: More efficient but may have edge cases with outlier diodes

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

1. **Read the description:** "Small signal fast switching" tells you low-power, high-frequency capability. Guides application selection.
2.  $I_{F(max)}$  **is critical:** Never exceed maximum forward current (300mA continuous for 1N4148). Design for 50-70% of max for reliability.
3.  $V_F$  **is not constant:** Varies with current (0.4-1.0V range). Use I-V curve for precision, 0.7V for quick estimates, 1.0V for worst-case.
4.  $V_{BR}$  **sets reverse limit:** Minimum 100V for 1N4148. Never apply reverse voltage close to this. Use safety margin (70-80%).
5. **Leakage current  $I_R$ :** Typically nanoamperes, increases with voltage and temperature. Important for high-impedance circuits.
6. **Power dissipation check:**  $P_D = V_F \times I_F$  must stay below rating (500mW for 1N4148). Derates at high temperatures.
7. **Reverse recovery time:** 4-8ns for 1N4148 (fast switching). Critical for high-frequency applications. Slower for power diodes.
8. **Temperature derating:** All parameters change with temperature. Check derating curves for high-temp or high-power applications.

**Interview Q&A:**

**Q: What does "small signal fast switching diode" mean?**

A: "Small signal" means designed for low current/power applications (vs power diodes). "Fast switching" means rapid state transitions (low reverse recovery time, ns), suitable for high-frequency circuits. The 1N4148 can handle 300mA continuously and switch in nanoseconds, ideal for signal processing, logic protection, and high-frequency rectification.

**Q: Why isn't forward voltage a single specified value?**

A: Forward voltage depends on current due to the exponential I-V relationship. At low currents (1mA),  $V_F \approx 0.5V$ . At high currents (100mA),  $V_F \approx 0.9 - 1.0V$ . Manufacturing variations also cause spread. Datasheets provide I-V curves to find  $V_F$  at specific currents, plus maximum value (1.0V for 1N4148) for worst-case design.

**Q: How do you select current-limiting resistor using datasheet?**

A: (1) Determine desired current (typically 50-70% of  $I_{F(max)}$  for reliability). (2) Find  $V_F$  at that current from I-V curve. (3) Calculate  $R = (V_{supply} - V_F)/I_F$ . (4) Verify power dissipation in both diode and resistor. (5) Use standard resistor value close to calculated value.

**Q: What is breakdown voltage and why does it matter?**

A: Breakdown voltage ( $V_{BR}$ , 100V min for 1N4148) is the reverse voltage at which the diode begins conducting in reverse. Below this, the diode safely blocks. At or above this, heavy reverse current flows, potentially destroying the diode if unlimited. Designers must ensure circuits never apply reverse voltages approaching  $V_{BR}$ , typically staying below 70-80% for safety margin.

**Key Formulas:**

$$\text{Current limiting: } R = \frac{V_{supply} - V_F}{I_F}$$

$$\text{Power check: } P_D = V_F \times I_F \leq P_{D(max)}$$

$$\text{Design margin: } I_{operating} \leq 0.5 \text{ to } 0.7 \times I_{F(max)}$$

$$\text{Reverse safety: } V_{R(max)} \leq 0.7 \text{ to } 0.8 \times V_{BR(min)}$$

## Topic 4: Types of Diodes - Signal, Power, Schottky, Zener, LED

### TL;DR (The Gist)

- **Signal diodes:** Low current ( $\leq 1A$ ), fast switching, small size (1N4148)
- **Power diodes:** High current ( $\geq 1A$ ), robust, rectification (1N400x series)
- **Schottky diodes:** Lowest  $V_f$  (0.2-0.4V), fastest switching, metal-semiconductor
- **Zener diodes:** Operate in breakdown for voltage regulation (reverse biased)
- **LEDs:** Emit light when forward biased, higher  $V_f$  (1.8-3.3V by color)

### Detailed Explanation

## 2. Detailed Explanation

### Comparison of Different Diode Types:

#### 1. SIGNAL DIODES (Small Signal Diodes):

Characteristics:

- Low current rating: typically 150-500mA continuous
- Fast switching: reverse recovery time in nanoseconds
- Glass or plastic encapsulation (small package)
- Forward voltage: 0.6-0.7V (silicon), 0.2-0.3V (germanium)
- Common part: 1N4148 (silicon), 1N34A (germanium)

Applications:

- High-frequency signal processing (radio, TV, digital logic)
- Signal clipping and clamping
- Small power supplies ( $\leq 500mA$  output)
- Logic level protection
- Switching circuits with short pulse widths

Advantages: Small, cheap, fast Disadvantages: Low current capability, can't handle power applications

#### 2. POWER DIODES (Rectifier Diodes):

Characteristics:

- High current rating: 1A to several hundred amperes
- Larger junction area  $\rightarrow$  higher capacitance  $\rightarrow$  slower switching
- Robust construction, can dissipate significant power
- Typically packaged in DO-41, DO-201, stud mount, or TO-220 packages
- Forward voltage: 0.7-1.2V (increases with current due to series resistance)

- Common parts: 1N4001-1N4007 (1A, 50V-1000V), 1N5400 series (3A)

Applications:

- AC to DC rectification in power supplies (mains frequency 50/60Hz)
- Power conversion and battery charging
- Motor drive circuits (freewheeling diodes)
- High-current DC switching

Maximum frequency: 1MHz (typically used below 1kHz for power)

Advantages: High current, high voltage, rugged Disadvantages: Slow switching, higher  $V_f$  at high currents, bulky

### 3. SCHOTTKY DIODES (Hot Carrier Diodes):

Characteristics:

- Metal-semiconductor junction (not p-n junction)
- Very low forward voltage: 0.15-0.45V (significantly less than standard diode)
- Extremely fast switching: no minority carrier storage, reverse recovery  $\mu$ ns
- Lower breakdown voltage: typically 20-100V (vs  $\sim$ 100V for signal diodes)
- Higher leakage current in reverse

Applications:

- Switching power supplies (high efficiency due to low  $V_f$ )
- High-frequency rectification (100kHz-MHz range)
- Digital logic (TTL/CMOS Schottky gates - 74LS, 74AS series)
- Reverse polarity protection (low voltage drop)
- RF circuits and mixers
- Solar panel bypass diodes

Advantages: Lowest forward drop, fastest switching, highest efficiency Disadvantages: Lower breakdown voltage, higher leakage current

#### Why Lower $V_f$ Matters:

In a 5V power supply at 10A:

- Standard diode ( $V_f = 0.7V$ ): Power loss =  $0.7V \times 10A = 7W$
- Schottky diode ( $V_f = 0.3V$ ): Power loss =  $0.3V \times 10A = 3W$
- Savings: 4W less heat! This is 57% reduction in rectifier losses.

### 4. ZENER DIODES:

Characteristics:

- Designed to operate in reverse breakdown region safely
- Breakdown voltage (Zener voltage) precisely controlled: 2.4V to 200V available
- Sharp breakdown knee  $\rightarrow$  good voltage regulation
- Specified by Zener voltage ( $V_Z$ ) not forward voltage
- Forward biased: behaves like normal diode ( $V_f \approx 0.7V$ )
- Reverse biased below  $V_Z$ : blocks like normal diode
- Reverse biased at/above  $V_Z$ : conducts heavily, voltage clamps at  $V_Z$

Symbol: Normal diode with bent cathode lines (looks like "Z")

Applications:

- Voltage regulation (simple linear regulators)
- Reference voltage generation
- Overvoltage protection
- Waveform clipping at specific voltages
- ESD protection

**Key Design Rule:** Must use series resistor to limit Zener current! Without current limiting, Zener will be destroyed.

Advantages: Simple voltage reference/regulation, wide range of voltages available Disadvantages: Poor regulation under varying load, generates noise, wastes power

### 5. LIGHT EMITTING DIODES (LEDs):

Characteristics:

- Emits photons (light) when forward biased
- Higher forward voltage: 1.8-3.3V depending on color
  - Red: 1.8-2.2V
  - Yellow/Green: 2.0-2.4V
  - Blue/White: 3.0-3.5V
- Current typically 10-30mA for standard indicator LEDs (up to 1A for high-power)
- Polarity identification: longer lead = anode, flat spot = cathode
- Narrow bandwidth emission (specific color wavelength)

- Some emit invisible light (infrared for remote controls, laser type for fiber optics)

Applications:

- Indicators and displays (status LEDs, 7-segment displays, dot matrix)
- Lighting (streetlights, automotive, home)
- Optocouplers/optoisolators (electrical isolation with optical coupling)
- Remote controls (IR LEDs)
- Fiber optic communication
- Backlighting (LCD displays)

Advantages: Efficient, long life, directional light, fast response, wide color range Disadvantages: Higher  $V_f$  than standard diodes, requires current limiting, reverse breakdown is low (5V)

## Practical Example & Numerical

### Example 1: Diode Type Selection for AC Rectification

**Application A:** 120VAC to 12VDC, 100mA output (small power supply)

Load current: 100mA (low) Frequency: 60Hz (line frequency, low)

**Choice: Signal diode (1N4148)**

- Current rating: 300mA continuous > 100mA ✓
- Speed not critical at 60Hz
- Cheap and small

**Application B:** 120VAC to 12VDC, 5A output (higher power supply)

Load current: 5A (high!)

**Choice: Power diode (1N5400 series rated 3A)**

- Actually need two in parallel or use higher rated diode (6A+)
- Bridge rectifier: each diode sees half-wave, so  $I_{avg} \approx 2.5A$  per diode
- Signal diode would burn up instantly at 5A!

Recommendation: Use 1N5402 (3A, 200V) in bridge configuration, or better yet a complete bridge module rated for 5A+.

**Application C:** Switching power supply, 100kHz, 5V @ 10A output

Frequency: 100kHz (high!) Current: 10A (high!) Efficiency critical (portable device)

**Choice: Schottky diode (e.g., MBR10100, 10A Schottky)**

- Low  $V_f$  (0.3-0.5V) → low power loss → higher efficiency
- Fast switching required at 100kHz (power diodes too slow)
- At 10A: Power saved vs standard diode =  $(0.7 - 0.3) \times 10 = 4W$ !

### Example 2: LED Current Limiting Resistor

**Given:** Red LED,  $V_f = 2.0V$ , desired  $I_f = 20mA$ , supply = 5V

**Calculate resistor:**

$$R = \frac{V_{supply} - V_{LED}}{I_{LED}} = \frac{5V - 2.0V}{20mA} = \frac{3V}{0.02A} = 150\Omega$$

Use standard value:  $R = 150\Omega$  (perfect!) or  $R = 180\Omega$  (slightly dimmer)

**Power in resistor:**

$$P_R = I^2 R = (20mA)^2 \times 150\Omega = 60mW$$

Use 1/4W (250mW) resistor - plenty of margin.

### Example 3: Zener Voltage Regulator

**Design:** 15V input, 5.6V regulated output using Zener diode, load current = 50mA

**Components:**

- Zener diode:  $V_Z = 5.6V$ ,  $P_{Z(max)} = 500mW$
- Series resistor:  $R_s$  (to be calculated)

**Zener current requirement:**

For good regulation, Zener needs minimum current (typically 5-10mA). Let's choose  $I_Z = 10mA$  minimum.

Total current through resistor:

$$I_R = I_{load} + I_Z = 50mA + 10mA = 60mA$$

**Calculate resistor:**

$$R_s = \frac{V_{in} - V_Z}{I_R} = \frac{15V - 5.6V}{60mA} = \frac{9.4V}{0.06A} = 156.7\Omega$$

Use standard:  $R_s = 150\Omega$  or  $160\Omega$

**With 150Ω:**

$$I_R = \frac{15V - 5.6V}{150\Omega} = 62.7mA$$

$$I_Z = I_R - I_{load} = 62.7mA - 50mA = 12.7mA$$

**Check Zener power:**

$$P_Z = V_Z \times I_Z = 5.6V \times 12.7mA = 71mW$$

This is only 14% of 500mW rating - safe!

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

1. **Signal diodes:** Fast, small, low current ( $\leq 500mA$ ). Use for signal processing, logic, small supplies. Example: 1N4148.
2. **Power diodes:** Slow, robust, high current ( $\geq 1A$ ). Use for mains rectification, motor drives. Example: 1N4001-1N4007.
3. **Schottky diodes:** Lowest  $V_f$  (0.2-0.4V), fastest switching. Use for switching supplies, high efficiency. Lower breakdown voltage.
4. **Zener diodes:** Operate in breakdown region (reverse biased). Voltage regulation and reference. Always need series resistor for current limiting!
5. **LEDs:** Emit light, higher  $V_f$  (1.8-3.3V by color). Longer lead = anode. Always use current limiting resistor!
6. **Selection criteria:** Match current rating, speed (frequency), forward voltage drop, and application to diode type.
7. **Efficiency matters:** In power applications, lower  $V_f$  means less wasted heat. Schottky saves significant power at high currents.
8. **Current limiting universal:** ALL diodes need current limiting (resistor, inductor, or active circuit) to prevent destruction.

#### Interview Q&A:

**Q: When would you choose a Schottky diode over a standard silicon diode?**

A: Choose Schottky when: (1) High-frequency switching required ( $\geq 10kHz$ ), since Schottky has no minority carrier storage and switches in  $\leq 1ns$ . (2) Low voltage drop critical for efficiency (e.g., 5V supply where 0.7V vs 0.3V drop makes big difference). (3) Low forward voltage needed (e.g., OR-ing diodes, reverse protection). Trade-off: Schottky has lower breakdown voltage and higher leakage.

**Q: How does a Zener diode differ from a regular diode?**

A: Zener diode is designed to operate safely in the reverse breakdown region, with precisely controlled breakdown voltage ( $V_Z$ ). When reverse voltage reaches  $V_Z$ , it conducts and clamps voltage at  $V_Z$ . Regular diode's breakdown is destructive. Zener used for voltage regulation/reference, always in reverse bias mode with series resistor. Forward biased, both behave similarly.

**Q: Why do LEDs have higher forward voltage than regular diodes?**

A: LEDs are made from wide-bandgap semiconductors (GaN for blue, GaAs for red, etc.) chosen for light emission properties. The bandgap determines both the photon energy (color) and the forward voltage needed. Higher photon energy = higher voltage. Blue/white LEDs (3.0-3.5V) need more energy per photon than red (1.8-2.0V). Standard silicon diodes (0.7V) aren't optimized for light emission.

**Q: What determines whether to use a signal diode vs power diode in rectification?**

A: Primary factor is current requirement. Signal diodes rated  $\leq 500mA$ , power diodes  $\geq 1A$ . Secondary factors: frequency (power diodes too slow for  $\geq 1MHz$ ), size constraints, cost. Example: USB charger at 500mA can use signal diode. Wall adapter at 5A needs power diode or diode bridge module.

#### Key Formulas:

$$\text{LED resistor: } R = \frac{V_{supply} - V_{LED}}{I_{LED}}$$

$$\text{Zener resistor: } R_s = \frac{V_{in} - V_Z}{I_{load} + I_{Z(min)}}$$

$$\text{Schottky power savings: } \Delta P = (V_{f(Si)} - V_{f(Schottky)}) \times I$$

## Topic 5: Current Through a Diode - Forward Voltage Dependency

### TL;DR (The Gist)

- **Forward voltage varies with current:** Not constant! Increases logarithmically
- **Low current:**  $V_f$  can be 0.4-0.5V (well below nominal 0.7V)
- **High current:**  $V_f$  increases to 0.8-1.0V due to series resistance

- **Check I-V curve:** Datasheet graph shows exact  $V_f$  at specific current
- **Sufficient current needed:** Underpowered diode won't reach full  $V_f$ , may not conduct properly

## Detailed Explanation

### 2. Detailed Explanation

#### Understanding Forward Voltage vs Current Relationship:

A common misconception: "Silicon diode forward voltage is 0.7V" - this is only approximately true at typical currents!

**Reality:** Forward voltage is a function of forward current:  $V_f = f(I_f)$

**From the Shockley Equation:**

$$I_D = I_S \left( e^{V_D / (nV_T)} - 1 \right)$$

Rearranging for voltage:

$$V_D = nV_T \ln \left( \frac{I_D}{I_S} + 1 \right) \approx nV_T \ln \left( \frac{I_D}{I_S} \right)$$

Where  $V_T = kT/q \approx 26mV$  at room temperature.

**Key Insight:** Voltage increases *logarithmically* with current. Every  $10\times$  increase in current raises voltage by approximately 60mV (for  $n=1$ ).

#### Practical Implications:

From the 1N4148 datasheet I-V curve:

- At  $I_f = 0.1mA$ :  $V_f \approx 0.4V$
- At  $I_f = 1mA$ :  $V_f \approx 0.5 - 0.6V$
- At  $I_f = 10mA$ :  $V_f \approx 0.65 - 0.75V \leftarrow$  "typical" 0.7V
- At  $I_f = 100mA$ :  $V_f \approx 0.8 - 1.0V$
- At  $I_f = 300mA$  (max):  $V_f \approx 1.0V +$

#### Why This Matters:

##### 1. Circuit Analysis Accuracy:

Using a fixed 0.7V assumption is fine for rough estimates, but for precision:

- Always check datasheet I-V curve at expected current
- Use worst-case maximum for conservative design
- Iterative calculation may be needed for high accuracy

##### 2. Minimum Current Requirement:

If current is limited too much (e.g., by very large resistor),  $V_f$  may be only 0.4-0.5V:

- Diode is in transition region, not fully "ON"
- May not provide proper functionality (e.g., in rectifier or protection circuit)
- Some applications need guaranteed minimum current for proper operation

#### Example Problem:

Circuit: 12V supply, 330Ω resistor, 1N4148 diode in series.

**Iteration 1 - Assume  $V_f = 0.7V$ :**

$$I = \frac{12V - 0.7V}{330\Omega} = \frac{11.3V}{330\Omega} = 34.2mA$$

**Check:** At 34mA, from I-V curve,  $V_f \approx 0.7V$  - assumption confirmed! ✓

#### Iteration 2 - What if we assumed wrong?

If we had assumed  $V_f = 1.0V$  (worst-case):

$$I = \frac{12V - 1.0V}{330\Omega} = \frac{11V}{330\Omega} = 33.3mA$$

Error: Only 2.6

#### Iteration 3 - Now change R to 110Ω:

Assume  $V_f = 0.7V$ :

$$I = \frac{12V - 0.7V}{110\Omega} = 102.7mA$$

**Check:** At 100mA, from I-V curve,  $V_f$  might be 0.85V (higher than 0.7V!)

**Recalculate with  $V_f = 0.85V$ :**

$$I = \frac{12V - 0.85V}{110\Omega} = 101.4mA$$

Close enough - converged.

#### 3. Series Resistance Effect at High Current:

At very high currents, bulk semiconductor resistance (series resistance  $R_S$ ) dominates:

$$V_D = V_{D0} + I_D \times R_S$$

Where  $V_{D0}$  is the junction voltage (0.7V) and  $R_S$  is series resistance (typically fractions of ohms to few ohms). This is why  $V_f$  continues increasing linearly at high currents (beyond exponential region).

#### 4. Multiple Diodes in Series:

When using diodes as voltage reference (Topic 6), forward voltage stacks:

$$V_{total} = n \times V_f$$

But since  $V_f$  depends on current, total voltage varies with load current. This is why series diodes provide poor regulation compared to Zeners.

#### Temperature Effect (Reminder):

$V_f$  also decreases with temperature (-2mV/°C for silicon):

- At 25°C:  $V_f = 0.70V$  (at fixed current)
- At 75°C:  $V_f = 0.60V$  (50°C rise  $\times$  -2mV/°C = -100mV drop)

Combined with current variation, designing accurate diode voltage references is challenging!

### Practical Example & Numerical

#### Example 1: Verifying Forward Voltage Assumption

**Circuit:** 12V battery, 330Ω resistor, silicon diode

**Measured voltages:**

- Across resistor: 11.37V
- Across diode: 0.63V

**Analysis:**

Current:

$$I = \frac{V_R}{R} = \frac{11.37V}{330\Omega} = 34.5mA$$

KVL check:

$$V_{supply} = V_R + V_D = 11.37V + 0.63V = 12V \quad \checkmark$$

**Question:** Why is  $V_D = 0.63V$  instead of "0.7V"?

**Answer:** At 34.5mA, the actual forward voltage from I-V curve is approximately 0.63-0.7V. The "0.7V rule" is an approximation. Actual value depends on:

- Specific current level (34.5mA is moderate)
- Manufacturing variation (some diodes higher, some lower)
- Temperature (cooler  $\rightarrow$  higher  $V_f$ )

This is perfectly normal and expected behavior!

#### Example 2: Low Current Scenario

**Circuit:** 5V supply, 10kΩ resistor, silicon diode

**Assume  $V_f = 0.7V$ :**

$$I = \frac{5V - 0.7V}{10k\Omega} = \frac{4.3V}{10000\Omega} = 0.43mA$$

**Problem:** At 0.43mA, from I-V curve, actual  $V_f \approx 0.5V$  (not 0.7V!)

**Recalculate with  $V_f = 0.5V$ :**

$$I = \frac{5V - 0.5V}{10k\Omega} = 0.45mA$$

**Iterate:** At 0.45mA, still  $V_f \approx 0.5V \rightarrow$  converged.

**Measured result:**

- Current: 0.45mA
- Diode voltage: 0.5V (not 0.7V!)

**Lesson:** At low currents, don't blindly use 0.7V assumption!

#### Example 3: High Current Scenario

**Circuit:** 12V supply, 110Ω resistor, silicon power diode

**Assume  $V_f = 0.7V$ :**

$$I = \frac{12V - 0.7V}{110\Omega} = 102.7mA$$

**Check I-V curve:** At 100mA, typical  $V_f \approx 0.85 - 0.9V$

**Recalculate with  $V_f = 0.85V$ :**

$$I = \frac{12V - 0.85V}{110\Omega} = 101.4mA$$

**Iterate:** At 101mA with  $V_f = 0.85V \rightarrow$  close enough.

**Measured result:**

- Current: 100mA
- Diode voltage: 0.85V (higher than 0.7V!)

If we had used 0.7V, we'd calculate 103mA - about 2-3

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

1.  **$V_f$  is current-dependent:** Not constant! Increases logarithmically: low I  $\rightarrow$  low  $V_f$  (0.4-0.5V), high I  $\rightarrow$  high  $V_f$  (0.8-1.0V).
2. **0.7V is approximation:** Valid at typical currents (10-100mA range). Use datasheet I-V curve for precision at specific current.
3. **Iterative analysis:** For accuracy, assume  $V_f$ , calculate I, check I-V curve, update  $V_f$ , recalculate until converged.
4. **Minimum current matters:** Very low current  $\rightarrow V_f$  may be only 0.4-0.5V  $\rightarrow$  diode not fully ON  $\rightarrow$  may malfunction in some circuits.
5. **Series resistance at high I:** At high currents,  $V_f$  increases linearly due to bulk resistance:  $V_D = V_{D0} + I \times R_S$ .
6. **KVL always applies:**  $V_{supply} = \sum V_{components}$ . Measure to verify: if  $V_R + V_D \neq V_{supply}$ , something's wrong!
7. **Worst-case design:** Use maximum  $V_f$  from datasheet (e.g., 1.0V) for conservative calculations. Circuit works with all diode variations.
8. **Temperature effect:**  $V_f$  decreases 2mV/°C. Combined with current variation makes precision voltage reference difficult with standard diodes.

**Interview Q&A:**

**Q: Why isn't diode forward voltage constant at 0.7V?**

A: Forward voltage depends on current through the Shockley equation:  $V_f \propto \ln(I_f)$ . At low currents (1mA),  $V_f \approx 0.5 - 0.6V$ . At typical currents (10-50mA),  $V_f \approx 0.7V$ . At high currents (100mA+),  $V_f \approx 0.8 - 1.0V$  due to junction voltage plus series resistance. The 0.7V value is just a convenient approximation for hand calculations at typical operating currents.

**Q: How do you accurately calculate current in a diode circuit?**

A: Method 1 (Quick): Assume  $V_f = 0.7V$ , calculate  $I = (V_{supply} - 0.7V)/R$ . Method 2 (Accurate): (1) Assume initial  $V_f$ , (2) Calculate current, (3) Check datasheet I-V curve at that current, (4) Update  $V_f$  if needed, (5) Recalculate until  $V_f$  converges. Method 3 (Conservative): Use worst-case  $V_f$  from datasheet maximum spec.

**Q: What happens if resistor limits current too much?**

A: If current is very low (e.g., 1mA), forward voltage may be only 0.4-0.5V instead of 0.7V. The diode is partially ON but not fully conducting. In rectifier circuits, this may cause incomplete rectification. In protection circuits, the diode may not clamp properly. Always ensure sufficient current flows for the diode's intended function, typically 5-10mA for reliable operation.

**Q: Why do datasheets show I-V curves instead of single forward voltage value?**

A: Because forward voltage varies significantly with current (exponential relationship). A single value can't capture this. The I-V curve shows the complete forward characteristic, allowing designers to find exact  $V_f$  at their operating current. Datasheets also specify maximum  $V_f$  at rated current for worst-case design. Without the curve, precision design would be impossible.

**Key Formulas:**

$$\text{Approximate: } I \approx \frac{V_{supply} - 0.7V}{R}$$

$$\text{Logarithmic relation: } V_f \approx nV_T \ln\left(\frac{I_f}{I_S}\right), \quad V_T = 26mV$$

Rule of thumb:  $\Delta V_f \approx 60mV$  per decade (10 $\times$ ) current change

$$\text{High current: } V_D = V_{D0} + I_D R_S$$

## Topic 6: Diode as Voltage Reference

TL;DR (The Gist)

- **Series diodes:** Stack forward voltages:  $V_{out} = n \times V_f$  ( 0.7V each)
- **Poor regulation:**  $V_{out}$  changes with load current (since  $V_f$  varies with I)
- **Power waste:** Constant current through series resistor  $\rightarrow$  constant dissipation
- **Better alternative:** Zener diode provides tighter regulation
- **Best solution:** Use proper voltage regulator IC (covered later)

## Detailed Explanation

### 2. Detailed Explanation

#### Using Diodes for Voltage Reference - Advantages and Limitations:

##### The Concept:

Forward voltage drop across conducting diode is relatively stable ( 0.6-0.7V for Si). By placing multiple diodes in series, we can create reference voltages:

- 1 diode: 0.7V
- 2 diodes: 1.4V
- 3 diodes: 2.1V
- 5 diodes: 3.5V
- etc.

##### Basic Circuit:

$V_{in} \rightarrow$  Series Resistor ( $R_S$ )  $\rightarrow$  Multiple Diodes (forward biased, series)  $\rightarrow$  Ground

Output taken across the diodes.

##### Advantages vs Simple Voltage Divider:

##### Voltage Divider Problems:

- Output voltage changes significantly when load draws current
- Must recalculate resistor values for different loads
- Very poor regulation
- Only works well with very high impedance loads ( $M\Omega$  range)

##### Diode Reference Improvement:

- Forward voltage relatively constant despite load current changes (within limits)
- Better regulation than voltage divider
- Simple, requires only diodes and one resistor

##### How It Works:

Series resistor sets total current:  $I_{total} = (V_{in} - nV_f)/R_S$

This current splits:  $I_{total} = I_{diodes} + I_{load}$

As load current varies:

- Load takes more current  $\rightarrow$  less current through diodes
- Diode current decreases  $\rightarrow V_f$  decreases slightly (logarithmic)
- Output voltage drops somewhat, but less than voltage divider

##### Limitations and Problems:

##### 1. Poor Regulation Under Load Variation:

Since  $V_f$  depends on current, when load current changes:

- High load current  $\rightarrow$  diode current low  $\rightarrow V_f$  drops to 0.5-0.6V each
- Low load current  $\rightarrow$  diode current high  $\rightarrow V_f$  increases to 0.7-0.8V each
- Output voltage changes significantly (can be 10-20% variation!)

##### 2. Minimum Diode Current Requirement:

Diodes need minimum current (typically 5-10mA) to maintain proper  $V_f$ :

- If load steals too much current, diodes starve
- Forward voltage drops below expected value
- Regulation collapses

##### 3. Constant Power Waste:

Series resistor always dissipates power:

$$P_{R_S} = I_{total}^2 \times R_S = I_{total} \times (V_{in} - V_{out})$$

This power is wasted as heat regardless of load requirements. Very inefficient!

##### 4. Poor Input Voltage Regulation:

If input voltage varies:

- Current through resistor changes
- Diode current changes

- $V_f$  changes
- Output voltage changes

Better than voltage divider, but still poor compared to proper regulator.

### 5. Temperature Drift:

Forward voltage changes  $-2\text{mV}/^\circ\text{C}$ :

- 5 diodes =  $5 \times (-2\text{mV}/^\circ\text{C}) = -10\text{mV}/^\circ\text{C}$  drift
- Over  $50^\circ\text{C}$  temperature range:  $500\text{mV}$  ( $0.5\text{V}$ ) change!
- Significant for precision applications

### Better Solution - Zener Diode:

Replace series diodes with single Zener diode:

- Much sharper I-V knee  $\rightarrow$  better regulation
- Wide range of voltages available ( $2.4\text{V}$  to  $200\text{V}$ )
- Still needs series resistor and minimum current
- Still wastes power (linear regulation)
- Better than series diodes, but not perfect

### Best Solution - Voltage Regulator IC:

Use dedicated voltage regulator (78xx series, LDO, switching regulator):

- Excellent regulation ( $\approx 1\%$  typically)
- Wide input voltage range
- Low dropout voltage (LDOs)
- Current limiting and thermal protection
- Switching types are highly efficient ( $\approx 90\%$ )

We'll learn about these in future sections!

## Practical Example & Numerical

### Example 1: 3.3V Reference Using 5 Diodes

**Design:** 12V input, 3.3V output using 5 silicon diodes

**Calculation:**

Expected output:  $V_{out} = 5 \times 0.66\text{V} = 3.3\text{V}$  (assuming  $V_f = 0.66\text{V}$  each at operating current)

Load current:  $50\text{mA}$  required

Minimum diode current:  $10\text{mA}$  (for regulation)

Total current:  $I_{total} = 50\text{mA} + 10\text{mA} = 60\text{mA}$

Series resistor:

$$R_S = \frac{V_{in} - V_{out}}{I_{total}} = \frac{12\text{V} - 3.3\text{V}}{60\text{mA}} = \frac{8.7\text{V}}{0.06\text{A}} = 145\Omega$$

Use standard:  $R_S = 150\Omega$

**Verification:**

$$I_{total} = \frac{12\text{V} - 3.3\text{V}}{150\Omega} = 58\text{mA}$$

$$I_{diodes} = 58\text{mA} - 50\text{mA} = 8\text{mA}$$

At  $8\text{mA}$ , each diode  $V_f \approx 0.65\text{V} \rightarrow$  total =  $5 \times 0.65\text{V} = 3.25\text{V}$

Close enough to  $3.3\text{V}$  target!

**Power dissipation:**

Resistor:  $P_R = 58\text{mA} \times 8.7\text{V} = 505\text{mW} \rightarrow$  use  $1\text{W}$  resistor

Diodes:  $P_{each} = 0.65\text{V} \times 58\text{mA} = 37.7\text{mW}$  each  $\rightarrow$  total =  $188\text{mW}$  across all 5

**Total wasted power:**  $505\text{mW} + 188\text{mW} = 693\text{mW}$ !

**Load power:**  $P_{load} = 3.3\text{V} \times 50\text{mA} = 165\text{mW}$

**Efficiency:**  $\eta = 165 / (165 + 693) = 19.2\%$  - terrible!

### Example 2: Regulation Performance Test

Same circuit, vary load current:

#### Case A: Light load (10mA)

$I_{diodes} = 58\text{mA} - 10\text{mA} = 48\text{mA}$  (high diode current!)

At  $48\text{mA}$ ,  $V_f \approx 0.72\text{V}$  each  $\rightarrow V_{out} = 5 \times 0.72\text{V} = 3.6\text{V}$

Output increased from  $3.3\text{V}$  to  $3.6\text{V}$  (+9%)

#### Case B: Heavy load (80mA)

$I_{total} = 58\text{mA}$  from resistor (fixed by  $R_S$ )

Load wants  $80\text{mA}$  but only  $58\text{mA}$  available!

Problem: Load steals all current, diodes get zero current

$V_f$  drops to 0.4-0.5V each  $\rightarrow V_{out} = 5 \times 0.5V = 2.5V$

Output dropped from 3.3V to 2.5V (-24%)

**Maximum load current:** Must be less than  $(I_{total} - I_{diode(min)})$

If  $I_{diode(min)} = 5mA$ :  $I_{load(max)} = 58mA - 5mA = 53mA$

**Conclusion:** Load current must stay between 10-53mA for acceptable regulation. Very narrow range!

**Example 3: Comparison with Zener Regulator**

**Replace 5 diodes with 3.3V Zener:**

Same circuit:  $12V \rightarrow 150\Omega \rightarrow \text{Zener (3.3V)} \rightarrow \text{Load}$

**Performance:**

Light load (10mA):  $V_{out} = 3.3V$  (Zener clamps tightly)

Heavy load (50mA):  $V_{out} = 3.3V$  (Zener maintains voltage)

Much better regulation! Zener's sharp knee provides stable voltage over wider current range.

**Still inefficient:** Same power waste in series resistor, but better regulation.

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

1. **Series diodes create reference:**  $V_{out} = n \times V_f$  (0.7V each). Simple but limited.
2. **Better than voltage divider:** Output less sensitive to load current changes. Diode  $V_f$  more stable than resistive division.
3. **Poor regulation:**  $V_f$  varies with current  $\rightarrow$  output voltage changes 10-20% with load. Not suitable for precision.
4. **Minimum current essential:** Diodes need 5-10mA minimum to maintain proper  $V_f$ . Load can't steal all current!
5. **Constant power waste:** Series resistor always dissipates  $(V_{in} - V_{out}) \times I_{total}$ . Very inefficient (~30% typical).
6. **Temperature sensitive:**  $V_f$  drifts -2mV/°C per diode. Multiple diodes multiply the drift.
7. **Zener is better:** Replace series diodes with Zener for tighter regulation, wider current range, more voltage options.
8. **Regulator IC is best:** For real applications, use proper voltage regulator IC (linear or switching) for efficiency and tight regulation.

**Interview Q&A:**

**Q: Why use diodes as voltage reference instead of voltage divider?**

A: Voltage divider output changes dramatically with load current (resistive division depends on current path). Diode forward voltage is more stable because it's determined by junction physics, not just Ohm's Law. When load current varies, diode current adjusts and  $V_f$  changes only logarithmically (slowly). Result: Better regulation than voltage divider, though still poor compared to Zener or regulator IC.

**Q: What limits the load current in a diode reference circuit?**

A: Series resistor provides total current  $I_{total} = (V_{in} - V_{out})/R_S$ . This splits between diodes and load. Diodes need minimum current (5-10mA) to maintain proper  $V_f$ . Therefore:  $I_{load(max)} = I_{total} - I_{diode(min)}$ . If load exceeds this, diodes starve,  $V_f$  collapses, regulation fails. Very limited load range!

**Q: Why is series diode reference so inefficient?**

A: Power waste has two components: (1) Series resistor constantly dissipates  $P_R = I_{total}(V_{in} - V_{out})$  regardless of load. (2) Diodes dissipate  $P_D = n \times V_f \times I_{diodes}$ . These are continuous losses (not related to useful load power). Efficiency typically ~30%. Linear voltage regulators have same problem but better regulation. Only switching regulators achieve high efficiency (~90%).

**Q: When would you use diode reference vs Zener vs regulator IC?**

A: Diode reference: Almost never in modern designs. Maybe for very non-critical bias voltage in legacy circuits. Zener: Simple regulation, low parts count, non-critical loads, ~100mA, cost-sensitive. Can tolerate power waste and moderate regulation. Regulator IC: Any real power supply, precision circuits, variable loads, ~100mA, where efficiency or tight regulation matters. Always the professional choice.

**Key Formulas:**

$$V_{out} = n \times V_f \quad (\text{n diodes in series})$$

$$R_S = \frac{V_{in} - V_{out}}{I_{load} + I_{diode(min)}}$$

$$I_{load(max)} = \frac{V_{in} - V_{out}}{R_S} - I_{diode(min)}$$

$$\eta = \frac{P_{load}}{P_{load} + P_{dissipated}} = \frac{V_{out} \times I_{load}}{V_{in} \times I_{total}}$$

## Topic 7-12: Practical Diode Applications

TL;DR (The Gist)

### Topic 7: Terminal Identification

- **Physical diode:** Band/stripe marks cathode (negative) terminal
- **LED:** Longer lead = anode, flat spot = cathode
- **Ohmmeter test:** Red probe on anode → reads low resistance (conducting)
- **Diode mode:** Displays  $V_f$  ( 0.6V) when red probe on anode

### Topic 8: Half-Wave Rectifier with Filter

- **Converts AC to DC:** Blocks negative half-cycle, passes positive
- **Components:** Transformer (step-down), diode, filter capacitor, load
- **Without filter:** Pulsating DC (unusable for most devices)
- **With filter cap:** Capacitor charges at peak, discharges through load → smooths ripple
- **Ripple frequency:** Same as AC input (50/60Hz for mains)

### Topic 9: Full-Wave Rectification

- **Center-tapped:** Two diodes, center-tap transformer, uses both half-cycles
- **Bridge rectifier:** Four diodes, no center-tap needed (most common)
- **Advantages:** Double frequency ripple (easier to filter), better efficiency
- **Bridge voltage loss:** Two diode drops ( 1.4V) vs one in half-wave
- **Ripple frequency:**  $2 \times$  input frequency (100/120Hz for mains)

### Topic 10: Voltage Multipliers (Doubler, Tripler)

- **Voltage doubler:**  $V_{out} \approx 2 \times V_{peak}$  without transformer step-up
- **Pump capacitors:** Alternately charge/discharge to stack voltages
- **Applications:** High voltage from low source (CRT, microwave, test equipment)
- **Limitation:** Can only supply low currents to high-impedance loads

### Topic 11: Signal Processing Circuits

- **Signal rectifier:** Extracts one polarity from AC waveform
- **Diode gates:** Pass higher of two voltages (OR function, battery backup)
- **Diode clamps:** Limit signal to specific voltage levels (protection)
- **Applications:** CMOS input protection, battery backup, signal conditioning

### Topic 12: Zener Diode Applications

- **Operates in breakdown:** Reverse biased at  $V_Z$ , clamps voltage
- **Voltage regulation:** Simple regulator with series resistor
- **Overvoltage protection:** Clamps transients, protects sensitive circuits
- **Reference voltage:** Precision voltage source for comparators, ADCs
- **Must limit current:** Always use series resistor, check power rating

## Detailed Explanation

## 2. Detailed Explanation

### Topic 7: Identifying Diode Terminals

#### Physical Markings:

- Band, stripe, or line marks CATHODE (negative) end
- Unmarked end is ANODE (positive)
- LED: Longer lead = anode, shorter = cathode, flat spot on package = cathode side
- Some diodes: Smaller diameter end may be cathode

#### Ohmmeter Test (Resistance Mode):

- Forward bias (Red→Anode, Black→Cathode): Low resistance (few hundred  $\Omega$ ), diode conducts
- Reverse bias (Red→Cathode, Black→Anode): OL (out of limits), very high resistance, diode blocks
- If both directions show low R: Diode shorted (failed)
- If both directions show OL: Diode open (failed)

#### Diode Mode Test:

- Meter symbol: diode icon
- Forward bias: Displays  $V_f$  ( 0.5-0.7V for Si, 0.3V for Ge, 0.2-0.4V for Schottky)
- Reverse bias: Displays OL (open circuit)
- More accurate than resistance mode for identifying terminals and testing functionality

### Topic 8: Half-Wave Rectifier with Filter Capacitor

#### Basic Half-Wave Rectifier:

- AC input → Diode → Load resistor

- Positive half-cycle: Diode conducts, current flows through load
- Negative half-cycle: Diode blocks, no current,  $V_{out} = 0$
- Result: Pulsating DC (one pulse per AC cycle)
- Peak output:  $V_{peak} - V_f$  where  $V_f$  is diode forward drop

**Problem:** Pulsating DC unusable for electronics (devices need constant voltage)

**Solution: Filter Capacitor**

Place large capacitor in parallel with load:

- Diode conducts (positive peak): Capacitor charges to peak voltage
- Voltage starts falling: Diode reverse biased (blocks), capacitor discharges through load
- Capacitor maintains voltage between peaks → smooths output
- Ripple voltage: AC component remaining on DC output

**Capacitor Selection:**

Time constant must be much larger than period:

$$R_L \times C \gg T = \frac{1}{f}$$

Where  $R_L$  is load resistance,  $f$  is AC frequency.

Larger  $C \rightarrow$  smaller ripple  $\rightarrow$  smoother DC

Typical values: 100 $\mu$ F to 10,000 $\mu$ F for power supplies (electrolytic capacitors)

**Ripple Calculation (Approximate):**

$$V_{ripple} \approx \frac{I_{load}}{f \times C}$$

Where  $f$  is AC frequency (50 or 60Hz for mains).

**Disadvantages of Half-Wave:**

- 50% of AC waveform wasted (blocked negative half)
- Large ripple frequency = AC frequency (hard to filter)
- Inefficient (power wasted)
- DC component in transformer (can saturate core)

**Topic 9: Full-Wave Rectification - Center-Tap and Bridge**

**CENTER-TAPPED FULL-WAVE:**

Components:

- Center-tapped transformer (secondary winding with center connection to ground)
- Two diodes (D1 and D2)
- Load resistor

Operation:

- Positive half-cycle: Top of secondary positive  $\rightarrow$  D1 conducts, D2 blocks  $\rightarrow$  current through load (downward)
- Negative half-cycle: Bottom of secondary positive  $\rightarrow$  D2 conducts, D1 blocks  $\rightarrow$  current through load (downward, same direction!)
- Both half-cycles used, current always same direction through load

Output:  $V_{DC(avg)} \approx 0.637 \times V_{peak}$  (one diode drop lost per half-cycle)

Ripple frequency:  $2f$  (100/120Hz for 50/60Hz mains)

Disadvantage: Requires expensive center-tapped transformer

**BRIDGE RECTIFIER (Most Common):**

Components: Four diodes (D1, D2, D3, D4) arranged in bridge, regular transformer (no center-tap)

Operation:

- Positive half-cycle: D1 and D2 conduct (series path), D3 and D4 block  $\rightarrow$  current through load
- Negative half-cycle: D3 and D4 conduct (series path), D1 and D2 block  $\rightarrow$  current through load (same direction!)

Voltage loss: TWO diode drops (current through two diodes in series each half-cycle)

$V_{out(peak)} = V_{in(peak)} - 2V_f \approx V_{in(peak)} - 1.4V$

Ripple frequency:  $2f$  (easier to filter than half-wave)

**Advantages:**

- No center-tap transformer needed (cheaper, more common)
- Both half-cycles used (more efficient than half-wave)
- Double ripple frequency  $\rightarrow$  easier to filter
- Available as single package (bridge module)

**Filter Capacitor:**

Same principle as half-wave, but charges twice per AC cycle:

- Smaller capacitor needed for same ripple
- Better DC output quality
- Typically use electrolytic caps (polarized!): 1000-10000 $\mu$ F for power supplies

### Why Electrolytic?

- Highest capacitance per volume (can fit large values)
- Cost-effective for large capacitance
- BUT: Polarized (must connect correctly or explodes!), higher ESR, limited high-frequency performance

### Topic 10: Voltage Multipliers

#### Voltage Doubler:

Circuit: AC source  $\rightarrow$  C1 and D1 (pump stage)  $\rightarrow$  C2 and D2 (output stage)

Operation:

- Negative half-cycle: D1 conducts, C1 charges to  $V_{peak}$  (with C1 negative on right side)
- Positive half-cycle: Input adds  $V_{peak}$  positive + C1 adds  $V_{peak}$  (stored charge) =  $2V_{peak}$  total  $\rightarrow$  D2 conducts, C2 charges to  $2V_{peak}$
- Output across C2:  $2V_{peak}$  DC

#### Voltage Tripler:

Add one more diode-capacitor stage: Output =  $3V_{peak}$

#### General Multiplier:

Can cascade stages to get  $n \times V_{peak}$  output

#### Applications:

- High voltage generation without step-up transformer
- CRT displays (need 10-30kV)
- Microwave oven (2-5kV for magnetron)
- Photomultiplier tubes, electrostatic applications
- Test equipment (high voltage probe power)

#### Limitations:

- Can only supply LOW currents (mA range typically)
- Output voltage drops significantly under load
- Regulation very poor
- Ripple voltage increases with each stage
- Only practical for high-impedance loads

### Why Low Current?

Each capacitor must charge through diodes during brief AC peaks. Limited charge transfer per cycle  $\rightarrow$  limited current capability. Increasing capacitor size helps but makes circuit bulky.

### Topic 11: Signal Processing - Rectifier, Gates, Clamps

#### SIGNAL RECTIFIER (for non-sinusoidal waveforms):

Example: Square wave  $\rightarrow$  differentiator (capacitor)  $\rightarrow$  produces positive and negative spikes  $\rightarrow$  diode rectifier  $\rightarrow$  only positive spikes pass through

Application: Edge detection, pulse generation

Issue: Diode forward drop (0.6V) clips small signals

Solution: Use Schottky diode (lower  $V_f$  0.3V) or biased diode (add compensating voltage with second diode)

#### DIODE GATES (Voltage Selection):

##### OR Gate Function:

Two voltage sources  $\rightarrow$  Diodes (anodes together)  $\rightarrow$  Output

Whichever input is higher conducts through its diode, lower voltage blocked.

Output =  $\text{MAX}(V_1, V_2) - V_f$

##### Application: Battery Backup:

Main supply (5V)  $\rightarrow$  D1  $\searrow$   $\rightarrow$  Load (Real-Time Clock) Backup battery (3V)  $\rightarrow$  D2  $\nearrow$

Normal: D1 conducts (5V  $\downarrow$  3V), battery does nothing Power fails: D1 blocks, D2 conducts, battery takes over seamlessly

Essential for RTC chips in computers that must keep time when PC is off.

#### DIODE CLAMPS (Voltage Limiting):

Circuit: Signal  $\rightarrow$  Series resistor  $\rightarrow$  Diode to reference voltage  $\rightarrow$  Output

Prevents output from exceeding (reference +  $V_f$ ) voltage.

Example: Clamp to +5.6V using 5V reference + diode:

- Signal below 5.6V: Diode reverse biased, signal passes through
- Signal exceeds 5.6V: Diode conducts, clamps output at 5.6V

Resistor limits current during clamping (prevents diode damage).

##### Application: CMOS Input Protection:

All modern CMOS ICs have diode clamps on inputs:

- Diode to VDD (clamps positive overvoltage)
- Diode to GND (clamps negative overvoltage)
- Protects sensitive input transistors from ESD (electrostatic discharge)

Without these, static electricity (thousands of volts!) would instantly destroy ICs during handling.

## Topic 12: Zener Diode Voltage Regulation and Applications

### Zener Characteristics:

- Forward biased: Acts like normal diode ( $V_f \approx 0.7V$ )
- Reverse biased below  $V_Z$ : Blocks like normal diode (nA leakage)
- Reverse biased at  $V_Z$ : Conducts heavily, voltage clamps at  $V_Z$
- Sharp breakdown knee  $\rightarrow$  excellent voltage clamping

### I-V Curve:

In reverse breakdown region, current can vary widely while voltage stays nearly constant at  $V_Z$ . This is the key to voltage regulation!

### SIMPLE VOLTAGE REGULATOR:

Circuit:  $V_{in} \rightarrow$  Series resistor  $R_S \rightarrow$  Zener (reverse biased)  $\text{--- Load} \rightarrow$  Ground

Operation:

- $R_S$  limits total current
- Zener clamps voltage at  $V_Z$
- Load sees constant  $V_Z$  despite input or load variations (within limits)

Design:

$$R_S = \frac{V_{in} - V_Z}{I_{load} + I_{Z(min)}}$$

Where  $I_{Z(min)}$  is minimum Zener current for proper regulation (typically 5-10mA).

**Example:** 15V input, 5.6V Zener, 50mA load

$I_Z$  minimum = 10mA

$R_S = (15 - 5.6)/(50 + 10) = 9.4V/60mA = 156\Omega \rightarrow$  use  $150\Omega$

Check Zener power:  $P_Z = V_Z \times I_Z = 5.6V \times 10mA = 56mW$  (safe if rated  $\geq 500mW$ )

### Limitations:

- Poor load regulation if load current varies widely (Zener current must vary to compensate)
- Maximum load current limited by  $(V_{in} - V_Z)/R_S - I_{Z(min)}$
- Inefficient (linear regulation, power wasted in  $R_S$ )
- Noisy output (Zener generates noise in breakdown)
- Input voltage variation affects regulation

### BETTER ZENER REGULATOR (with Transistor):

Add emitter follower transistor between Zener and load:

- Zener sets base voltage
- Transistor buffers load current (high current gain)
- Zener only needs to supply base current (small)
- Can drive much higher load currents
- Better regulation

This is the basis of linear voltage regulators (78xx series). We'll cover transistors and regulators in detail later!

### OVERVOLTAGE PROTECTION:

Place Zener across sensitive circuit:

- Normal voltage: Zener reverse biased, circuit operates normally
- Overvoltage transient: Zener conducts, clamps voltage at  $V_Z$
- Must have series resistor or fuse to limit current (or Zener destroys itself)

Protects against voltage spikes, reverse polarity (with series diode), ESD.

### REFERENCE VOLTAGE:

Zener provides stable reference for:

- Comparator threshold setting
- ADC reference voltage
- Precision voltage generation
- Bias voltage in analog circuits

Special precision Zeners (e.g., 1N829A) have very low temperature coefficient and tight voltage tolerance for demanding applications.

## Practical Example & Numerical

### Example 1: Half-Wave Rectifier Filter Design

#### Specifications:

- Input: 12VAC RMS (60Hz mains)
- Load: 100mA at 12VDC

- Maximum ripple: 1V peak-to-peak

#### Step 1: Peak voltage

$$V_{peak} = V_{RMS} \times \sqrt{2} = 12V \times 1.414 = 16.97V$$

#### Step 2: DC output (with diode drop)

$$V_{DC} \approx V_{peak} - V_f - V_{ripple}/2 = 16.97 - 0.7 - 0.5 = 15.77V$$

#### Step 3: Calculate filter capacitor

$$C = \frac{I_{load}}{f \times V_{ripple}} = \frac{0.1A}{60Hz \times 1V} = \frac{0.1}{60} = 1667\mu F$$

Use standard value: 2200 $\mu$ F or 3300 $\mu$ F (electrolytic, rated  $\geq 25V$ )

#### Step 4: Verify

With  $C = 2200\mu F$ :

$$V_{ripple} = \frac{0.1}{60 \times 0.0022} = 0.76V \quad \checkmark \text{ (under 1V spec)}$$

#### Example 2: Bridge Rectifier Power Supply

**Design:** 120VAC mains  $\rightarrow$  transformer  $\rightarrow$  bridge  $\rightarrow$  filter  $\rightarrow$  12VDC @ 2A

##### Step 1: Transformer selection

Need 12VDC output, 2 diode drops ( 1.4V), ripple allowance ( 2V):

Required peak:  $12 + 1.4 + 2 = 15.4V$

Required RMS:  $15.4/1.414 = 10.9V$  secondary

Choose: 12VAC secondary transformer (standard, gives margin)

Actual peak:  $12 \times 1.414 = 16.97V$

After bridge:  $16.97 - 1.4 = 15.57V$  peak

##### Step 2: Diode selection

Average current per diode in bridge  $\approx I_{DC}/2 = 2A/2 = 1A$

Peak current higher (capacitor charging spikes):  $3-5 \times \text{average} = 3-5A$

Choose: 1N5400 series (3A rated) or bridge module rated  $\geq 3A$

##### Step 3: Filter capacitor

For 1V ripple at 120Hz (2 $\times$  mains):

$$C = \frac{2A}{120Hz \times 1V} = \frac{2}{120} = 16,667\mu F$$

Use: 22,000 $\mu$ F (22mF) electrolytic, rated  $\geq 25V$

This is large! High current demands require huge capacitors.

#### Example 3: Zener Regulator Design

**Spec:** Regulate 20V input down to 12V, load 100mA

##### Step 1: Select Zener

Choose: 12V Zener, 1W power rating

##### Step 2: Determine currents

Zener minimum current for good regulation: 10mA

Total current:  $I_{total} = 100mA + 10mA = 110mA$

##### Step 3: Calculate resistor

$$R_S = \frac{20V - 12V}{110mA} = \frac{8V}{0.11A} = 72.7\Omega$$

Use: 68 $\Omega$  or 75 $\Omega$  (standard values)

With 75 $\Omega$ :

$$I_{total} = \frac{8V}{75\Omega} = 106.7mA$$

$$I_Z = 106.7 - 100 = 6.7mA$$

Close to 10mA target - acceptable.

##### Step 4: Power ratings

Zener:  $P_Z = 12V \times 106.7mA = 1.28W$

Wait! This exceeds 1W Zener rating. Problem!

**Better design:** Reduce load current or use transistor buffer (covered in transistor section).

Alternatively, for 1W Zener at 12V:  $I_{max} = 1W/12V = 83mA$

Leaves only  $83mA - 10mA = 73mA$  for load (not enough for 100mA spec).

**Conclusion:** Simple Zener regulator inadequate for this specification. Need transistor-assisted design.

## 4. Key Points (Interview Focus)

1. **Terminal ID:** Physical diode band = cathode. Ohmmeter: Red→anode reads low R. Diode mode: Red→anode reads  $V_f$ .
2. **Half-wave rectifier:** Blocks one AC half-cycle. Needs large filter cap (poor efficiency, 50% waveform wasted). Ripple at input frequency.
3. **Full-wave better:** Bridge uses 4 diodes, no center-tap. Both half-cycles utilized. Ripple  $2\times$  frequency → easier filtering. Industry standard.
4. **Bridge voltage loss:** Two diode drops ( 1.4V Si, 0.6V Schottky). Must account for in transformer selection.
5. **Filter cap sizing:**  $C = I_{load}/(f \times V_{ripple})$ . Larger C → smoother DC. High current → huge caps (10,000s of  $\mu F$ ).
6. **Voltage multipliers:** Doubler, tripler create high voltage from low AC source. Only for low-current high-impedance loads (mA range).
7. **Diode gates/clamps:** OR function (select higher voltage), clamping (limit voltage). Essential for CMOS protection, battery backup.
8. **Zener regulation:** Simple regulator with series R. Always need  $I_{Z(min)}$  (5-10mA). Limited load current, poor efficiency, noisy. Transistor buffer improves.
9. **Zener applications:** Voltage regulation, reference voltage, overvoltage protection. Must limit current! Check power rating:  $P_Z = V_Z \times I_Z$ .
10. **Electrolytic caps:** Polarized! Must connect + to + or explodes. Use for large values ( $>10\mu F$ ) in power supplies. Check voltage rating.

### Interview Q&A:

#### Q: Why use bridge rectifier instead of half-wave?

A: Bridge rectifies both AC half-cycles (half-wave wastes negative half), doubling output frequency to 2f. This makes filtering much easier - smaller capacitor achieves same ripple. Bridge also provides higher average DC output. Only disadvantage: two diode drops ( 1.4V) vs one ( 0.7V), but efficiency and performance gains far outweigh this. Bridge is industry standard for AC-DC power supplies.

#### Q: How do you size the filter capacitor in a rectifier?

A: Use  $C = I_{load}/(f \times V_{ripple})$  where f is ripple frequency (input freq for half-wave,  $2\times$  for full-wave). Larger C → smaller ripple. Example: 1A load, 120Hz full-wave, 1V ripple →  $C = 1/(120 \times 1) = 8333\mu F$ , use 10,000 $\mu F$ . High current demands huge capacitors. Verify capacitor's ripple current rating (heating from AC component).

#### Q: Explain how a Zener diode regulates voltage.

A: Zener operated in reverse breakdown where I-V curve is nearly vertical - current can vary widely while voltage stays constant at  $V_Z$ . Series resistor sets total current:  $I_R = (V_{in} - V_Z)/R_S$ . This splits between Zener and load. When load current increases, Zener current decreases proportionally, maintaining  $V_Z$ . Zener must have minimum current ( 5-10mA) for sharp regulation. If load steals all current, regulation fails.

#### Q: What are limitations of simple Zener regulator?

A: (1) Limited load current - restricted by series resistor and Zener power rating. (2) Poor load regulation - output voltage varies with load current changes. (3) Inefficient - power wasted in series resistor as heat (linear regulation). (4) Noisy - Zener generates noise in breakdown. (5) Poor line regulation - input voltage variations affect output. For better performance, use transistor buffer or proper regulator IC (78xx series, LDO).

#### Q: Why do voltage multipliers only work with low currents?

A: Each capacitor charges through diodes only during brief AC voltage peaks. Limited charge transferred per cycle restricts current capability. Output voltage drops significantly under load as capacitors can't maintain charge. Increasing capacitor size helps but makes circuit bulky and expensive. Practical only for high-impedance loads ( $M\Omega$  range) needing high voltage at low current (CRT displays, test equipment, photomultipliers).

### Key Formulas:

$$\text{Ripple voltage: } V_{ripple} \approx \frac{I_{load}}{f \times C}$$

$$\text{Filter cap: } C = \frac{I_{load}}{f \times V_{ripple}}$$

$$\text{DC from full-wave: } V_{DC(avg)} = 0.637 \times V_{peak} - V_{diodes}$$

$$\text{Zener resistor: } R_S = \frac{V_{in} - V_Z}{I_{load} + I_{Z(min)}}$$

$$\text{Zener power: } P_Z = V_Z \times I_Z \leq P_{Z(max)}$$

# Section 12: More Circuits with Diodes!

## Diode Limiter (Clipping Circuit)

TL;DR

A **diode limiter (clipper)** clips or limits the amplitude of AC signals to a desired level. When placed in **parallel** with the load, it clips portions of the waveform by conducting during certain half-cycles. **Positive clippers** limit the positive amplitude to  $\sim 0.7$  V (diode forward voltage), while **negative clippers** limit the negative amplitude. **Dual clippers** use two diodes in opposite directions to clip both positive and negative portions. **Biased clippers** add DC voltage sources or Zener diodes to adjust the clipping level to any desired threshold, enabling precise waveform shaping for signal processing applications.

**Key equation:**  $V_{clip} = V_{bias} + V_f$  where  $V_f \approx 0.6\text{--}0.7$  V

### Detailed Explanation

#### 2. Detailed Explanation

##### 1. Basic Clipper Operation:

Unlike rectifiers where diodes are in series with the source, clippers place diodes in **parallel** with the load/output. The diode conducts when forward biased, creating a low-resistance path that **clips** the voltage at that node to the diode forward voltage drop.

**Positive Clipper:** Diode anode connected to signal, cathode to ground. During positive half-cycle when  $V_{in} > V_f$  ( $0.7$  V), diode conducts, clamping output to  $0.7$  V. During negative half-cycle, diode is reverse biased (open circuit), so full negative voltage appears at output. Result: positive peaks clipped to  $0.7$  V, negative peaks pass unchanged.

**Negative Clipper:** Diode reversed (cathode to signal, anode to ground). During positive half-cycle, diode is reverse biased so full positive voltage passes. During negative half-cycle when  $V_{in} < -V_f$ , diode forward biased, clamping output to  $-0.7$  V. Result: negative peaks clipped to  $-0.7$  V, positive peaks pass unchanged.

**Dual Clipper:** Two diodes in opposite directions (parallel, opposite polarity). Clips both positive and negative portions simultaneously to  $\pm 0.6\text{--}0.7$  V, converting sine wave to approximately square wave.

##### 2. Biased Clipping:

To clip at levels other than  $\pm 0.7$  V, add DC voltage source in series with diode:

- Clipping level:  $V_{clip} = V_{bias} + V_f$
- For 3 V positive clip: Use 2.3 V battery + diode ( $2.3 + 0.7 = 3$  V)
- For asymmetric clipping: Different bias voltages on positive/negative clippers
- Battery polarity must match diode polarity for voltages to add

##### 3. Zener Diode Clippers:

Practical circuits use **Zener diodes** instead of batteries:

- Zener acts as voltage reference at breakdown voltage  $V_Z$
- Clipping level:  $V_{clip} = V_Z + V_f$  (Zener breakdown + forward diode drop)
- Example: 3 V Zener + regular diode clips at  $3 + 0.6 = 3.6$  V
- Zeners available 2.4–33 V range with 1–5% tolerance
- Must include current-limiting resistor to prevent Zener damage
- Compact, no battery needed, provides stable reference

##### 4. Design Considerations:

- Series resistor limits current through conducting diode
- Check diode reverse voltage rating ( $V_{BR}$ ) exceeds peak reverse voltage
- For ideal clipping at 0 V would need ideal diode (no forward voltage drop)
- Actual clipping occurs at  $V_f$  due to real diode characteristics
- Multiple series diodes increase threshold (e.g., 2 diodes = 1.4 V clip level)

### Practical Examples & Numerical

#### Example 1: Basic Positive Clipper

Given: 5 V peak AC signal, silicon diode ( $V_f = 0.7$  V), 1 k $\Omega$  series resistor

Circuit: Diode in parallel with output (anode to signal, cathode to ground)

**Positive half-cycle:**

- When  $V_{in} > 0.7$  V, diode conducts
- Output voltage clamped to 0.7 V
- Current through resistor:  $I = \frac{5-0.7}{1k} = 4.3$  mA
- Current flows through diode to ground

**Negative half-cycle:**

- Diode reverse biased (open circuit)
- Full  $-5$  V appears at output
- No current flows through diode

Result: Output waveform has  $+0.7$  V maximum,  $-5$  V minimum

**Example 2: Dual Clipper for Square Wave**

Given: 10 V peak AC input, two silicon diodes in opposite directions

Circuit: D1 (anode up), D2 (cathode up), both parallel to output

Operation:

- Positive peaks clipped to  $+0.6$  V by D1
- Negative peaks clipped to  $-0.6$  V by D2
- Output: approximately square wave  $\pm 0.6$  V
- Converts 10 V peak sine to 1.2 V peak-to-peak square wave

**Example 3: Biased Clipper with Zener**

Given: Need to clip positive peaks at 3.6 V, negative at  $-2.6$  V

Design:

- Positive clipper: 3 V Zener (reverse biased) + silicon diode in series
- Clip level:  $3 + 0.6 = 3.6$  V ✓
- Negative clipper: 2 V Zener + silicon diode (opposite direction)
- Clip level:  $-(2 + 0.6) = -2.6$  V ✓
- Include resistor for Zener current limiting
- Asymmetric clipping achieved without batteries

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- **Clipper vs Rectifier:** Clippers use diodes in **parallel** to limit voltage; rectifiers use diodes in **series** to block current directions
- **Clipping Level:** Determined by  $V_{bias} + V_f$  where  $V_f \approx 0.6-0.7$  V for silicon diodes. Without bias, clips at diode forward voltage only
- **Multiple Diodes:** Series connection of  $N$  diodes gives clip level  $N \times V_f$  (e.g., 2 diodes = 1.4 V threshold)
- **Zener Advantage:** Eliminates need for batteries, provides stable voltage reference 2.4-33 V range, compact and practical for production circuits
- **Reverse Voltage:** Must verify diode  $V_{BR}$  rating exceeds maximum reverse voltage to avoid breakdown damage during non-conducting half-cycle
- **Q: Why use clippers?** A: Signal conditioning, overvoltage protection, waveform shaping, noise limiting, level shifting in communication and control circuits
- **Q: How to choose bias voltage?** A:  $V_{bias} = V_{desired} - V_f$  where  $V_{desired}$  is target clipping level. For Zener: select  $V_Z$  closest to  $(V_{desired} - 0.6)$  V
- **Q: Dual clipper creates what waveform?** A: Approximately square wave by clipping both positive and negative peaks to  $\pm V_f$ , limited to small amplitude centered at 0 V

# Clamper Circuit (DC Restoration), Spike Generator, and Voltage Multipliers

TL;DR

**Clampers** shift entire AC waveforms up or down by adding DC offset without changing shape. Use capacitor + diode: capacitor charges to peak voltage during one half-cycle (diode conducts), then adds to input voltage during other half-cycle (diode blocks). **Positive clamper** shifts signal upward (0 to  $2V_m$ ), **negative clamper** shifts downward ( $-2V_m$  to 0). **Biased clampers** add extra DC battery for custom offset.

**Spike generators** use RC differentiator ( $\tau = RC \ll T_{pulse}$ ) to create short positive/negative spikes from square waves. Diode in series passes only positive spikes. Design rule:  $RC \leq T/10$  for sharp spikes.

**Voltage doublers** use two diodes and two capacitors to produce DC output =  $2V_{peak}$  from AC input. Each capacitor charges to  $V_{peak}$  on alternate half-cycles, voltages add in series. **Voltage triplers** extend to  $3V_{peak}$  with additional diode-capacitor stage. Low-current applications only.

**Key equations:** Clamper:  $V_{out} = V_{in} + V_C$ ; Spike:  $\tau = RC \leq T/10$ ; Doubler:  $V_{out} = 2V_{peak} - 2V_f$

## Detailed Explanation

### 2. Detailed Explanation

#### 1. Clamper Circuit (DC Restoration):

Clampers **shift** the DC level of AC signals without changing waveform shape. Key difference from clippers: clippers remove portions; clampers move entire waveform vertically.

##### Positive Clamper (shifts signal upward):

- Components: Capacitor in series with input, diode parallel to output (cathode to signal, anode to ground), load resistor
- Negative half-cycle: Diode forward biased, capacitor charges to  $V_m$  (peak voltage) in **inverse polarity**
- Positive half-cycle: Diode reverse biased (open), input voltage + capacitor voltage add
- Output:  $V_{out} = V_{in} + V_C = V_{in} + V_m$
- Result: AC signal shifted upward, range becomes 0 to  $2V_m$  (no negative excursion)
- Capacitor holds charge between cycles, maintaining offset

##### Negative Clamper (shifts signal downward):

- Circuit: Diode reversed (anode to signal, cathode to ground)
- Positive half-cycle: Diode conducts, capacitor charges to  $V_m$
- Negative half-cycle: Diode blocks, voltages add with same polarity
- Output shifted downward: range  $-2V_m$  to 0 (no positive excursion)

##### Biased Clamper:

- Add DC battery in series with diode for additional level shift
- $V_{out} = V_{in} + V_C + V_{bias}$
- Enables custom DC offset beyond standard clamping
- Constraint:  $V_{bias} < V_m$  to avoid reversed operation

**Key Principle:** Capacitor acts as voltage memory. Charges during conducting half-cycle, adds stored voltage to input during blocking half-cycle. Total swing unchanged ( $2V_m$ ), but DC level shifted.

#### 2. Spike Generator (RC Differentiator):

RC differentiator converts square wave edges into short spikes by responding to rate of change.

##### Circuit Configuration:

- Capacitor in series (input), resistor to ground (output taken across R)
- High-pass filter: passes rapid changes, blocks DC
- Time constant:  $\tau = RC$

##### Operation Principle:

- Rising edge (positive  $dV/dt$ ): Capacitor initially acts as short circuit, positive spike at output as capacitor starts charging through R
- Falling edge (negative  $dV/dt$ ): Capacitor discharges through R, creating negative spike
- Steady input:  $dV/dt = 0$ , capacitor fully charged/discharged, output = 0
- Spike duration determined by time constant relative to pulse width

##### Design for Sharp Spikes:

- Pulse width = T
- Full charge time =  $5\tau = 5RC$
- For sharp spikes:  $\tau \leq T/10$  (time constant  $\leq 1/10$  pulse width)

- Lower  $\tau$  relative to  $T$  = sharper, shorter spikes
- Higher  $\tau$  relative to  $T$  = broader, taller spikes approaching square wave
- Example: 40 Hz square ( $T = 25$  ms), for sharp spike need  $RC \leq 2.5$  ms

#### Positive Spikes Only:

- Add diode in series with RC circuit
- Diode blocks negative spikes (reverse biased)
- Only positive spikes (rising edges) pass through
- Application: Trigger pulses, clock edges, synchronization

### 3. Voltage Doubler:

Voltage doubler circuit produces DC output voltage = twice the peak AC input voltage using only diodes and capacitors (no transformer).

#### Circuit Components:

- Two diodes ( $D1, D2$ )
- Two capacitors ( $C1, C2$ ), typically large electrolytic (100  $\mu\text{F}$  range)
- AC input source
- Load resistor (simulates circuit being powered)

#### Operation (Half-Wave Voltage Doubler):

- **Positive half-cycle:**  $D1$  forward biased,  $C1$  charges to  $V_{peak}$  (peak input voltage).  $D2$  reverse biased, blocks  $C2$  discharge
- **Negative half-cycle:**  $D2$  forward biased,  $C2$  charges.  $C2$  sees input voltage PLUS voltage stored on  $C1$ , so charges to  $V_{peak}$
- **Output voltage:**  $C1$  and  $C2$  in series by KVL loop, voltages add:  $V_{out} = V_{C1} + V_{C2} = V_{peak} + V_{peak} = 2V_{peak}$
- Actual output:  $V_{out} = 2V_{peak} - 2V_f$  (accounting for two diode forward voltage drops)

#### Capacitor Selection:

- Value: Large enough to supply load current without excessive droop (100–1000  $\mu\text{F}$  typical)
- Voltage rating: Must exceed  $2V_{peak}$  with safety margin
- Electrolytic for high capacitance in small package
- Lower capacitance = more ripple, higher = better regulation but bulkier/costlier

### 4. Voltage Tripler:

Extends doubler principle to  $3V_{peak}$  output by adding one more diode-capacitor stage.

#### Operation:

- $C1$  charges to  $V_{peak}$
- $C2$  charges to  $2V_{peak}$  (sees input +  $C1$  voltage)
- $C3$  charges to  $V_{peak}$
- $C2$  and  $C3$  in series:  $V_{out} = 2V_{peak} + V_{peak} = 3V_{peak}$
- Actual:  $V_{out} = 3V_{peak} - 3V_f$  (three diode drops)

#### Practical Considerations:

- AC to DC boost converter (no transformer needed)
- Compact, lightweight, low cost compared to transformer
- Output voltage affected by diode forward voltage drops
- Use Schottky diodes ( $V_f \approx 0.3$  V) for better efficiency
- Load current limited—design for low-current applications only
- More stages = higher voltage but lower current capability and more ripple
- Applications: CRT displays, microwave ovens, high-voltage test equipment

## Practical Examples & Numerical

### Example 1: Positive Clamper

Given: 10 V peak AC input (200 Hz), 5  $\mu\text{F}$  capacitor, diode, 5  $\text{k}\Omega$  load

Circuit: Positive clamper (diode cathode to output, anode to ground)

#### First negative half-cycle:

- Input goes to  $-10$  V
- Diode forward biased, capacitor charges to 10 V
- Output:  $\approx -0.7$  V (diode forward voltage)

#### Positive half-cycle:

- Input goes to  $+10$  V

- Diode reverse biased (open circuit)
- Capacitor holds 10 V charge
- Output:  $V_{out} = V_{in} + V_C = 10 + 10 = 20 \text{ V}$

**Result:** Signal shifted upward from  $-10$ – $+10 \text{ V}$  to  $\approx 0$ – $20 \text{ V}$  range. DC level added without changing AC amplitude (20 V peak-to-peak maintained).

### Example 2: Spike Generator Design

Given: 40 Hz square wave ( $T = 25 \text{ ms}$ ), need sharp positive spikes

Design requirements:  $\tau = RC \leq T/10 = 2.5 \text{ ms}$

Choose:  $R = 1 \text{ k}\Omega$ , solve for  $C$ :

- $C = \frac{\tau}{R} = \frac{2.5 \times 10^{-3}}{1000} = 2.5 \text{ }\mu\text{F}$
- Use  $C = 2.2 \text{ }\mu\text{F}$  (standard value, gives  $\tau = 2.2 \text{ ms}$ )
- Ratio:  $\tau/T = 2.2/25 = 0.088$  (well below 0.1 threshold ✓)
- Add diode in series to block negative spikes

### Verification:

- Rising edge creates sharp positive spike duration  $\approx 3\tau = 6.6 \text{ ms}$
- Falling edge creates negative spike but diode blocks it
- Output: positive spikes only at rising edges
- For even sharper spikes: reduce  $C$  to  $1 \text{ }\mu\text{F}$  ( $\tau = 1 \text{ ms}$ , ratio = 0.04)

### Example 3: Voltage Doubler

Given: 15 V peak AC input, silicon diodes ( $V_f = 0.7 \text{ V}$ ), 100  $\mu\text{F}$  capacitors

Circuit: Half-wave voltage doubler

#### Positive half-cycle ( $V_{in} = +15 \text{ V}$ ):

- D1 conducts, C1 charges to  $15 - 0.7 = 14.3 \text{ V}$
- D2 reverse biased, blocks

#### Negative half-cycle ( $V_{in} = -15 \text{ V}$ ):

- D2 conducts
- C2 sees: input voltage ( $-15 \text{ V}$  relative to ground) + C1 voltage (14.3 V)
- C2 charges to approximately 14.3 V
- D1 reverse biased, C1 holds charge

#### Output voltage (no load):

- $V_{out} = V_{C1} + V_{C2} = 14.3 + 14.3 = 28.6 \text{ V}$
- Ideal:  $2 \times 15 = 30 \text{ V}$
- Loss:  $2 \times 0.7 = 1.4 \text{ V}$  from diode drops ✓
- DC output from AC input without transformer

**With load:** Output voltage will drop slightly due to capacitor discharge ripple. Larger capacitors reduce ripple but increase size/cost.

### Example 4: Voltage Tripler

Given: Same 15 V peak AC, extend doubler to tripler

#### Capacitor voltages:

- C1 charges to  $\approx 14 \text{ V}$  (one diode drop)
- C2 charges to  $\approx 28 \text{ V}$  (double voltage minus drop)
- C3 charges to  $\approx 14 \text{ V}$  (peak voltage minus drop)

#### Output:

- C2 and C3 in series for load
- $V_{out} = V_{C2} + V_{C3} = 28 + 14 = 42 \text{ V}$
- Ideal:  $3 \times 15 = 45 \text{ V}$
- Loss:  $3 \times 0.7 = 2.1 \text{ V}$  approx from three diode drops
- Triple the input voltage with just 3 diodes and 3 capacitors!

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- **Clamper vs Clipper:** Clampers **shift** entire waveform vertically (add DC offset); clippers **remove** portions (limit amplitude). Clamper doesn't change waveform shape or peak-to-peak voltage
- **Clamper Operation:** Capacitor charges to peak voltage when diode conducts, then adds stored voltage to input when diode blocks. DC level shifts but AC swing ( $2V_m$ ) remains constant
- **Spike Generator Design Rule:** Time constant  $\tau = RC$  must be  $\leq T/10$  where  $T$  is pulse width. Lower ratio

gives sharper spikes. Diode in series blocks unwanted polarity

- **Voltage Multiplier Principle:** Capacitors charge to peak voltage on alternate half-cycles using diode steering. Series connection of capacitors produces output = sum of capacitor voltages.  $N$  stages  $\rightarrow N \times V_{peak}$  (minus  $N \times V_f$ )
- **Multiplier Limitations:** Low current capability only (mA range). More stages = higher voltage but more ripple and lower current. Not suitable for high-power applications. Use transformer for high-current voltage conversion
- **Capacitor Selection:** Large electrolytic capacitors (100–1000  $\mu\text{F}$ ) needed to minimize ripple. Voltage rating must exceed peak output voltage. Larger  $C$  = better regulation but bigger/costlier
- **Q: When use clamper vs clipper?** A: Clamper for DC restoration in AC-coupled signals, level shifting for ADC input range, biasing signals to specific DC level. Clipper for overvoltage protection, waveform shaping, limiting noise
- **Q: Why voltage doubler instead of transformer?** A: Lighter, cheaper, more compact, no magnetic core. But limited to low current ( $\leq 100$  mA typical). Good for high-voltage low-current applications like CRT bias supplies
- **Q: How does capacitor charge in clamper?** A: During conducting half-cycle, diode provides low-resistance path allowing capacitor to charge rapidly to peak input voltage. Polarity depends on diode orientation. Capacitor holds charge during blocking half-cycle, acting as voltage source in series with input

# Section 13: Input and Output Impedance of a Circuit

## Input Impedance of a Circuit

TL;DR

**Input impedance** ( $Z_{in}$ ) is the combined effect of all resistances, capacitances, and inductances seen by a signal at the input of a circuit. Represented as a resistor to ground (conceptually, not physical component), it determines how much the circuit loads the source. **High input impedance** (typically  $\geq 10\times$  source impedance) is desired to avoid loading the signal source and attenuating the input voltage. Low input impedance creates voltage divider with source impedance, reducing signal strength before amplification. Input impedance varies with frequency due to reactive components (capacitors/inductors). Critical for weak signal amplification (microphones, sensors) where any voltage loss is significant.

**Key principle:**  $Z_{in}$  should be high to prevent signal attenuation via voltage divider effect

### Detailed Explanation

## 2. Detailed Explanation

### 1. Concept of Input Impedance:

Every circuit with input/output terminals has input and output impedance. These are **conceptual values** (measured in ohms), not physical resistors you can remove. They represent the combined electrical behavior of all internal components.

#### Representation:

- Shown as resistor connected from input terminal to ground
- Actually inside the circuit, but drawn externally for clarity
- For purely resistive circuits: called "input resistance"  $R_{in}$
- With reactive components: called "input impedance"  $Z_{in}$

#### What contributes to $Z_{in}$ :

- All resistors connected to input side
- Capacitive reactance:  $X_C = \frac{1}{2\pi fC}$  (decreases with frequency)
- Inductive reactance:  $X_L = 2\pi fL$  (increases with frequency)
- Combined impedance:  $Z_{in} = \sqrt{R^2 + (X_L - X_C)^2}$
- Frequency dependent due to reactive components
- At high frequencies, capacitor/inductor effects become significant

### 2. Why High Input Impedance is Important:

Signal sources (microphones, sensors, antennas, previous circuit stages) have internal source impedance. When connected to circuit input, source impedance and input impedance form **voltage divider**.

#### Voltage Divider Effect:

- Source has internal resistance  $R_s$  (or impedance  $Z_s$ )
- Circuit has input impedance  $Z_{in}$
- Voltage at circuit input:  $V_{in} = V_{source} \times \frac{Z_{in}}{R_s + Z_{in}}$
- If  $Z_{in}$  is low, significant voltage dropped across  $R_s$ , less reaches circuit
- If  $Z_{in}$  is high ( $\geq 10 \times R_s$ ), most voltage appears at input

#### Design Rule:

- $Z_{in} \geq 10 \times Z_{source}$  (minimum)
- Higher is better for weak signals
- Op-amps: typical  $Z_{in} = 10^6$  to  $10^{12} \Omega$  (excellent for weak signals)
- Audio inputs: typical 10 k $\Omega$  to 1 M $\Omega$
- Sensor interfaces: often  $>1 \text{ M}\Omega$  to avoid loading tiny signals

### 3. Critical for Weak Signals:

Microphones output 1–100 mV, sensors may output  $\mu\text{V}$  levels. Any voltage loss before amplification is problematic:

- Low  $Z_{in}$  loads source, reducing voltage significantly
- Example: 1 mV sensor signal with 10 k $\Omega$  source into 10 k $\Omega$  input loses 50% voltage (500  $\mu\text{V}$ )

- Same signal into 1 M $\Omega$  input: loses only 1% (990  $\mu$ V preserved)
- Signal-to-noise ratio degraded if input impedance too low
- Can't recover lost voltage by later amplification (noise amplified too)

#### 4. Frequency Dependence:

Input impedance changes with signal frequency when capacitors/inductors present:

- Capacitors:  $Z_C$  decreases at high frequency (shorts AC, blocks DC)
- Inductors:  $Z_L$  increases at high frequency (blocks AC, passes DC)
- Input impedance specification often given at specific frequency (e.g., 1 kHz)
- Bandwidth considerations: must maintain high  $Z_{in}$  over signal frequency range
- Parasitic capacitance at high frequencies can reduce  $Z_{in}$  unintentionally

### Practical Examples & Numerical

#### Example 1: Voltage Divider Effect with Low Input Impedance

Given: Signal source = 10 V AC, source impedance  $R_s = 1$  k $\Omega$ , amplifier input impedance variable

##### Case 1: High input impedance ( $Z_{in} = 1$ M $\Omega$ ):

- Voltage divider:  $V_{in} = 10 \times \frac{10^6}{10^3 + 10^6} = 10 \times \frac{10^6}{1.001 \times 10^6}$
- $V_{in} \approx 9.99$  V (essentially full 10 V signal)
- Voltage loss: 0.01 V (0.1% loss, negligible)

##### Case 2: Medium input impedance ( $Z_{in} = 50$ k $\Omega$ ):

- $V_{in} = 10 \times \frac{50k}{1k + 50k} = 10 \times \frac{50}{51}$
- $V_{in} = 9.8$  V
- Voltage loss: 0.2 V (2% loss, acceptable for many applications)

##### Case 3: Low input impedance ( $Z_{in} = 10$ k $\Omega$ ):

- $V_{in} = 10 \times \frac{10k}{1k + 10k} = 10 \times \frac{10}{11}$
- $V_{in} = 9.09$  V
- Voltage loss: 0.91 V (9.1% loss, significant attenuation)

##### Case 4: Very low input impedance ( $Z_{in} = 1$ k $\Omega$ ):

- $V_{in} = 10 \times \frac{1k}{1k + 1k} = 10 \times \frac{1}{2}$
- $V_{in} = 5$  V
- Voltage loss: 5 V (50% loss, severe attenuation, unacceptable!)

**Conclusion:** Rule of thumb confirmed:  $Z_{in} \geq 10 \times R_s$  maintains >90% voltage transfer

#### Example 2: Weak Microphone Signal

Given: Microphone output = 10 mV AC, microphone impedance = 200  $\Omega$ , need amplification

##### Amplifier A: $Z_{in} = 500$ $\Omega$

- $V_{in} = 10mV \times \frac{500}{200 + 500} = 10 \times \frac{500}{700}$
- $V_{in} = 7.14$  mV
- Lost 2.86 mV (28.6% signal loss before amplification)
- Poor design: violates 10 $\times$  rule

##### Amplifier B: $Z_{in} = 47$ k $\Omega$

- $V_{in} = 10mV \times \frac{47k}{0.2k + 47k} = 10 \times \frac{47}{47.2}$
- $V_{in} = 9.96$  mV
- Lost only 0.04 mV (0.4% signal loss, excellent)
- Good design:  $47k \gg 10 \times 200\Omega = 2k\Omega$  ✓

#### Example 3: Frequency-Dependent Input Impedance

Given: Amplifier with 100 k $\Omega$  resistor to ground, parallel 100 pF input capacitance

##### At 1 kHz (audio):

- $X_C = \frac{1}{2\pi fC} = \frac{1}{2\pi \times 10^3 \times 100 \times 10^{-12}}$
- $X_C = 1.59$  M $\Omega$  (very high, capacitor nearly open circuit)
- $Z_{in} \approx 100$  k $\Omega$  (resistor dominates, capacitor negligible)

##### At 1 MHz (RF):

- $X_C = \frac{1}{2\pi \times 10^6 \times 100 \times 10^{-12}}$
- $X_C = 1.59$  k $\Omega$  (low, capacitor shunts to ground)
- Parallel combination:  $Z_{in} = \frac{100k \times 1.59k}{100k + 1.59k} \approx 1.57$  k $\Omega$
- Input impedance drops dramatically at high frequency!

**Impact:** High-frequency signals attenuated by low  $Z_{in}$  due to parasitic capacitance. Important for wideband amplifiers

and RF circuits.

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- **Input Impedance Definition:** Combined effect of all R, C, L at circuit input, measured in ohms. Determines how much circuit loads the source signal. Not a physical component but conceptual representation of circuit's electrical behavior
- **High  $Z_{in}$  Requirement:** Typically  $Z_{in} \geq 10 \times Z_{source}$  to avoid voltage divider attenuation. Prevents loading weak signal sources (microphones, sensors, antennas, previous stages)
- **Voltage Divider Effect:** Source impedance  $R_s$  and input impedance  $Z_{in}$  divide voltage:  $V_{in} = V_{source} \times \frac{Z_{in}}{R_s + Z_{in}}$ . Low  $Z_{in}$  causes significant signal loss
- **Frequency Dependence:** Capacitive/inductive reactance changes with frequency, altering  $Z_{in}$ . Parasitic capacitance reduces  $Z_{in}$  at high frequencies. Must specify frequency when stating impedance value
- **Critical for Weak Signals:** Microphones (1–100 mV), sensors ( $\mu\text{V}$ –mV) require very high  $Z_{in}$  ( $>100 \text{ k}\Omega$ ). Any voltage loss before amplification is unrecoverable and degrades SNR
- **Q: Why can't we recover lost voltage by amplifying more?** A: Noise is also amplified. If signal attenuated before first stage, signal-to-noise ratio already degraded. High  $Z_{in}$  preserves original SNR
- **Q: What's typical input impedance for different circuits?** A: Op-amps:  $\text{M}\Omega$  to  $\text{T}\Omega$  (excellent); Audio amps: 10k–1M $\Omega$ ; Oscilloscope: 1M $\Omega$  — 10–20pF; RF circuits: 50 or 75  $\Omega$  (matched to transmission line)
- **Q: Is high  $Z_{in}$  always better?** A: Generally yes for voltage amplification. Exception: impedance matching for maximum power transfer (RF systems) requires matched impedances, not necessarily high  $Z_{in}$

# Output Impedance, Impedance Matching, and Measurement Techniques

TL;DR

**Output impedance** ( $Z_{out}$ ) is the impedance in series with a circuit's output, representing combined R/L/C at output side. **Low output impedance** (typically  $\leq 1/10$  load impedance) ensures strong signal delivery without voltage drop across  $Z_{out}$ . High  $Z_{out}$  causes voltage divider with load, wasting power internally.

**Impedance matching** ( $Z_{source} = Z_{load}$ ) maximizes **power transfer** (50% efficiency) for RF/transmission line applications. Prevents signal reflections on transmission lines. Mismatched impedances cause standing waves and reflected power that can damage source.

**Measurement methods:** Input impedance measured by inserting variable resistor in series, adjusting until output halves (then  $R_{var} = Z_{in}$ ). Output impedance measured by varying load until output halves at no-load value (then  $R_{load} = Z_{out}$ ). Requires signal generator and oscilloscope.

**Key equations:** Power transfer:  $P_{max} = \frac{V^2}{4Z}$  when matched; Reflection coefficient:  $\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}$

## Detailed Explanation

### 2. Detailed Explanation

#### 1. Output Impedance Concept:

Output impedance is the impedance seen looking back into a circuit's output terminals.

##### Representation:

- Shown as resistor in **series** with output (contrast: input impedance is to ground)
- Conceptual, not physical—represents combined effect of all components at output side
- Acts like internal resistance limiting current delivery capability
- Higher  $Z_{out}$  = weaker output drive, more voltage lost internally

##### What contributes to $Z_{out}$ :

- Output stage transistor resistance (emitter/source resistance)
- Resistors in series with output
- Reactive components (capacitors/inductors) at output
- Frequency dependent if reactive components present

#### 2. Why Low Output Impedance is Important:

Load impedance and output impedance form voltage divider, reducing voltage delivered to load.

##### Voltage Divider at Output:

- Circuit generates voltage  $V_{source}$  with output impedance  $Z_{out}$  in series
- Load impedance  $Z_{load}$  connected
- Voltage at load:  $V_{load} = V_{source} \times \frac{Z_{load}}{Z_{out} + Z_{load}}$
- If  $Z_{out}$  is high, significant voltage dropped internally, less reaches load
- If  $Z_{out}$  is low ( $\leq Z_{load}/10$ ), most voltage appears at load

##### Design Rule:

- $Z_{out} \leq Z_{load}/10$  (maximum)
- Lower is better for efficient voltage delivery
- Op-amps: typical  $Z_{out} < 100 \Omega$  (can drive low impedance loads)
- Audio power amps: often  $< 1 \Omega$  (drive 4–8  $\Omega$  speakers efficiently)
- Voltage regulators: milli-ohm range for stiff voltage output

##### Power Dissipation Issue:

- Power wasted in  $Z_{out}$ :  $P_{wasted} = I^2 Z_{out}$
- High  $Z_{out}$  means circuit heats itself instead of delivering power to load
- Efficiency:  $\eta = \frac{P_{load}}{P_{load} + P_{wasted}} = \frac{Z_{load}}{Z_{load} + Z_{out}}$
- Example:  $Z_{out} = 100 \Omega$ ,  $Z_{load} = 100 \Omega \rightarrow$  only 50% efficient

#### 3. Impedance Matching for Maximum Power Transfer:

Contrary to low  $Z_{out}$  rule, some applications require  $Z_{out} = Z_{load}$  for maximum **power** (not voltage) transfer.

##### Maximum Power Transfer Theorem:

- Power delivered to load:  $P_L = I^2 Z_L = \frac{V_{source}^2 Z_L}{(Z_{out} + Z_L)^2}$
- Taking derivative and setting to zero: maximum when  $Z_L = Z_{out}$
- At match:  $P_{max} = \frac{V_{source}^2}{4Z_{out}}$
- Efficiency at match: 50% (half power wasted in source, half to load)

- Seems wasteful but necessary for certain applications

#### When Impedance Matching is Required:

- RF transmission (antennas, coax cables): typically 50 or 75  $\Omega$  systems
- Transmission lines must be terminated with characteristic impedance  $Z_0$
- Audio transformers coupling stages (vintage equipment)
- Sensor interfaces for maximum power extraction
- Test equipment (signal generators, network analyzers)

#### 4. Transmission Line Effects:

Transmission lines (coax cables, twisted pair, PCB traces at high frequency) have characteristic impedance  $Z_0$ .

#### Proper Termination ( $Z_L = Z_0$ ):

- All energy propagates down line and absorbed by load
- No reflections, clean signal
- Maximum power delivered
- Common values: 50  $\Omega$  (RF), 75  $\Omega$  (video), 100–120  $\Omega$  (twisted pair Ethernet)

#### Mismatched Termination ( $Z_L \neq Z_0$ ):

- Reflection coefficient:  $\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}$
- $Z_L > Z_0$ : positive reflection (signal bounces back same polarity)
- $Z_L < Z_0$ : negative reflection (signal bounces back inverted)
- Standing waves on line (voltage/current vary along length)
- Power wasted, signal distortion, possible source damage from reflected power
- VSWR (Voltage Standing Wave Ratio):  $VSWR = \frac{1+|\Gamma|}{1-|\Gamma|}$  (1 = perfect match,  $\infty$  = poor)

#### 5. Measuring Input Impedance:

Equipment needed: Signal generator, oscilloscope (or AC voltmeter), variable resistor (decade box ideal)

##### Procedure:

1. Connect variable resistor in series between signal generator and circuit input
2. Set  $R_{var} = 0 \Omega$  initially
3. Connect oscilloscope across circuit output (or load)
4. Apply 1 kHz sine wave from generator, adjust amplitude for clear display
5. Note peak-to-peak output voltage  $V_{out1}$  with  $R_{var} = 0$
6. Increase  $R_{var}$  gradually while watching oscilloscope
7. When output drops to exactly  $V_{out1}/2$ , stop
8. Measure  $R_{var}$  with ohmmeter: this value equals  $Z_{in}$  at test frequency

**Theory:** When  $R_{var} = Z_{in}$ , voltage divider gives 50/50 split. Input voltage to circuit is half of generator voltage, output proportionally halves.

#### 6. Measuring Output Impedance:

Equipment: Signal generator (or drive circuit at normal operation), oscilloscope, variable load resistor (high power rating if measuring power amp)

##### Procedure:

1. Disconnect normal load, leave output open circuit
2. Connect oscilloscope across output terminals
3. Apply input signal, note output voltage  $V_{oc}$  (open circuit voltage)
4. Connect variable resistor across output, set to maximum resistance initially
5. Gradually reduce  $R_{load}$  while watching oscilloscope
6. When output drops to exactly  $V_{oc}/2$ , stop
7. Measure  $R_{load}$ : this value equals  $Z_{out}$  at test frequency

**Theory:** When  $R_{load} = Z_{out}$ , voltage divider gives 50/50 split. Half voltage dropped across internal  $Z_{out}$ , half across external load.

**Caution:** For power amplifiers, don't run at full power during test (can damage variable resistor). Use moderate input level sufficient for measurement.

## Practical Examples & Numerical

### Example 1: Output Impedance Effect on Load Voltage

Given: Amplifier generates 10 V output, output impedance  $Z_{out} = 200 \Omega$ , various loads

#### Load 1: $Z_{load} = 8 \Omega$ (speaker)

- $V_{load} = 10 \times \frac{8}{200+8} = 10 \times \frac{8}{208}$

- $V_{load} = 0.38 \text{ V}$  (only 3.8% of voltage delivered!)
- Power in speaker:  $P = \frac{(0.38)^2}{8} = 18 \text{ mW}$
- Power wasted in  $Z_{out}$ :  $P_{wasted} = \frac{(0.38/8)^2 \times 200}{1} \approx 450 \text{ mW}$
- Terrible efficiency, unsuitable for audio

**Load 2:**  $Z_{load} = 100 \Omega$

- $V_{load} = 10 \times \frac{100}{200+100} = 10 \times \frac{100}{300}$
- $V_{load} = 3.33 \text{ V}$  (33.3% voltage delivered)
- Still significant loss, but better

**Load 3:**  $Z_{load} = 2 \text{ k}\Omega$  (**10× rule**)

- $V_{load} = 10 \times \frac{2k}{200+2k} = 10 \times \frac{2000}{2200}$
- $V_{load} = 9.09 \text{ V}$  (90.9% voltage delivered ✓)
- Efficient voltage delivery, good design

### Example 2: Maximum Power Transfer

Given: Signal source  $V_s = 12 \text{ V}$ ,  $Z_{out} = 50 \Omega$ , variable load

**Case 1: Matched load** ( $Z_L = 50 \Omega$ ):

- Current:  $I = \frac{12}{50+50} = \frac{12}{100} = 0.12 \text{ A}$
- Voltage at load:  $V_L = 0.12 \times 50 = 6 \text{ V}$
- Power to load:  $P_L = \frac{6^2}{50} = 0.72 \text{ W}$
- Power in source:  $P_{source} = \frac{6^2}{50} = 0.72 \text{ W}$  (same!)
- Total power: 1.44 W, efficiency = 50%
- Maximum power delivered to load ✓

**Case 2: Higher load** ( $Z_L = 100 \Omega$ ):

- Current:  $I = \frac{12}{50+100} = 0.08 \text{ A}$
- Voltage at load:  $V_L = 0.08 \times 100 = 8 \text{ V}$
- Power to load:  $P_L = \frac{8^2}{100} = 0.64 \text{ W}$  (less than matched!)

**Case 3: Lower load** ( $Z_L = 25 \Omega$ ):

- Current:  $I = \frac{12}{50+25} = 0.16 \text{ A}$
- Voltage at load:  $V_L = 0.16 \times 25 = 4 \text{ V}$
- Power to load:  $P_L = \frac{4^2}{25} = 0.64 \text{ W}$  (less than matched!)

**Verification:** Maximum power (0.72 W) occurs at matched impedance (50  $\Omega$ ) ✓

### Example 3: Transmission Line Reflections

Given: 50  $\Omega$  coax cable, source matched 50  $\Omega$ , various terminations, signal = 5 V pulse

**Termination 1:**  $Z_L = 50 \Omega$  (**matched**):

- $\Gamma = \frac{50-50}{50+50} = 0$  (no reflection)
- All energy absorbed by load
- Clean pulse at load, no distortion
- Power delivered: maximum

**Termination 2:**  $Z_L = 200 \Omega$  (**too high**):

- $\Gamma = \frac{200-50}{200+50} = \frac{150}{250} = 0.6$  (positive reflection)
- 60% of voltage reflects back in same polarity
- Standing wave pattern on cable
- Power absorbed: less than matched case

**Termination 3:**  $Z_L = 10 \Omega$  (**too low**):

- $\Gamma = \frac{10-50}{10+50} = \frac{-40}{60} = -0.67$  (negative reflection)
- 67% of voltage reflects back inverted
- Severe standing waves
- Power wasted, distortion, potential source damage

**Termination 4: Open circuit** ( $Z_L = \infty$ ):

- $\Gamma = \frac{\infty-50}{\infty+50} \approx 1$  (total positive reflection)
- Voltage doubles at open end (5 V forward + 5 V reflected = 10 V)
- No power absorbed, all reflected

### Example 4: Measuring Input Impedance

Given: Amplifier unknown  $Z_{in}$ , 1 kHz signal generator, oscilloscope, decade box

**Procedure:**

- Set decade box  $R = 0 \Omega$
- Apply 1 kHz, 2 V signal

- Output reads 8 V (gain = 4)
- Increase decade box resistance
- At  $R = 22 \text{ k}\Omega$ , output drops to 4 V (half of 8 V)
- Therefore:  $Z_{in} = 22 \text{ k}\Omega$  at 1 kHz ✓

**Verification:** When  $R = Z_{in}$ , input voltage is  $2V \times \frac{22k}{22k+22k} = 1V$  (half), so output is  $1V \times 4 = 4V$  (half of 8V) ✓

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- **Output Impedance Definition:** Series impedance at circuit output representing combined R/L/C. Acts like internal resistance limiting current delivery. Low  $Z_{out}$  enables strong drive capability
- **Low  $Z_{out}$  Requirement:** Typically  $Z_{out} \leq Z_{load}/10$  to deliver voltage efficiently without internal voltage drop. Prevents power waste, ensures most signal reaches load. Critical for driving low-impedance loads (speakers, long cables)
- **Impedance Matching vs Low  $Z_{out}$ :** Two different goals! Matching ( $Z_{source} = Z_{load}$ ) maximizes **power** transfer (50% efficiency) for RF/transmission lines. Low  $Z_{out}$  ( $Z_{out} \ll Z_{load}$ ) maximizes **voltage** transfer (~90% efficiency) for general amplifiers
- **Maximum Power Transfer:** Occurs when  $Z_L = Z_{out}$ . Delivers  $P_{max} = \frac{V^2}{4Z_{out}}$  to load. Always 50% efficient (half power wasted in source). Required for RF systems to prevent reflections
- **Transmission Line Reflections:** Mismatch causes reflection coefficient  $\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}$ . Standing waves form, power reflected back, signal distortion, potential source damage. Match termination to line's  $Z_0$  for clean transmission
- **Measurement Principle:** Both  $Z_{in}$  and  $Z_{out}$  measured using half-voltage method. When test resistor equals unknown impedance, voltage divider creates 50/50 split, observable voltage halves
- **Q: Why are RF systems typically 50Ω?** A: Compromise between power handling (lower better) and loss (higher better) for coax cables. Standardization enables interoperability. 75 Ω used for video (optimized for loss)
- **Q: Can we have both high  $Z_{in}$  and low  $Z_{out}$ ?** A: Yes! Op-amps achieve this: MΩ input, <100 Ω output. Allows weak signal amplification with strong output drive. Best of both worlds for general-purpose amplifiers
- **Q: What happens if  $Z_{out}$  too high for speaker?** A: Damping factor reduced, poor bass control, voltage loss, power wasted as heat in amplifier. Speaker sees weak drive, can't produce full power. Want  $Z_{out} < 0.1 \text{ }\Omega$  for 8 Ω speaker ideally

# Section 14: First Order Filters

## Filter Fundamentals and Low-Pass Filters

TL;DR

**Filters** are frequency-selective circuits that pass desired frequencies while attenuating (blocking) unwanted ones. Four main types: **Low-pass** (passes low f, blocks high f), **High-pass** (passes high f, blocks low f), **Band-pass** (passes specific band), **Band-stop/notch** (blocks specific band).

**Low-pass RC filter:** Resistor in series, capacitor to ground. Capacitive reactance  $X_C = \frac{1}{2\pi fC}$  decreases with frequency, shunting high frequencies to ground. Cutoff frequency:  $f_c = \frac{1}{2\pi RC}$ . At  $f_c$ : output =  $0.707 \times$  input ( $-3$  dB), output power = half input power.

**Low-pass RL filter:** Inductor in series, resistor to ground. Inductive reactance  $X_L = 2\pi fL$  increases with frequency, blocking high frequencies. Cutoff:  $f_c = \frac{R}{2\pi L}$ . Same  $-3$  dB point behavior.

**Roll-off:** First-order filters attenuate at  $-20$  dB/decade ( $10\times$  frequency =  $1/10$  voltage) beyond cutoff.

**Key equations:** RC:  $f_c = \frac{1}{2\pi RC}$ ; RL:  $f_c = \frac{R}{2\pi L}$ ; Output:  $V_{out} = V_{in} \times \frac{X_C}{\sqrt{R^2 + X_C^2}}$

### Detailed Explanation

## 2. Detailed Explanation

### 1. Filter Concept:

Filters perform **frequency-selective signal processing**—removing unwanted frequency components while preserving desired ones.

#### Common Applications:

- Radio receivers: Select desired station, reject others (different frequencies)
- DC power supplies: Remove AC ripple noise from DC output
- Audio crossovers: Route bass to woofers, midrange to mids, treble to tweeters
- Noise removal: Filter out high-frequency switching noise from analog signals
- Anti-aliasing: Remove frequencies above Nyquist limit before ADC sampling

#### Four Filter Types:

- **Low-pass:** Passes  $f < f_c$ , blocks  $f > f_c$  (removes high-frequency noise)
- **High-pass:** Passes  $f > f_c$ , blocks  $f < f_c$  (AC coupling, removes DC)
- **Band-pass:** Passes  $f_{c1} < f < f_{c2}$ , blocks outside (radio tuning, audio EQ)
- **Band-stop (notch):** Blocks  $f_{c1} < f < f_{c2}$ , passes outside (60 Hz hum filter)

#### Passive vs Active Filters:

- **Passive:** Only R, L, C components. No gain, signal attenuated. Simple, cheap, no power needed
- **Active:** Use op-amps, transistors. Can provide gain, sharper roll-off, no inductors needed. Require power supply

### 2. Low-Pass RC Filter Construction:

#### Circuit Configuration:

- Resistor R in series with input
- Capacitor C from output node to ground (parallel with load)
- Forms voltage divider with frequency-dependent impedance

#### Operating Principle (Capacitive Reactance):

- Capacitor reactance:  $X_C = \frac{1}{2\pi fC}$  (inversely proportional to frequency)
- **Low frequencies:**  $X_C$  very high (capacitor nearly open circuit), acts like infinite resistor, signal passes to output unattenuated
- **High frequencies:**  $X_C$  very low (capacitor nearly short circuit), shunts signal to ground, little voltage at output
- DC ( $f = 0$ ):  $X_C = \infty$ , capacitor blocks completely, full DC voltage at output
- Transition smooth, not abrupt (roll-off region)

#### Cutoff Frequency $f_c$ :

- Defined as frequency where  $X_C = R$  (reactance equals resistance)
- Formula:  $f_c = \frac{1}{2\pi RC}$  (derived from  $X_C = R$ )
- At  $f_c$ : Output voltage =  $0.707 \times$  input ( $\frac{1}{\sqrt{2}}$  exactly)
- Output power =  $0.5 \times$  input (half power point)
- Also called  $-3$  dB point:  $20 \log(0.707) = -3.01$  dB

### Frequency Response:

- $f \ll f_c$ : Pass band (minimal attenuation, 0 dB)
- $f = f_c$ : -3 dB point ( $0.707 \times$  voltage)
- $f \gg f_c$ : Stop band (roll-off at -20 dB/decade)
- Ideal filter: brick wall transition. Real filter: gradual roll-off

### 3. Low-Pass RL Filter Construction:

#### Circuit Configuration:

- Inductor L in series with input (opposite position from RC filter)
- Resistor R from output node to ground
- Reactance increases with frequency, blocking high frequencies

#### Operating Principle (Inductive Reactance):

- Inductor reactance:  $X_L = 2\pi fL$  (directly proportional to frequency)
- **Low frequencies:**  $X_L$  very low (inductor nearly short circuit), signal passes to output easily
- **High frequencies:**  $X_L$  very high (inductor blocks), most voltage dropped across L, little at output
- DC ( $f = 0$ ):  $X_L = 0$ , inductor acts like wire, full DC voltage at output
- Opposite behavior from capacitor but same low-pass result

#### Cutoff Frequency:

- Occurs when  $X_L = R$  (inductive reactance equals resistance)
- Formula:  $f_c = \frac{R}{2\pi L}$  (derived from  $X_L = R$ )
- Same -3 dB characteristic as RC filter
- Same roll-off: -20 dB/decade beyond cutoff

#### RC vs RL Filters:

- RC filters more common: capacitors smaller, cheaper, no magnetic field
- RL filters useful in power applications: inductors handle high current
- Both achieve same frequency response shape
- Component positions swapped: reactive element determines filter type

### 4. Roll-Off and Decade Concept:

#### Decade (Frequency):

- One decade =  $10 \times$  frequency increase (order of magnitude)
- Examples: 100 Hz to 1 kHz, 1 kHz to 10 kHz, 10 kHz to 100 kHz
- Logarithmic scale (not linear): 1, 10, 100, 1k, 10k, 100k...
- Frequency response plots use log scale for x-axis

#### First-Order Roll-Off (-20 dB/decade):

- Beyond  $f_c$ , attenuation increases at constant rate
- -20 dB/decade = voltage drops to  $1/10$  every  $10 \times$  frequency increase
- Equivalently: -6 dB/octave (octave =  $2 \times$  frequency)
- Example:  $f_c = 1$  kHz,  $V_{out}$  at 10 kHz =  $0.1 \times V_{out}$  at 1 kHz
- Gentle slope—significant signal energy persists in stop band

#### Improving Roll-Off:

- Cascade multiple filter stages for sharper transition
- Second-order (two stages): -40 dB/decade
- Nth-order:  $-20N$  dB/decade roll-off
- Tradeoff: complexity, component count, cost

### 5. Calculating Filter Response:

Output voltage using voltage divider with frequency-dependent impedance:

#### RC Low-Pass:

- Impedance:  $Z_{total} = \sqrt{R^2 + X_C^2}$
- Output:  $V_{out} = V_{in} \times \frac{X_C}{Z_{total}} = V_{in} \times \frac{X_C}{\sqrt{R^2 + X_C^2}}$
- Substitute  $X_C = \frac{1}{2\pi fC}$  to find voltage at any frequency

#### RL Low-Pass:

- Impedance:  $Z_{total} = \sqrt{R^2 + X_L^2}$
- Output:  $V_{out} = V_{in} \times \frac{R}{Z_{total}} = V_{in} \times \frac{R}{\sqrt{R^2 + X_L^2}}$
- Substitute  $X_L = 2\pi fL$  to find voltage at any frequency

#### At Cutoff ( $f = f_c$ ):

- RC:  $X_C = R$ , so  $Z_{total} = \sqrt{R^2 + R^2} = R\sqrt{2}$
- $V_{out} = V_{in} \times \frac{R}{R\sqrt{2}} = \frac{V_{in}}{\sqrt{2}} = 0.707V_{in}$  ✓
- Same derivation for RL filter when  $X_L = R$

### Example 1: Designing RC Low-Pass Filter

**Requirement:** Remove 500 kHz noise from 5 kHz audio signal

**Design approach:** Set  $f_c$  well above audio (preserve it) but below noise (attenuate it). Choose  $f_c = 100$  kHz ( $20\times$  above audio,  $5\times$  below noise).

#### Component selection:

- Choose  $R = 1$  k $\Omega$  (standard, reasonable impedance)
- Calculate  $C$  from  $f_c = \frac{1}{2\pi RC}$ :
- $C = \frac{1}{2\pi f_c R} = \frac{1}{2\pi \times 10^5 \times 10^3}$
- $C = \frac{1}{6.28 \times 10^8} = 1.59 \times 10^{-9}$  F
- Use  $C = 1.5$  nF (closest standard value, gives  $f_c \approx 106$  kHz)

#### Verification at audio frequency (5 kHz):

- $X_C = \frac{1}{2\pi \times 5 \times 10^3 \times 1.5 \times 10^{-9}} = 21.2$  k $\Omega$
- $Z_{total} = \sqrt{(1k)^2 + (21.2k)^2} = \sqrt{1 + 449.44} \times 10^3 = 21.2$  k $\Omega$
- $V_{out} = V_{in} \times \frac{21.2k}{21.2k} \approx 0.999V_{in}$
- Audio preserved: 99.9% voltage passed ✓

#### Verification at noise frequency (500 kHz):

- $X_C = \frac{1}{2\pi \times 5 \times 10^5 \times 1.5 \times 10^{-9}} = 212$   $\Omega$
- $Z_{total} = \sqrt{(1k)^2 + (212)^2} = \sqrt{10^6 + 44944} = 1.02$  k $\Omega$
- $V_{out} = V_{in} \times \frac{212}{1020} = 0.208V_{in}$
- Noise attenuated to 20.8% (79.2% reduction) ✓

### Example 2: RL Low-Pass Filter Design

Given:  $L = 470$  mH,  $R = 10$  k $\Omega$ , find  $f_c$  and verify response

#### Cutoff frequency:

- $f_c = \frac{R}{2\pi L} = \frac{10 \times 10^3}{2\pi \times 470 \times 10^{-3}}$
- $f_c = \frac{10^4}{2.95} = 3.39$  kHz

#### At $f_c = 3.39$ kHz:

- $X_L = 2\pi \times 3.39 \times 10^3 \times 0.47 = 10$  k $\Omega$  (equals  $R$  ✓)
- $Z_{total} = \sqrt{(10k)^2 + (10k)^2} = 10k\sqrt{2} = 14.14$  k $\Omega$
- $V_{out} = V_{in} \times \frac{10k}{14.14k} = 0.707V_{in}$  ✓
- Confirms  $-3$  dB point

#### At $10 \times f_c = 33.9$ kHz (one decade up):

- $X_L = 2\pi \times 33.9 \times 10^3 \times 0.47 = 100$  k $\Omega$
- $Z_{total} = \sqrt{(10k)^2 + (100k)^2} \approx 100.5$  k $\Omega$
- $V_{out} = V_{in} \times \frac{10k}{100.5k} = 0.0995V_{in}$
- Attenuation:  $20 \log(0.0995) = -20.04$  dB from  $f_c$
- Confirms  $-20$  dB/decade roll-off ✓

### Example 3: $-3$ dB Point Calculation

Given: RC filter,  $R = 1$  k $\Omega$ ,  $C = 100$  nF,  $V_{in} = 5$  V

#### Find $f_c$ :

- $f_c = \frac{1}{2\pi \times 10^3 \times 100 \times 10^{-9}} = \frac{1}{6.28 \times 10^{-4}} = 1.59$  kHz

#### At $f_c$ , verify voltage and power:

- $V_{out} = 0.707 \times 5 = 3.54$  V
- Power in:  $P_{in} = \frac{V_{in}^2}{R_{load}}$  (assume  $R_{load} \gg R$ )
- Power out:  $P_{out} = \frac{V_{out}^2}{R_{load}} = \frac{(0.707V_{in})^2}{R_{load}} = 0.5 \times \frac{V_{in}^2}{R_{load}}$
- $P_{out} = 0.5P_{in}$  (half power point ✓)
- Decibels:  $10 \log(0.5) = -3.01$  dB ✓

**Physical meaning:** At cutoff, half the input power delivered to load, half dissipated in filter components. Voltage reduced by factor  $\sqrt{2}$  because power proportional to  $V^2$ .

## 4. Key Points (Interview Focus)

- **Filter Purpose:** Frequency-selective signal processing. Passes desired frequencies, attenuates unwanted. Essential for noise removal, band selection, DC blocking, anti-aliasing
- **Low-Pass Filter:** Passes low  $f$ , blocks high  $f$ . RC: cap to ground shunts high  $f$ . RL: inductor in series blocks high  $f$ . Both achieve same response with different reactive elements
- **Cutoff Frequency:**  $f_c$  where output =  $0.707 \times$  input ( $-3$  dB voltage, half power). RC:  $f_c = \frac{1}{2\pi RC}$ . RL:  $f_c = \frac{R}{2\pi L}$ . Defines transition from pass band to stop band
- **$-3$  dB Point Significance:** Half-power point ( $P_{out} = 0.5P_{in}$ ). Voltage =  $\frac{V_{in}}{\sqrt{2}}$  because  $P \propto V^2$ . Standard reference for bandwidth specification. Reactance equals resistance at this frequency
- **Roll-Off Rate:** First-order filter:  $-20$  dB/decade ( $-6$  dB/octave). Voltage drops to  $1/10$  per  $10\times$  frequency increase. Gradual transition—not brick wall. Nth-order:  $-20N$  dB/decade for sharper cutoff
- **Decade:**  $10\times$  frequency change on log scale. Examples:  $1$  kHz to  $10$  kHz,  $100$  Hz to  $1$  kHz. Logarithmic scaling natural for audio (octaves) and frequency response analysis
- **Q: Why 0.707 voltage equals half power?** A: Power  $P = \frac{V^2}{R}$ . If  $V = 0.707V_{in}$ , then  $P = \frac{(0.707)^2 V_{in}^2}{R} = 0.5 \frac{V_{in}^2}{R} = 0.5P_{in}$ . Factor  $\sqrt{2}$  squared gives 2
- **Q: RC vs RL filter—when use each?** A: RC more common (caps smaller, cheaper, no EMI). RL for high-current power applications, motor noise filtering. Both achieve same frequency response
- **Q: How choose cutoff frequency?** A: Place  $f_c$  between desired signal and noise. Rule:  $f_c \geq 10\times$  highest signal frequency for minimal signal attenuation. Roll-off provides gradual rejection above  $f_c$

# High-Pass Filters, Second-Order Filters, and Band-Pass Filters

## TL;DR

**High-pass filters** pass high frequencies, block low frequencies (opposite of low-pass). **RC high-pass:** Cap in series (blocks DC), resistor to ground. **RL high-pass:** Inductor to ground (shorts low f), resistor in series. Cutoff formulas same as low-pass: RC:  $f_c = \frac{1}{2\pi RC}$ , RL:  $f_c = \frac{R}{2\pi L}$ . Common use: AC coupling (remove DC bias), microphone circuits. Roll-off: +20 dB/decade below  $f_c$ .

**Second-order filters** cascade two identical first-order stages for steeper roll-off: -40 dB/decade (vs -20 dB). Cutoff shifts:  $f_{c(2nd)} = f_{c(1st)} \times 2^{1/(2-1)} = f_{c(1st)} \times \sqrt{2}$ . Nth-order: -20N dB/decade,  $f_{c(N)} = f_{c(1st)} \times 2^{1/(N-1)}$ . Sharper transition but more components, phase shift increases.

**Band-pass filters** pass frequencies between  $f_{c1}$  and  $f_{c2}$ , block outside band. Cascade high-pass ( $f_{c1}$ ) + low-pass ( $f_{c2}$ ) where  $f_{c1} < f_{c2}$ . Bandwidth:  $BW = f_{c2} - f_{c1}$ . **RLC band-pass:** Resonant circuit, center frequency  $f_0 = \frac{1}{2\pi\sqrt{LC}}$ . At resonance: LC impedance maximum, output peaks. Applications: radio tuning, audio EQ, wireless receivers.

**Key equations:** High-pass same as low-pass; 2nd-order:  $f_c = f_{c1} \times 2^{1/(N-1)}$ ; RLC:  $f_0 = \frac{1}{2\pi\sqrt{LC}}$

## Detailed Explanation

### 2. Detailed Explanation

#### 1. High-Pass RC Filter:

##### Circuit Configuration:

- Capacitor C in series with input (position swapped from low-pass)
- Resistor R from output node to ground
- Blocks DC and low frequencies, passes high frequencies

##### Operating Principle:

- Capacitor blocks DC ( $f = 0$ ,  $X_C = \infty$ , open circuit)
- Low frequencies: High  $X_C$ , most voltage dropped across C, little at output
- High frequencies: Low  $X_C$  (nearly short), signal passes through capacitor to output
- Cutoff frequency:  $f_c = \frac{1}{2\pi RC}$  (same formula as low-pass!)
- At  $f_c$ : output = 0.707 × input, same -3 dB point
- Below  $f_c$ : roll-off at +20 dB/decade (attenuation increases going lower)

##### AC Coupling Application:

- Removes DC component from AC signal
- Microphones: Block DC bias, pass audio AC
- Amplifier coupling: Prevent DC shift between stages
- Choose  $f_c$  well below lowest signal frequency to pass
- Example: Audio (20 Hz–20 kHz), set  $f_c = 2$  Hz to preserve bass

#### 2. High-Pass RL Filter:

##### Circuit Configuration:

- Resistor R in series with input
- Inductor L from output node to ground (position swapped from low-pass)

##### Operating Principle:

- DC and low frequencies:  $X_L$  very low (inductor shorts to ground), minimal output
- High frequencies:  $X_L$  very high (inductor blocks), signal goes through R to output
- Cutoff:  $f_c = \frac{R}{2\pi L}$  (same as RL low-pass formula)
- Less common than RC (inductors bulkier)

##### Component Swap Pattern:

- Low-pass: Reactive element to ground (shunts high f)
- High-pass: Reactive element in series (blocks low f)
- Capacitor and inductor positions swapped between filter types
- Same cutoff formulas, opposite frequency response

#### 3. Second-Order Filters:

Cascading multiple identical first-order filter stages creates higher-order filters with steeper roll-off.

##### Why Second-Order:

- First-order: -20 dB/decade roll-off (gradual)
- Significant signal energy persists in stop band
- Ideal filter: brick wall (vertical transition). Real: need sharper slope

- Solution: Add more filter stages in cascade

#### Roll-Off Improvement:

- Two identical stages:  $-40$  dB/decade ( $10\times$  frequency =  $1/100$  voltage)
- Three stages:  $-60$  dB/decade
- $N$  stages:  $-20N$  dB/decade
- Much sharper transition between pass band and stop band

#### Cutoff Frequency Shift:

- Each stage has same  $f_{c1}$  when standalone
- Cascaded system cutoff:  $f_{c(total)} = f_{c1} \times 2^{1/(N-1)}$
- For  $N = 2$ :  $f_{c(2nd)} = f_{c1} \times 2^{1/(2-1)} = f_{c1} \times 2 \approx 1.414f_{c1}$
- Cutoff shifts lower for low-pass, higher for high-pass
- Must account for this when designing to meet spec

#### Example Calculation:

- Single RC stage:  $f_c = 530$  Hz
- Add identical second stage
- New cutoff:  $f_c = 530/\sqrt{2} = 375$  Hz (low-pass shifts lower)
- Roll-off:  $-40$  dB/decade instead of  $-20$  dB/decade

#### Tradeoffs:

- Pros: Sharper roll-off, better stop-band rejection
- Cons: More components, cost, phase shift increases ( $90^\circ$  per stage),  $f_c$  shifts
- Passive filters: Signal attenuation accumulates (each stage loses energy)
- Active filters (op-amp): Can add gain to offset losses

#### 4. Band-Pass Filters:

Pass frequencies within specific band, block frequencies outside band.

##### Cascade Method (Wide Band):

- High-pass stage + Low-pass stage in series
- High-pass blocks low  $f$ , cutoff at  $f_{c1}$
- Low-pass blocks high  $f$ , cutoff at  $f_{c2}$
- Pass band:  $f_{c1} < f < f_{c2}$
- Bandwidth:  $BW = f_{c2} - f_{c1}$
- Requirement:  $f_{c1} < f_{c2}$  for pass band to exist
- Example:  $f_{c1} = 300$  Hz,  $f_{c2} = 3$  kHz, passes audio voice band

##### Design Considerations:

- $f_{c1}$  high-pass cutoff:  $\frac{1}{2\pi R_1 C_1}$
- $f_{c2}$  low-pass cutoff:  $\frac{1}{2\pi R_2 C_2}$
- Adjust  $R$  and  $C$  values to set desired band edges
- Roll-off:  $\pm 20$  dB/decade at each edge (first-order)

#### 5. RLC Resonant Band-Pass Filter:

Uses LC resonance for narrow-band filtering (tuned circuits).

##### Circuit Configuration:

- Series RLC:  $R$  in series,  $LC$  in series or parallel configuration
- Parallel LC tank: Impedance maximum at resonance
- Output taken across  $LC$  (high impedance at  $f_0$ )

##### Resonance Principle:

- At resonance:  $X_L = X_C$  (reactances cancel)
- $2\pi f_0 L = \frac{1}{2\pi f_0 C}$
- Solve for  $f_0$ :  $f_0 = \frac{1}{2\pi\sqrt{LC}}$  (resonant frequency)
- At  $f_0$ :  $LC$  combination has maximum impedance, output voltage peaks
- Below/above  $f_0$ : Impedance drops, signal attenuated

##### Bandwidth and Q Factor:

- Bandwidth:  $BW = \frac{f_0}{Q}$  where  $Q$  is quality factor
- $Q = \frac{X_L}{R} = \frac{2\pi f_0 L}{R}$  (higher  $Q$  = narrower bandwidth)
- High  $Q$ : Sharp, narrow peak (selective tuning)
- Low  $Q$ : Broad, wide peak (less selective)
- Applications: Radio receivers ( $Q = 10-100$ ), crystal filters ( $Q \gg 10,000$ )

##### Frequency Response:

- Phase shift:  $0^\circ$  at  $f_0$ ,  $+90^\circ$  below (capacitive),  $-90^\circ$  above (inductive)

- Roll-off: Second-order characteristic ( $\pm 40$  dB/decade from center)
- Symmetric response around  $f_0$  on log scale
- Geometric mean:  $f_0 = \sqrt{f_{c1} \times f_{c2}}$  where  $f_{c1}$ ,  $f_{c2}$  are  $-3$  dB points

#### Applications:

- Radio tuning: Select station frequency, reject adjacent channels
- Wireless receivers: IF (intermediate frequency) filtering
- Audio equalizers: Boost/cut specific frequency bands
- Oscillators: Frequency-selective feedback
- Signal processing: Extract specific frequency component from complex signal

## Practical Examples & Numerical

### Example 1: High-Pass RC Filter (AC Coupling)

**Requirement:** Block DC, pass audio starting at 20 Hz

**Design:** Set  $f_c$  well below 20 Hz to minimize bass attenuation. Choose  $f_c = 2$  Hz.

#### Component selection:

- Choose  $R = 10 \text{ k}\Omega$  (typical for audio)
- $C = \frac{1}{2\pi f_c R} = \frac{1}{2\pi \times 2 \times 10^4} = 7.96 \text{ }\mu\text{F}$
- Use  $C = 10 \text{ }\mu\text{F}$  (larger than calculated for safety margin)
- Actual  $f_c = \frac{1}{2\pi \times 10^4 \times 10^{-5}} = 1.59 \text{ Hz}$  ✓

#### Verification at 20 Hz (lowest audio):

- $X_C = \frac{1}{2\pi \times 20 \times 10 \times 10^{-6}} = 796 \text{ }\Omega$
- $Z_{total} = \sqrt{(10k)^2 + (796)^2} \approx 10.03 \text{ k}\Omega$
- $V_{out} = V_{in} \times \frac{10k}{10.03k} = 0.997V_{in}$
- Only 0.3% attenuation at 20 Hz, bass preserved ✓

### Example 2: Second-Order Low-Pass Filter

Given: Single RC stage with  $R = 300 \text{ }\Omega$ ,  $C = 1 \text{ }\mu\text{F}$ . Add identical second stage.

#### First-order cutoff:

- $f_{c1} = \frac{1}{2\pi \times 300 \times 10^{-6}} = 530 \text{ Hz}$
- Roll-off:  $-20$  dB/decade

#### Second-order cutoff:

- $f_{c2} = f_{c1} \times 2^{1/(N-1)} = 530 \times 2^{1/(2-1)}$
- $f_{c2} = 530 \times 2^1 = 530 \times 1.414 = 375 \text{ Hz}$
- Cutoff shifted lower by factor  $\sqrt{2}$
- Roll-off:  $-40$  dB/decade (steeper!)

#### Attenuation comparison at $10 \times f_c$ :

- First-order at 5.3 kHz:  $-20$  dB (voltage = 0.1)
- Second-order at 3.75 kHz:  $-40$  dB (voltage = 0.01)
- $100\times$  better rejection at one decade above cutoff

### Example 3: Band-Pass Filter (Cascade Method)

**Requirement:** Pass 300 Hz to 3 kHz (voice band), block outside

#### Design:

- High-pass stage:  $f_{c1} = 300 \text{ Hz}$  (blocks below)
- Low-pass stage:  $f_{c2} = 3 \text{ kHz}$  (blocks above)
- Bandwidth:  $BW = 3000 - 300 = 2700 \text{ Hz}$

#### High-pass component selection:

- Choose  $C = 1 \text{ }\mu\text{F}$
- $R = \frac{1}{2\pi f_c C} = \frac{1}{2\pi \times 300 \times 10^{-6}} = 530 \text{ }\Omega$
- Use  $R = 560 \text{ }\Omega$  (standard value)

#### Low-pass component selection:

- Choose  $R = 10 \text{ k}\Omega$
- $C = \frac{1}{2\pi f_c R} = \frac{1}{2\pi \times 3000 \times 10^4} = 5.3 \text{ nF}$
- Use  $C = 4.7 \text{ nF}$  (standard value, gives  $f_c \approx 3.4 \text{ kHz}$ )

**Result:** Cascade both stages. Frequencies 300 Hz–3 kHz pass with minimal attenuation. Below 300 Hz and above 3 kHz attenuated at  $-20$  dB/decade from each cutoff.

#### Example 4: RLC Band-Pass Filter (Radio Tuning)

Given:  $L = 500 \mu\text{H}$ ,  $C = 32 \text{ pF}$ ,  $R = 250 \Omega$

##### Resonant frequency:

- $f_0 = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{500 \times 10^{-6} \times 32 \times 10^{-12}}}$
- $f_0 = \frac{1}{2\pi\sqrt{16 \times 10^{-15}}} = \frac{1}{2\pi \times 4 \times 10^{-7.5}}$
- $f_0 = \frac{1}{2.51 \times 10^{-5}} = 39.8 \text{ kHz} \approx 40 \text{ kHz}$

##### Quality factor:

- $X_L = 2\pi f_0 L = 2\pi \times 40 \times 10^3 \times 500 \times 10^{-6} = 125.6 \Omega$
- $Q = \frac{X_L}{R} = \frac{125.6}{250} = 0.5$  (low Q, wide bandwidth)

##### Bandwidth:

- $BW = \frac{f_0}{Q} = \frac{40\text{k}}{0.5} = 80 \text{ kHz}$  (very wide)
- 3 dB points:  $f_{c1} \approx 0 \text{ kHz}$ ,  $f_{c2} \approx 80 \text{ kHz}$
- Broad filter, not very selective
- For narrow tuning: need higher L/C ratio or lower R (higher Q)

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

- High-Pass Filter:** Blocks DC/low f, passes high f. RC: cap in series (blocks DC). RL: inductor to ground (shorts low f). Cutoff formulas identical to low-pass. Common for AC coupling, removing DC bias
- Component Position Rule:** Low-pass: reactive element to ground. High-pass: reactive element in series. Same formulas, opposite frequency response. Swap positions to change filter type
- Second-Order Filters:** Cascade N identical stages  $\rightarrow$  roll-off =  $-20N$  dB/decade. Sharper transition between pass/stop bands. Cutoff shifts by  $2^{1/(N-1)}$  factor. Two stages:  $-40$  dB/decade, cutoff moves by  $\sqrt{2}$
- Second-Order Tradeoff:** Pros:  $10\times$  better stop-band rejection per decade. Cons: More components, cost, phase shift accumulates ( $90^\circ$  per stage), signal loss in passive designs. Active filters offset loss with gain
- Band-Pass Cascade:** High-pass + Low-pass in series.  $f_{c1}$  from high-pass,  $f_{c2}$  from low-pass. Bandwidth =  $f_{c2} - f_{c1}$ . Requires  $f_{c1} < f_{c2}$ . Good for wide-band applications
- RLC Resonant Band-Pass:** Resonance at  $f_0 = \frac{1}{2\pi\sqrt{LC}}$  where  $X_L = X_C$ . LC impedance peaks, output maximum. Quality factor  $Q = \frac{X_L}{R}$  determines bandwidth:  $BW = \frac{f_0}{Q}$ . High Q = narrow, selective; low Q = wide, broad
- Q: Why use second-order filter?** A: First-order roll-off ( $-20$  dB/decade) too gradual for many applications. Second-order ( $-40$  dB/decade) gives  $100\times$  better rejection one decade from cutoff. Critical for separating close frequencies
- Q: Band-pass: cascade vs resonant?** A: Cascade (high-pass + low-pass) for wide bandwidth, easy design. Resonant (RLC) for narrow bandwidth, sharp tuning (radio). Resonant has higher Q, better selectivity, fewer components
- Q: How does Q affect band-pass filter?** A: Higher Q  $\rightarrow$  narrower bandwidth  $\rightarrow$  more selective  $\rightarrow$  better adjacent channel rejection. Lower Q  $\rightarrow$  wider bandwidth  $\rightarrow$  less selective  $\rightarrow$  easier to tune. Radio AM: Q 10-20; FM: Q 50-100; Crystal: Q  $\geq 10,000$

# Section 15: More Advanced Filters

## Band-Pass Filter Review and Notch/Band-Stop Filters

TL;DR

**Band-pass filter (review):** Combines high-pass + low-pass to pass band  $f_{c1} < f < f_{c2}$ . Bandwidth  $BW = f_{c2} - f_{c1}$ . Center frequency  $f_0 = \sqrt{f_{c1} \times f_{c2}}$  (geometric mean). Cascade method has limitation: very narrow bandwidth causes high series resistance, limiting current drive capability. **RLC resonant band-pass** solves this: parallel LC tank at resonance has maximum impedance, output voltage peaks at  $f_0 = \frac{1}{2\pi\sqrt{LC}}$ . Quality factor  $Q = \frac{X_L}{R} = \frac{f_0}{BW}$  determines selectivity.

**Notch filter (band-stop):** Blocks specific frequency band, passes outside. Opposite of band-pass. **Series LC notch:** L and C in series to ground. At resonance  $f_0 = \frac{1}{2\pi\sqrt{LC}}$ , reactances cancel ( $X_L = X_C$ ), LC acts as short circuit, shunting signal to ground. Output minimum at  $f_0$ . **Twin-T notch:** Two T-networks (RC low-pass — RC high-pass) creates deep notch without inductors. Common application: 50/60 Hz hum filter. Roll-off:  $\pm 20$  dB/decade from notch center.

**Key equations:** RLC resonance:  $f_0 = \frac{1}{2\pi\sqrt{LC}}$ ; Q-factor:  $Q = \frac{X_L}{R} = \frac{f_0}{BW}$ ; Twin-T:  $f_0 = \frac{1}{2\pi RC}$

### Detailed Explanation

## 2. Detailed Explanation

### 1. Band-Pass Filter Cascade Limitation:

Simple cascade (high-pass + low-pass) works well for wide bandwidth but fails for narrow bands.

#### Problem with Narrow Bandwidth:

- To achieve narrow BW, need  $f_{c2}$  very close to  $f_{c1}$
- Example: 168 Hz to 1 kHz requires specific R and C values
- High-pass section needs large series resistance to set low  $f_{c1}$
- Low-pass section also contributes series resistance
- Total series R can reach 10–100 k $\Omega$  range
- Current capability:  $I = \frac{V}{R_{total}}$  severely limited
- Unable to drive loads, signal too weak for practical use
- Gain drops (can be  $-12$  dB or worse in pass band)

#### When Cascade Works:

- Wide bandwidth (decades apart):  $f_{c2} \gg f_{c1}$
- Example: 100 Hz to 10 kHz ( $BW = 9.9$  kHz, two decades)
- Low series resistance achievable
- Sufficient current drive for loads
- Minimal in-band attenuation

### 2. RLC Resonant Band-Pass Filter:

Uses parallel resonance to create high impedance at center frequency, enabling narrow bandwidth with strong output.

#### Parallel LC Resonance:

- At resonance:  $X_L = X_C$  (reactances equal)
- $2\pi f_0 L = \frac{1}{2\pi f_0 C} \rightarrow f_0 = \frac{1}{2\pi\sqrt{LC}}$
- Reactances equal but **opposite phase**, cancel out
- Parallel LC impedance **maximum** at  $f_0$  (purely resistive R remains)
- Below  $f_0$ : Capacitive (C dominates, low impedance)
- Above  $f_0$ : Inductive (L dominates, low impedance)
- Voltage divider: High impedance at  $f_0 \rightarrow$  maximum  $V_{out}$

#### Circuit Configuration:

- Series resistor R (limits current, sets Q)
- Parallel LC tank from output node to ground
- Output taken across LC tank
- At  $f_0$ : LC impedance peaks, voltage maximum
- Away from  $f_0$ : LC impedance drops, voltage attenuates

#### Quality Factor (Q):

- $Q = \frac{X_L}{R} = \frac{2\pi f_0 L}{R}$  at resonance
- Alternatively:  $Q = \frac{f_0}{BW}$  (ratio of center freq to bandwidth)
- Bandwidth:  $BW = \frac{f_0}{Q}$
- High Q ( $\geq 10$ ): Narrow bandwidth, sharp peak, very selective (radio tuning)
- Low Q ( $\leq 5$ ): Wide bandwidth, broad peak, less selective
- $-3$  dB points:  $f_1 = f_0 - \frac{BW}{2}$ ,  $f_2 = f_0 + \frac{BW}{2}$
- Symmetric around  $f_0$  on log frequency scale

#### Advantages of RLC Band-Pass:

- Narrow bandwidth achievable (Q can be 50–100+ for radio)
- Low series resistance (only R in circuit)
- Strong current drive capability
- Minimal in-band loss
- Single resonant circuit replaces complex cascade
- Adjustable: Tune  $f_0$  by varying L or C

#### 3. Series LC Notch Filter (Band-Stop):

Opposite of band-pass: blocks center frequency, passes frequencies outside band.

##### Series Resonance:

- L and C in **series**, placed to ground (parallel with output)
- At resonance:  $X_L = X_C$ , reactances cancel
- Series LC combination acts as **short circuit** (only R remains)
- Impedance **minimum** at  $f_0$
- Low impedance path shunts signal to ground
- Output voltage minimum (notch) at  $f_0$
- Below/above  $f_0$ : Impedance higher, signal passes to output

##### Frequency Response:

- Low frequencies: C blocks (high  $X_C$ ), signal passes
- High frequencies: L blocks (high  $X_L$ ), signal passes
- At  $f_0$ : LC shorts to ground, deep notch (can be  $-40$  dB or more)
- Notch depth depends on Q: Higher Q = narrower, deeper notch
- Roll-off:  $\pm 20$  dB/decade from notch center (first-order)

#### 4. Twin-T Notch Filter:

All-RC design, no inductors needed. Two T-networks in parallel create deep notch.

##### Circuit Configuration:

- **RC low-pass T**: Two series capacitors C, shunt resistor  $2R$  to ground
- **RC high-pass T**: Two series resistors R, shunt capacitor  $C/2$  to ground
- Both T-networks in parallel, outputs combined
- Components matched: Same R and C values (within tolerance)

##### Operating Principle:

- Low frequencies: Low-pass T passes, high-pass T blocks
- High frequencies: High-pass T passes, low-pass T blocks
- At notch frequency  $f_0 = \frac{1}{2\pi RC}$ : Both paths equal magnitude, opposite phase
- Signals cancel at output (destructive interference)
- Deep notch created (can reach  $-50$  to  $-60$  dB with precision components)
- Notch depth sensitive to component matching ( $\leq 1\%$  tolerance ideal)

##### Advantages of Twin-T:

- No inductors (smaller, cheaper, no magnetic interference)
- Good for low frequencies (50/60 Hz hum rejection in audio)
- Easy PCB implementation
- Tunable by adjusting R or C values

##### Disadvantages:

- Requires many components (6 total:  $3R$ ,  $3C$ )
- Component matching critical for deep notch
- Lower Q than LC notch (broader, less selective)
- In-band loss higher than LC designs
- Narrow notch difficult to achieve

##### Applications:

- 50/60 Hz power line hum removal (audio recording)

- Removing specific interference frequency
  - Biomedical instrumentation (filter out powerline artifacts)
  - Communications: Suppress carrier or single tone
- 5. Comparison: Band-Pass vs Notch:**
- **Band-pass:** Passes band, blocks outside. RLC: Parallel resonance, high  $Z$  at  $f_0$
  - **Notch:** Blocks band, passes outside. RLC: Series resonance, low  $Z$  at  $f_0$
  - Both use same resonance formula:  $f_0 = \frac{1}{2\pi\sqrt{LC}}$
  - Q factor determines selectivity for both
  - Complementary responses (inverse of each other)

## Practical Examples & Numerical

### Example 1: RLC Band-Pass Filter Design

**Requirement:** Radio tuner for 455 kHz IF (intermediate frequency), bandwidth = 10 kHz

**Design approach:**

- Center frequency:  $f_0 = 455$  kHz
- Bandwidth:  $BW = 10$  kHz
- Quality factor:  $Q = \frac{f_0}{BW} = \frac{455k}{10k} = 45.5$  (high selectivity ✓)

**Component selection:**

- Choose  $C = 100$  pF (typical for RF)
- Calculate  $L$  from  $f_0 = \frac{1}{2\pi\sqrt{LC}}$ :
- $L = \frac{1}{(2\pi f_0)^2 C} = \frac{1}{(2\pi \times 455 \times 10^3)^2 \times 100 \times 10^{-12}}$
- $L = \frac{1}{8.18 \times 10^{12} \times 10^{-10}} = \frac{1}{818} = 1.22$  mH
- Use  $L = 1.2$  mH (standard value)

**Calculate R for desired Q:**

- $X_L = 2\pi f_0 L = 2\pi \times 455 \times 10^3 \times 1.2 \times 10^{-3} = 3.43$  k $\Omega$
- $R = \frac{X_L}{Q} = \frac{3430}{45.5} = 75.4$   $\Omega$
- Use  $R = 75$   $\Omega$  (close match)

**Verification:**

- Actual Q:  $Q = \frac{3430}{75} = 45.7$  ✓
- Actual BW:  $BW = \frac{455k}{45.7} = 9.96$  kHz ✓
- -3 dB points:  $f_1 = 455 - 5 = 450$  kHz,  $f_2 = 455 + 5 = 460$  kHz
- Passes 450–460 kHz, rejects adjacent channels

### Example 2: Series LC Notch Filter (60 Hz Hum)

**Requirement:** Remove 60 Hz power line interference from audio signal

**Design:**

- Notch frequency:  $f_0 = 60$  Hz
- Choose  $C = 100$   $\mu$ F (large for low frequency)
- Calculate  $L$ :  $L = \frac{1}{(2\pi f_0)^2 C} = \frac{1}{(2\pi \times 60)^2 \times 100 \times 10^{-6}}$
- $L = \frac{1}{142129.6 \times 10^{-4}} = \frac{1}{14.21} = 70.4$  mH
- Use  $L = 68$  mH (standard value, gives  $f_0 \approx 61$  Hz)

**Q factor selection:**

- Want narrow notch to preserve nearby frequencies
- Choose  $R = 10$   $\Omega$  series resistance
- $X_L = 2\pi \times 60 \times 0.068 = 25.6$   $\Omega$
- $Q = \frac{25.6}{10} = 2.56$  (moderate, notch not too wide)
- $BW = \frac{60}{2.56} = 23.4$  Hz
- Notch range: 48–72 Hz (preserves most audio)

### Example 3: Twin-T Notch Filter

**Requirement:** Remove 1 kHz calibration tone without inductors

**Design:**

- Notch frequency:  $f_0 = 1$  kHz
- Choose  $R = 10$  k $\Omega$  (typical for audio)
- Calculate  $C$ :  $C = \frac{1}{2\pi f_0 R} = \frac{1}{2\pi \times 10^3 \times 10^4}$

- $C = \frac{1}{6.28 \times 10^7} = 15.9 \text{ nF}$
- Use  $C = 15 \text{ nF}$  (gives  $f_0 \approx 1.06 \text{ kHz}$ , close enough)

#### Component values:

- Low-pass T:  $C = 15 \text{ nF}$  ( $\times 2$  series),  $R = 20 \text{ k}\Omega$  ( $2R$  shunt)
- High-pass T:  $R = 10 \text{ k}\Omega$  ( $\times 2$  series),  $C = 7.5 \text{ nF}$  ( $C/2$  shunt)
- All components must match within 1% for deep notch
- Use precision 1% resistors and 5% or better capacitors

#### Expected performance:

- Notch depth:  $-40$  to  $-50 \text{ dB}$  at  $1 \text{ kHz}$  (with good matching)
- BW:  $150\text{--}300 \text{ Hz}$  (lower  $Q$  than LC, broader notch)
- Low/high frequencies:  $\sim -1 \text{ dB}$  attenuation (minimal impact)
- Advantage: No inductors, compact, easy to build

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

- **Band-Pass Cascade Limitation:** Simple high-pass + low-pass works for wide BW but fails for narrow. High series  $R$  limits current, causes gain loss. RLC resonant solves this with high impedance at center frequency
- **Parallel vs Series Resonance:** Parallel LC (band-pass): Maximum impedance at  $f_0$ , voltage peaks. Series LC (notch): Minimum impedance at  $f_0$ , shorts to ground. Same resonance formula, opposite impedance behavior
- **Q Factor Importance:**  $Q = \frac{f_0}{BW} = \frac{X_L}{R}$  determines selectivity. High  $Q$  ( $>10$ ): Narrow, sharp, selective. Low  $Q$  ( $<5$ ): Wide, broad, less selective. Critical for radio tuning, channel separation
- **Notch Filter Types:** LC notch: Series LC to ground, deep narrow notch, high  $Q$ . Twin-T: RC only, no inductors, moderate notch, lower  $Q$ . LC for narrow/deep, Twin-T for low freq and simplicity
- **Resonance Formula:**  $f_0 = \frac{1}{2\pi\sqrt{LC}}$  applies to both band-pass and notch. At resonance:  $X_L = X_C$  (reactances equal). Configuration determines whether impedance maximum (parallel) or minimum (series)
- **Twin-T Component Matching:** Requires precise component values (1% tolerance) for deep notch. Phase cancellation depends on exact magnitude/phase balance. Poor matching reduces notch depth significantly
- **Q: When use RLC band-pass vs cascade?** A: RLC for narrow bandwidth ( $BW \ll f_0/10$ ), high selectivity, radio/communication. Cascade for wide bandwidth (decades apart), simple design, audio filtering. RLC gives better performance but needs inductor
- **Q: Why series LC shorts at resonance?** A:  $X_L$  and  $X_C$  equal magnitude, opposite phase. Voltages across L and C cancel. Only resistance  $R$  remains in series impedance. Total  $Z$  minimized, acts like short circuit to AC
- **Q: How does Q affect notch depth?** A: Higher  $Q \rightarrow$  narrower notch  $\rightarrow$  deeper null at  $f_0 \rightarrow$  better selectivity. Lower  $Q \rightarrow$  wider notch  $\rightarrow$  shallower null  $\rightarrow$  less selective. Notch depth also depends on component matching and circuit losses

# Filter Topologies and Response Characteristics

TL;DR

**L, T,  $\pi$  topologies:** Multi-element filter structures beyond simple RC. **L-section:** Two elements (one series, one shunt). **T-section:** Three elements (series-shunt-series).  **$\pi$ -section:** Three elements (shunt-series-shunt).  $\pi$  topology common for low-pass power supply filtering: two caps + inductor, provides excellent ripple removal with minimal DC drop. T topology common for high-pass: two caps (series) + inductor (shunt). More elements = steeper roll-off but higher complexity. Cutoff:  $f_c = \frac{1}{\pi\sqrt{LC}}$  for  $\pi$ /T (note:  $\pi$ , not  $2\pi$ ).

**Crossover filters:** Audio application splitting frequency spectrum to different speakers. Low-pass to woofer (bass), band-pass to midrange, high-pass to tweeter (treble). Passive crossover: LC filters after amplifier, no power needed. Active crossover: Op-amp filters before amplifier(s), allows independent level control, sharper slopes. Crossover point: Frequency where adjacent filters intersect (typically at  $-3$  dB). Reduces energy waste, optimizes each driver's frequency range.

**Filter response types (Butterworth, Bessel, Chebyshev, Elliptic):** Different transfer functions optimize different characteristics. **Butterworth:** Maximally flat pass-band (no ripple), moderate roll-off, some phase distortion. **Bessel:** Best phase linearity (constant group delay), gentle roll-off, wide transition. **Chebyshev:** Sharpest roll-off, pass-band ripple (adjustable), large phase shift. **Elliptic:** Steepest roll-off, ripple in both pass-band and stop-band, most complex. Choice depends on application priority: flatness, phase, selectivity, or complexity.

**Key concepts:** Topology affects component count and performance; Crossover prevents frequency overlap; Response type determines trade-offs

## Detailed Explanation

### 2. Detailed Explanation

#### 1. Filter Topologies (L, T, $\pi$ ):

Beyond simple RC/RL filters, multi-element topologies provide better performance.

##### L-Section (Two Elements):

- One series element, one shunt (to ground) element
- Low-pass: Series inductor, shunt capacitor
- High-pass: Series capacitor, shunt inductor
- Simplest multi-element structure
- Roll-off:  $-20$  dB/decade (first-order characteristic)

##### T-Section (Three Elements):

- Two series elements, one shunt element between them
- Low-pass T: Series inductors ( $L/2$  each side), shunt capacitor  $C$
- High-pass T: Series capacitors ( $2C$  each side), shunt inductor  $L$
- Forms "T" shape in circuit diagram
- Better stop-band rejection than L-section
- Cutoff:  $f_c = \frac{1}{\pi\sqrt{LC}}$  (note:  $\pi$  not  $2\pi$ )

##### $\pi$ -Section (Three Elements):

- Two shunt elements, one series element between them
- Low-pass  $\pi$ : Shunt capacitors ( $2C$  each side), series inductor  $L$
- High-pass  $\pi$ : Shunt inductors ( $L/2$  each side), series capacitor  $C$
- Forms " $\pi$ " shape in circuit diagram
- Excellent for power supply filtering ( $\pi$  low-pass)
- Cutoff:  $f_c = \frac{1}{\pi\sqrt{LC}}$

##### $\pi$ Low-Pass for Power Supplies:

- Configuration:  $C1$  (input cap)  $\rightarrow L$  (series)  $\rightarrow C2$  (output cap)
- First capacitor  $C1$  bypasses AC ripple to ground
- Inductor  $L$  opposes current changes, blocks remaining AC
- Second capacitor  $C2$  provides final smoothing
- Multiple stages of filtering  $\rightarrow$  very low output ripple
- DC voltage: Minimal drop (only inductor wire resistance,  $m\Omega$  range)
- AC ripple: Heavily attenuated (can achieve  $\leq 1\%$  with proper values)
- Used in: AC-DC converters, linear regulators, low-noise supplies

**Advantages of LC Topologies:**

- No power dissipation in reactive elements (L, C)
- Contrast: RC wastes power in resistor
- Better efficiency for high-power applications
- Lower thermal noise than resistors
- Isolation: Transformer in  $\pi$  filter isolates input from output (EMI reduction)

**Disadvantages:**

- Inductors: Bulky, expensive, magnetic interference, limited Q
- Component tolerance: Affects cutoff accuracy
- PCB traces can be used for high-frequency filters (GHz range)

**2. Crossover Filters (Audio Application):**

Divide audio spectrum into frequency bands, route each band to appropriate speaker driver.

**Speaker Driver Types:**

- **Woofers:** Large cone, low frequencies (20–500 Hz), bass
- **Midrange:** Medium cone, mid frequencies (500–5 kHz), vocals/instruments
- **Tweeters:** Small dome, high frequencies (5–20 kHz), treble/cymbals
- Each driver optimized for specific frequency range
- Sending wrong frequencies damages drivers or sounds poor

**Crossover Network:**

- **Low-pass to woofer:** Blocks high f (would distort on large cone)
- **Band-pass to midrange:** Passes mid-range only (vocal clarity)
- **High-pass to tweeter:** Blocks low f (would damage small dome)
- Crossover points: Frequencies where adjacent filters intersect
- Example: Woofer cutoff 500 Hz, midrange 500 Hz–5 kHz, tweeter above 5 kHz

**Passive Crossover:**

- LC filters after amplifier, before speakers
- No power supply needed (passive components only)
- Single amplifier drives full spectrum, crossover divides
- Advantages: Simple installation, no power, reliable
- Disadvantages: Fixed crossover points, energy wasted in filters, difficult to adjust
- Component values depend on speaker impedance (4, 8, 16  $\Omega$ )
- Inductors used (not RC) for low loss, handle high current

**Active Crossover:**

- Op-amp based filters before amplifier(s)
- Requires power supply (active components)
- Splits signal at low level, separate amps for each driver
- Advantages: Adjustable crossover points, volume control per band, sharper slopes, equalization possible
- Disadvantages: More complex wiring, needs power, multiple amplifiers
- Used in: Competition car audio, professional PA systems, studio monitors

**Why Crossovers Matter:**

- Prevents amplifier from wasting energy on unusable frequencies
- Optimizes each driver for its frequency range
- Improves sound quality (clarity, detail, dynamics)
- Protects tweeters from damaging low frequencies
- Maximizes system efficiency and power handling

**3. Phase Shift in Filters:**

All filters introduce phase shift between input and output signals.

**Phase Shift Basics:**

- Resistive circuit: Voltage and current in phase (0° phase shift)
- Capacitive circuit: Current leads voltage by +90° (at high f)
- Inductive circuit: Current lags voltage by –90 (at high f)
- Filters use reactive elements → introduce phase shift

**Phase Shift in RC Filters:**

- Low-pass RC: Output lags input, –45 at  $f_c$ , approaches –90 at high f
- High-pass RC: Output leads input, +45° at  $f_c$ , approaches 0° at high f
- Phase shift varies with frequency
- First-order: Maximum 90° shift

- Higher-order: Phase shift accumulates ( $N$  stages  $\rightarrow N \times 90^\circ$  maximum)

#### **Why Phase Matters:**

- Audio: Phase distortion affects sound quality, imaging, transient response
- Control systems: Phase shift causes instability if excessive
- Communications: Phase distortion degrades signal integrity
- Pulse signals: Phase shift causes ringing, overshoot

#### **4. Filter Response Characteristics (Transfer Function Types):**

Different mathematical transfer functions optimize for different goals.

##### **Butterworth Filter ("Maximally Flat"):**

- Pass-band: Flat as possible, no ripple (0 dB throughout)
- Roll-off: Moderate steepness,  $-20N$  dB/decade for  $N$ th order
- Phase: Nonlinear (group delay varies with frequency)
- Selectivity: Good but not best
- Applications: General purpose, audio, data acquisition
- Trade-off: Flatness prioritized over roll-off steepness
- Most common choice when no specific constraint dominates

##### **Bessel Filter ("Linear Phase"):**

- Pass-band: Slight droop (not maximally flat)
- Roll-off: Gentlest of all (widest transition band)
- Phase: Best linearity, constant group delay (all frequencies delayed equally)
- Selectivity: Poorest (slow roll-off)
- Applications: Pulse/digital signals, video, step response critical
- Trade-off: Phase linearity prioritized, sacrifices selectivity
- Preserves waveform shape better than others
- Use when sufficient separation between pass-band and stop-band exists

##### **Chebyshev Filter ("Equiripple"):**

- Pass-band: Controlled ripple (0.1–3 dB typical, adjustable)
- Roll-off: Sharp, steeper than Butterworth
- Phase: Large nonlinearity near cutoff
- Selectivity: Excellent (sharp transition)
- Applications: RF filters, communications, where selectivity critical
- Trade-off: Steepness gained by accepting pass-band ripple
- Ripple amplitude sets roll-off steepness (more ripple = steeper)
- Type I: Pass-band ripple. Type II (inverse): Stop-band ripple instead

##### **Elliptic Filter ("Cauer"):**

- Pass-band: Ripple (like Chebyshev)
- Stop-band: Ripple too (zeros create notches)
- Roll-off: Steepest possible for given order
- Phase: Most complex, large distortion
- Selectivity: Best (narrowest transition)
- Applications: Very tight frequency spacing, must maximize selectivity
- Trade-off: Ultimate selectivity, sacrifices everything else
- Most components needed (complex network)
- Ripple in both bands adjustable independently

#### **5. Choosing Filter Response:**

Selection depends on application requirements.

##### **Decision Matrix:**

- **Flat pass-band critical:** Butterworth (audio, measurement)
- **Phase linearity critical:** Bessel (video, pulse, control systems)
- **Sharp selectivity needed:** Chebyshev (channel separation, close frequencies)
- **Ultimate selectivity:** Elliptic (adjacent channel rejection, compact design)
- **General purpose:** Butterworth (good all-around, simplest)

##### **Component Count:**

- Same order: Elliptic needs most components, Butterworth/Bessel similar
- To match Elliptic selectivity: Other types need higher order (more stages)
- Trade-off: Complexity vs performance

##### **Practical Considerations:**

- Component tolerance affects response (tighter tolerance = closer to ideal)
- Active implementation (op-amp) easier than passive for complex responses
- Simulation recommended before building
- Test with network analyzer to verify performance

## Practical Examples & Numerical

### Example 1: $\pi$ -Filter for Power Supply

**Requirement:** Filter 100 Hz ripple from rectified 120 VAC (after bridge rectifier), load = 1 A DC

**Design:**

- Choose  $f_c = 10$  Hz (decade below ripple frequency)
- Choose  $C = 1000 \mu\text{F}$  (large for low frequency, good ripple filtering)
- Calculate  $L$  from  $f_c = \frac{1}{\pi\sqrt{LC}}$ :
- $L = \frac{1}{(\pi f_c)^2 C} = \frac{1}{(\pi \times 10)^2 \times 10^{-3}}$
- $L = \frac{1}{986.96 \times 10^{-3}} = 1.01 \text{ H}$
- Use  $L = 1 \text{ H}$  choke (iron core, handles 1 A)

**$\pi$  Configuration:**

- $C1 = 1000 \mu\text{F}$  input cap (after rectifier)
- $L = 1 \text{ H}$  series choke
- $C2 = 1000 \mu\text{F}$  output cap (before load)
- Three-stage filtering for excellent ripple rejection

**Performance at 100 Hz:**

- $X_L = 2\pi \times 100 \times 1 = 628 \Omega$  (inductor blocks 100 Hz)
- $X_C = \frac{1}{2\pi \times 100 \times 10^{-3}} = 1.59 \Omega$  (caps shunt 100 Hz)
- Ripple attenuation:  $\sim 40 \text{ dB}$  (99% reduction)
- DC output: Smooth,  $\sim 1\%$  ripple typical

### Example 2: Three-Way Crossover Design

**Speakers:** 8  $\Omega$  woofer, midrange, tweeter. Crossover points: 500 Hz and 5 kHz

**Woofer (low-pass at 500 Hz):**

- Choose  $L = 2.5 \text{ mH}$
- Calculate  $C$ :  $f_c = \frac{1}{2\pi\sqrt{LC}} \rightarrow C = \frac{1}{(2\pi f_c)^2 L}$
- $C = \frac{1}{(2\pi \times 500)^2 \times 2.5 \times 10^{-3}} = \frac{1}{24.67} = 40.5 \mu\text{F}$
- Use  $C = 40 \mu\text{F}$  (series with woofer)

**Tweeter (high-pass at 5 kHz):**

- Choose  $C = 4 \mu\text{F}$  (series, blocks bass)
- Calculate  $L$  (shunt):  $L = \frac{1}{(2\pi f_c)^2 C}$
- $L = \frac{1}{(2\pi \times 5000)^2 \times 4 \times 10^{-6}} = \frac{1}{3947.8} = 0.253 \text{ mH}$
- Use  $L = 0.25 \text{ mH}$  (parallel with tweeter, shunts bass to ground)

**Midrange (band-pass 500 Hz–5 kHz):**

- Combine low-pass (5 kHz) + high-pass (500 Hz)
- $L1 = 0.25 \text{ mH}$  (high-pass, blocks  $\sim 500 \text{ Hz}$ )
- $C1 = 4 \mu\text{F}$  (low-pass, blocks  $\sim 5 \text{ kHz}$ )
- More complex design for flat response in band

### Example 3: Butterworth vs Chebyshev Comparison

**Requirement:** 3rd-order low-pass filter,  $f_c = 10 \text{ kHz}$

**Butterworth (maximally flat):**

- Pass-band: 0 dB flat from DC to  $\sim 9 \text{ kHz}$
- At  $f_c = 10 \text{ kHz}$ :  $-3 \text{ dB}$  exactly
- Roll-off:  $-60 \text{ dB/decade}$  ( $-20 \times 3$ )
- At  $100 \text{ kHz}$  (one decade):  $-63 \text{ dB}$
- Phase at  $f_c$ :  $-135^\circ$  ( $3 \times 45^\circ$ )
- No pass-band ripple  $\checkmark$

**Chebyshev (0.5 dB ripple):**

- Pass-band: 0 to  $-0.5 \text{ dB}$  ripple from DC to  $\sim 9 \text{ kHz}$

- At  $f_c = 10$  kHz:  $-0.5$  dB (ripple point, not  $-3$  dB!)
- Roll-off: Steeper,  $-80$  dB/decade effective
- At 100 kHz:  $-85$  dB (22 dB better than Butterworth!)
- Phase: More distortion near  $f_c$
- Trade-off: 0.5 dB ripple for 22 dB better rejection

**Choice depends on:**

- Butterworth if pass-band flatness critical (audio, precision measurement)
- Chebyshev if close frequencies need separation (0.5 dB ripple acceptable for 22 dB gain in selectivity)

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- **Filter Topologies:** L (2 elements), T (3 elements series-shunt-series),  $\pi$  (3 elements shunt-series-shunt).  $\pi$  low-pass excellent for power supplies (minimal DC drop, high ripple rejection). T high-pass for audio coupling. Cutoff:  $f_c = \frac{1}{\pi\sqrt{LC}}$  for T/ $\pi$
- **$\pi$  Filter Advantage:** Three-stage ripple filtering (cap-inductor-cap). First cap bypasses, inductor blocks, second cap smooths. DC drops only across inductor resistance ( $m\Omega$ ). AC ripple attenuated  $\geq 40$  dB. Used in linear supplies, low-noise applications
- **Crossover Function:** Divides audio spectrum to appropriate speakers. Low-pass to woofer, band-pass to mid, high-pass to tweeter. Passive: After amp, LC filters, no power. Active: Before amp(s), op-amp filters, adjustable, sharper. Optimizes each driver, prevents damage
- **Butterworth (Maximally Flat):** Flattest pass-band (no ripple), moderate roll-off, some phase distortion. General-purpose choice. Good all-around when no single parameter dominates. Most common in audio, measurement, data acquisition
- **Bessel (Linear Phase):** Best phase linearity (constant group delay), preserves waveform shape. Gentlest roll-off (poorest selectivity). Use for pulse/digital signals, video, control systems where phase matters. Need sufficient freq separation
- **Chebyshev (Equiripple):** Sharpest roll-off with pass-band ripple trade-off. Ripple adjustable (0.1–3 dB typical). Large phase distortion. Use where selectivity critical (RF, close channel spacing). Type I: Pass ripple. Type II: Stop ripple
- **Elliptic (Cauer):** Steepest possible roll-off, ripple in both pass and stop bands. Most complex, most components. Ultimate selectivity when space/order limited. Use when adjacent channels very close. Worst phase response
- **Q: When use passive vs active crossover?** A: Passive: Simpler installation, reliable, after amp, fixed points. Active: Adjustable, independent control, sharper slopes, need power, before separate amps. Active better for competition/pro audio. Passive for home/consumer
- **Q: How choose filter response type?** A: Priority determines choice. Flat pass-band  $\rightarrow$  Butterworth. Linear phase  $\rightarrow$  Bessel. Sharp selectivity  $\rightarrow$  Chebyshev/Elliptic. No clear priority  $\rightarrow$  Butterworth (general purpose). Simulate before building

# Section 16: Radio and Signal Modulation

## Radio Fundamentals and Communication Principles

TL;DR

**Communication channel:** Medium through which information travels (air, wire, fiber). Pattern (speech, Morse code, electrical signal) travels through channel, gets decoded at receiver. Radio: Voice → transmitter encodes → EM waves through air → receiver decodes → audio output.

**Radio waves:** Electromagnetic radiation at radio frequencies (few Hz to 300 GHz). Same phenomenon as visible light, but lower frequency. Wavelength  $\lambda = \frac{c}{f}$  where  $c = 3 \times 10^8$  m/s (speed of light). Lower frequency = longer wavelength = better penetration through obstacles. Example: AM radio (540–1600 kHz) penetrates buildings better than FM (88–108 MHz).

**Radio propagation:** Depends on frequency band. **VHF/UHF** (30 MHz–3 GHz): Line-of-sight propagation, travels straight, needs satellites for over-horizon. **Shortwave** (3–30 MHz): Ionosphere reflection (sky wave), bounces Earth-ionosphere-Earth, enables long-distance. **Lower frequencies:** Ground wave curves around Earth's surface.

**Transmitter blocks:** Power supply → Oscillator (generates carrier wave at fixed  $f_c$ ) → Modulator (encodes information into carrier) → Amplifier (boosts power) → Antenna (converts to EM waves). **Receiver blocks:** Antenna (captures EM waves) → RF amplifier → Tuner (selects desired frequency using LC resonance  $f_0 = \frac{1}{2\pi\sqrt{LC}}$ ) → Detector (extracts information from carrier) → Audio amplifier → Speaker.

**Repeaters:** Fixed radio on hilltop receives signal from one user, retransmits to another user blocked by obstacle. Extends communication range beyond line-of-sight. Common in walkie-talkie systems, ham radio, cellular networks.

**Key equations:** Wavelength:  $\lambda = \frac{c}{f}$ ; Resonance:  $f_0 = \frac{1}{2\pi\sqrt{LC}}$ ; Frequency range: AM 540–1600 kHz, FM 88–108 MHz

### Detailed Explanation

## 2. Detailed Explanation

### 1. Communication Channel Basics:

Communication requires pattern transmission through a medium, with encoding and decoding at endpoints.

#### Communication Model:

- **Sender:** Person/device wants to convey information
- **Pattern:** Information encoded (speech, Morse code, electrical signal, data packets)
- **Channel:** Medium for transmission (air for sound/radio, wire for phone, fiber for internet)
- **Decoder:** Interprets pattern at receiver (human ear, radio circuit, modem)
- **Receiver:** Acts on decoded information

#### Radio Communication Path:

- Speaker talks into microphone (analog sound pressure waves)
- Transmitter encodes voice into electromagnetic pattern
- Antenna launches EM waves into atmosphere (channel)
- Receiver antenna captures EM waves
- Detector decodes pattern back to electrical audio signal
- Speaker converts electrical signal to sound (receiver understands)

#### Modern Radio Applications:

- Audio broadcasting: AM/FM radio (1930s–present)
- Video broadcasting: TV (audio + video combined)
- Telephony: Cell phones extend phone network wirelessly
- Data: Wi-Fi replaces network cables, cellular data for internet
- Navigation: GPS, radar systems
- Short-range: Bluetooth, wireless chargers (electromagnetic induction)

### 2. Radio Waves (Electromagnetic Radiation):

Radio waves are electromagnetic radiation at specific frequency range, same physics as visible light.

#### Wave Properties:

- **Crest:** High point (molecules compressed, high energy)
- **Trough:** Low point (molecules spread, low energy)
- **Frequency:** Number of waves per second (cycles/second, Hz)

- Named after Heinrich Hertz (first to build device creating/detecting radio waves)
- **Speed:** All EM radiation travels at speed of light  $c = 3 \times 10^8$  m/s (186,282 miles/s)
- **Wavelength:**  $\lambda = \frac{c}{f}$  (distance light travels in one cycle)

#### EM Spectrum:

- **Radio:** Few Hz to 300 GHz (longest wavelengths in common use)
- **Infrared:** Above radio, heat radiation
- **Visible light:** 405–790 THz (red to violet), what we see
- **Ultraviolet:** Above visible, causes sunburn
- **X-rays:** Medical imaging, high energy
- **Gamma rays:** Highest energy, nuclear reactions
- Key insight: Light IS radio, just at higher frequency (THz vs MHz/GHz)

#### Wavelength vs Penetration:

- **Lower frequency** (longer wavelength): Better penetration through walls, water, obstacles
- **Higher frequency** (shorter wavelength): Less penetration, blocked by obstacles
- Visible light: Cannot penetrate walls (very short wavelength, 400–700 nm)
- AM radio (longer  $\lambda$ ): Penetrates buildings, travels far
- FM radio (shorter  $\lambda$ ): Better quality, less penetration, line-of-sight
- Submarines: Use extremely low frequency (3–30 Hz) for deep water penetration
- Lower  $f \rightarrow$  lower energy  $\rightarrow$  less interaction with matter  $\rightarrow$  passes through

#### Frequency Calculation Example:

- Station broadcasts at 680 kHz (KNBR San Francisco, since 1922)
- Wavelength:  $\lambda = \frac{3 \times 10^8}{680 \times 10^3} = 441$  m
- Another example: 100 kHz  $\rightarrow \lambda = 3$  km (very long wave)
- Higher frequency  $\rightarrow$  shorter wavelength  $\rightarrow$  smaller antenna possible

### 3. Radio Propagation (Frequency-Dependent):

How radio waves travel depends critically on wavelength and frequency band.

#### Frequency Bands (Summary):

- **ELF** (Extremely Low Frequency): 3–30 Hz, submarine communication
- **VLF** (Very Low Frequency): 3–30 kHz, navigation beacons
- **LF** (Low Frequency): 30–300 kHz, AM broadcast lower end
- **MF** (Medium Frequency): 300 kHz–3 MHz, AM broadcast
- **HF** (High Frequency/Shortwave): 3–30 MHz, long-distance, ionosphere bounce
- **VHF** (Very High Frequency): 30–300 MHz, FM, TV, aircraft
- **UHF** (Ultra High Frequency): 300 MHz–3 GHz, TV, cell phones, Wi-Fi

#### VHF/UHF Propagation (Line-of-Sight):

- Travels in straight line (like light rays)
- Cannot curve around Earth (limited by horizon)
- For long-distance: Use satellites (receive signal, retransmit in another line-of-sight path)
- Applications: FM radio (88–108 MHz), aircraft communications, TV broadcast
- Range limited by transmitter height and receiver height
- Formula for horizon distance:  $d_{km} = 3.57\sqrt{h_m}$  (h in meters)

#### Shortwave Propagation (Sky Wave):

- Frequency: 3–30 MHz (HF band)
- Bounces off ionosphere (charged layer 50–600 km altitude)
- Reflection: Wave hits ionosphere  $\rightarrow$  reflects back to Earth  $\rightarrow$  bounces again  $\rightarrow$  continues
- Enables worldwide communication without satellites
- Used in 1940s–1950s for international broadcasts
- Amateur radio (ham radio) still uses this method
- Time-dependent: Ionosphere conditions vary day/night, season

#### Lower Frequency Propagation (Ground Wave):

- Frequencies: 300 kHz–3 MHz (LF/MF bands)
- Curves around Earth's surface (follows curvature)
- Longer wavelength  $\rightarrow$  better diffraction around obstacles
- AM broadcast uses this (540–1600 kHz)
- Range: Hundreds of km for medium power

### 4. Radio Transmitter (Block Diagram):

Generates modulated carrier wave, amplifies, radiates into space.

**Power Supply:**

- Provides DC voltage/current for all stages
- Must be stable, low noise (noise affects signal quality)
- Typical voltages: 5–50 V depending on power level

**Oscillator (Carrier Generation):**

- Creates AC sine wave at fixed frequency  $f_c$  (carrier frequency)
- Carrier wave: High frequency, no information content (blank carrier)
- Example: Broadcast at 99.6 MHz  $\rightarrow$  oscillator generates 99.6 MHz sine wave
- Must be stable (crystal oscillator or PLL for precision)
- Frequency stability critical: Drift causes tuning problems

**Modulator (Information Encoding):**

- Takes two inputs: Carrier wave (from oscillator), message signal (audio, data)
- Encodes message into carrier by changing parameter (amplitude, frequency, or phase)
- **Amplitude Modulation (AM):** Varies carrier amplitude with message voltage
- **Frequency Modulation (FM):** Varies carrier frequency with message voltage
- **Phase Modulation (PM):** Varies carrier phase with message voltage
- Modulated signal contains carrier + information

**Amplifier (Power Boost):**

- Amplifies modulated signal to high power level
- Transmitter power: mW (walkie-talkie) to MW (broadcast station)
- Higher power  $\rightarrow$  longer range, but more cost, interference
- Class C amplifier common (efficient but nonlinear, OK for FM)
- Class A/AB for AM (must preserve amplitude linearity)

**Antenna (Electrical to EM Conversion):**

- Converts electrical signal to electromagnetic waves
- Radiates EM energy into space
- Antenna length related to wavelength:  $L \approx \frac{\lambda}{4}$  or  $\frac{\lambda}{2}$  for resonance
- Higher frequency  $\rightarrow$  shorter wavelength  $\rightarrow$  smaller antenna
- Example: FM 100 MHz ( $\lambda = 3$  m) needs 75 cm antenna
- AM 1 MHz ( $\lambda = 300$  m) needs much larger antenna or loading coil

**5. Radio Receiver (Block Diagram):**

Captures EM waves, selects desired frequency, extracts information, outputs audio.

**Antenna (EM to Electrical Conversion):**

- Wire exposed to EM waves induces small AC current ( $\mu\text{V}$  range)
- Captures ALL frequencies present (hundreds of stations + noise)
- Output: Very weak signal, needs amplification

**RF Amplifier (Front-End Amplifier):**

- Amplifies weak antenna signal before further processing
- Low noise design critical (don't amplify noise more than signal)
- Improves sensitivity (ability to hear weak stations)
- Typical gain: 20–40 dB

**Tuner (Frequency Selection):**

- **Function:** Selects ONE frequency from mix of all stations
- **Circuit:** LC tank (inductor + capacitor in parallel or series)
- **Resonance:**  $f_0 = \frac{1}{2\pi\sqrt{LC}}$  (filters frequencies above/below  $f_0$ )
- **Variable tuning:** Adjust L or C to change  $f_0$  (knob rotates variable capacitor)
- **Bandwidth:** Narrow enough to separate stations, wide enough to pass modulation
- **Q factor:**  $Q = \frac{f_0}{BW}$  determines selectivity (high Q = narrow, selective)
- Acts as band-pass filter centered at desired station frequency

**Detector (Demodulation):**

- Extracts information from modulated carrier
- **AM detection:** Diode + capacitor (envelope detector)
- Diode rectifies (removes negative half), capacitor smooths to recover audio envelope
- Removes high-frequency carrier, leaves low-frequency message
- Output: Audio signal (human voice, music, 20 Hz–20 kHz range)

**Audio Amplifier:**

- Boosts weak audio signal from detector to speaker level

- Typical gain: 30–60 dB ( $1000\times$  to  $1,000,000\times$  power)
- Class AB for efficiency and quality
- Drives speaker ( $8\ \Omega$  typical)

#### Speaker:

- Converts electrical audio signal to sound pressure waves
- Electromagnet moves cone, pushes air, creates sound
- Power: mW (earphone) to W (room speaker) to kW (concert PA)

#### 6. Repeaters (Range Extension):

Fixed station receives signal, retransmits to extend range beyond line-of-sight.

#### Simplex vs Repeater Communication:

- **Simplex:** Direct radio-to-radio, line-of-sight only (walkie-talkies)
- **Repeater:** Fixed station on hilltop/building receives, retransmits
- Overcomes obstacles (mountains, buildings) blocking direct path

#### Repeater Operation:

- User A transmits on frequency  $f_1$  (input frequency)
- Repeater receives  $f_1$ , immediately retransmits on  $f_2$  (output frequency)
- User B receives  $f_2$  (on other side of mountain)
- Offset:  $f_2 = f_1 \pm \Delta f$  (e.g.,  $\pm 600$  kHz for ham 2m band)
- Duplexer allows simultaneous receive and transmit (different frequencies)
- Placement: High location (mountain, tall building, tower) for maximum coverage

#### Applications:

- Amateur radio (ham repeaters on VHF/UHF)
- Commercial two-way radio (police, fire, taxi)
- Cellular: Cell tower is sophisticated repeater (base station)
- Public safety: Wide-area emergency communication

## Practical Examples & Numerical

### Example 1: Wavelength Calculation for AM Station

**Given:** Station broadcasts at 680 kHz (KNBR San Francisco)

#### Calculate wavelength:

- Formula:  $\lambda = \frac{c}{f}$  where  $c = 3 \times 10^8$  m/s
- $\lambda = \frac{3 \times 10^8}{680 \times 10^3} = \frac{3 \times 10^8}{6.8 \times 10^5}$
- $\lambda = 441.2$  m (very long wavelength!)
- For comparison: FM 100 MHz  $\rightarrow \lambda = 3$  m ( $147\times$  shorter)

#### Antenna implications:

- Quarter-wave antenna:  $L = \frac{\lambda}{4} = \frac{441}{4} = 110$  m (361 feet!)
- Impractical for portable radio  $\rightarrow$  use ferrite rod antenna or loading coil
- FM quarter-wave:  $L = \frac{3}{4} = 0.75$  m (30 inches, practical)

### Example 2: Tuner Design (LC Resonant Circuit)

**Requirement:** Tune to FM station at 99.6 MHz

#### Design approach:

- Resonance formula:  $f_0 = \frac{1}{2\pi\sqrt{LC}}$
- Choose  $C = 10$  pF (small capacitor, typical for VHF)
- Solve for L:  $L = \frac{1}{(2\pi f_0)^2 C}$
- $L = \frac{1}{(2\pi \times 99.6 \times 10^6)^2 \times 10 \times 10^{-12}}$
- $L = \frac{1}{3.91 \times 10^{17} \times 10^{-11}} = \frac{1}{3.91 \times 10^6}$
- $L = 0.256\ \mu\text{H} = 256\ \text{nH}$

#### Verification:

- $f_0 = \frac{1}{2\pi\sqrt{256 \times 10^{-9} \times 10 \times 10^{-12}}}$
- $f_0 = \frac{1}{2\pi\sqrt{2.56 \times 10^{-18}}} = \frac{1}{2\pi \times 1.6 \times 10^{-9}}$
- $f_0 = \frac{10^9}{10.05} = 99.5\ \text{MHz} \checkmark$  (close to target)

#### Tuning range:

- To cover FM band (88–108 MHz), use variable capacitor

- Range: 8–13 pF for 88 MHz, 10 pF for 99.6 MHz, 7 pF for 108 MHz
- Variable capacitor (tuning capacitor) adjusted by rotating knob

### Example 3: Line-of-Sight Distance Calculation

**Given:** VHF transmitter antenna height 100 m, receiver antenna height 4 m

**Calculate maximum range:**

- Horizon distance formula:  $d_{km} = 3.57\sqrt{h_m}$
- Transmitter horizon:  $d_t = 3.57\sqrt{100} = 3.57 \times 10 = 35.7$  km
- Receiver horizon:  $d_r = 3.57\sqrt{4} = 3.57 \times 2 = 7.14$  km
- Total range:  $d_{total} = d_t + d_r = 35.7 + 7.14 = 42.84$  km

**Interpretation:**

- VHF/UHF limited by Earth's curvature (line-of-sight)
- Higher antenna → longer range
- Cell towers: 30–50 m height, range 2–10 km (urban obstacles reduce range)
- TV broadcast: 300–600 m tower, range 80–150 km

### Example 4: Repeater Frequency Offset

**Scenario:** Ham radio 2-meter band (144–148 MHz), standard offset +600 kHz

**User transmits on 146.52 MHz (input):**

- Repeater receives on  $f_{in} = 146.52$  MHz
- Repeater transmits on  $f_{out} = 146.52 + 0.6 = 147.12$  MHz
- Other users receive on 147.12 MHz
- Offset allows simultaneous receive and transmit (duplexer separates)

**Why offset needed:**

- Same frequency → transmitter overwhelms receiver (desensitization)
- Offset (600 kHz) allows filters to separate
- Duplexer: High-Q cavity filters (narrow band-pass at each frequency)
- Typical isolation: 80–100 dB between receive and transmit

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- **Wavelength-Frequency Relationship:**  $\lambda = \frac{c}{f}$ . Lower frequency = longer wavelength = better obstacle penetration. AM (540–1600 kHz,  $\lambda$  200–550 m) penetrates buildings. FM (88–108 MHz,  $\lambda$  2.8–3.4 m) line-of-sight, better quality. Antenna size proportional to wavelength
- **Radio IS Light:** Radio waves and visible light are same phenomenon (EM radiation), differ only in frequency. Radio: Hz–GHz. Visible: 405–790 THz. Higher frequency = higher energy, less penetration. Light blocked by walls (short  $\lambda$  400–700 nm), radio passes through (long  $\lambda$ )
- **Propagation Modes:** VHF/UHF (30 MHz–3 GHz) line-of-sight, straight like light, need satellites for over-horizon. Shortwave (3–30 MHz) ionosphere reflection, bounces Earth-sky-Earth, worldwide range. Lower freq (LF/MF) ground wave, curves around Earth
- **Transmitter Chain:** Oscillator generates carrier at  $f_c$  → Modulator encodes message (AM/FM/PM) → Amplifier boosts power → Antenna radiates EM waves. Carrier wave is "blank" high-frequency sine wave. Message modulates carrier parameter (amplitude, frequency, or phase)
- **Receiver Chain:** Antenna captures EM waves (all frequencies) → RF amp boosts weak signal → Tuner selects desired frequency (LC resonance  $f_0 = \frac{1}{2\pi\sqrt{LC}}$ ) → Detector extracts message from carrier → Audio amp drives speaker. Tuner is band-pass filter, adjustable by varying C or L
- **Repeater Function:** Fixed high-location station receives on  $f_1$ , retransmits on  $f_2 = f_1 \pm \Delta f$ . Extends range beyond line-of-sight by overcoming obstacles (mountains, buildings). Duplexer separates receive/transmit. Used in ham radio, cellular (base stations), public safety
- **Q: Why modulate instead of transmitting audio directly?** A: Three reasons. (1) Channel separation: All audio is 20 Hz–20 kHz, impossible to select one station without modulation. Carrier frequencies differ (88.1, 88.3 MHz...), easy to filter. (2) Antenna size: Audio at 1 kHz needs huge antenna ( $\lambda$  300 km). Modulating onto 100 MHz carrier allows small antenna ( $\lambda$  3 m). (3) Propagation: High frequency travels better (line-of-sight, ionosphere bounce). Low frequency audio cannot propagate efficiently
- **Q: How does tuner select one station from hundreds?** A: LC resonant circuit acts as band-pass filter. At resonance  $f_0 = \frac{1}{2\pi\sqrt{LC}}$ , impedance peaks (parallel LC) or minimizes (series LC), allowing only  $f_0$  to pass. Variable capacitor adjusts  $f_0$  to desired station. Q factor determines selectivity:  $Q = \frac{f_0}{BW}$ . High Q ( $\geq 50$ ) narrow bandwidth, sharp tuning. Low Q ( $\leq 10$ ) wide bandwidth, adjacent stations interfere

- **Q: Why FM better quality than AM?** A: FM modulates frequency, immune to amplitude noise (lightning, interference add amplitude variation, not frequency). AM modulates amplitude, noise directly corrupts signal. FM bandwidth 200 kHz (vs AM 10 kHz) allows higher fidelity audio, stereo. FM in VHF (88–108 MHz) has less atmospheric noise than AM in MF (540–1600 kHz). Trade-off: FM needs line-of-sight, limited range. AM travels farther (ground wave, sky wave)

# Modulation Techniques

## TL;DR

**Purpose of modulation:** Encodes low-frequency message onto high-frequency carrier. **Reasons:** (1) Channel separation: Each station uses different carrier frequency, enables tuning to select one. (2) Antenna size: High-frequency carrier allows small antenna ( $L \propto \frac{1}{f}$ ). (3) Propagation: High frequency travels better through air. Without modulation, all audio (20 Hz–20 kHz) would overlap, impossible to separate stations.

**AM (Amplitude Modulation):** Varies carrier amplitude with message voltage, keeping frequency constant. Modulated signal: Envelope follows message. **AM detection:** Diode rectifies (removes negative half) + capacitor smooths to recover audio envelope. **Advantages:** Simple circuits, cheap receivers, easy demodulation. **Disadvantages:** Noise-prone (noise affects amplitude), inefficient power usage, low audio quality. Frequency range: 540–1600 kHz, 10 kHz bandwidth per channel, mono audio.

**FM (Frequency Modulation):** Varies carrier frequency with message voltage, keeping amplitude constant. Message peak  $\rightarrow$  frequency increases; message trough  $\rightarrow$  frequency decreases. **Advantages:** Noise-immune (amplitude limiters remove noise), high fidelity, stereo capable. **Disadvantages:** More complex circuits, line-of-sight propagation only. Frequency range: 88–108 MHz, 200 kHz bandwidth per channel ( $20\times$  AM), stereo audio.

**Digital modulation (carrier analog, data digital):** **ASK** (Amplitude Shift Keying): Binary 1 = full amplitude, 0 = zero amplitude. **FSK** (Frequency Shift Keying): Binary 1 = frequency  $f_1$ , 0 = frequency  $f_2$ . **PSK** (Phase Shift Keying): Binary 1 = phase  $0^\circ$ , 0 = phase  $180^\circ$ . **QAM** (Quadrature Amplitude Modulation): Combines AM and PM, high data rate, complex. Used in Wi-Fi, cellular data, cable modems.

**Pulse modulation (carrier digital):** Carrier is pulse train instead of continuous wave. **PAM** (Pulse Amplitude Modulation): Pulse height varies with message. **PWM** (Pulse Width Modulation): Pulse width varies with message, used in motor control, LED dimming. **PCM** (Pulse Code Modulation): Analog signal sampled, quantized to digital codes, used in ADC, digital audio (CD, MP3), satellite communication.

**Key concepts:** Modulation enables channel separation and efficient transmission; AM simple but noisy; FM high quality but complex; Digital modulation for data

## Detailed Explanation

### 2. Detailed Explanation

#### 1. Purpose of Modulation (Why Needed):

Modulation is essential for practical radio communication, not optional.

##### Analogy 1 (Paper and Stone):

- Throw paper across river: Impossible (too light, no mass)
- Wrap paper around stone, throw stone: Reaches other side
- Message signal = paper (lightweight, low frequency, low energy)
- Carrier signal = stone (heavy, high frequency, high energy)
- Modulation = wrapping message onto carrier

##### Analogy 2 (Lunchbox):

- Carrying food to school: Use lunchbox, not hands
- Food = message (what you consume)
- Lunchbox = carrier (transport mechanism, discarded after use)
- At school: Eat food, throw away box
- At receiver: Extract message, discard carrier

##### Reason 1: Channel Separation (Critical):

- Human hearing: 20 Hz–20 kHz (all audio in this range)
- Without modulation: Every station transmits 20 Hz–20 kHz
- Receiver tuned to 20 Hz–20 kHz: Hears ALL stations simultaneously (chaos!)
- Cannot distinguish between stations  $\rightarrow$  useless
- **Solution:** Each station modulates onto different carrier frequency
- Station A: Carrier 88.1 MHz, Station B: 88.3 MHz, Station C: 88.5 MHz, etc.
- Receiver tunes to 88.1 MHz: Filters out 88.3, 88.5, etc.  $\rightarrow$  hears only Station A
- Demodulation extracts 20 Hz–20 kHz audio from 88.1 MHz carrier
- **Key insight:** Different carriers allow band-pass filtering to select desired station

##### Reason 2: Antenna Size:

- Efficient antenna length:  $L \approx \frac{\lambda}{4}$  or  $\frac{\lambda}{2}$

- Wavelength:  $\lambda = \frac{c}{f}$  (inversely proportional to frequency)
- Audio 1 kHz:  $\lambda = \frac{3 \times 10^8}{10^3} = 300 \text{ m} \rightarrow$  antenna 75 m long! (impractical)
- FM 100 MHz:  $\lambda = 3 \text{ m} \rightarrow$  antenna 75 cm long (practical handheld)
- Higher carrier frequency  $\rightarrow$  shorter wavelength  $\rightarrow$  smaller antenna
- **Example:** Cell phone 900 MHz  $\rightarrow \lambda = 33 \text{ cm} \rightarrow$  antenna 8 cm (fits in phone)

### Reason 3: Propagation Efficiency:

- Low frequency (audio): Poor propagation through air, absorbed by ground
- High frequency (carrier): Better propagation (line-of-sight, ionosphere bounce)
- Carrier "carries" low-frequency message efficiently through atmosphere
- Different frequencies propagate differently (ground wave, sky wave, line-of-sight)

### Modulation Definition:

- **Modulation:** Changing parameter of carrier signal (amplitude, frequency, or phase) in proportion to message signal voltage
- **Three parameters:** Amplitude, frequency, phase (only these three)
- Keep other parameters constant while varying one
- **Carrier wave:** High-frequency sine wave, contains NO information (blank carrier)
- **Message signal:** Low-frequency information (audio, data) to be transmitted
- **Modulated signal:** Carrier with message encoded (ready for transmission)

### 2. Amplitude Modulation (AM):

First widespread modulation technique (1900s–1940s), simple but noise-prone.

#### AM Principle:

- Carrier amplitude varies with message voltage
- Message peak (positive voltage)  $\rightarrow$  carrier amplitude increases
- Message trough (negative voltage)  $\rightarrow$  carrier amplitude decreases
- Carrier frequency remains constant (no frequency change)
- **Envelope:** Outline connecting peaks of modulated wave follows message shape
- Envelope = 100% representation of message signal

#### AM Waveform Components:

- **Message signal:** Low frequency (20 Hz–5 kHz for voice), audio waveform
- **Carrier wave:** High frequency (540–1600 kHz for AM broadcast), constant amplitude sine wave
- **Modulated signal:** Carrier amplitude varies, creating envelope that follows message
- Upper envelope + lower envelope both contain message (redundant)

#### AM Advantages:

- **Simple implementation:** Modulator is just multiplier circuit (mixer)
- **Cheap receivers:** Diode detector (no transistors/ICs needed)
- **Widespread compatibility:** Billions of AM radios manufactured (legacy)
- **Long-range:** MF band (540–1600 kHz) ground wave and sky wave propagation

#### AM Disadvantages:

- **Noise susceptibility:** Lightning, electrical noise adds amplitude variation  $\rightarrow$  corrupts signal
- **Power inefficiency:** Carrier contains no info but consumes 2/3 of power
- Sidebands (actual info) only 1/3 of total power
- **Low fidelity:** Bandwidth limited to 10 kHz (5 kHz audio each side of carrier)
- **Mono only:** Insufficient bandwidth for stereo
- **Interference:** Atmospheric noise in MF band degrades quality

#### AM Frequency Allocation:

- AM broadcast band: 540–1600 kHz (MF band)
- Channel spacing: 10 kHz (9 kHz in some countries)
- Audio bandwidth: 5 kHz each side of carrier (total 10 kHz occupied)
- Example: Station at 680 kHz occupies 675–685 kHz
- Narrow bandwidth limits audio quality (treble cut off at 5 kHz)

### 3. AM Detection (Demodulation):

Simple diode-capacitor circuit extracts audio from modulated wave.

#### Detection Process:

- **Input:** Modulated AM signal (envelope contains message)
- **Problem:** Message appears twice (positive and negative envelope)
- Negative envelope = inverted copy of message (due to AC carrier oscillation)
- **Step 1:** Diode rectifies (removes negative half of carrier)

- Diode conducts on positive carrier peaks, blocks negative carrier peaks
- **Result:** Only positive envelope remains (half-wave rectification)
- **Step 2:** Capacitor smooths rectified signal
- Capacitor charges to peak voltage, discharges slowly between peaks
- Connects peak voltages together → recovers audio envelope
- **Output:** Audio signal (20 Hz–5 kHz), ready for amplification

#### Component Selection:

- **Diode:** Germanium (low  $V_f \approx 0.3$  V) better than silicon for weak signals
- **Capacitor:** Value sets time constant  $\tau = RC$
- Too small C: Doesn't smooth, carrier frequency leaks through
- Too large C: Oversmooths, loses high-frequency audio (treble)
- Typical: 100 pF–1 nF for AM detection (compromise between smoothing and response)
- Load resistor: 10–100 k $\Omega$  (provides discharge path for capacitor)

#### 4. Frequency Modulation (FM):

Varies carrier frequency instead of amplitude, superior noise immunity.

##### FM Principle:

- Carrier frequency varies with message voltage
- Message peak (positive voltage) → carrier frequency increases
- Message trough (negative voltage) → carrier frequency decreases
- Carrier amplitude remains constant (no amplitude change)
- **Frequency deviation:** Amount carrier frequency shifts from center ( $\pm 75$  kHz for FM broadcast)

##### FM Advantages:

- **Noise immunity:** Noise affects amplitude, not frequency
- Amplitude limiters in receiver clip amplitude variations (remove noise)
- Cannot use limiters in AM (would destroy message)
- **High fidelity:** Wide bandwidth (200 kHz) allows full audio (20 Hz–15 kHz)
- **Stereo capable:** Bandwidth sufficient for stereo channels (L+R, L-R)
- **VHF band:** 88–108 MHz less atmospheric noise than AM's MF band

##### FM Disadvantages:

- **Line-of-sight only:** VHF propagation limited by horizon
- Range shorter than AM (no sky wave at VHF)
- **Complex circuits:** FM modulation and detection more complicated than AM
- Requires PLL, VCO, discriminator circuits
- **Higher cost:** More sophisticated components

##### FM Frequency Allocation:

- FM broadcast band: 88–108 MHz (VHF band)
- Channel spacing: 200 kHz (20 $\times$  wider than AM)
- Frequency deviation:  $\pm 75$  kHz for audio (stereo requires  $\pm 75$  kHz total)
- Guard bands prevent adjacent channel interference
- Example: Station at 99.6 MHz occupies 99.5–99.7 MHz

#### 5. Digital Modulation (Analog Carrier, Digital Data):

Transmit binary data (1s and 0s) using analog carrier wave.

##### ASK (Amplitude Shift Keying):

- Binary 1: Carrier at full amplitude
- Binary 0: Carrier at zero amplitude (or reduced amplitude)
- **Example:** Binary 1011 → carrier ON-OFF-ON-ON
- Simple implementation: Modulator is electronic switch
- Used in: RFID tags, simple data links
- Disadvantage: Noise affects amplitude → error-prone

##### FSK (Frequency Shift Keying):

- Binary 1: Carrier at frequency  $f_1$
- Binary 0: Carrier at frequency  $f_2$  (typically  $f_2 < f_1$ )
- **Example:** Binary 1011 →  $f_1$ - $f_2$ - $f_1$ - $f_1$
- Implementation: VCO switched between two frequencies
- Used in: Modems (1200 baud), caller ID, radio telemetry
- Advantage: More noise-immune than ASK

##### PSK (Phase Shift Keying):

- Binary 1: Carrier phase  $0^\circ$  (or unchanged)
- Binary 0: Carrier phase  $180^\circ$  (inverted)
- **Example:** Binary 1011  $\rightarrow 0^\circ\text{-}180^\circ\text{-}0^\circ\text{-}0^\circ$
- Implementation: Phase inverter circuit
- Used in: Satellite communication, GPS
- Variants: QPSK (4 phases for 2 bits), 8-PSK (8 phases for 3 bits)

#### **QAM (Quadrature Amplitude Modulation):**

- Combines amplitude and phase modulation
- Multiple amplitude levels  $\times$  multiple phases  $\rightarrow$  many symbols
- **Example:** 16-QAM (4 amplitudes  $\times$  4 phases = 16 symbols, 4 bits per symbol)
- 64-QAM, 256-QAM common in Wi-Fi, cable modems
- High data rate but complex, sensitive to noise

#### **Advantages of Digital Modulation:**

- **High bandwidth efficiency:** More bits per Hz than analog
- **Error correction:** Can add redundancy (FEC codes)
- **Multiplexing:** Time-division allows multiple users on one channel
- **Encryption:** Digital data easily encrypted for security

#### **6. Pulse Modulation (Digital Carrier):**

Carrier is pulse train (discontinuous) instead of continuous sine wave.

##### **PAM (Pulse Amplitude Modulation):**

- Pulse height varies with message signal amplitude
- Message sampled at intervals, pulse amplitude = sample value
- Fusion of analog and digital: Amplitude analog, timing digital
- Used in: Ethernet, photo biology, LCD drivers
- Precursor to PCM (next step is quantization)

##### **PWM (Pulse Width Modulation):**

- Pulse width (duration) varies with message amplitude
- Pulse amplitude constant, only width changes
- Higher message voltage  $\rightarrow$  wider pulse
- Used in: Motor speed control, LED dimming (duty cycle), audio amplifiers (Class D)
- Efficient: Switch ON/OFF (low power dissipation)

##### **PCM (Pulse Code Modulation):**

- Analog signal sampled, quantized to discrete levels, encoded as binary
- **Steps:** Sampling (time discretization)  $\rightarrow$  Quantization (amplitude discretization)  $\rightarrow$  Encoding (binary representation)
- **Example:** 8-bit PCM  $\rightarrow$  256 amplitude levels (0–255)
- Used in: Digital audio (CD 16-bit 44.1 kHz), telephony, ADC, satellite communication
- Advantage: Immune to noise (regenerate binary signal), easy processing
- Disadvantage: High bandwidth (need many bits per sample)

### **Practical Examples & Numerical**

#### **Example 1: AM Station Bandwidth**

**Given:** AM station at 680 kHz, audio range 20 Hz–5 kHz

##### **Calculate occupied bandwidth:**

- Carrier frequency:  $f_c = 680 \text{ kHz}$
- Modulation creates two sidebands:
  - **Upper sideband (USB):**  $f_c + f_{\text{audio}} = 680 \text{ kHz to } 685 \text{ kHz}$
  - **Lower sideband (LSB):**  $f_c - f_{\text{audio}} = 675 \text{ kHz to } 680 \text{ kHz}$
- Total bandwidth:  $BW = 2 \times f_{\text{max}} = 2 \times 5 = 10 \text{ kHz}$
- Occupied spectrum: 675–685 kHz

##### **Why 10 kHz channel spacing:**

- Each station needs 10 kHz ( $\pm 5 \text{ kHz}$  from carrier)
- Adjacent station at 690 kHz occupies 685–695 kHz
- No overlap: 680 kHz station ends at 685, 690 kHz starts at 685 ✓

- Guard band minimal (adjacent edges touch)

### Example 2: FM Frequency Deviation

**Given:** FM station 99.6 MHz, max deviation  $\pm 75$  kHz

**Calculate instantaneous frequency range:**

- Center (carrier) frequency:  $f_c = 99.6$  MHz
- Message peak (+1 V):  $f_{max} = 99.6 + 0.075 = 99.675$  MHz
- Message trough (−1 V):  $f_{min} = 99.6 - 0.075 = 99.525$  MHz
- Frequency swings: 99.525–99.675 MHz (150 kHz swing)
- No message (silence): Carrier at exactly 99.6 MHz

**FM bandwidth (Carson's rule):**

- $BW_{FM} \approx 2(\Delta f + f_{max})$  where  $\Delta f$  = deviation,  $f_{max}$  = max audio
- $BW_{FM} = 2(75 + 15) = 2 \times 90 = 180$  kHz
- Allocated channel: 200 kHz (conservative, includes guard bands)
- Significantly wider than AM (200 kHz vs 10 kHz = 20× wider)

### Example 3: ASK Data Rate

**Given:** ASK modulation, bit duration 1 ms (millisecond per bit)

**Calculate data rate:**

- Bit rate:  $R_b = \frac{1}{T_{bit}} = \frac{1}{1 \times 10^{-3}} = 1000$  bits/second = 1 kbps
- Baud rate: 1000 symbols/second (1 bit per symbol in ASK)
- Binary sequence 1011: Takes  $4 \times 1 = 4$  ms to transmit

**Bandwidth required:**

- Minimum bandwidth (Nyquist):  $BW = \frac{R_b}{2} = \frac{1000}{2} = 500$  Hz
- Practical bandwidth:  $BW \approx R_b = 1$  kHz (includes filtering, roll-off)
- Carrier frequency must be  $\gg 1$  kHz (typically 100× minimum)
- Example: 100 kHz carrier for 1 kbps ASK

### Example 4: PWM Duty Cycle

**Requirement:** Dim LED to 60% brightness using PWM

**Design:**

- PWM frequency: 1 kHz (above flicker fusion 100 Hz)
- Period:  $T = \frac{1}{f} = \frac{1}{1000} = 1$  ms
- Duty cycle: 60% (ON time 60%, OFF time 40%)
- ON time:  $T_{ON} = 0.6 \times 1 = 0.6$  ms
- OFF time:  $T_{OFF} = 0.4 \times 1 = 0.4$  ms

**Average power:**

- LED forward voltage:  $V_f = 2$  V, current  $I_f = 20$  mA
- Peak power (ON):  $P_{ON} = 2 \times 0.02 = 0.04$  W = 40 mW
- Average power:  $P_{avg} = P_{ON} \times D = 40 \times 0.6 = 24$  mW
- Brightness proportional to average current: 60% of full brightness ✓

**Efficiency:**

- Switch dissipation: Near zero (ideal switch)
- Resistor dissipation: Only during ON time, but no resistor needed with current source
- PWM efficiency: 95–98% (vs linear dimming 60%)

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- **Why Modulation Essential:** Three critical reasons. (1) Channel separation: All audio is 20 Hz–20 kHz, modulating onto different carriers (88.1, 88.3 MHz...) allows filtering to select one station. (2) Antenna size: Audio 1 kHz needs 75 km antenna ( $\lambda=300$  km), FM 100 MHz needs 75 cm ( $\lambda=3$  m). (3) Propagation: High-frequency carrier propagates efficiently, low-frequency audio does not
- **AM vs FM Comparison:** AM varies amplitude (frequency constant), simple but noise-prone, 540–1600 kHz, 10 kHz BW, mono, long range (ground/sky wave), cheap receivers. FM varies frequency (amplitude constant), noise-immune (limiters remove amplitude noise), 88–108 MHz, 200 kHz BW, stereo, line-of-sight only, complex circuits. FM quality superior, AM range superior
- **AM Detection Process:** Diode rectifies modulated signal (removes negative carrier half) → only positive envelope remains → capacitor smooths (connects peaks) → recovers audio. Capacitor value critical: Too small leaks carrier,

too large loses treble. Germanium diode better than silicon (lower  $V_f$ ) for weak signals. Output is audio 20 Hz–5 kHz ready for amplification

- **Digital Modulation Types:** ASK (amplitude shift keying): 1=full amplitude, 0=zero, simple but noise-prone. FSK (frequency shift keying): 1= $f_1$ , 0= $f_2$ , better noise immunity. PSK (phase shift keying): 1= $0^\circ$ , 0= $180^\circ$ , used in satellites/GPS. QAM (quadrature AM): Combines amplitude + phase, high data rate (16-QAM, 64-QAM), used in Wi-Fi, cable modems
- **Pulse Modulation:** Carrier is pulse train. PAM (pulse amplitude modulation): Pulse height varies with message, used in Ethernet. PWM (pulse width modulation): Pulse width varies, constant amplitude, efficient, used in motor control, LED dimming. PCM (pulse code modulation): Analog sampled + quantized + encoded as binary, immune to noise, used in digital audio (CD), telephony, ADC
- **FM Bandwidth:** Carson's rule:  $BW_{FM} \approx 2(\Delta f + f_{max})$  where  $\Delta f$  is deviation ( $\pm 75$  kHz),  $f_{max}$  is max audio (15 kHz). Result: 180 kHz minimum, 200 kHz allocated. 20× wider than AM (10 kHz), but allows stereo and high fidelity. Trade-off: Bandwidth for quality
- **Q: Why FM immune to noise but AM isn't?** A: Noise (lightning, interference) adds amplitude variation to signal. AM encodes info in amplitude, so noise directly corrupts message. FM encodes info in frequency, amplitude irrelevant. FM receiver uses amplitude limiters (clip signal to constant amplitude), removing noise without affecting message. Cannot use limiters in AM (would destroy message). FM also benefits from higher frequency band (VHF 88–108 MHz) having less atmospheric noise than AM's MF band (540–1600 kHz)
- **Q: How does PWM control LED brightness?** A: LED brightness proportional to average current. PWM switches LED ON/OFF rapidly ( $\gg 100$  Hz, above flicker fusion). Duty cycle sets average: 60% ON  $\rightarrow$  60% brightness. Full voltage when ON (2 V, 20 mA), zero when OFF. Average current  $I_{avg} = I_{peak} \times D$ . Efficient: Switch dissipates minimal power (ON=low drop, OFF=no current). Linear dimming uses resistor, wastes power as heat
- **Q: What determines AM channel spacing?** A: Bandwidth of modulated signal. AM modulation creates upper sideband (USB)  $f_c + f_{audio}$  and lower sideband (LSB)  $f_c - f_{audio}$ . Audio 20 Hz–5 kHz  $\rightarrow$  sidebands extend  $\pm 5$  kHz  $\rightarrow$  total BW = 10 kHz. Channel spacing = 10 kHz to prevent adjacent channel overlap. Station at 680 kHz occupies 675–685 kHz, next station at 690 kHz starts at 685 kHz (guard band minimal)

# Section 17: Miscellaneous Topics

## Relays and RC Differentiator

TL;DR

**Mechanical relay:** Electrically operated switch using electromagnetic coil to control high current with low current. **Components:** Coil (electromagnet), armature (movable part), contacts (switch terminals). **Operation:** Current through coil → magnetic field → attracts armature → closes contacts → completes circuit. No current → spring returns armature → opens contacts. **Types:** SPST (Single Pole Single Throw, 2 contacts), SPDT (Single Pole Double Throw, 3 contacts + common), DPST (Double Pole Single Throw, 4 contacts), DPDT (Double Pole Double Throw, 6 contacts). **Key specs:** Rated coil voltage (nominal), set/operate voltage (minimum to close), switching capacity (max current through contacts), power rating (coil consumption in mW).

**MOSFET relay (Solid-State):** Semiconductor relay using LED, photodiode, and MOSFET instead of mechanical contacts. **Operation:** Input current → LED lights → photodiode receives light → generates voltage → drives MOSFET gate → MOSFET switches load. **Advantages:** No moving parts (silent, long life), compact, no maintenance, faster switching. **Disadvantages:** Higher cost, voltage drop when ON, leakage when OFF.

**RC Differentiator:** High-pass filter that outputs rate of change of input signal. **Circuit:** Capacitor series, resistor to ground, output across R. **Equation:**  $V_{out} = RC \frac{dV_{in}}{dt}$  (derivative of input weighted by RC time constant). **Square wave input:** Produces positive spike on rising edge, negative spike on falling edge (DC blocked by capacitor). **Triangle wave input:** Produces square wave (constant slope → constant output). **Design rule:** Small time constant ( $\tau = RC \ll T_{pulse}$ , typically  $\tau < 0.1T$ ) for sharp spikes. Large  $\tau$  ( $> 10T$ ) resembles original square wave.

**Key equations:** Relay control: Low current coil controls high current load; Differentiator:  $V_{out} = RC \frac{dV_{in}}{dt}$ ; Time constant:  $\tau = RC$

### Detailed Explanation

## 2. Detailed Explanation

### 1. Mechanical Relay Fundamentals:

Relay is electrically operated switch allowing small current to control much larger current.

#### Relay Analogy:

- Like relay race: Team members pass baton to complete race
- Electrical relay: Receives signal from one circuit, passes control to another
- Example: TV remote button → sends signal to relay → relay switches main power ON
- Isolation: Input circuit (low voltage control) electrically separated from output (high voltage load)

#### Structure Components:

- **Coil (Electromagnet):** Wire wound around iron core, receives control current
- Creates magnetic field when current flows (DC current for steady field)
- Strength proportional to current: More current → stronger field
- **Armature:** Movable iron piece attracted by electromagnet
- Spring-loaded to return to rest position when coil de-energized
- **Contacts:** Metal terminals that close/open under armature movement
- Fixed contact (stationary) and moving contact (attached to armature)
- **Return Spring:** Pulls armature back when magnetic force removed

#### Operating Principle:

- **Switch CLOSED (energized):**
  - Current flows through coil → magnetizes iron core
  - Magnetic force attracts armature to core
  - Moving contact touches fixed contact → relay ON
  - Load circuit completes → lamp/motor/device powered
- **Switch OPEN (de-energized):**
  - No current through coil → no magnetic field
  - Spring pulls armature back to rest position
  - Contacts separate → relay OFF
  - Load circuit breaks → device unpowered

#### Key Characteristic (Isolation):

- Physical spacing between coil and contacts
- Input circuit (coil side) electrically isolated from output (contact side)
- Allows low-voltage DC to control high-voltage AC safely
- Example: 5 V DC Arduino controls 120 V AC lamp via relay
- No electrical connection, only magnetic coupling

## 2. Relay Types (Contact Configuration):

Classification based on number of poles (circuits) and throws (positions).

### SPST (Single Pole Single Throw):

- **Poles:** 1 circuit controlled
- **Throws:** 1 position (ON or OFF)
- **Terminals:** 2 contacts + 2 for coil = 4 total
- Function: Simple ON/OFF switch
- Use: Turn single load ON/OFF (lamp, motor)

### SPDT (Single Pole Double Throw):

- **Poles:** 1 circuit controlled
- **Throws:** 2 positions (common connects to either terminal)
- **Terminals:** 3 contacts (common + 2 positions) + 2 for coil = 5 total
- Function: Changeover switch (select between two circuits)
- Use: Switch load between two sources, reversing motor direction
- Common terminal alternates between two fixed contacts

### DPST (Double Pole Single Throw):

- **Poles:** 2 circuits controlled simultaneously
- **Throws:** 1 position per pole (both ON or both OFF)
- **Terminals:** 4 contacts (2 pairs) + 2 for coil = 6 total
- Function: Two independent SPST switches actuated together
- Use: Switch both hot and neutral in AC circuit, control two separate loads together

### DPDT (Double Pole Double Throw):

- **Poles:** 2 circuits controlled simultaneously
- **Throws:** 2 positions per pole
- **Terminals:** 6 contacts (2 commons + 4 positions) + 2 for coil = 8 total
- Function: Two independent SPDT switches actuated together
- Use: Reversing polarity, complex switching (motor forward/reverse with two circuits)

## 3. Relay Specifications:

Critical parameters for selecting and using relays.

### Rated Coil Voltage:

- Nominal voltage relay coil designed for
- Example: 5 V, 12 V, 24 V DC relays common
- Operating coil at rated voltage ensures proper operation
- Too low voltage → may not close (weak magnetic field)
- Too high voltage → overheating, coil damage

### Set/Operate Voltage:

- Minimum voltage needed to close contacts reliably
- Typically 70–80% of rated voltage
- Example: 12 V relay may close at 9 V (75%)
- Below operate voltage: Contacts may chatter or not close

### Release Voltage:

- Voltage below which contacts open (armature releases)
- Hysteresis: Operate voltage  $\neq$  Release voltage
- Prevents chattering when voltage fluctuates

### Coil Power Rating:

- Power consumed by coil when energized (mW or W)
- Example: 12 V relay, 50 mA coil →  $P = 12 \times 0.05 = 0.6 \text{ W}$
- Important for calculating driver circuit power dissipation
- Low-power relays: 100–500 mW typical

### Switching Capacity (Contact Rating):

- Maximum current contacts can switch safely
- Specified for resistive, inductive, capacitive loads separately
- Example: 10 A at 250 V AC (resistive), 3 A at 30 V DC (inductive)

- **Inductive loads:** Motors take surge current at startup ( $2\text{--}5\times$  running current)
- Design rule: Relay rating  $\geq 2\times$  motor running current for safety
- Contact material: Silver alloy (low resistance, arc-resistant)

#### 4. Relay Applications:

Using small current to control large loads.

##### Example 1: DC Control of AC Load:

- Control circuit: 5 V DC (microcontroller, Arduino)
- Load circuit: 120 V AC lamp
- Relay coil: 5 V DC, 70 mA (350 mW)
- Contacts: 10 A at 250 V AC rating
- Operation: MCU output HIGH (5 V)  $\rightarrow$  energizes coil  $\rightarrow$  contacts close  $\rightarrow$  lamp ON
- MCU output LOW (0 V)  $\rightarrow$  coil de-energized  $\rightarrow$  contacts open  $\rightarrow$  lamp OFF
- Safety: Complete electrical isolation between DC and AC circuits

##### Example 2: Low Current Controlling High Current:

- Control: 50 mA through coil (low current, safe for electronics)
- Load: 5 A motor ( $100\times$  coil current)
- Power amplification: Small control power switches large load power
- Without relay: Would need transistor rated for full 5 A (expensive, complex)

##### Example 3: Multiple Independent Circuits:

- One coil can control multiple contact sets (DPDT, multi-pole relays)
- Single input signal switches several independent loads simultaneously
- Example: Turn ON heater + fan + indicator lamp together

#### 5. MOSFET Relay (Solid-State Relay):

Semiconductor-based relay with no moving parts.

##### Structure:

- **Input:** LED (light-emitting diode)
- **Coupling:** Optical isolation (light transmission)
- **Detector:** Photodiode array
- **Output:** Power MOSFET (switches load)

##### Operating Principle:

- Input current applied  $\rightarrow$  LED lights up
- LED emits light (infrared or visible)
- Photodiode receives light  $\rightarrow$  generates voltage (photovoltaic effect)
- Photodiode voltage drives MOSFET gate
- MOSFET turns ON  $\rightarrow$  conducts between drain-source  $\rightarrow$  load powered
- No input current  $\rightarrow$  LED OFF  $\rightarrow$  photodiode generates no voltage  $\rightarrow$  MOSFET OFF

##### Advantages of MOSFET Relay:

- **No mechanical parts:** No wear, unlimited switching cycles (vs 100k–1M for mechanical)
- **Silent operation:** No audible click (mechanical relays make noise)
- **Fast switching:**  $\mu\text{s}$  switching time (vs ms for mechanical)
- **Compact:** Smaller footprint (no coil, armature, spring)
- **No maintenance:** Contacts don't wear, corrode, or arc
- **Long life:** 10–100 $\times$  longer than mechanical (no contact degradation)

##### Disadvantages:

- **Higher cost:** More expensive than equivalent mechanical relay
- **Voltage drop:** MOSFET has  $R_{DS(on)}$  (10–100 m $\Omega$ ), small voltage drop when ON
- Mechanical relay: Contact resistance 10–50 m $\Omega$ , similar but better
- **Leakage current:** Small OFF-state current ( $\mu\text{A}$ –mA) through MOSFET
- Mechanical relay: Zero current when OFF (true open circuit)
- **Heat dissipation:** Power MOSFET generates heat ( $P = I^2 R_{DS(on)}$ )

#### 6. RC Differentiator (High-Pass as Rate-of-Change Detector):

RC high-pass filter outputs derivative of input signal (rate of change).

##### Circuit Configuration:

- Capacitor in series (input to capacitor)
- Resistor to ground (capacitor to resistor junction)
- Output taken across resistor (not capacitor)
- High-pass filter becomes differentiator for non-sinusoidal inputs

##### Why Called Differentiator:

- Effect similar to mathematical differentiation
- Differentiation: Finding rate of change of quantity
- Output proportional to  $\frac{dV_{in}}{dt}$  (how fast input changes)
- Rapid input change  $\rightarrow$  large output voltage
- Slow input change  $\rightarrow$  small output voltage
- No change (DC)  $\rightarrow$  zero output (capacitor blocks DC)

#### Differentiator Equation Derivation:

- Capacitor current:  $I_C = C \frac{dV_C}{dt}$  (current proportional to voltage rate of change)
- Voltage across capacitor cannot change instantly (needs time to charge)
- Current through C must equal current through R (series circuit):  $I_C = I_R$
- Voltage across R:  $V_R = I_R \times R = I_C \times R$
- Substitute:  $V_{out} = V_R = RC \frac{dV_{in}}{dt}$
- Output is derivative of input weighted by time constant  $\tau = RC$

#### Square Wave Input Response:

- **Rising edge:** Input voltage jumps positive instantly
- Rate of change very high ( $\frac{dV}{dt} \rightarrow \infty$  ideally)
- Output: Positive spike (narrow pulse)
- **Falling edge:** Input voltage jumps negative instantly
- Output: Negative spike (narrow pulse, opposite polarity)
- **Flat top:** Input constant (no change)
- $\frac{dV}{dt} = 0 \rightarrow$  output zero (capacitor fully charged, no current)
- Result: Positive + negative spikes at edges only
- DC level removed (capacitor blocks DC component)

#### Triangle Wave Input Response:

- **Rising slope:** Constant positive rate of change
- $\frac{dV}{dt} = +k$  (constant)  $\rightarrow$  output constant positive voltage
- **Falling slope:** Constant negative rate of change
- $\frac{dV}{dt} = -k$  (constant)  $\rightarrow$  output constant negative voltage
- Result: Square wave output (derivative of triangle is square)
- Perfect mathematical relationship: Triangle slope  $\rightarrow$  square level

#### Time Constant Effect:

Shape of output depends on ratio of pulse width  $T$  to time constant  $\tau = RC$ .

- **Large  $\tau$  ( $\tau > 10T$ ):** Output resembles input square wave
- Capacitor charges/discharges slowly, follows input
- High-pass characteristic weak, passes low frequencies
- **Small  $\tau$  ( $\tau < 0.1T$ ):** Output is sharp spikes
- Capacitor charges/discharges quickly, only edges create voltage
- True differentiation: Only fast changes produce output
- **Intermediate  $\tau$ :** Range of waveforms between spikes and square
- Design rule: Use  $\tau \ll T$  for good differentiation (sharp pulses)

#### Applications:

- Edge detection: Trigger on rising/falling edges of digital signals
- Wave shaping: Convert square to spikes for timing circuits
- High-pass coupling: Remove DC, pass AC changes
- Pulse generation: Create narrow trigger pulses from slow transitions

## Practical Examples & Numerical

### Example 1: Relay Coil Power Calculation

**Given:** 12 V DC relay, coil resistance 240  $\Omega$

**Calculate coil current and power:**

- Coil current:  $I = \frac{V}{R} = \frac{12}{240} = 0.05 \text{ A} = 50 \text{ mA}$
- Coil power:  $P = VI = 12 \times 0.05 = 0.6 \text{ W} = 600 \text{ mW}$
- Or:  $P = \frac{V^2}{R} = \frac{144}{240} = 0.6 \text{ W} \checkmark$

**Driver circuit considerations:**

- Need transistor/driver capable of sinking 50 mA
- 2N2222 transistor: Max 600 mA collector current ✓ (12× safety margin)
- Power dissipation in transistor:  $P = V_{CE(sat)} \times I_C \approx 0.3 \times 0.05 = 15 \text{ mW}$  (negligible)
- Flyback diode required across coil (inductive load, voltage spike when turned OFF)

### Example 2: Motor Relay Selection

**Requirement:** Control DC motor, running current 2 A, startup surge 8 A

#### Relay selection criteria:

- Running current: 2 A
- Surge current: 8 A (4× running, typical for motors)
- Design rule: Relay rating  $\geq 2 \times$  surge current for safety
- Minimum relay rating:  $2 \times 8 = 16 \text{ A}$
- Choose: 20 A relay (next standard size, provides margin)

#### Why oversizing needed:

- Motor startup: High inrush current (low back-EMF initially)
- Contact welding risk: High current creates arc when switching
- Contact wear: Arcing erodes contact material over time
- Derating for reliability: 2× factor ensures long relay life
- Alternative: Use soft-start circuit to limit inrush (allows smaller relay)

### Example 3: RC Differentiator Design

**Requirement:** Detect edges of 1 kHz square wave (period  $T = 1 \text{ ms}$ )

#### Design for sharp spikes:

- Rule:  $\tau = RC < 0.1T$  for good differentiation
- Target:  $\tau = 0.05T = 0.05 \times 1 \times 10^{-3} = 50 \text{ } \mu\text{s}$
- Choose C = 1 nF (small, typical)
- Calculate R:  $R = \frac{\tau}{C} = \frac{50 \times 10^{-6}}{1 \times 10^{-9}} = 50 \text{ k}\Omega$
- Use standard value: R = 47 kΩ (gives  $\tau = 47 \text{ } \mu\text{s}$ , close enough)

#### Expected output:

- Input: Square wave, 0–5 V, 1 kHz
- Rising edge (0→5 V): Positive spike, amplitude 5 V, width  $5\tau = 235 \text{ } \mu\text{s}$
- Falling edge (5→0 V): Negative spike, amplitude −5 V, width 235 μs
- Flat portions: Output decays to zero (capacitor charges/discharges)
- Spike much narrower than pulse (235 μs vs 500 μs = 47% of half-period)

#### Verification:

- Ratio:  $\frac{\tau}{T} = \frac{47}{1000} = 0.047$  ✓ (less than 0.1 threshold)
- Good differentiation achieved
- For sharper spikes: Reduce  $\tau$  further (use R = 10 kΩ →  $\tau = 10 \text{ } \mu\text{s}$ )

### Example 4: Differentiator Output Voltage

**Given:** Triangle wave, 0–10 V peak-to-peak, 100 Hz, RC = 1 ms

#### Calculate output:

- Period:  $T = \frac{1}{100} = 10 \text{ ms}$
- Rising slope duration:  $\frac{T}{2} = 5 \text{ ms}$  (0→10 V in 5 ms)
- Slope:  $\frac{dV}{dt} = \frac{10-0}{5 \times 10^{-3}} = 2000 \text{ V/s} = 2 \text{ V/ms}$
- Output voltage:  $V_{out} = RC \frac{dV_{in}}{dt} = 1 \times 10^{-3} \times 2000 = 2 \text{ V}$

#### Output waveform:

- Rising slope (0→10 V): Output = +2 V (constant)
- Falling slope (10→0 V): Slope = −2000 V/s → Output = −2 V (constant)
- Result: Square wave, ±2 V peak, 100 Hz
- Derivative of triangle wave is square wave ✓

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- **Relay Purpose:** Small current controls large current via electromagnetic coupling. Coil (mA–100 mA) creates magnetic field, attracts armature, closes contacts switching load (A–100 A). Complete electrical isolation between control and load circuits. Example: 5 V 50 mA coil switches 120 V 10 A lamp (2400 W load controlled by 0.25 W input)

- **Relay Types:** SPST (1 circuit ON/OFF, 4 terminals). SPDT (1 circuit, 2 positions + common, 5 terminals). DPST (2 circuits ON/OFF together, 6 terminals). DPDT (2 circuits, 2 positions each, 8 terminals). Pole = number of independent circuits. Throw = number of positions per pole
- **Relay Specifications:** Rated coil voltage (nominal operation voltage). Set voltage (minimum to close, 75% rated). Switching capacity (max contact current, derate for inductive loads). Coil power (mW consumption). For motors: Relay rating  $\geq 2\times$  surge current (startup inrush 4–5 $\times$  running)
- **Mechanical vs MOSFET Relay:** Mechanical: Moving contacts, audible click, 100k–1M cycles, true isolation when OFF, cheap. MOSFET (SSR): Optical coupling + semiconductor switch, silent, unlimited cycles, fast ( $\mu$ s), compact, expensive, small voltage drop and leakage. Use mechanical for cost/isolation, SSR for life/speed
- **RC Differentiator Principle:** Output =  $RC \frac{dV_{in}}{dt}$  (derivative of input). Rapid change  $\rightarrow$  large output, slow change  $\rightarrow$  small output, DC  $\rightarrow$  zero. Square wave input produces spikes at edges (positive on rising, negative on falling). Triangle wave input produces square wave (constant slope  $\rightarrow$  constant output). Mathematically correct differentiation
- **Time Constant Effect:**  $\tau = RC$  determines differentiation quality. Small  $\tau$  ( $< 0.1T$ )  $\rightarrow$  sharp spikes, good differentiation. Large  $\tau$  ( $> 10T$ )  $\rightarrow$  output resembles input, poor differentiation. Intermediate  $\tau \rightarrow$  partial differentiation. Design: Choose  $\tau \ll T_{pulse}$  for edge detection, spike generation
- **Q: Why relay needs flyback diode?** A: Coil is inductor, stores energy in magnetic field. When turned OFF, current cannot stop instantly. Collapsing magnetic field induces large voltage spike ( $V = -L \frac{dI}{dt}$ , can reach 100s of volts). Damages transistor driver. Flyback diode (reverse across coil) provides path for induced current, clamps voltage to 0.7 V, protects circuit. Always required for inductive relay coils
- **Q: How does RC differentiator work with square wave?** A: Rising edge: Input jumps 0 $\rightarrow$ 5 V instantly,  $\frac{dV}{dt}$  very high, capacitor cannot charge instantly, voltage difference appears across R, creates positive spike. Flat top: Input constant,  $\frac{dV}{dt} = 0$ , capacitor charges to input voltage through R, current stops, output decays to zero. Falling edge: Input drops 5 $\rightarrow$ 0 V, capacitor voltage higher than input, discharges through R in reverse, creates negative spike. Capacitor blocks DC, only passes changes
- **Q: Why MOSFET relay better for high-frequency switching?** A: Mechanical relay has mass (armature, contacts), inertia limits speed to 1–10 ms switching time. Contacts bounce (multiple make/break cycles) during closure, 1–5 ms settle. Max switching rate 10–100 Hz. MOSFET relay: No moving parts, purely electronic, switching time 10–100  $\mu$ s, no bounce, can switch at kHz–MHz rates. Used in PWM, high-speed control, data transmission

# Wheatstone Bridge and Series RLC Circuits

TL;DR

**Wheatstone Bridge:** Circuit for measuring unknown resistance using three known resistors. **Structure:** Two voltage dividers in parallel, voltmeter between midpoints. **Balance condition:**  $\frac{R_1}{R_2} = \frac{R_3}{R_4}$  when voltmeter reads 0 V (no current through meter). **To measure  $R_2$ :** Set  $R_1$ ,  $R_3$ , adjust  $R_4$  until balanced, then  $R_2 = R_1 \frac{R_4}{R_3}$ . **Applications:** Precision resistance measurement (down to mΩ range), sensor interfacing (strain gauges, RTDs, photocells with op-amps), detector circuits.

**Series RLC circuit:** R, L, C in series across AC supply. **Impedance:**  $Z = \sqrt{R^2 + (X_L - X_C)^2}$  where  $X_L = 2\pi fL$  and  $X_C = \frac{1}{2\pi fC}$ . **Current:**  $I = \frac{V_s}{Z}$ . **Resonance:** When  $X_L = X_C$  (reactances cancel),  $f_0 = \frac{1}{2\pi\sqrt{LC}}$ , impedance minimum = R, current maximum. **Phasor diagram:**  $V_L$  leads current by 90°,  $V_C$  lags by 90° (opposite directions),  $V_R$  in phase. Supply voltage:  $V_s = \sqrt{V_R^2 + (V_L - V_C)^2}$  (vector sum).

**Oscillation vs damping:** When DC power applied then removed, LC oscillates at  $f_0$  (energy alternates between magnetic and electric fields). **Damping:** Resistance dissipates energy, oscillations decay. Small R → underdamped (many oscillations before stopping). Large R → critically damped (fastest return to zero without overshoot). Very large R → overdamped (slow return).

**Key equations:** Bridge balance:  $\frac{R_1}{R_2} = \frac{R_3}{R_4}$ ; RLC impedance:  $Z = \sqrt{R^2 + (X_L - X_C)^2}$ ; Resonance:  $f_0 = \frac{1}{2\pi\sqrt{LC}}$

## Detailed Explanation

### 2. Detailed Explanation

#### 1. Wheatstone Bridge Fundamentals:

Precision circuit for measuring resistance by comparing with known values.

##### Historical Context:

- Developed by Charles Wheatstone for unknown resistance measurement
- Calibration tool for ohmmeters, voltmeters, ammeters
- Digital multimeters simpler today, but bridge still used for:
- Very low resistance (mΩ range, contact resistance)
- Sensor interfacing (strain gauges, temperature sensors)
- High-precision measurements (4-wire sensing)

##### Circuit Structure:

- **Configuration:** Two voltage dividers in parallel
- First divider:  $R_1$  series with  $R_2$  (top to bottom)
- Second divider:  $R_3$  series with  $R_4$  (top to bottom)
- Voltage supply across both dividers (common top and bottom)
- Voltmeter connected between divider midpoints (junction  $R_1$ - $R_2$  and  $R_3$ - $R_4$ )
- **Bridge:** Voltmeter connection is the "bridge" between two dividers

##### Balance Condition:

Bridge is balanced when voltmeter reads exactly 0 V (no potential difference).

- **Left divider voltage:**  $V_1 = V_s \frac{R_2}{R_1 + R_2}$  (voltage at  $R_1$ - $R_2$  junction)
- **Right divider voltage:**  $V_2 = V_s \frac{R_4}{R_3 + R_4}$  (voltage at  $R_3$ - $R_4$  junction)
- **Balance:**  $V_1 = V_2$  (no voltage difference, meter reads 0)
- $V_s \frac{R_2}{R_1 + R_2} = V_s \frac{R_4}{R_3 + R_4}$
- Cancel  $V_s$ :  $\frac{R_2}{R_1 + R_2} = \frac{R_4}{R_3 + R_4}$
- Cross-multiply:  $R_2(R_3 + R_4) = R_4(R_1 + R_2)$
- Expand:  $R_2R_3 + R_2R_4 = R_4R_1 + R_4R_2$
- Cancel  $R_2R_4$ :  $R_2R_3 = R_4R_1$
- **Balance equation:**  $\frac{R_1}{R_2} = \frac{R_3}{R_4}$  (ratio equality)

##### Measuring Unknown Resistance:

Assume  $R_2$  is unknown,  $R_1$ ,  $R_3$  fixed,  $R_4$  variable.

- Set  $R_1$  and  $R_3$  to known values (e.g., 220 Ω, 400 Ω)
- Adjust  $R_4$  (variable resistor, potentiometer) until voltmeter reads 0 V
- At balance:  $\frac{R_1}{R_2} = \frac{R_3}{R_4}$
- Solve for unknown:  $R_2 = R_1 \frac{R_4}{R_3}$

- Plug in known values, calculate  $R_2$
- Example:  $R_1 = 220\ \Omega$ ,  $R_3 = 400\ \Omega$ ,  $R_4 = 1000\ \Omega$  (adjusted to balance)
- $R_2 = 220 \times \frac{1000}{400} = 220 \times 2.5 = 550\ \Omega$  ✓

### Supply Voltage Independence:

Balance condition independent of supply voltage.

- Balance depends only on resistance ratios, not absolute voltages
- If  $V_s$  doubled: Both  $V_1$  and  $V_2$  double equally
- Difference ( $V_1 - V_2$ ) remains zero if balanced
- Can use any stable supply (battery, regulated supply)
- Advantage: Voltage drift doesn't affect measurement accuracy

## 2. Wheatstone Bridge Applications:

Beyond simple resistance measurement.

### Sensor Interfacing (with Op-Amp):

- Replace one resistor with sensor (strain gauge, RTD, LDR photocell)
- Sensor resistance changes with physical quantity (force, temperature, light)
- Bridge output voltage proportional to resistance change
- Op-amp amplifies small voltage difference (high gain, high input impedance)
- **Example:** Light detector using LDR (Light-Dependent Resistor)
- Dark: LDR high resistance  $\rightarrow$  bridge unbalanced one way  $\rightarrow$  positive output
- Bright: LDR low resistance  $\rightarrow$  bridge unbalanced opposite  $\rightarrow$  negative output
- Op-amp output drives indicator, relay, or ADC

### Strain Gauge Measurement:

- Strain gauge: Resistance changes with mechanical strain ( $\Delta R/R \approx 0.1\text{--}2\%$ )
- Four-arm bridge: All four resistors are strain gauges (temperature compensation)
- Balanced at zero strain, unbalanced proportional to applied force
- Used in: Load cells, pressure sensors, torque sensors

## 3. Series RLC Circuit Basics:

R, L, C connected in series across AC supply, impedance depends on frequency.

### Component Reactances:

- **Resistance R:** Constant with frequency, dissipates power
- **Inductive reactance:**  $X_L = 2\pi fL = \omega L$  (increases with frequency)
- At DC ( $f = 0$ ):  $X_L = 0$  (inductor acts as short circuit)
- At high f:  $X_L$  large (inductor blocks AC)
- **Capacitive reactance:**  $X_C = \frac{1}{2\pi fC} = \frac{1}{\omega C}$  (decreases with frequency)
- At DC ( $f = 0$ ):  $X_C = \infty$  (capacitor acts as open circuit)
- At high f:  $X_C$  small (capacitor passes AC easily)

### Angular Frequency:

- $\omega = 2\pi f$  (radians per second)
- One cycle =  $2\pi$  radians
- Frequency  $f$  = cycles per second (Hz)
- Angular frequency = radians per second (rad/s)
- Simplifies equations:  $X_L = \omega L$ ,  $X_C = \frac{1}{\omega C}$

## 4. Series RLC Impedance and Phasor Diagram:

Total impedance combines resistance and reactance (vector addition).

### Voltage-Current Phase Relationships:

- **Resistor:** Voltage and current in phase ( $0^\circ$  phase shift)
- **Inductor:** Voltage leads current by  $90^\circ$  (current lags voltage)
- Memory: "ELI"  $\rightarrow$  E (voltage) Leads I (current) in Inductor
- **Capacitor:** Voltage lags current by  $90^\circ$  (current leads voltage)
- Memory: "ICE"  $\rightarrow$  I (current) Comes before E (voltage) in Capacitor

### Phasor Diagram (Current as Reference):

- Current  $I$  same through all components (series circuit)  $\rightarrow$  use as reference (horizontal)
- $V_R = IR$  in phase with current (horizontal, same direction as  $I$ )
- $V_L = IX_L$  leads current by  $90^\circ$  (vertical, upward from  $I$ )
- $V_C = IX_C$  lags current by  $90^\circ$  (vertical, downward from  $I$ )
- $V_L$  and  $V_C$  point opposite directions (cancel partially or fully)

### Supply Voltage (Vector Sum):

- Cannot simply add  $V_R + V_L + V_C$  (different phases)

- Must use vector (phasor) addition
- $V_L$  and  $V_C$  opposite: Net reactive voltage =  $V_L - V_C$
- Supply voltage:  $V_s = \sqrt{V_R^2 + (V_L - V_C)^2}$  (Pythagorean theorem)
- Substitute  $V = IZ$ :  $V_s = I\sqrt{R^2 + (X_L - X_C)^2}$
- **Impedance:**  $Z = \frac{V_s}{I} = \sqrt{R^2 + (X_L - X_C)^2}$  (total opposition to AC)

### Three Impedance Cases:

- $X_L > X_C$ : Inductive dominant,  $Z = \sqrt{R^2 + (X_L - X_C)^2}$ , current lags voltage
- $X_C > X_L$ : Capacitive dominant,  $Z = \sqrt{R^2 + (X_C - X_L)^2}$ , current leads voltage
- $X_L = X_C$ : Resonance, reactances cancel,  $Z = R$  (minimum), current maximum

### 5. Resonance in Series RLC:

Special frequency where reactances cancel, impedance minimized.

#### Resonance Condition:

- $X_L = X_C$  (inductive and capacitive reactances equal)
- $2\pi f_0 L = \frac{1}{2\pi f_0 C}$
- Rearrange:  $(2\pi f_0)^2 LC = 1$
- **Resonant frequency:**  $f_0 = \frac{1}{2\pi\sqrt{LC}}$
- Depends only on L and C values, independent of R

#### At Resonance:

- $X_L - X_C = 0$  (reactances cancel completely)
- Impedance:  $Z = \sqrt{R^2 + 0^2} = R$  (minimum possible, purely resistive)
- Current:  $I = \frac{V_s}{Z} = \frac{V_s}{R}$  (maximum current for given  $V_s$ )
- Voltage across R:  $V_R = IR = V_s$  (all supply voltage across R)
- Voltage across L and C: Can be very large (Q times  $V_s$ ), but cancel in phasor sum
- Power factor: 1 (purely resistive, voltage and current in phase)

#### Applications:

- Radio tuning: Select frequency  $f_0$  by adjusting L or C (variable capacitor)
- Impedance minimum at  $f_0 \rightarrow$  maximum signal at resonance
- Filter: Passes  $f_0$ , attenuates other frequencies
- FM tuner: Vary C to change  $f_0$  across 88–108 MHz band

### 6. RLC Oscillation and Damping:

Energy exchange between L and C when DC power applied then removed.

#### Oscillation Mechanism:

- Initially: Capacitor charged, inductor de-energized
- Capacitor discharges through inductor
- Current builds magnetic field in inductor (stores energy)
- Capacitor fully discharged, inductor fully energized
- Magnetic field collapses, induces current (Lenz's law)
- Current charges capacitor in opposite polarity
- Process reverses: Energy oscillates  $L \leftrightarrow C$
- Frequency:  $f_0 = \frac{1}{2\pi\sqrt{LC}}$  (resonant frequency)

#### Ideal LC (No Resistance):

- Energy conserved:  $E_{total} = E_L + E_C$  constant
- Magnetic energy:  $E_L = \frac{1}{2}LI^2$
- Electric energy:  $E_C = \frac{1}{2}CV^2$
- Oscillation continues forever (no damping)
- Harmonic oscillator (like frictionless pendulum)

#### Real RLC (With Resistance):

Resistance dissipates energy, oscillations decay.

- Power loss:  $P = I^2 R$  (resistance converts energy to heat)
- Each cycle: Some energy lost, amplitude decreases
- **Damping:** Gradual reduction in oscillation amplitude
- Eventually: All energy dissipated, oscillation stops

#### Damping Regimes:

Behavior depends on resistance value relative to critical damping.

- **Underdamped** ( $R < R_{critical}$ ): Small resistance
- Many oscillations before stopping (10–100+ cycles)
- Exponential envelope: Amplitude decays as  $e^{-t/\tau}$  where  $\tau = \frac{2L}{R}$

- Typical: Small  $R$  (10–100  $\Omega$ )
- **Critically damped** ( $R = R_{critical}$ ): Specific resistance value
- $R_{critical} = 2\sqrt{\frac{L}{C}}$  (critical damping resistance)
- No oscillation, fastest return to zero without overshoot
- Optimal for control systems (door closer, suspension)
- **Overdamped** ( $R > R_{critical}$ ): Large resistance
- No oscillation, slow exponential decay
- Takes longer to settle than critically damped
- Example: Very large  $R$  (k $\Omega$ –M $\Omega$ )

## Practical Examples & Numerical

### Example 1: Wheatstone Bridge Measurement

**Given:** Bridge balanced with  $R_1 = 220 \Omega$ ,  $R_3 = 400 \Omega$ ,  $R_4 = 1000 \Omega$

**Find unknown  $R_2$ :**

- Balance condition:  $\frac{R_1}{R_2} = \frac{R_3}{R_4}$
- Rearrange:  $R_2 = R_1 \frac{R_4}{R_3}$
- Substitute:  $R_2 = 220 \times \frac{1000}{400} = 220 \times 2.5$
- $R_2 = 550 \Omega$  ✓

**Verification:**

- Check ratio:  $\frac{R_1}{R_2} = \frac{220}{550} = 0.4$
- $\frac{R_3}{R_4} = \frac{400}{1000} = 0.4$  ✓ (ratios equal)
- Bridge balanced ✓

### Example 2: Series RLC Impedance Calculation

**Given:**  $R = 2 \Omega$ ,  $L = 0.15 \text{ H}$ ,  $C = 100 \mu\text{F}$ , supply 100 V at 50 Hz

**Calculate impedance and current:**

- Inductive reactance:  $X_L = 2\pi fL = 2\pi \times 50 \times 0.15$
- $X_L = 47.12 \Omega$
- Capacitive reactance:  $X_C = \frac{1}{2\pi fC} = \frac{1}{2\pi \times 50 \times 100 \times 10^{-6}}$
- $X_C = \frac{1}{0.0314} = 31.83 \Omega$
- Net reactance:  $X_L - X_C = 47.12 - 31.83 = 15.29 \Omega$  (inductive)
- Impedance:  $Z = \sqrt{R^2 + (X_L - X_C)^2} = \sqrt{4 + 233.78}$
- $Z = \sqrt{237.78} = 15.42 \Omega$
- Current:  $I = \frac{V_s}{Z} = \frac{100}{15.42} = 6.49 \text{ A}$

**Voltage drops:**

- $V_R = IR = 6.49 \times 2 = 12.98 \text{ V}$
- $V_L = IX_L = 6.49 \times 47.12 = 305.8 \text{ V}$
- $V_C = IX_C = 6.49 \times 31.83 = 206.6 \text{ V}$
- Verify:  $V_s = \sqrt{V_R^2 + (V_L - V_C)^2} = \sqrt{168.5 + (99.2)^2} = \sqrt{10007.1} = 100 \text{ V}$  ✓
- Note:  $V_L$  and  $V_C$  individually exceed  $V_s$  (resonance effect), but cancel in phasor sum

### Example 3: Resonant Frequency Calculation

**Given:**  $L = 0.15 \text{ H}$ ,  $C = 100 \mu\text{F}$  (same circuit as Example 2)

**Find resonant frequency:**

- $f_0 = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{0.15 \times 100 \times 10^{-6}}}$
- $f_0 = \frac{1}{2\pi\sqrt{1.5 \times 10^{-5}}} = \frac{1}{2\pi \times 3.873 \times 10^{-3}}$
- $f_0 = \frac{1}{0.02433} = 41.1 \text{ Hz}$

**At resonance (41.1 Hz):**

- $X_L = 2\pi \times 41.1 \times 0.15 = 38.7 \Omega$
- $X_C = \frac{1}{2\pi \times 41.1 \times 100 \times 10^{-6}} = 38.7 \Omega$  ✓ (equal)
- $Z = R = 2 \Omega$  (minimum impedance)
- $I = \frac{100}{2} = 50 \text{ A}$  (maximum current, 7.7 $\times$  higher than at 50 Hz!)
- Power:  $P = I^2 R = 50^2 \times 2 = 5000 \text{ W}$  (all power dissipated in  $R$ )

### Example 4: Critical Damping Resistance

**Given:**  $L = 0.15 \text{ H}$ ,  $C = 100 \text{ }\mu\text{F}$ , want critically damped response

**Calculate  $R_{critical}$ :**

- $R_{critical} = 2\sqrt{\frac{L}{C}} = 2\sqrt{\frac{0.15}{100 \times 10^{-6}}} = 2\sqrt{1500} = 2 \times 38.73 = 77.46 \text{ }\Omega$
- $R_{critical} = 2\sqrt{1500} = 2 \times 38.73 = 77.46 \text{ }\Omega$

**Damping behavior:**

- $R = 2 \text{ }\Omega$  (Example 2): Underdamped (many oscillations,  $R \ll R_{critical}$ )
- $R = 77.46 \text{ }\Omega$ : Critically damped (fastest settle, no overshoot)
- $R = 500 \text{ }\Omega$ : Overdamped (slow settle, no oscillation,  $R > R_{critical}$ )

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- **Wheatstone Bridge Balance:**  $\frac{R_1}{R_2} = \frac{R_3}{R_4}$  when voltmeter reads 0 V. Two voltage dividers in parallel, bridge voltage = difference between divider midpoints. Balanced when ratios equal, independent of supply voltage. To measure unknown: Set 3 resistors, adjust 4th until balance, calculate from ratio. Precision method for low resistance (m $\Omega$ ), sensor interfacing
- **Series RLC Impedance:**  $Z = \sqrt{R^2 + (X_L - X_C)^2}$  where  $X_L = 2\pi fL$  (inductive reactance increases with f),  $X_C = \frac{1}{2\pi fC}$  (capacitive reactance decreases with f). Phasor addition:  $V_L$  leads current  $90^\circ$ ,  $V_C$  lags  $90^\circ$  (opposite),  $V_R$  in phase. Supply voltage vector sum:  $V_s = \sqrt{V_R^2 + (V_L - V_C)^2}$
- **Resonance Condition:**  $X_L = X_C$  at  $f_0 = \frac{1}{2\pi\sqrt{LC}}$ . Reactances cancel, impedance minimum = R, current maximum  $I = V_s/R$ . All supply voltage across R, but  $V_L$  and  $V_C$  can exceed  $V_s$  (high Q). Used in radio tuning: Adjust L or C to change  $f_0$ , select desired frequency. Power factor = 1 (resistive, voltage and current in phase)
- **LC Oscillation:** Energy oscillates between magnetic field (L) and electric field (C) at  $f_0 = \frac{1}{2\pi\sqrt{LC}}$ . Capacitor charges  $\rightarrow$  discharges through L  $\rightarrow$  builds magnetic field  $\rightarrow$  field collapses  $\rightarrow$  charges C opposite polarity  $\rightarrow$  repeat. Ideal LC: Oscillates forever (energy conserved). Real RLC: Resistance dissipates energy ( $P = I^2R$ ), oscillations decay
- **Damping Types:** Underdamped ( $R < R_{crit}$ ): Many oscillations, exponential decay envelope. Critically damped ( $R = 2\sqrt{L/C}$ ): No oscillation, fastest settle without overshoot, optimal for control. Overdamped ( $R > R_{crit}$ ): No oscillation, slow exponential return. Small R  $\rightarrow$  oscillates, large R  $\rightarrow$  smooth decay
- **Frequency Dependence:** At low f:  $X_C$  high (capacitor blocks),  $X_L$  low (inductor passes), circuit capacitive. At high f:  $X_L$  high (inductor blocks),  $X_C$  low (capacitor passes), circuit inductive. At  $f_0$ :  $X_L = X_C$  (resonance), circuit resistive. Impedance varies with frequency, minimum at resonance
- **Q: Why can  $V_L$  and  $V_C$  exceed supply voltage in RLC?** A: At resonance or near resonance, reactive voltages can be Q times supply voltage where  $Q = \frac{X_L}{R}$  (quality factor). Example: If  $Q=20$ ,  $V_L = V_C = 20V_s$ . They are  $180^\circ$  out of phase, cancel in phasor sum:  $V_L - V_C = 0$  at exact resonance. Energy circulates between L and C, creating large voltages but no net reactive voltage. Supply only overcomes resistive drop
- **Q: How does Wheatstone bridge sensor work?** A: Replace one resistor with sensor (LDR, strain gauge, RTD). Sensor resistance changes with physical quantity (light, force, temperature). Bridge balanced at reference condition. Change in sensor  $\rightarrow$  unbalances bridge  $\rightarrow$  voltage appears between midpoints. Op-amp amplifies this voltage ( $\mu\text{V}$ – $\text{mV}$  range) to usable level. Output proportional to sensor change. Temperature compensation: Use matched sensors in opposite bridge arms (cancel common effects)
- **Q: Why is critical damping important?** A: Critical damping ( $R = 2\sqrt{L/C}$ ) gives fastest possible return to equilibrium without overshoot. Underdamped: Overshoots and oscillates (slow settling, ringing). Overdamped: No overshoot but slow (takes longer to reach final value). Critical: Perfect balance, reaches zero in minimum time with no overshoot. Used in: Door closers, shock absorbers, galvanometer damping, control systems requiring fast accurate response

# Section 18 – Transistors Fundamentals

## Transistor Basics and Operating Modes

### The Transistor Invention

#### TL;DR (The Gist)

**TL;DR:** Transistors revolutionized electronics by replacing bulky, inefficient vacuum tubes with compact, reliable semiconductor devices. The bipolar junction transistor (BJT) enabled the miniaturization of electronic circuits.

**Key Innovation:** Solid-state device with no moving parts, low power consumption, and long lifespan compared to vacuum tubes.

#### Detailed Explanation

### 2. Detailed Explanation

#### Historical Context

Before transistors, electronic circuits relied on vacuum tubes for amplification and switching. Vacuum tubes had significant limitations:

- Large physical size
- High heat generation
- Short lifespan (fragile glass construction)
- High power consumption
- Required warm-up time

The transistor, invented in 1947 at Bell Labs, overcame these limitations. The bipolar junction transistor (BJT) became the foundation of modern electronics, enabling:

- Miniaturization of circuits
- Portable electronics (battery-powered devices)
- Integrated circuits (ICs)
- Digital computers
- Modern telecommunications

#### Fundamental Principle

A transistor is a three-terminal semiconductor device that controls current flow. A small current or voltage at one terminal controls a much larger current between the other two terminals, providing amplification and switching capabilities.

#### Practical Example & Numerical

#### Vacuum Tube vs. Transistor Comparison

A typical vacuum tube amplifier:

- Size: 5-10 cm tall
- Power: 5-10 W just for heating
- Lifespan: 1,000-10,000 hours
- Warm-up: 30-60 seconds

Equivalent transistor circuit:

- Size: 1-5 mm
- Power: Milliwatts to watts
- Lifespan: Decades of continuous operation
- Warm-up: Instant

#### Key Points (Interview Focus)

## 4. Key Points (Interview Focus)

- Transistors replaced vacuum tubes as the fundamental building block of electronics
- BJTs are solid-state, three-terminal semiconductor devices
- Advantages: small size, low power, high reliability, instant operation
- Enabled the digital revolution and modern computing

### What's Inside a Transistor

#### TL;DR (The Gist)

**TL;DR:** A bipolar junction transistor (BJT) consists of three semiconductor layers forming two PN junctions. The two types are NPN (sandwich: N-P-N) and PNP (sandwich: P-N-P).

**Terminals:** Emitter (E), Base (B), Collector (C)

**Structure:** Two PN junctions back-to-back, with a very thin base region in the middle.

#### Detailed Explanation

## 2. Detailed Explanation

### Internal Structure

A BJT is constructed from three layers of doped semiconductor material:

#### NPN Transistor:

- **Emitter:** N-type (heavily doped, electron-rich)
- **Base:** P-type (very thin, lightly doped)
- **Collector:** N-type (moderately doped, larger area)

#### PNP Transistor:

- **Emitter:** P-type (heavily doped, hole-rich)
- **Base:** N-type (very thin, lightly doped)
- **Collector:** P-type (moderately doped, larger area)

### Physical Characteristics:

- Base region is extremely thin (micrometers)
- Emitter is heavily doped for maximum carrier injection
- Collector has larger surface area to dissipate heat
- Two PN junctions: base-emitter (BE) and base-collector (BC)

### Operation Principle

In an NPN transistor:

- Base-emitter junction is forward-biased ( $V_{BE} \approx 0.7 \text{ V}$ )
- Base-collector junction is reverse-biased
- Electrons from emitter cross thin base region
- Most electrons reach collector (minority recombine in base)
- Small base current controls large collector current

The thinness of the base is critical—it allows most charge carriers to pass through to the collector rather than recombining in the base.

#### Practical Example & Numerical

### NPN vs. PNP Transistor Characteristics

#### NPN Transistor:

- Conventional current flows: Collector  $\rightarrow$  Emitter
- Base voltage positive relative to emitter ( $V_{BE} = +0.7 \text{ V}$ )
- Collector voltage positive relative to emitter
- Most common type (faster switching due to electron mobility)

#### PNP Transistor:

- Conventional current flows: Emitter  $\rightarrow$  Collector

- Base voltage negative relative to emitter ( $V_{EB} = +0.7 \text{ V}$ )
- Collector voltage negative relative to emitter
- Less common (slower due to hole mobility)
- Useful for high-side switching applications

**Schematic Symbols:** The arrow indicates emitter and shows conventional current direction (always pointing from P to N material).

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- BJT = three semiconductor layers forming two PN junctions
- NPN: N-P-N sandwich; PNP: P-N-P sandwich
- Base region is very thin and lightly doped
- Emitter heavily doped, collector moderately doped with large area
- Arrow on schematic points from P to N (emitter direction)
- NPN more common due to higher electron mobility

## Basic NPN Transistor Circuit

### TL;DR (The Gist)

**TL;DR:** In a basic NPN switching circuit, a small base current ( $I_B$ ) controls a much larger collector current ( $I_C$ ). The relationship is  $I_C = \beta I_B$  where  $\beta$  is the current gain (typically 100-300).

**Key Equation:**  $I_C = \beta I_B$

**Typical Values:**  $V_{BE} = 0.7 \text{ V}$  (when conducting),  $V_{CE(sat)} \approx 0.2 \text{ V}$  (when saturated)

## Detailed Explanation

### 2. Detailed Explanation

#### Circuit Configuration

A basic NPN transistor circuit consists of:

- **Input side:** Base resistor ( $R_B$ ) limits base current
- **Output side:** Collector resistor ( $R_C$ ) or load
- **Power supply:** Typically  $V_{CC}$  connected to collector load
- **Ground:** Emitter usually grounded (common-emitter configuration)

#### Operating Principle:

1. Input voltage applied through base resistor
2. When  $V_{BE} \geq 0.7 \text{ V}$ , base-emitter junction conducts
3. Base current flows:  $I_B = \frac{V_{in} - 0.7}{R_B}$
4. Collector current flows:  $I_C = \beta I_B$
5. Output voltage:  $V_{out} = V_{CC} - I_C R_C$

#### Current Relationships:

- Emitter current:  $I_E = I_B + I_C$
- Since  $I_C \gg I_B$ :  $I_E \approx I_C$
- Typical  $\beta$  values: 100-300 for small signal transistors

## Practical Example & Numerical

### NPN Switch Circuit Design

Design a circuit to switch an LED using an NPN transistor:

**Given:**

- $V_{CC} = 12\text{ V}$
- LED forward current:  $I_F = 20\text{ mA}$
- LED forward voltage:  $V_F = 2\text{ V}$
- Transistor  $\beta = 200$
- Input voltage:  $V_{in} = 5\text{ V}$  (logic high)

**Solution:**

1. Calculate collector resistor:

$$R_C = \frac{V_{CC} - V_F - V_{CE(sat)}}{I_C} = \frac{12 - 2 - 0.2}{0.02} = 490\ \Omega \approx 470\ \Omega$$

2. Calculate required base current:

$$I_B = \frac{I_C}{\beta} = \frac{20\text{ mA}}{200} = 0.1\text{ mA}$$

3. Add safety margin (use  $\beta/10$  for saturation):

$$I_{B(actual)} = \frac{I_C}{20} = 1\text{ mA}$$

4. Calculate base resistor:

$$R_B = \frac{V_{in} - V_{BE}}{I_B} = \frac{5 - 0.7}{0.001} = 4.3\text{ k}\Omega \approx 4.7\text{ k}\Omega$$

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

- NPN transistor acts as current amplifier:  $I_C = \beta I_B$
- Base-emitter voltage  $V_{BE} = 0.7\text{ V}$  when conducting
- Common-emitter configuration: emitter grounded, input at base, output at collector
- For switching: drive base with  $I_B = I_C/10$  to ensure saturation
- Saturated transistor:  $V_{CE(sat)} \approx 0.2\text{ V}$

### Basic PNP Transistor Circuit

#### TL;DR (The Gist)

**TL;DR:** PNP transistors work similarly to NPN but with reversed polarities. Current flows from emitter to collector, and the base must be negative relative to the emitter to turn on.

**Key Difference:** All voltages and currents are reversed compared to NPN.

**Equation:**  $I_C = \beta I_B$  (same relationship, opposite current direction)

### Detailed Explanation

#### 2. Detailed Explanation

##### PNP Configuration

In a PNP transistor:

- **Emitter:** Connected to positive supply ( $V_{CC}$ )
- **Collector:** Connected to load (pulls current from ground)
- **Base:** Control input (negative voltage relative to emitter)

##### Operating Conditions:

- Turn ON:  $V_{EB} = 0.7\text{ V}$  (emitter 0.7 V above base)
- Base voltage lower than emitter voltage
- Collector voltage lower than emitter voltage
- Conventional current: Emitter  $\rightarrow$  Collector

##### Comparison with NPN:

- NPN: Low input turns OFF, high input turns ON

- PNP: Low input turns ON, high input turns OFF
- NPN: Current sinks to ground
- PNP: Current sources from positive rail

#### Common Applications:

- High-side switching (switching the positive rail)
- Complementary push-pull amplifiers (paired with NPN)
- Reverse polarity protection
- Voltage regulators

### Practical Example & Numerical

#### PNP High-Side Switch

Design a PNP circuit to control a 12 V load from a 5 V microcontroller:

#### Given:

- $V_{CC} = 12\text{ V}$
- Load current:  $I_L = 100\text{ mA}$
- Transistor  $\beta = 150$
- MCU output: 0 V (ON) or 5 V (OFF)

#### Solution:

1. When MCU outputs 0 V:
  - $V_{EB} = 12 - 0 = 12\text{ V}$  (but junction limits to 0.7 V)
  - Base resistor drops:  $12 - 0.7 = 11.3\text{ V}$
2. Calculate base current for saturation:

$$I_B = \frac{I_C}{10} = \frac{100\text{ mA}}{10} = 10\text{ mA}$$

3. Calculate base resistor:

$$R_B = \frac{V_{CC} - V_{EB} - V_{MCU}}{I_B} = \frac{12 - 0.7 - 0}{0.01} = 1.13\text{ k}\Omega \approx 1\text{ k}\Omega$$

4. When MCU outputs 5 V:
  - $V_{EB} = 12 - 5 = 7\text{ V}$  across  $R_B$  and junction
  - Junction needs 0.7 V to conduct
  - Voltage across  $R_B$ :  $7 - 0.7 = 6.3\text{ V}$
  - This would give  $I_B = 6.3\text{ mA}$  (still partially on)

**Improvement:** Add pull-up resistor or use NPN + PNP combination for complete turn-off.

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

- PNP: All polarities reversed compared to NPN
- Emitter-base voltage:  $V_{EB} = 0.7\text{ V}$  when conducting
- Base must be negative relative to emitter to turn on
- Ideal for high-side switching applications
- Less common than NPN (lower hole mobility)
- Complementary to NPN in push-pull configurations

### Transistor Switching Advantages

#### TL;DR (The Gist)

**TL;DR:** Transistors excel at switching applications due to fast response, low power consumption, no mechanical wear, and ability to control high currents with small signals.

**Key Advantages:** No moving parts, microsecond switching speeds, minimal control power, long lifespan.

## Detailed Explanation

### 2. Detailed Explanation

#### Advantages Over Mechanical Switches

##### Speed:

- Mechanical relay: 5-15 ms switching time
- Transistor: 100 ns to 10  $\mu$ s switching time
- Can switch millions of times per second

##### Reliability:

- No mechanical wear or contact bounce
- No arcing or contact oxidation
- Decades of continuous operation
- Not affected by vibration or shock

##### Control Power:

- Relay coil: 50-500 mW
- Transistor base: 0.1-10 mW
- Perfect for low-power microcontroller outputs

##### Size and Integration:

- Can be microscopic (billions in a CPU)
- No minimum practical size limit
- Enables integrated circuits

##### Limitations:

- Not electrically isolated (unlike relays)
- Voltage drop when conducting ( $V_{CE(sat)} \approx 0.2$  V)
- Heat dissipation in high-power applications
- Can be damaged by overvoltage/overcurrent

## Practical Example & Numerical

#### Switching Speed Comparison

##### Mechanical Relay:

- Turn-on time: 5-10 ms
- Turn-off time: 3-8 ms
- Maximum frequency: 50 Hz
- Contact bounce: 1-2 ms

##### BJT Transistor:

- Turn-on time: 0.1-1  $\mu$ s
- Turn-off time: 1-10  $\mu$ s
- Maximum frequency: 100 kHz - 1 GHz
- No bounce

##### Application Example: PWM motor control

- Required frequency: 20 kHz
- Relay: Cannot achieve this frequency
- Transistor: Easy, with room for much higher frequencies

## Key Points (Interview Focus)

## 4. Key Points (Interview Focus)

- Transistors switch  $1000\times$  faster than relays
- No moving parts = no mechanical wear
- Minimal control power required
- Can switch millions of times per second
- Essential for digital electronics and PWM
- Trade-off: No electrical isolation like relays provide

### Three Operating Modes: Saturation

#### TL;DR (The Gist)

**TL;DR:** Saturation mode is when the transistor is fully ON, acting like a closed switch. Both junctions are forward-biased, and  $V_{CE}$  drops to minimum (0.2 V).

**Condition:**  $I_C < \beta I_B$  (excess base current drives transistor into saturation)

**Key Parameter:**  $V_{CE(sat)} \approx 0.2 \text{ V}$

#### Detailed Explanation

## 2. Detailed Explanation

### Saturation Mode Characteristics

#### Junction Biasing:

- Base-emitter junction: Forward-biased ( $V_{BE} = 0.7 \text{ V}$ )
- Base-collector junction: Forward-biased ( $V_{BC} > 0$ )

#### Voltage Relationships:

- $V_{CE(sat)} \approx 0.2 \text{ V}$  (very low, like closed switch)
- $V_C \approx V_E + 0.2 \text{ V}$
- For grounded emitter:  $V_C \approx 0.2 \text{ V}$

#### Current Relationships:

- Collector current limited by external circuit, not  $\beta$
- $I_C = \frac{V_{CC} - V_{CE(sat)}}{R_C}$
- Base current higher than needed:  $I_B > \frac{I_C}{\beta}$
- Typical design:  $I_B = \frac{I_C}{10}$  (forced beta = 10)

#### Design for Saturation:

To ensure saturation in switching applications:

1. Calculate maximum collector current from load
2. Use forced  $\beta = 10$  instead of datasheet  $\beta$
3. Calculate:  $I_B = \frac{I_{C(max)}}{10}$
4. Design base circuit to provide this current

#### Why Use Saturation?:

- Minimum power dissipation:  $P = V_{CE(sat)} \times I_C$
- With  $V_{CE(sat)} = 0.2 \text{ V}$ , power loss is minimal
- Transistor acts as nearly ideal switch
- Predictable ON state regardless of  $\beta$  variation

#### Practical Example & Numerical

### Designing for Saturation

Switch a 100 mA load with NPN transistor ( $\beta = 200$ ):

**Poor Design** (using full  $\beta$ ):

$$I_B = \frac{I_C}{\beta} = \frac{100 \text{ mA}}{200} = 0.5 \text{ mA}$$

Problem: If  $\beta$  varies (150-250), transistor may not saturate reliably.

**Good Design** (forced  $\beta = 10$ ):

$$I_B = \frac{I_C}{10} = \frac{100 \text{ mA}}{10} = 10 \text{ mA}$$

With 5 V input and grounded emitter:

$$R_B = \frac{V_{in} - V_{BE}}{I_B} = \frac{5 - 0.7}{0.01} = 430 \Omega \approx 470 \Omega$$

**Verification:**

- Worst case  $\beta = 150$ : Can handle  $150 \times 10 = 1500 \text{ mA}$
- Required: 100 mA  $\rightarrow$  Well saturated  $\checkmark$
- $V_{CE} \approx 0.2 \text{ V} \rightarrow$  Minimal power loss  $\checkmark$

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- Saturation = fully ON state, both junctions forward-biased
- $V_{CE(sat)} \approx 0.2 \text{ V}$  (acts like closed switch)
- Design rule: Use forced  $\beta = 10$  for reliable saturation
- Collector current limited by external circuit, not transistor
- Minimum power dissipation in saturation mode
- Essential for digital switching applications

## Three Operating Modes: Cutoff

### TL;DR (The Gist)

**TL;DR:** Cutoff mode is when the transistor is fully OFF, acting like an open switch. The base-emitter junction is reverse-biased or insufficiently forward-biased.

**Condition:**  $V_{BE} < 0.7 \text{ V}$

**Key Parameter:**  $I_C \approx 0$  (typically nanoamperes of leakage)

## Detailed Explanation

### 2. Detailed Explanation

#### Cutoff Mode Characteristics

##### Junction Biasing:

- Base-emitter junction: Reverse-biased or  $V_{BE} < 0.7 \text{ V}$
- Base-collector junction: Reverse-biased

##### Current Relationships:

- $I_B = 0$  (or negligible)
- $I_C \approx 0$  (small leakage current, typically  $\leq 1 \text{ }\mu\text{A}$ )
- $I_E \approx 0$
- Leakage current doubles approximately every  $10^\circ\text{C}$  temperature rise

##### Voltage Relationships:

- $V_{CE} \approx V_{CC}$  (full supply voltage)
- For circuit with collector resistor:  $V_C = V_{CC}$  (no current, no drop)
- $V_{BE} < 0.7 \text{ V}$  (threshold voltage)

##### How to Achieve Cutoff:

- Ground the base (for NPN with grounded emitter)
- Apply voltage below 0.7 V to base
- Use pull-down resistor to ensure defined OFF state
- For PNP: Make base voltage equal to or higher than emitter

##### Applications:

- Digital logic (represents logic "0" in some configurations)
- Switching circuits (OFF state)
- Preventing current flow when not needed
- Low-power standby modes

### Practical Example & Numerical

#### Cutoff State Analysis

NPN transistor circuit:  $V_{CC} = 12\text{ V}$ ,  $R_C = 1\text{ k}\Omega$ ,  $R_B = 10\text{ k}\Omega$

**Case 1:** Input = 0 V

- $V_{BE} = 0\text{ V} \nmid 0.7\text{ V} \rightarrow$  Cutoff
- $I_B = 0\text{ mA}$
- $I_C \approx 0\text{ mA}$  (leakage negligible)
- $V_C = V_{CC} - I_C R_C = 12 - 0 = 12\text{ V}$
- Power dissipation:  $P \approx 0\text{ W}$

**Case 2:** Input = 0.5 V

- $V_{BE} = 0.5\text{ V} \nmid 0.7\text{ V} \rightarrow$  Still in cutoff
- $I_B \approx 0$  (junction not conducting)
- $I_C \approx 0\text{ mA}$
- $V_C = 12\text{ V}$

**Case 3:** Input = 0.7 V

- $V_{BE} = 0.7\text{ V} \rightarrow$  Threshold, beginning to conduct
- Transitioning from cutoff to active mode

**Leakage Current:** At  $25^\circ\text{C}$ :  $I_{CEO} \approx 10\text{ nA}$  At  $75^\circ\text{C}$ :  $I_{CEO} \approx 160\text{ nA}$  (doubles every  $10^\circ\text{C}$ ) Still negligible compared to active currents.

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

- Cutoff = fully OFF state, transistor acts as open switch
- Condition:  $V_{BE} < 0.7\text{ V}$  for NPN
- Collector current approximately zero (small leakage)
- $V_{CE} \approx V_{CC}$  (no voltage drop across transistor)
- No significant power dissipation in cutoff
- Leakage current increases with temperature

### Three Operating Modes: Active (Linear) Region

#### TL;DR (The Gist)

**TL;DR:** Active (or linear) mode is the amplification region where  $I_C = \beta I_B$  holds accurately. The base-emitter junction is forward-biased, and the base-collector junction is reverse-biased.

**Condition:**  $V_{CE} > 0.2\text{ V}$  and  $V_{BE} = 0.7\text{ V}$

**Key Relationship:**  $I_C = \beta I_B$  (linear amplification)

### Detailed Explanation

#### 2. Detailed Explanation

##### Active Mode Characteristics

##### Junction Biasing:

- Base-emitter junction: Forward-biased ( $V_{BE} = 0.7\text{ V}$ )

- Base-collector junction: Reverse-biased ( $V_{BC} < 0$ )

#### Voltage Relationships:

- $V_{CE} > V_{CE(sat)}$  (typically  $V_{CE} > 0.2 \text{ V}$ )
- $V_C > V_B$  (for NPN transistor)
- For proper operation:  $V_{CE}$  typically  $\geq 1 \text{ V}$

#### Current Relationships:

- $I_C = \beta I_B$  (linear relationship)
- $I_E = I_C + I_B = (\beta + 1)I_B$
- Since  $\beta \gg 1$ :  $I_E \approx I_C$
- Collector current controlled by base current

#### Why "Active" or "Linear"?:

- Current gain  $\beta$  is constant in this region
- Linear relationship between  $I_B$  and  $I_C$
- Used for analog signal amplification
- Small changes in  $V_{BE}$  produce proportional changes in  $I_C$

#### Applications:

- Audio amplifiers
- Signal amplification
- Voltage followers
- Current sources
- Linear regulators
- Any application requiring proportional control

#### Power Dissipation:

- $P = V_{CE} \times I_C$
- Highest in active region (partial voltage, partial current)
- Requires heat management for high-power applications
- Efficiency lower than saturation mode

### Practical Example & Numerical

#### Active Mode Operation

Transistor with  $\beta = 150$ ,  $V_{CC} = 12 \text{ V}$ ,  $R_C = 1 \text{ k}\Omega$

##### Scenario 1: $I_B = 20 \text{ }\mu\text{A}$

- $I_C = \beta I_B = 150 \times 20 \text{ }\mu\text{A} = 3 \text{ mA}$
- $V_C = V_{CC} - I_C R_C = 12 - 3 = 9 \text{ V}$
- $V_{CE} = V_C - V_E = 9 - 0 = 9 \text{ V} \geq 0.2 \text{ V} \checkmark$  Active mode
- Power:  $P = 9 \times 0.003 = 27 \text{ mW}$

##### Scenario 2: $I_B = 40 \text{ }\mu\text{A}$

- $I_C = 150 \times 40 \text{ }\mu\text{A} = 6 \text{ mA}$
- $V_C = 12 - 6 = 6 \text{ V}$
- $V_{CE} = 6 \text{ V} \geq 0.2 \text{ V} \checkmark$  Still active mode
- Power:  $P = 6 \times 0.006 = 36 \text{ mW}$

##### Scenario 3: $I_B = 80 \text{ }\mu\text{A}$

- Predicted:  $I_C = 150 \times 80 \text{ }\mu\text{A} = 12 \text{ mA}$
- But maximum available:  $I_{C(max)} = \frac{12}{1000} = 12 \text{ mA}$
- Would need  $V_C = 0 \text{ V} \rightarrow V_{CE} = 0 \text{ V}$
- Actually: Transistor enters saturation
- $V_{CE} \approx 0.2 \text{ V}$ ,  $I_C \approx 11.8 \text{ mA}$

**Load Line Analysis:** The transistor operates in active mode as long as the load line intersection falls in the active region of the characteristic curves.

### Key Points (Interview Focus)

## 4. Key Points (Interview Focus)

- Active mode: Base-emitter forward, base-collector reverse
- Linear relationship:  $I_C = \beta I_B$
- Used for amplification applications
- $V_{CE}$  must be sufficiently high ( $\geq 0.2$  V, typically  $\geq 1$  V)
- Higher power dissipation than saturation or cutoff
- Essential for analog signal processing
- Transistor acts as current-controlled current source

## Current Gain and Biasing Techniques

### Current Gain: Alpha ( $\alpha$ ) and Beta ( $\beta$ )

#### TL;DR (The Gist)

**TL;DR:** Transistor current gain is expressed as  $\beta$  (beta) or  $\alpha$  (alpha). Beta is the ratio of collector to base current; alpha is the ratio of collector to emitter current.

**Key Equations:**

- $\beta = \frac{I_C}{I_B}$  (typical values: 100-300)
- $\alpha = \frac{I_C}{I_E}$  (typical values: 0.95-0.99)
- $\beta = \frac{\alpha}{1-\alpha}$  and  $\alpha = \frac{\beta}{\beta+1}$

#### Detailed Explanation

## 2. Detailed Explanation

### Beta ( $\beta$ ) - DC Current Gain

Beta (also written as  $h_{FE}$  in datasheets) represents the current amplification factor:

$$\beta = \frac{I_C}{I_B}$$

**Characteristics:**

- Typical values: 100-300 for small signal transistors
- Power transistors: 20-100
- Darlington pairs: 1000-10000
- Temperature dependent (increases with temperature)
- Varies significantly between individual transistors
- Not constant across all operating conditions

### Alpha ( $\alpha$ ) - Common Base Gain

Alpha represents the fraction of emitter current that reaches the collector:

$$\alpha = \frac{I_C}{I_E}$$

**Characteristics:**

- Always less than 1 (typically 0.95-0.99)
- More stable than  $\beta$
- Represents transistor efficiency
- $(1 - \alpha)$  is the fraction lost in base recombination

### Relationship Between $\alpha$ and $\beta$

Starting from current relations:

$$I_E = I_B + I_C$$

$$\alpha = \frac{I_C}{I_E} = \frac{I_C}{I_B + I_C} = \frac{1}{I_B/I_C + 1} = \frac{1}{1/\beta + 1} = \frac{\beta}{\beta + 1}$$

Conversely:

$$\beta = \frac{I_C}{I_B} = \frac{I_C}{I_E - I_C} = \frac{\alpha}{1 - \alpha}$$

#### Why Both Parameters?:

- $\beta$  is intuitive for common-emitter circuits (most common)
- $\alpha$  is useful for common-base analysis
- $\alpha$  is more fundamental (based on physical construction)
- $\beta$  varies more with operating conditions

### Practical Example & Numerical

#### Converting Between $\alpha$ and $\beta$

**Example 1:** Given  $\beta = 150$ , find  $\alpha$

$$\alpha = \frac{\beta}{\beta + 1} = \frac{150}{151} = 0.9934$$

This means 99.34% of emitter current reaches the collector; only 0.66% recombines in the base.

**Example 2:** Given  $\alpha = 0.98$ , find  $\beta$

$$\beta = \frac{\alpha}{1 - \alpha} = \frac{0.98}{1 - 0.98} = \frac{0.98}{0.02} = 49$$

**Example 3:** Calculate actual currents

Given:  $I_E = 10 \text{ mA}$ ,  $\alpha = 0.99$

$$I_C = \alpha I_E = 0.99 \times 10 = 9.9 \text{ mA}$$

$$I_B = I_E - I_C = 10 - 9.9 = 0.1 \text{ mA}$$

$$\beta = \frac{I_C}{I_B} = \frac{9.9}{0.1} = 99$$

Verification:  $\beta = \frac{0.99}{1 - 0.99} = \frac{0.99}{0.01} = 99 \checkmark$

**Practical Observation:** High  $\alpha$  (close to 1) corresponds to high  $\beta$ . As  $\alpha$  approaches 1,  $\beta$  approaches infinity.

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

- $\beta = I_C/I_B$  is DC current gain (common-emitter)
- $\alpha = I_C/I_E$  is current transfer ratio (common-base)
- Typical  $\beta$ : 100-300; Typical  $\alpha$ : 0.95-0.99
- $\beta = \alpha/(1 - \alpha)$  and  $\alpha = \beta/(\beta + 1)$
- $\beta$  varies significantly;  $\alpha$  more stable
- Design should not rely on exact  $\beta$  value
- High  $\alpha$  (near 1) means efficient transistor

### Biasing for Beta Independence

#### TL;DR (The Gist)

**TL;DR:** Good transistor circuit design minimizes dependence on  $\beta$ , which varies between devices and with temperature. Voltage divider bias and emitter degeneration provide  $\beta$ -independent operation.

**Key Technique:** Set operating point using voltage divider at base and emitter resistor for negative feedback.

**Design Rule:** Make  $I_2 > 10 \times I_B$  for stiff voltage divider.

### Detailed Explanation

## 2. Detailed Explanation

### Why Beta Independence Matters

Problems with  $\beta$ -dependent designs:

- $\beta$  varies  $\pm 50\%$  between transistors of same type
- $\beta$  increases with temperature (  $0.5\%/^{\circ}\text{C}$  )
- $\beta$  varies with collector current
- Circuit behavior becomes unpredictable
- Mass production requires selection/trimming

### Voltage Divider Bias

The most common  $\beta$ -independent biasing technique:

#### Circuit Elements:

- $R_1$ : Upper divider resistor (from  $V_{CC}$  to base)
- $R_2$ : Lower divider resistor (from base to ground)
- $R_E$ : Emitter resistor (stabilization)
- $R_C$ : Collector resistor (load)

#### Design Methodology:

1. Choose Q-point (quiescent operating point):
  - Set  $V_{CE}$  at midpoint:  $V_{CE} \approx V_{CC}/2$
  - Choose  $I_C$  based on application
2. Calculate emitter voltage:

$$V_E = I_C R_E$$

3. Base voltage (0.7 V above emitter):

$$V_B = V_E + 0.7$$

4. Design voltage divider:

- Choose  $I_2 = 10 \times I_B$  (rule of thumb)
- $R_2 = V_B / I_2$
- $R_1 = (V_{CC} - V_B) / I_2$

5. Calculate collector resistor:

$$R_C = \frac{V_{CC} - V_{CE} - V_E}{I_C}$$

#### Why This Works:

- Voltage divider sets  $V_B$  relatively independent of  $I_B$
- $V_E = V_B - 0.7$  (fixed by junction)
- $I_E = V_E / R_E$  (independent of  $\beta$ )
- Since  $I_C \approx I_E$ , collector current is stabilized
- Negative feedback: If  $I_C$  increases  $\rightarrow V_E$  increases  $\rightarrow V_{BE}$  decreases  $\rightarrow I_C$  decreases

#### Emitter Degeneration

The emitter resistor  $R_E$  provides:

- DC stabilization (sets operating point)
- Temperature compensation
- Negative feedback for linearity
- Reduced gain but increased stability

Trade-off: Emitter resistor reduces voltage swing and AC gain. Can be bypassed with capacitor for AC signals.

## Practical Example & Numerical

### Design Beta-Independent Bias Circuit

Given:

- $V_{CC} = 12\text{ V}$
- Desired  $I_C = 2\text{ mA}$
- Desired  $V_{CE} = 6\text{ V}$  (mid-supply)
- Transistor  $\beta = 100$  (but we'll design for independence)

Solution:

1. Choose emitter voltage (typically 10-20% of  $V_{CC}$ ):

$$V_E = 0.1 \times 12 = 1.2\text{ V}$$

2. Calculate  $R_E$ :

$$R_E = \frac{V_E}{I_C} = \frac{1.2}{0.002} = 600 \Omega \approx 560 \Omega$$

3. Calculate base voltage:

$$V_B = V_E + 0.7 = 1.2 + 0.7 = 1.9 \text{ V}$$

4. Design voltage divider:

$$I_B = \frac{I_C}{\beta} = \frac{2}{100} = 0.02 \text{ mA}$$

$$I_2 = 10 \times I_B = 0.2 \text{ mA}$$

$$R_2 = \frac{V_B}{I_2} = \frac{1.9}{0.0002} = 9.5 \text{ k}\Omega \approx 10 \text{ k}\Omega$$

$$R_1 = \frac{V_{CC} - V_B}{I_2} = \frac{12 - 1.9}{0.0002} = 50.5 \text{ k}\Omega \approx 47 \text{ k}\Omega$$

5. Calculate collector resistor:

$$V_C = V_{CE} + V_E = 6 + 1.2 = 7.2 \text{ V}$$

$$R_C = \frac{V_{CC} - V_C}{I_C} = \frac{12 - 7.2}{0.002} = 2.4 \text{ k}\Omega \approx 2.2 \text{ k}\Omega$$

**Verification with Different  $\beta$ :**

If  $\beta = 50$ :

- $I_B = 0.04 \text{ mA}$  (doubled)
- $V_B \approx 1.9 \text{ V}$  (still rigid,  $I_2 = 5 \times I_B$  minimum met)
- $V_E \approx 1.2 \text{ V}$
- $I_C \approx 2 \text{ mA}$  (unchanged!)

If  $\beta = 200$ :

- $I_B = 0.01 \text{ mA}$  (halved)
- $V_B \approx 1.9 \text{ V}$
- $I_C \approx 2 \text{ mA}$  (unchanged!)

The circuit maintains stable operation despite  $4\times$  variation in  $\beta$ .

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- $\beta$  varies significantly; good designs are  $\beta$ -independent
- Voltage divider bias: Most common stabilization technique
- Design rule: Make divider current  $I_2 > 10 \times I_B$
- Emitter resistor provides negative feedback and stabilization
- Set  $V_E$  to 10-20% of  $V_{CC}$  for good headroom
- Q-point at mid-supply ( $V_{CE} \approx V_{CC}/2$ ) maximizes swing
- Stable against  $\beta$  variation and temperature changes

## High-Side Switching with PNP

### TL;DR (The Gist)

**TL;DR:** PNP transistors are ideal for high-side switching (controlling the positive supply rail). They turn ON when the base is pulled LOW and OFF when the base is at the same voltage as the emitter.

**Key Concept:** NPN + PNP combination allows low-voltage logic to control high-voltage loads on the positive rail.

**Control Logic:** LOW input = Load ON, HIGH input = Load OFF

### Detailed Explanation

## 2. Detailed Explanation

### Why High-Side Switching?

#### Advantages:

- Load always has defined ground connection
- Safety: Load disconnected from positive when off
- Common ground for control and load circuits
- Prevents ground loops in some applications
- Necessary for certain loads (e.g., loads requiring grounded negative)

#### Disadvantages of PNP Alone:

- Inverted logic (LOW = ON)
- Difficult to drive from positive logic (5 V MCU with 12 V supply)
- Base must go to emitter voltage for complete turn-off

### NPN + PNP Driver Solution

A common configuration uses an NPN to drive a PNP:

#### Circuit Operation:

1. NPN transistor (Q1) is control switch
2. PNP transistor (Q2) is high-side power switch
3. Q1 collector connected to Q2 base through resistor
4. Q1 emitter grounded
5. Q2 emitter connected to  $V_{CC}$

#### Logic Flow:

- Input HIGH  $\rightarrow$  Q1 ON  $\rightarrow$  Q1 collector LOW  $\rightarrow$  Q2 base pulled LOW  $\rightarrow$  Q2 ON  $\rightarrow$  Load ON
- Input LOW  $\rightarrow$  Q1 OFF  $\rightarrow$  Q2 base pulled to  $V_{CC}$  through  $R$   $\rightarrow$  Q2 OFF  $\rightarrow$  Load OFF

#### Design Considerations:

1. **Pull-up resistor** to Q2 base:
  - Must pull base to  $V_{CC}$  when Q1 is off
  - Value: 1 k $\Omega$  - 10 k $\Omega$  typical
  - Trade-off: Lower  $R$  = faster turn-off, higher current when Q1 ON
2. **Q2 base current:**
  - Provided through Q1 when saturated
  - Q1 must sink  $I_{B(Q2)} + I_{pullup}$
3. **Voltage levels:**
  - Works with any  $V_{CC}$  higher than logic level
  - Q1 handles voltage translation
  - Q2 switches full  $V_{CC}$

## Practical Example & Numerical

### High-Side Switch Design

Control a 12 V, 500 mA load from a 5 V microcontroller:

#### Given:

- $V_{CC} = 12$  V
- Load current: 500 mA
- MCU output: 0-5 V
- Q2 (PNP):  $\beta = 100$
- Q1 (NPN):  $\beta = 150$

#### Solution:

1. Calculate Q2 base current (forced  $\beta = 10$ ):

$$I_{B(Q2)} = \frac{I_L}{10} = \frac{500 \text{ mA}}{10} = 50 \text{ mA}$$

2. Choose pull-up resistor (when Q1 OFF):

$$R_{pullup} = \frac{V_{CC}}{I_{max}} = \frac{12}{0.005} = 2.4 \text{ k}\Omega \approx 2.2 \text{ k}\Omega$$

(Choosing 5 mA as acceptable standby current)

3. When Q1 ON, it must sink:

$$I_{Q1} = I_{B(Q2)} + I_{pullup} = 50 + \frac{12}{2200} = 50 + 5.45 = 55.45 \text{ mA}$$

4. Calculate Q1 base resistor:

$$I_{B(Q1)} = \frac{I_{Q1}}{10} = \frac{55.45}{10} = 5.545 \text{ mA}$$
$$R_{B(Q1)} = \frac{V_{in} - V_{BE}}{I_{B(Q1)}} = \frac{5 - 0.7}{0.005545} = 775 \Omega \approx 820 \Omega$$

**Operation Verification:**

- MCU HIGH (5 V): Q1 saturated  $\rightarrow$  pulls Q2 base to 0.2 V  $\rightarrow$  Q2 ON  $\rightarrow$  Load gets 12 V
- MCU LOW (0 V): Q1 off  $\rightarrow$  Q2 base at 12 V  $\rightarrow$  Q2 OFF  $\rightarrow$  Load disconnected

**MCU Current:**

$$I_{MCU} = \frac{5 - 0.7}{820} = 5.2 \text{ mA}$$

Well within typical MCU pin capability (20-40 mA).

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- High-side switching controls positive supply rail
- PNP transistor ideal for high-side applications
- NPN + PNP combination provides non-inverted logic
- Pull-up resistor on PNP base ensures complete turn-off
- NPN driver allows low-voltage control of high-voltage load
- Common configuration: MCU  $\rightarrow$  NPN  $\rightarrow$  PNP  $\rightarrow$  Load
- Design for forced  $\beta = 10$  for reliable saturation

## Pulse Generators and Switching Applications

### Pulse Generator Part I - Introduction

#### TL;DR (The Gist)

**TL;DR:** A pulse generator creates periodic rectangular waveforms using RC timing networks and transistor switching. The basic astable multivibrator uses two transistors that alternately turn ON and OFF.

**Key Components:** Two transistors, two RC timing networks, cross-coupling capacitors.

**Frequency:** Determined by  $R$  and  $C$  values:  $f \approx \frac{1}{1.4RC}$  (for symmetric circuit)

#### Detailed Explanation

### 2. Detailed Explanation

#### Astable Multivibrator Principle

An astable multivibrator is a free-running oscillator with no stable states. It continuously switches between two states.

**Circuit Elements:**

- Two NPN transistors (Q1, Q2)
- Two collector resistors ( $R_{C1}$ ,  $R_{C2}$ )
- Two base resistors ( $R_{B1}$ ,  $R_{B2}$ )
- Two timing capacitors ( $C_1$ ,  $C_2$ )

**Operating Principle:**

**State 1** (Q1 ON, Q2 OFF):

1. Q1 saturated:  $V_{C1} \approx 0.2 \text{ V}$
2.  $C1$  charges through  $R_{B2}$
3. Q2 off:  $V_{C2} \approx V_{CC}$

4. C2 initially holds Q1 base at 0.7 V
5. C2 charges toward  $V_{CC}$  through  $R_{B1}$

**Transition:**

- C1 charges until Q2 base reaches 0.7 V
- Q2 begins to conduct
- Q2 collector voltage drops
- Coupled through C2, Q1 base voltage drops
- Q1 turns off
- Positive feedback accelerates transition

**State 2 (Q1 OFF, Q2 ON):**

- Mirror image of State 1
- C2 charges through  $R_{B1}$
- Eventually triggers Q1 to turn on
- Cycle repeats

**Period Calculation:**

For each half-cycle:

$$t = 0.7RC$$

Total period (if symmetric):

$$T = 0.7R_{B1}C_2 + 0.7R_{B2}C_1$$

For  $R_{B1} = R_{B2} = R$  and  $C_1 = C_2 = C$ :

$$T = 1.4RC$$

$$f = \frac{1}{T} = \frac{1}{1.4RC} \approx 0.7/RC$$

**Duty Cycle:**

For symmetric circuit: 50% duty cycle

For asymmetric ( $R_{B1} \neq R_{B2}$  or  $C_1 \neq C_2$ ):

$$D = \frac{0.7R_{B1}C_2}{0.7R_{B1}C_2 + 0.7R_{B2}C_1} \times 100\%$$

## Practical Example & Numerical

### Design 1 kHz Pulse Generator

**Target:** 1 kHz, 50% duty cycle

**Solution:**

1. Calculate period:

$$T = \frac{1}{f} = \frac{1}{1000} = 1 \text{ ms}$$

2. For symmetric circuit:

$$T = 1.4RC$$

$$RC = \frac{T}{1.4} = \frac{0.001}{1.4} = 714 \mu\text{s}$$

3. Choose capacitor value:

$$C = 100 \text{ nF} = 0.1 \mu\text{F}$$

4. Calculate resistor:

$$R = \frac{714 \mu\text{s}}{0.1 \mu\text{F}} = 7.14 \text{ k}\Omega \approx 6.8 \text{ k}\Omega$$

5. Verify frequency:

$$f = \frac{1}{1.4 \times 6800 \times 0.1 \times 10^{-6}} = \frac{1}{0.000952} = 1050 \text{ Hz}$$

Close enough! Adjust to 7.5 k $\Omega$  for closer match:

$$f = \frac{1}{1.4 \times 7500 \times 0.1 \times 10^{-6}} = 952 \text{ Hz}$$

**Complete Design:**

- $R_{B1} = R_{B2} = 7.5 \text{ k}\Omega$
- $C_1 = C_2 = 0.1 \mu\text{F}$

- $R_{C1} = R_{C2} = 1 \text{ k}\Omega$  (collector load)
- $V_{CC} = 5 \text{ V}$

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- Astable multivibrator = free-running oscillator
- Two transistors alternately switch ON and OFF
- Frequency:  $f \approx 0.7/RC$  for symmetric circuit
- Period:  $T = 1.4RC$  (50% duty cycle)
- RC timing networks determine pulse width
- Cross-coupling capacitors provide feedback
- Duty cycle adjustable by making circuit asymmetric
- Simple, reliable square wave generator

## Pulse Generator Part II - Detailed Operation

### TL;DR (The Gist)

**TL;DR:** During each half-cycle, the timing capacitor exponentially charges toward  $V_{CC}$  through the base resistor until the opposite transistor's base reaches 0.7 V and triggers switching.

**Capacitor Charging:** Follows exponential curve:  $V_C(t) = V_{CC}(1 - e^{-t/RC})$

**Switching Threshold:** When capacitor voltage reaches  $V_{CC} - 0.7 \text{ V}$

### Detailed Explanation

### 2. Detailed Explanation

#### Detailed State Analysis

#### Initial Condition - Q1 Just Turned ON:

- Q1: Saturated,  $V_{C1} = 0.2 \text{ V}$ ,  $V_{B1} = 0.7 \text{ V}$
- Q2: Off,  $V_{C2} = V_{CC}$
- C2: Just discharged Q1 base, now at approximately  $-V_{CC}$  on Q1 side
- C1: Charged positive, begins charging Q2 base

#### During State (Q1 ON):

1. **C1 charges through  $R_{B2}$ :**
  - Initial voltage:  $V_{C1} = 0.2 \text{ V}$  (from saturated Q1)
  - Charges toward:  $V_{CC}$  through  $R_{B2}$
  - Q2 base voltage:  $V_{B2}(t) = 0.2 + (V_{CC} - 0.2)(1 - e^{-t/R_{B2}C_1})$
2. **C2 charges through  $R_{B1}$ :**
  - Keeps Q1 base forward-biased
  - Initially at negative voltage
  - Charges toward  $V_{CC}$
3. **Switching occurs when:**
  - $V_{B2}$  reaches 0.7 V (Q2 turns on)
  - Q2 collector drops
  - Coupled through C2, Q1 base voltage drops
  - Q1 turns off
  - Regenerative action (positive feedback) makes transition rapid

#### Timing Calculation:

The time for one half-cycle is when  $V_{B2} = 0.7 \text{ V}$ :

$$0.7 = 0.2 + (V_{CC} - 0.2)(1 - e^{-t/RC})$$

Solving for  $t$  (with  $V_{CC} \gg 0.7 \text{ V}$ ):

$$t \approx 0.7RC$$

This is a simplification. More accurate (for  $V_{CC} = 5\text{ V}$ ):

$$t = RC \ln \left( \frac{V_{CC} - 0.2}{V_{CC} - 0.7} \right) = RC \ln \left( \frac{4.8}{4.3} \right) \approx 0.11RC$$

But conventional formula uses  $0.7RC$  accounting for full cycle dynamics.

**Waveform Characteristics:**

- Collector voltages: Rectangular (switch between  $V_{CC}$  and  $0.2\text{ V}$ )
- Base voltages: Exponential charging/discharging
- Capacitor voltages: Exponential with offset
- Fast transitions due to positive feedback

## Practical Example & Numerical

### Waveform Analysis

Circuit:  $V_{CC} = 12\text{ V}$ ,  $R_B = 10\text{ k}\Omega$ ,  $C = 0.47\text{ }\mu\text{F}$

**Half-period:**

$$t = 0.7RC = 0.7 \times 10000 \times 0.47 \times 10^{-6} = 3.29\text{ ms}$$

**Full period:**

$$T = 2t = 6.58\text{ ms}$$

**Frequency:**

$$f = \frac{1}{T} = 152\text{ Hz}$$

### Voltage Waveforms:

**Collector Voltages** ( $V_{C1}$ ,  $V_{C2}$ ):

- Rectangular waves,  $180^\circ$  out of phase
- HIGH =  $12\text{ V}$ , LOW =  $0.2\text{ V}$
- Peak-to-peak:  $11.8\text{ V}$
- Sharp transitions (limited by transistor switching speed)

**Base Voltages** ( $V_{B1}$ ,  $V_{B2}$ ):

- Exponential charging curves
- Swing from approximately  $-11.3\text{ V}$  to  $+0.7\text{ V}$
- Stay at  $0.7\text{ V}$  while transistor is ON
- Dip negative during switching

**Capacitor Voltages:**

- AC coupled exponential waveforms
- Charge/discharge cycles
- Average DC value: Approximately  $V_{CC}/2$

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- Timing determined by RC exponential charging
- Half-period:  $t = 0.7RC$
- Switching occurs when base reaches  $0.7\text{ V}$  threshold
- Positive feedback creates fast, clean transitions
- Collector outputs: Rectangular complementary waveforms
- Base voltages: Exponential with negative-going spikes
- Capacitors AC-couple the feedback

## Pulse Generator Part III - Practical Design

### TL;DR (The Gist)

**TL;DR:** Practical pulse generator design involves selecting component values for desired frequency, ensuring transistor saturation, and considering load effects and stability.

**Design Steps:** Choose frequency  $\rightarrow$  Calculate  $RC \rightarrow$  Select  $C \rightarrow$  Calculate  $R \rightarrow$  Choose collector resistors  $\rightarrow$  Verify saturation.

**Practical Considerations:** Component tolerance, temperature stability, load impedance, supply voltage variations.

## Detailed Explanation

### 2. Detailed Explanation

#### Component Selection Guidelines

##### Timing Capacitors ( $C_1, C_2$ ):

- Range: 0.01  $\mu\text{F}$  to 100  $\mu\text{F}$  typically
- Lower frequency  $\rightarrow$  Larger capacitance
- Tolerance:  $\pm 10\%$  typical (frequency will vary accordingly)
- Type: Ceramic or film for stability; electrolytic for large values
- Match capacitors for 50% duty cycle

##### Base Resistors ( $R_{B1}, R_{B2}$ ):

- Range: 1  $\text{k}\Omega$  to 1  $\text{M}\Omega$
- Lower frequency  $\rightarrow$  Higher resistance
- Must provide sufficient base current
- Minimum:  $R_B < \beta R_C$  for reliable switching
- Maximum: Limited by capacitor leakage
- Match resistors for 50% duty cycle

##### Collector Resistors ( $R_{C1}, R_{C2}$ ):

- Typical: 470  $\Omega$  to 10  $\text{k}\Omega$
- Sets output voltage swing
- Must allow transistor saturation:  $R_C < \beta R_B$
- Affects rise/fall times (with load capacitance)
- Power rating:  $P = (V_{CC}/R_C)^2 \times R_C = V_{CC}^2/R_C$

##### Transistor Selection:

- General-purpose NPN (2N2222, 2N3904, BC547)
- $\beta \geq 100$  preferred
- $V_{CEO} > V_{CC}$
- $I_{C(max)} > V_{CC}/R_C$
- Fast switching preferred (low  $t_{on}, t_{off}$ )

##### Design Constraints:

###### 1. Saturation check:

$$I_C = \frac{V_{CC}}{R_C}$$

$$I_B = \frac{V_{CC}}{R_B}$$

$$\text{Forced } \beta = \frac{I_C}{I_B} = \frac{R_B}{R_C}$$

Require: Forced  $\beta < \beta_{min}/2$  for reliable saturation

###### 2. Frequency accuracy:

- Tolerance:  $\pm 20\%$  typical with 10% components
- Use 1% resistors and film capacitors for  $\pm 5\%$  accuracy
- Temperature coefficient: 200 ppm/ $^{\circ}\text{C}$  for resistors

###### 3. Frequency range:

- Practical minimum: 0.1 Hz (large RC)
- Practical maximum: 100 kHz (limited by transistor speed)
- Beyond 100 kHz: Use 555 timer or crystal oscillator

##### Output Considerations:

- Output impedance:  $R_C$  when HIGH, 10  $\Omega$  when LOW
- Can drive small loads directly
- Use buffer for heavy loads

- Add pull-up/pull-down for logic levels
- Consider Schmitt trigger for clean edges with slow loads

## Practical Example & Numerical

### Complete Pulse Generator Design

#### Requirements:

- Frequency: 10 kHz  $\pm$  10%
- Duty cycle: 50%
- Supply: 5 V
- Output: 0-5 V logic levels

#### Design:

1. Calculate  $RC$  product:

$$T = \frac{1}{10000} = 100 \mu s$$

$$RC = \frac{T}{1.4} = \frac{100 \mu s}{1.4} = 71.4 \mu s$$

2. Choose capacitor (prefer smaller for high frequency):

$$C = 10 \text{ nF}$$

3. Calculate resistor:

$$R = \frac{71.4 \mu s}{10 \text{ nF}} = 7.14 \text{ k}\Omega \approx 7.5 \text{ k}\Omega$$

4. Choose collector resistor:

$$R_C = 1 \text{ k}\Omega$$

5. Verify saturation:

$$I_C = \frac{5}{1000} = 5 \text{ mA}$$

$$I_B = \frac{5}{7500} = 0.67 \text{ mA}$$

$$\text{Forced } \beta = \frac{5}{0.67} = 7.5$$

For 2N3904 ( $\beta_{min} = 100$ ):  $7.5 \ll 50$  ✓ Well saturated

6. Final component list:

- Q1, Q2: 2N3904 NPN
- $R_{B1} = R_{B2} = 7.5 \text{ k}\Omega$  (1% tolerance)
- $C_1 = C_2 = 10 \text{ nF}$  (5% film capacitor)
- $R_{C1} = R_{C2} = 1 \text{ k}\Omega$

#### Expected Performance:

- Frequency: 9.5-10.5 kHz (component tolerance)
- Duty cycle: 48-52% (component matching)
- Rise/fall time:  $\leq 100 \text{ ns}$  (2N3904 switching speed)
- Output levels: 0.2 V (LOW), 5 V (HIGH)

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- Start with frequency requirement, calculate  $RC$  product
- Choose capacitor, then calculate resistor
- Verify forced  $\beta$  for saturation ( $R_B/R_C < \beta/2$ )
- Component tolerance directly affects frequency accuracy
- Practical range: 0.1 Hz to 100 kHz
- Match components for symmetric waveform
- Consider load impedance in output design

- Use buffer for heavy loads or long lines

## Schmitt Trigger with Transistors

### TL;DR (The Gist)

**TL;DR:** A Schmitt trigger provides hysteresis (two different threshold voltages) for clean switching from noisy or slowly-changing input signals. It uses positive feedback to create snap-action switching.

**Key Feature:** Upper threshold  $V_{TH}$ , Lower threshold (hysteresis band)

**Application:** Converts slow/noisy signals to clean digital pulses.

### Detailed Explanation

## 2. Detailed Explanation

### Schmitt Trigger Principle

#### Hysteresis:

- Two threshold voltages:  $V_{TH}$  (upper) and  $V_{TL}$  (lower)
- When rising: Switches at  $V_{TH}$
- When falling: Switches at  $V_{TL}$
- Hysteresis band:  $\Delta V = V_{TH} - V_{TL}$

#### Benefits:

- Immunity to noise (within hysteresis band)
- Clean transitions from slow input signals
- No output oscillation at threshold
- Debouncing mechanical switches

### Two-Transistor Schmitt Trigger Circuit:

#### Configuration:

- Q1: Input transistor (common-emitter)
- Q2: Switching transistor
- Shared emitter resistor ( $R_E$ ) provides positive feedback
- Voltage divider biases Q2 base

#### Operation:

##### State 1 (Q1 OFF, Q2 ON):

- Input voltage low ( $< V_{TL}$ )
- Q1 off,  $I_1 = 0$
- Q2 conducting, current  $I_2$  through  $R_E$
- Emitter voltage:  $V_E = I_2 R_E$
- For Q1 to turn on:  $V_{in} > V_E + 0.7 \text{ V}$
- Upper threshold:  $V_{TH} = I_2 R_E + 0.7$

##### Transition to State 2:

- Input rises above  $V_{TH}$
- Q1 begins conducting
- Q1 current adds to emitter current
- $V_E$  increases (positive feedback!)
- Q2 base-emitter voltage decreases
- Q2 turns off rapidly
- Output switches

##### State 2 (Q1 ON, Q2 OFF):

- Q1 conducting, Q2 off
- Only Q1 current through  $R_E$
- Emitter voltage:  $V_E = I_1 R_E$  (lower than before)
- For Q1 to turn off:  $V_{in} < V_E + 0.7 \text{ V}$
- Lower threshold:  $V_{TL} = I_1 R_E + 0.7$

#### Hysteresis Calculation:

$$\Delta V = V_{TH} - V_{TL} = (I_2 - I_1)R_E$$

The hysteresis is determined by the difference in emitter currents and the emitter resistor value.

**Design Parameters:**

- Larger  $R_E \rightarrow$  More hysteresis
- Voltage divider ratio sets nominal threshold
- Supply voltage affects threshold range

## Practical Example & Numerical

### Schmitt Trigger Design

Design a Schmitt trigger for a noisy 5 V logic signal:

**Requirements:**

- $V_{TH} = 3$  V
- $V_{TL} = 2$  V
- Hysteresis: 1 V
- $V_{CC} = 5$  V

**Solution:**

1. Calculate emitter current when Q2 is ON: Assume  $I_2 = 2$  mA (reasonable choice)
2. Calculate emitter resistor for  $V_{TH}$ :

$$V_{TH} = I_2 R_E + 0.7$$

$$3 = 0.002 \times R_E + 0.7$$

$$R_E = \frac{2.3}{0.002} = 1.15 \text{ k}\Omega \approx 1.2 \text{ k}\Omega$$

3. Calculate Q1 emitter current for  $V_{TL}$ :

$$V_{TL} = I_1 R_E + 0.7$$

$$2 = I_1 \times 1200 + 0.7$$

$$I_1 = \frac{1.3}{1200} = 1.08 \text{ mA}$$

4. Verify hysteresis:

$$\Delta V = (I_2 - I_1)R_E = (2 - 1.08) \times 1.2 = 1.1 \text{ V}$$

Close to 1 V target ✓

5. Design voltage divider for Q2 base: For Q2 to conduct at 2 mA when Q1 is off:

$$V_{B2} = I_2 R_E + 0.7 = 2.4 + 0.7 = 3.1 \text{ V}$$

Choose divider current = 10 mA:

$$R_2 = \frac{3.1}{0.01} = 310 \Omega \approx 330 \Omega$$

$$R_1 = \frac{5 - 3.1}{0.01} = 190 \Omega \approx 180 \Omega$$

**Performance:**

- Rising input: Output switches at 3 V
- Falling input: Output switches at 2 V
- Noise immunity:  $\pm 0.5$  V around threshold
- Fast, clean output transitions even with slow input

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- Schmitt trigger has two thresholds:  $V_{TH}$  (upper) and  $V_{TL}$  (lower)
- Hysteresis =  $V_{TH} - V_{TL}$  provides noise immunity
- Positive feedback creates rapid transitions
- Shared emitter resistor generates hysteresis
- Larger  $R_E \rightarrow$  more hysteresis

- Essential for debouncing and noise rejection
- Converts slow analog signals to clean digital pulses
- No oscillation at threshold like simple comparators

# Emitter Follower Design and Applications

## Emitter Follower - Theory

### TL;DR (The Gist)

**TL;DR:** An emitter follower (common-collector configuration) is a unity-gain buffer with high input impedance and low output impedance. The output voltage follows the input with a 0.7 V offset.

**Key Equation:**  $V_{out} = V_{in} - 0.7 \text{ V}$

**Gain:**  $A_V \approx 1$  (unity gain)

**Purpose:** Impedance transformation, buffering, current amplification.

### Detailed Explanation

## 2. Detailed Explanation

### Circuit Configuration

#### Common-Collector Topology:

- Input: Applied to base
- Output: Taken from emitter
- Collector: Connected to  $V_{CC}$  (common to input/output, hence "common-collector")
- Load resistor: Connected from emitter to ground

#### Voltage Relationships:

$$V_{out} = V_E = V_B - V_{BE} = V_{in} - 0.7 \text{ V}$$

The output voltage "follows" the input with a constant 0.7 V drop.

#### Current Relationships:

$$I_E = \frac{V_E}{R_E} = \frac{V_{in} - 0.7}{R_E}$$

$$I_B = \frac{I_E}{\beta + 1} \approx \frac{I_E}{\beta}$$

The transistor provides current gain: a small base current controls a large emitter current.

#### Voltage Gain:

$$A_V = \frac{V_{out}}{V_{in}} = \frac{V_{in} - 0.7}{V_{in}}$$

For  $V_{in} \gg 0.7 \text{ V}$ :  $A_V \approx 1$

More precisely (AC analysis):

$$A_V = \frac{\beta R_E}{\beta R_E + r_e}$$

Where  $r_e = \frac{26 \text{ mV}}{I_E}$  is the emitter dynamic resistance.

For typical values:  $A_V \approx 0.95 - 0.99$

#### Input Impedance:

The input impedance looking into the base is:

$$Z_{in} = \beta R_E$$

This is typically very high (tens to hundreds of k $\Omega$ ).

#### Output Impedance:

The output impedance looking from the emitter is:

$$Z_{out} = \frac{R_S}{\beta} + r_e$$

Where  $R_S$  is the source resistance. This is typically very low (few ohms to tens of ohms).

**Key Characteristics:**

- Voltage gain: 1 (unity)
- Current gain:  $\beta$  (high)
- Power gain:  $\beta$  (high)
- Input impedance: High ( $\beta R_E$ )
- Output impedance: Low ( $\sim 10 \Omega$ )
- No phase inversion (unlike common-emitter)

**Applications:**

- Impedance matching (buffer between high-Z source and low-Z load)
- Current amplification
- Voltage level shifting (down by 0.7 V)
- Output stages of amplifiers
- Driving long cables or capacitive loads

## Practical Example & Numerical

### Basic Emitter Follower Analysis

Circuit:  $V_{CC} = 12 \text{ V}$ ,  $R_E = 1 \text{ k}\Omega$ ,  $\beta = 150$ ,  $V_{in} = 5 \text{ V}$

**DC Analysis:**

1. Output voltage:

$$V_{out} = V_{in} - 0.7 = 5 - 0.7 = 4.3 \text{ V}$$

2. Emitter current:

$$I_E = \frac{V_E}{R_E} = \frac{4.3}{1000} = 4.3 \text{ mA}$$

3. Base current:

$$I_B = \frac{I_E}{\beta + 1} = \frac{4.3}{151} = 0.0285 \text{ mA} = 28.5 \mu\text{A}$$

4. Input impedance:

$$Z_{in} = \beta R_E = 150 \times 1000 = 150 \text{ k}\Omega$$

5. Output impedance (with  $R_S = 10 \text{ k}\Omega$ ):

$$r_e = \frac{26 \text{ mV}}{I_E} = \frac{0.026}{0.0043} = 6 \Omega$$

$$Z_{out} = \frac{R_S}{\beta} + r_e = \frac{10000}{150} + 6 = 67 + 6 = 73 \Omega$$

**Buffer Action:**

If a  $100 \Omega$  load is connected:

- Without buffer:  $V_{out} = V_{in} \times \frac{100}{10000+100} = 0.01V_{in}$  (massive loss!)
- With buffer:  $V_{out} = V_{in} \times \frac{100}{73+100} = 0.58V_{in}$  (much better!)
- Accounting for 0.7 V drop:  $V_{out} = (V_{in} - 0.7) \times 0.58$

The emitter follower significantly improves loading performance.

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- Emitter follower = common-collector configuration
- Voltage gain  $\approx 1$ , output follows input minus 0.7 V
- High input impedance:  $Z_{in} = \beta R_E$
- Low output impedance:  $Z_{out} \approx 10 - 100 \Omega$
- Current gain:  $\beta$  (significant)
- No phase inversion
- Ideal for impedance matching and buffering
- Output can source large currents to loads

## Input and Output Impedance

### TL;DR (The Gist)

**TL;DR:** The emitter follower transforms impedances: high input impedance prevents loading the source, while low output impedance can drive heavy loads effectively.

**Input Impedance:**  $Z_{in} = \beta(R_E \parallel R_L) + (1 + \beta)r_e$

**Output Impedance:**  $Z_{out} = \frac{R_S}{\beta} + r_e$  where  $r_e = 26 \text{ mV}/I_E$

### Detailed Explanation

## 2. Detailed Explanation

### Input Impedance Analysis

#### Looking into the Base:

The base sees the emitter circuit multiplied by  $(\beta + 1)$ :

$$Z_{in(base)} = (\beta + 1)(r_e + R_E \parallel R_L)$$

Where:

- $r_e = \frac{26 \text{ mV}}{I_E}$  is the dynamic emitter resistance
- $R_E$  is the emitter resistor
- $R_L$  is the load resistance
- $R_E \parallel R_L = \frac{R_E R_L}{R_E + R_L}$

#### Including Base Bias Resistors:

If a voltage divider ( $R_1, R_2$ ) biases the base:

$$Z_{in(total)} = R_1 \parallel R_2 \parallel Z_{in(base)}$$

#### Typical Values:

- $r_e$ : 5-50  $\Omega$  (depends on  $I_E$ )
- $Z_{in(base)}$ : 10 k $\Omega$  - 1 M $\Omega$
- $Z_{in(total)}$ : Limited by bias resistors (1-100 k $\Omega$  typical)

### Output Impedance Analysis

#### Looking into the Emitter:

The output impedance is the Thevenin resistance looking back from the emitter:

$$Z_{out} = r_e + \frac{R_S \parallel (R_1 \parallel R_2)}{\beta + 1}$$

Where  $R_S$  is the source resistance driving the base.

#### Simplified (Common Case):

If  $R_S \ll R_1 \parallel R_2$ :

$$Z_{out} \approx r_e + \frac{R_S}{\beta}$$

#### Typical Values:

- With low  $R_S$  (< 1 k $\Omega$ ):  $Z_{out} = 10\text{-}30 \Omega$
- With moderate  $R_S$  (10 k $\Omega$ ):  $Z_{out} = 50\text{-}100 \Omega$
- Still much lower than most signal sources

#### Impedance Transformation Ratio:

$$\text{Transformation ratio} = \frac{Z_{in}}{Z_{out}} \approx \beta^2$$

For  $\beta = 100$ : The ratio is 10,000!

#### Practical Implications:

##### Input Side:

- Minimal loading of source circuit
- Can connect to high-impedance sources without attenuation
- Preserves signal voltage

##### Output Side:

- Can drive low-impedance loads

- Minimal voltage loss to load
- Can drive capacitive loads without significant roll-off
- Can drive long cables

**Design Trade-offs:**

- Larger  $R_E \rightarrow$  Higher  $Z_{in}$  but less output swing
- Higher  $I_E \rightarrow$  Lower  $r_e$  and  $Z_{out}$  but more power consumption
- Larger  $\beta \rightarrow$  Better impedance transformation

## Practical Example & Numerical

### Impedance Matching Example

Connect a 100 k $\Omega$  sensor to a 100  $\Omega$  load using an emitter follower:

**Given:**

- Sensor output impedance:  $R_S = 100 \text{ k}\Omega$
- Sensor signal: 1 V AC
- Load:  $R_L = 100 \Omega$
- $V_{CC} = 12 \text{ V}$ ,  $\beta = 150$

**Without Buffer:**

$$V_{load} = 1 \text{ V} \times \frac{100}{100000 + 100} = 0.001 \text{ V} = 1 \text{ mV}$$

Loss: 99.9%! Unacceptable.

**With Emitter Follower:**

1. Choose DC bias:  $I_E = 10 \text{ mA}$  for low  $r_e$
2. Calculate  $R_E$ :

$$R_E = \frac{V_E}{I_E} = \frac{5}{0.01} = 500 \Omega$$

(Choosing  $V_E = 5 \text{ V}$  for headroom)

3. Calculate  $r_e$ :

$$r_e = \frac{26 \text{ mV}}{10 \text{ mA}} = 2.6 \Omega$$

4. Calculate input impedance:

$$Z_{in} = \beta(R_E \parallel R_L) = 150 \times \frac{500 \times 100}{600} = 150 \times 83.3 = 12.5 \text{ k}\Omega$$

5. Calculate output impedance:

$$Z_{out} = \frac{100000}{150} + 2.6 = 667 + 2.6 = 670 \Omega$$

6. Signal at base (loading from sensor):

$$V_B = 1 \text{ V} \times \frac{12500}{100000 + 12500} = 0.11 \text{ V}$$

7. Signal at emitter output:

$$V_{out(oc)} = 0.11 \text{ V}$$

8. Signal at load:

$$V_{load} = 0.11 \text{ V} \times \frac{100}{670 + 100} = 0.014 \text{ V} = 14 \text{ mV}$$

Result: 14 mV vs. 1 mV without buffer = 14 $\times$  improvement!

**Better Design:** Use higher bias current or Darlington for even lower  $Z_{out}$ .

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- Input impedance:  $Z_{in} = \beta(R_E \parallel R_L)$ , typically 10-100 k $\Omega$
- Output impedance:  $Z_{out} = R_S/\beta + r_e$ , typically 10-100  $\Omega$
- Impedance transformation ratio:  $\sim \beta^2$
- Lower  $I_E$  increases  $r_e$  and  $Z_{out}$

- Higher  $\beta$  improves both impedances
- Essential for interfacing high-Z sources to low-Z loads
- Base bias resistors reduce effective  $Z_{in}$

## Emitter Follower Detailed Design

### TL;DR (The Gist)

**TL;DR:** Designing an emitter follower requires selecting bias point, calculating component values for desired impedance characteristics, and ensuring adequate voltage headroom for signal swing.

**Design Steps:** Set Q-point  $\rightarrow$  Choose  $I_E \rightarrow$  Calculate  $R_E \rightarrow$  Design bias network  $\rightarrow$  Calculate coupling capacitors  $\rightarrow$  Verify headroom.

**Key Constraint:** Output swing limited by  $V_{CE(sat)}$  (bottom) and  $V_{CC} - V_E$  (top).

### Detailed Explanation

## 2. Detailed Explanation

### Design Methodology

#### Step 1: Determine Operating Point

##### 1. Choose emitter quiescent voltage ( $V_E$ ):

- Rule of thumb:  $V_E = V_{CC}/2$  for maximum swing
- Minimum:  $V_{E(min)} > V_{signal(pk)} + 1 \text{ V}$
- Consider output load requirements

##### 2. Choose emitter quiescent current ( $I_E$ ):

- Higher current  $\rightarrow$  Lower  $r_e \rightarrow$  Lower  $Z_{out}$
- Higher current  $\rightarrow$  More power dissipation
- Typical: 1-10 mA for small signal, 50-500 mA for power applications
- Must be significantly greater than peak load current
- Rule:  $I_E > 10 \times I_{load(peak)}$

#### Step 2: Calculate Emitter Resistor

$$R_E = \frac{V_E}{I_E}$$

This sets the DC operating point.

#### Step 3: Design Base Bias Network

Base voltage:  $V_B = V_E + 0.7 \text{ V}$

For voltage divider bias:

- Choose  $I_2 = 10 \times I_B$
- $I_B = I_E/\beta$
- $R_2 = V_B/I_2$
- $R_1 = (V_{CC} - V_B)/I_2$

#### Step 4: Calculate Coupling Capacitors

##### Input capacitor ( $C_1$ ):

- Forms high-pass filter with input impedance
- Cutoff:  $f_L = \frac{1}{2\pi(R_S + Z_{in})C_1}$
- Choose  $f_L$  decade below lowest signal frequency
- $C_1 = \frac{1}{2\pi f_L(R_S + Z_{in})}$

##### Output capacitor ( $C_2$ ) (if AC coupling needed):

- Forms high-pass filter with load impedance
- Cutoff:  $f_L = \frac{1}{2\pi(Z_{out} + R_L)C_2}$
- Choose same criterion as input
- $C_2 = \frac{1}{2\pi f_L(Z_{out} + R_L)}$

#### Step 5: Verify Signal Headroom

Maximum positive swing:

$$V_{out(max)} = V_E + V_{signal(pk)}$$

Must satisfy:  $V_{out(max)} < V_{CC} - 1 \text{ V}$

**Maximum negative swing:**

$$V_{out(min)} = V_E - V_{signal(pk)}$$

Must satisfy:  $V_{out(min)} > V_{CE(sat)} \approx 0.2 \text{ V}$

**Step 6: Calculate Power Dissipation**

$$P_Q = (V_{CC} - V_E) \times I_E$$

Ensure transistor can handle this power.

**Design Considerations:**

1. **Output capacitance:** Emitter follower drives capacitive loads well 2. **Frequency response:** Limited by  $\beta$  roll-off at high frequency 3. **Thermal stability:** Use heat sink for power applications 4. **Bootstrap:** Can use bootstrap capacitor to increase input impedance 5. **Darlington:** Use for extremely high input impedance

## Practical Example & Numerical

### Complete Design Example

Design emitter follower to buffer audio signal:

**Requirements:**

- Input: 1 V peak audio (20 Hz - 20 kHz)
- Source impedance: 50 k $\Omega$
- Load: 500  $\Omega$  (headphones)
- Supply: 12 V
- $\beta = 200$

**Design:**

1. Choose operating point:
  - $V_E = 6 \text{ V}$  (mid-supply for max swing)
  - $I_E = 20 \text{ mA}$  (much larger than load current)
2. Calculate  $R_E$ :

$$R_E = \frac{6}{0.02} = 300 \Omega \approx 330 \Omega$$

3. Design bias network:

$$V_B = 6 + 0.7 = 6.7 \text{ V}$$

$$I_B = \frac{20}{200} = 0.1 \text{ mA}$$

$$I_2 = 10 \times 0.1 = 1 \text{ mA}$$

$$R_2 = \frac{6.7}{0.001} = 6.7 \text{ k}\Omega \approx 6.8 \text{ k}\Omega$$

$$R_1 = \frac{12 - 6.7}{0.001} = 5.3 \text{ k}\Omega \approx 5.6 \text{ k}\Omega$$

4. Calculate impedances:

$$r_e = \frac{26}{20} = 1.3 \Omega$$

$$Z_{in} = 200 \times (330 \parallel 500) = 200 \times 196 = 39.2 \text{ k}\Omega$$

$$Z_{out} = \frac{50000}{200} + 1.3 = 250 + 1.3 = 251 \Omega$$

5. Calculate coupling capacitors (for  $f_L = 2 \text{ Hz}$ , decade below 20 Hz):

$$C_1 = \frac{1}{2\pi \times 2 \times (50000 + 39200)} = 892 \text{ nF} \approx 1 \mu\text{F}$$

$$C_2 = \frac{1}{2\pi \times 2 \times (251 + 500)} = 106 \mu\text{F} \approx 100 \mu\text{F}$$

6. Verify headroom:

- Max:  $6 + 1 = 7 \text{ V}$  ;  $11 \text{ V}$  ✓
- Min:  $6 - 1 = 5 \text{ V}$  ;  $0.2 \text{ V}$  ✓

7. Power dissipation:

$$P = (12 - 6) \times 0.02 = 120 \text{ mW}$$

Standard transistor handles this easily.

**Final Component List:**

- Q1: 2N3904 or BC547
- $R_1 = 5.6 \text{ k}\Omega$ ,  $R_2 = 6.8 \text{ k}\Omega$
- $R_E = 330 \Omega$
- $C_1 = 1 \mu\text{F}$ ,  $C_2 = 100 \mu\text{F}$  (electrolytic)

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- Set  $V_E \approx V_{CC}/2$  for maximum output swing
- Choose  $I_E > 10 \times I_{load}$  for good buffering
- Higher  $I_E$  gives lower  $Z_{out}$  but more power consumption
- Design bias network for  $\beta$  independence
- Input capacitor with  $(R_S + Z_{in})$  sets low-frequency cutoff
- Output capacitor with  $(Z_{out} + R_L)$  sets low-frequency cutoff
- Verify headroom:  $V_{out(max)} < V_{CC} - 1 \text{ V}$ ,  $V_{out(min)} > 0.2 \text{ V}$
- Calculate  $P_Q = (V_{CC} - V_E)I_E$  for heat management

## Practical Applications of Emitter Followers

### TL;DR (The Gist)

**TL;DR:** Emitter followers are used in numerous practical applications including LED drivers, voltage regulators, cascaded current amplifiers, and buffer stages in analog circuits.

**Common Applications:** High-power LED drivers, voltage followers in regulators, impedance buffers, Darlington configurations, level shifters.

## Detailed Explanation

### 2. Detailed Explanation

#### Application 1: High-Power LED Driver

**Problem:** Microcontroller pins limited to 10-20 mA, but LED requires 500 mA.

**Solution:** Cascaded transistor configuration (Darlington-like):

**Configuration:**

- First transistor (Q1): Driven by MCU
- Second transistor (Q2): Driven by Q1's emitter
- LED in Q2's emitter circuit
- Overall current gain:  $\beta_1 \times \beta_2$

**Analysis:**

$$I_{LED} = 500 \text{ mA}$$

$$I_{E1} = I_{B2} = \frac{I_{LED}}{\beta_2} = \frac{500}{100} = 5 \text{ mA}$$

$$I_{MCU} = I_{B1} = \frac{I_{E1}}{\beta_1} = \frac{5}{100} = 0.05 \text{ mA} = 50 \mu\text{A}$$

Current reduction factor:  $\frac{500}{0.05} = 10,000!$

MCU easily provides 50  $\mu\text{A}$ , controlling 500 mA LED.

#### Application 2: Voltage Regulator with Zener Diode

**Basic Zener Regulator Problem:**

- Zener provides stable voltage reference
- But limited current capability (tens of mA)

- Poor load regulation with varying load

### Improved with Emitter Follower:

#### Configuration:

- Zener diode sets base voltage
- Transistor emitter follower buffers output
- Output voltage:  $V_{out} = V_Z - 0.7 \text{ V}$
- Load current supplied by transistor, not Zener

#### Advantages:

- Zener current remains constant regardless of load
- Can supply much higher load current
- Better load regulation
- Base resistor can be increased (lower current from supply)

#### Example:

- Zener: 5.7 V, 5 mA
- Output: 5.0 V
- Load: 0-500 mA
- Transistor  $\beta = 100$
- Maximum base current: 5 mA
- Maximum load: 500 mA with only 5 mA through Zener
- $R_1$  can be 10× larger than without buffer

### Application 3: Cascaded Current Amplifier

Multiple emitter followers in series provide extremely high current gain:

$$\beta_{total} = \beta_1 \times \beta_2 \times \beta_3 \times \dots$$

#### Three-stage example:

- Each  $\beta = 100$
- Total gain:  $100^3 = 1,000,000$
- Input: 1  $\mu\text{A}$
- Output: 1 A!

Used in power amplifiers and high-current drivers.

### Application 4: Level Shifter

Emitter follower shifts voltage down by 0.7 V:

#### Uses:

- Interface 5 V logic to 3.3 V logic (4.3 V output)
- Create voltage reference below another reference
- Bias shifting in amplifier stages

Multiple emitter followers in series:

- 2 transistors: 1.4 V drop
- 3 transistors: 2.1 V drop
- Creates stable voltage reference

### Application 5: Impedance Buffer in Audio

Scenario: High-impedance microphone → Low-impedance headphones

#### Without buffer:

- Massive signal loss
- Frequency response affected
- Noise pickup

#### With emitter follower buffer:

- Minimal loading of microphone
- Can drive headphones directly
- Preserved frequency response
- Better signal-to-noise ratio

### Application 6: Darlington Pair

Integrated Darlington transistor:

- Two transistors in one package
- $\beta = 1000\text{-}10000$
- Very high input impedance
- Very low output impedance
- Common types: TIP120, TIP122, MPSA14

#### Trade-offs:

- Advantage: Extremely high gain
- Disadvantage: 1.4 V drop (two  $V_{BE}$ )
- Disadvantage: Slower switching
- Advantage: Direct MCU interface for high loads

## Practical Example & Numerical

### High-Power LED Driver Design

Drive 10 W LED from Arduino (40 mA limit per pin):

**Given:**

- LED: 10 W, 9 V forward voltage, 1.11 A
- Supply: 12 V
- Arduino: 5 V logic, 40 mA maximum
- Transistors:  $\beta = 100$

**Single Transistor Check:**

$$I_B = \frac{1.11}{100} = 11.1 \text{ mA}$$

Exceeds Arduino limit! Need cascaded configuration.

**Cascaded Solution:**

1. Q2 (power transistor) emitter current:

$$I_{E2} = 1.11 \text{ A}$$

2. Q2 base current:

$$I_{B2} = \frac{1.11}{100} = 11.1 \text{ mA}$$

3. Q1 (driver) emitter current:

$$I_{E1} = I_{B2} = 11.1 \text{ mA}$$

4. Q1 base current:

$$I_{B1} = \frac{11.1}{100} = 0.111 \text{ mA} = 111 \mu\text{A}$$

Well within Arduino capability!

5. Base resistor for Q1:

$$R_B = \frac{5 - 0.7}{0.000111} = 38.7 \text{ k}\Omega \approx 39 \text{ k}\Omega$$

6. Current limiting resistor for LED:

$$R_{LED} = \frac{12 - 9 - 1.4}{1.11} = 1.44 \Omega \approx 1.5 \Omega$$

(1.4 V = two  $V_{BE}$  drops)

7. Power dissipation in  $R_{LED}$ :

$$P = 1.5 \times 1.11^2 = 1.85 \text{ W}$$

Use 3 W resistor.

**Result:** Arduino pin sources 111  $\mu\text{A}$ , controls 1.11 A = 10,000 $\times$  amplification!

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- Emitter followers enable microcontrollers to drive high-power loads
- Cascaded configuration provides very high current gain ( $\beta^n$ )
- Voltage regulator buffering improves load regulation
- Level shifting: Useful for voltage translation (down by 0.7 V per stage)
- Audio buffering: Matches impedances between source and load
- Darlington pairs: Integrated high-gain solution (TIP120, etc.)
- Trade-off: Multiple stages increase voltage drop but provide huge gain
- Essential building block in power electronics and analog circuits

# Section 19 – Review + More Circuits with Transistors

## Transistor Fundamentals Review

### NPN vs PNP: Similarities and Differences

TL;DR (The Gist)

**TL;DR:** Both NPN and PNP transistors are current-controlled devices that provide amplification and switching. They differ in polarity: NPN requires positive base voltage, PNP requires negative (base lower than emitter).

**Key Similarity:** Both amplify current:  $I_C = \beta I_B$

**Key Difference:** Current flow directions are opposite.

### Detailed Explanation

## 2. Detailed Explanation

### Similarities Between NPN and PNP

#### Functional Equivalence:

- Both are bipolar junction transistors (BJTs)
- Both are current-controlled devices (not voltage-controlled)
- Both provide current amplification
- Both can function as switches or amplifiers
- Both have three terminals: Base, Emitter, Collector
- Both have same current gain relationship:  $I_C = \beta I_B$

#### Operating Principle:

- Small base current controls large collector current
- Base-emitter junction must be forward-biased ( $\approx 0.7$  V)
- Collector-base junction must be reverse-biased (active mode)
- Both have saturation, cutoff, and active regions

### Differences Between NPN and PNP

#### Voltage Polarity:

##### NPN Transistor:

- Collector: Positive voltage relative to emitter
- Base: Positive voltage relative to emitter ( $V_{BE} = +0.7$  V)
- Emitter: Typically grounded or at lowest potential
- Current flows: Collector  $\rightarrow$  Emitter

##### PNP Transistor:

- Emitter: Positive voltage (connected to  $V_{CC}$ )
- Base: Negative relative to emitter ( $V_{EB} = +0.7$  V)
- Collector: Negative relative to emitter
- Current flows: Emitter  $\rightarrow$  Collector

#### Current Direction:

##### NPN:

- Base current: Flows INTO base
- Requires positive current sourced to base
- Conventional current: Down through device (C  $\rightarrow$  E)

##### PNP:

- Base current: Flows OUT OF base
- Requires current sinking from base to ground
- Conventional current: Up through device (E  $\rightarrow$  C)

#### Internal Construction:

**NPN:** N-P-N sandwich (two N-type layers sandwiching P-type base)

**PNP:** P-N-P sandwich (two P-type layers sandwiching N-type base)

#### Biasing Requirements:

##### NPN:

- Turn ON: Apply positive voltage to base ( $\geq 0.7$  V above emitter)
- Turn OFF: Ground base or make  $V_{BE} < 0.7$  V
- "Normally OFF" device

#### PNP:

- Turn ON: Pull base LOW (0.7 V below emitter)
- Turn OFF: Make base equal to emitter voltage
- Can conduct without explicit base bias if emitter is powered

#### Typical Applications:

##### NPN:

- Low-side switching (switching ground)
- Most common configuration
- Source current to loads
- Digital logic (active high)

##### PNP:

- High-side switching (switching positive rail)
- Sink current from loads
- Complementary to NPN in push-pull
- Digital logic (active low)

## Practical Example & Numerical

### Switching an LED: NPN vs PNP

#### NPN Configuration:

- LED and resistor from  $V_{CC}$  to collector
- Emitter grounded
- Base driven from microcontroller (0-5 V)
- Logic: HIGH = LED ON, LOW = LED OFF
- When base = 5 V:  $V_{BE} = 5 - 0 = 5$  V  $\rightarrow$  Transistor ON
- Collector current:  $I_C = \frac{V_{CC} - V_{LED} - V_{CE(sat)}}{R}$

#### PNP Configuration:

- Emitter to  $V_{CC}$
- LED and resistor from collector to ground
- Base driven from microcontroller
- Logic: LOW = LED ON, HIGH = LED OFF
- When base = 0 V:  $V_{EB} = V_{CC} - 0 = V_{CC}$  (limited to 0.7 V by junction)  $\rightarrow$  ON
- Emitter current:  $I_E = \frac{V_{CC} - V_{LED} - V_{EC(sat)}}{R}$

#### Current Gain Verification:

Both NPN and PNP with  $\beta = 100$ ,  $I_C = 20$  mA:

$$I_B = \frac{I_C}{\beta} = \frac{20 \text{ mA}}{100} = 0.2 \text{ mA}$$

For saturation, use forced  $\beta = 10$ :

$$I_B = \frac{20 \text{ mA}}{10} = 2 \text{ mA}$$

Same calculation for both types, just opposite polarities.

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- NPN and PNP functionally equivalent but with opposite polarities
- Both are current-controlled:  $I_C = \beta I_B$
- NPN: Base positive, current flows IN to base,  $C \rightarrow E$
- PNP: Base negative (vs emitter), current flows OUT of base,  $E \rightarrow C$
- NPN is "normally OFF", PNP can be "normally ON"
- Internal structure: NPN = N-P-N, PNP = P-N-P

- NPN for low-side switching, PNP for high-side switching
- Both require  $V_{BE}$  (or  $V_{EB}$ )  $\approx 0.7$  V to conduct

## NPN Transistor: Diode Model

### TL;DR (The Gist)

**TL;DR:** An NPN transistor can be visualized as two diodes with cathodes connected at the base. The base-emitter diode must be forward-biased ( $V_{BE} = 0.7$  V) for the transistor to conduct collector-emitter current.

**Key Concept:** Diode model is a simplified visualization, not actual operation (base-collector diode doesn't conduct in normal use).

**Turn-ON Condition:**  $V_{BE} \geq 0.7$  V

### Detailed Explanation

## 2. Detailed Explanation

### Diode Model Representation

#### Simplified Model:

An NPN transistor can be thought of as two diodes:

- **Diode 1:** Base-Emitter (B-E junction)
- **Diode 2:** Base-Collector (B-C junction)
- Both cathodes connected to base
- Anodes at emitter and collector respectively

#### Important Limitation:

This model is only for understanding the base-emitter forward voltage requirement. It is NOT accurate for understanding:

- Why current flows from collector to emitter (not through B-C diode)
- The amplification mechanism
- The actual internal physics

#### How the Model Helps:

##### Base-Emitter Junction:

- Acts like a forward-biased diode when ON
- Requires approximately 0.7 V to conduct
- Current flows from base to emitter through this "diode"
- This is the control junction

##### Base-Collector Junction:

- Reverse-biased in normal (active) operation
- Does NOT conduct current like a regular diode would
- This is where the transistor magic happens (beyond simple diode model)

#### Operating Mechanism:

**Step 1:** Apply voltage to base ( $\geq 0.7$  V relative to emitter)

- Base-emitter "diode" becomes forward-biased
- Small base current begins to flow

**Step 2:** Base-emitter junction conducts

- Voltage drop:  $V_{BE} = 0.7$  V
- Base current:  $I_B = \frac{V_{in} - 0.7}{R_B}$

**Step 3:** Collector-emitter channel opens

- Much larger current flows from collector to emitter
- $I_C = \beta I_B$
- This is NOT explained by simple diode model

#### Why 0.7 V?

The 0.7 V drop is characteristic of silicon PN junctions:

- Silicon diode forward voltage:  $\approx 0.7$  V at room temperature
- Base-emitter junction is a PN junction
- Same physics as regular diode
- Temperature dependent: decreases  $\approx 2$  mV/ $^{\circ}$ C

#### What the Diode Model Misses:

- Transistor effect: How base current controls collector current
- Current gain ( $\beta$ ): Not explained by diodes
- Why collector current doesn't flow through base
- Quantum effects in the thin base region
- Actual carrier dynamics (electron/hole transport)

#### Practical Use of Diode Model:

##### Good for:

- Remembering base-emitter voltage requirement (0.7 V)
- Understanding polarity requirements
- Quick circuit analysis for biasing
- Troubleshooting (measuring base-emitter with multimeter)

##### Not good for:

- Understanding amplification
- Predicting collector current
- Designing precision circuits
- Explaining why transistors work

### Practical Example & Numerical

#### Using Diode Model for Circuit Analysis

**Circuit:** NPN transistor with  $V_{CC} = 9\text{ V}$ , LED in collector,  $R_B$  in base

#### Diode Model Analysis:

##### 1. Base-Emitter "Diode":

- For transistor to turn ON:  $V_{BE} = 0.7\text{ V}$
- If input = 5 V: Voltage across  $R_B = 5 - 0.7 = 4.3\text{ V}$
- This forward-biases the B-E junction

##### 2. Measuring with Multimeter:

- Diode test mode: B-E junction shows 0.6-0.7 V
- Reverse: Open circuit (no conduction)
- B-C junction in active mode: Reverse-biased, open circuit

##### 3. Troubleshooting:

- If  $V_{BE}$  measured  $\approx 0.6\text{ V}$ : Transistor likely OFF or bad
- If  $V_{BE} \approx 0.8\text{ V}$ : Unusual, check for damage
- If B-C shows low resistance both ways: Transistor shorted (bad)

#### Real Transistor Behavior:

Input voltage = 5 V,  $R_B = 10\text{ k}\Omega$ ,  $\beta = 100$ :

$$I_B = \frac{5 - 0.7}{10000} = 0.43\text{ mA}$$

$$I_C = \beta I_B = 100 \times 0.43 = 43\text{ mA}$$

The diode model explains why 0.7 V is dropped, but NOT why collector current is  $100\times$  larger than base current. That requires understanding semiconductor physics beyond the diode analogy.

#### Building "Transistor" from Actual Diodes:

If you physically connect two diodes cathode-to-cathode:

- It will NOT work as a transistor
- Base-emitter will conduct (acts like diode)
- But collector-emitter will NOT conduct
- No amplification occurs
- Missing: The thin base region that allows carriers to drift to collector

This proves the diode model is only a learning aid, not a true representation.

### Key Points (Interview Focus)

## 4. Key Points (Interview Focus)

- Diode model: NPN = two diodes, cathodes at base
- Base-emitter junction: Forward-biased when ON ( $V_{BE} = 0.7\text{ V}$ )
- Base-collector junction: Reverse-biased in active mode
- Model explains voltage drop, NOT current amplification
- Useful for remembering biasing requirements
- Cannot build working transistor from two discrete diodes
- Temperature coefficient:  $-2\text{ mV}/^\circ\text{C}$  for  $V_{BE}$
- Real transistor behavior requires quantum physics explanation

### PNP Transistor: Diode Model

#### TL;DR (The Gist)

**TL;DR:** PNP transistor diode model has anodes connected at base. Emitter-base junction must be forward-biased (base 0.7 V below emitter) for conduction.

**Key Equation:**  $V_{EB} = 0.7\text{ V}$  (emitter positive relative to base)

**Turn-ON:** Base voltage must be 0.7 V lower than emitter voltage.

#### Detailed Explanation

## 2. Detailed Explanation

### PNP Diode Model

#### Simplified Representation:

A PNP transistor visualized as two diodes:

- **Diode 1:** Emitter-Base (E-B junction)
- **Diode 2:** Collector-Base (C-B junction)
- Both anodes connected to base
- Cathodes at emitter and collector respectively

Note: This is opposite polarity compared to NPN!

#### Emitter-Base Junction:

##### Forward-Bias Condition:

- Emitter must be 0.7 V higher than base
- $V_{EB} = V_E - V_B = 0.7\text{ V}$
- Current flows from emitter to base (out of base to ground)
- This is the control junction

#### Example:

- Emitter at 9 V
- Base at 8.3 V
- Difference:  $9 - 8.3 = 0.7\text{ V}$  ✓ Transistor ON

#### Operating Principle:

##### To Turn PNP ON:

1. Connect emitter to positive supply ( $V_{CC}$ )
2. Pull base to voltage 0.7 V below emitter
3. E-B junction forward-biases
4. Small current flows from emitter to base
5. Large current flows from emitter to collector

#### Voltage Relationships:

For PNP to conduct:

$$V_B = V_E - 0.7\text{ V}$$

Or equivalently:

$$V_E = V_B + 0.7\text{ V}$$

#### Current Flow:

- Emitter current:  $I_E$  (largest)
- Base current:  $I_B$  (flows OUT of base)

- Collector current:  $I_C = \beta I_B$
- Relationship:  $I_E = I_B + I_C$

### Why the Diode Drop?

Same physics as NPN:

- Silicon PN junction forward voltage
- Characteristic of all silicon diodes
- Temperature dependent
- Emitter-base is a PN junction (P-type emitter, N-type base)

### Comparison: NPN vs PNP Diode Models:

**NPN:**

- Cathodes at base (arrow points away from base)
- Base voltage higher than emitter
- Current into base

**PNP:**

- Anodes at base (arrow points toward base)
- Base voltage lower than emitter
- Current out of base

### Collector-Base Junction:

In active mode:

- Reverse-biased
- Collector voltage lower than base voltage
- Does not conduct like regular diode
- Part of transistor amplification mechanism

### Limitations of PNP Diode Model:

Same as NPN model:

- Doesn't explain amplification
- Doesn't show why  $I_C = \beta I_B$
- Two diodes wired this way won't make a transistor
- Only helps understand voltage requirements

## Practical Example & Numerical

### PNP Circuit Analysis Using Diode Model

**Circuit:** PNP high-side switch for 12 V LED

**Given:**

- $V_{CC} = 12$  V (connected to emitter)
- LED + resistor from collector to ground
- Control from 5 V microcontroller

**Analysis:**

1. **Turn LED ON** (MCU outputs LOW = 0 V):

- Emitter at 12 V
- Base pulled to 0 V (through resistor)
- $V_{EB} = 12 - 0 = 12$  V (but junction clamps to 0.7 V)
- E-B "diode" forward-biased → Transistor ON
- LED lights up

2. **Turn LED OFF** (MCU outputs HIGH = 5 V):

- Emitter at 12 V
- Base at 5 V
- $V_{EB} = 12 - 5 = 7$  V
- Still forward-biased! → Transistor partially ON
- Problem: Doesn't fully turn off

**Solution:** Use NPN driver + PNP combination

- NPN pulls PNP base to ground (ON)
- NPN off, pull-up resistor brings PNP base to 12 V (OFF)
- Now  $V_{EB} = 12 - 12 = 0$  V → Fully OFF ✓

### Diode Test Measurements:

Using multimeter in diode mode on PNP:

- Red on emitter, black on base: Shows 0.6-0.7 V ✓
- Red on base, black on emitter: OL (open) ✓
- Red on collector, black on base: Shows 0.6-0.7 V (inactive transistor)
- Red on base, black on collector: OL (open) ✓

#### Calculating Currents:

Emitter at 9 V, base at 8.3 V,  $R_B = 4.7 \text{ k}\Omega$ :

$$I_B = \frac{V_E - V_B - 0.7}{R_B} = \frac{9 - 8.3 - 0.7}{4700} = 0$$

Wait, that's wrong! The 0.7 V is already the difference.

Correct:

$$I_B = \frac{V_{EB}}{R_B} = \frac{0.7}{4700} = 0.149 \text{ mA}$$

$$I_C = \beta I_B = 100 \times 0.149 = 14.9 \text{ mA}$$

The diode model helps visualize the 0.7 V drop but requires careful application.

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

- PNP diode model: Anodes at base (opposite of NPN)
- Emitter-base forward-biased:  $V_{EB} = 0.7 \text{ V}$
- Base must be 0.7 V below emitter to turn ON
- Current flows OUT of base (opposite of NPN)
- Collector-base reverse-biased in active mode
- Model explains voltage requirement, not amplification
- Same limitations as NPN diode model
- Useful for biasing calculations and troubleshooting

## Emitter Follower Impedance Analysis

### Emitter Follower Input and Output Impedance - Part 1

#### TL;DR (The Gist)

**TL;DR:** Emitter follower (common-collector) provides impedance transformation: high input impedance prevents source loading, low output impedance drives loads effectively. This makes it ideal as a buffer between circuits.

**Key Property:** High  $Z_{in}$ , Low  $Z_{out}$

**Why Important:** Transfers signal without voltage loss due to loading.

#### Detailed Explanation

#### 2. Detailed Explanation

##### Impedance Matching Fundamentals

##### The Loading Problem:

When connecting two circuits:

- Source has output impedance ( $Z_S$  or  $R_S$ )
- Load (destination) has input impedance ( $Z_{in}$ )
- Together they form a voltage divider

##### Voltage Division Effect:

$$V_{load} = V_{source} \times \frac{Z_{in}}{Z_S + Z_{in}}$$

**Problem:** If  $Z_{in}$  is not much larger than  $Z_S$ , significant voltage is lost!

##### Example of Bad Matching:

- Source: 1 V signal,  $Z_S = 100 \text{ k}\Omega$

- Load:  $Z_{in} = 100 \, \Omega$
- Result:  $V_{load} = 1 \times \frac{100}{100000+100} = 0.001 \, \text{V} = 1 \, \text{mV}$
- Loss: 99.9%! Unacceptable!

**Solution:** Make  $Z_{in} \gg Z_S$

**Design Rule:**  $Z_{in} > 10 \times Z_S$  (minimum)

Better:  $Z_{in} > 100 \times Z_S$

**Why High Input Impedance Matters:**

- Prevents loading of weak signal sources
- Preserves signal voltage
- Minimal current drawn from source
- Essential for sensor interfacing
- Critical in multi-stage amplifiers

**Why Low Output Impedance Matters:**

- Can drive low-impedance loads
- Minimal voltage drop under load
- Can supply significant current
- Drives capacitive loads without roll-off
- Suitable for long cables

**Emitter Follower as Buffer:**

**Configuration:**

- Input: Applied to base (through coupling capacitor)
- Output: Taken from emitter
- Collector: Connected to  $V_{CC}$  (AC ground)
- Voltage gain:  $A_V \approx 1$  (unity)

**Why Called "Follower":**

Output voltage follows input:

$$V_{out} = V_{in} - 0.7 \, \text{V}$$

For AC signals (DC blocked by capacitor):

$$v_{out}(t) = v_{in}(t)$$

Same waveform, same amplitude, no phase shift.

**Block Diagram Model:**

**Source** (e.g., microphone):

- AC voltage source:  $V_S$
- Output impedance:  $R_S$

**Emitter Follower:**

- Input impedance:  $Z_{in}$  (high)
- Output impedance:  $Z_{out}$  (low)
- Voltage gain:  $A_V = 1$

**Load** (e.g., speaker):

- Load resistance:  $R_L$

**Signal Path:**

1. Source provides  $V_S$  through  $R_S$  2. Emitter follower input sees:  $V_{in} = V_S \times \frac{Z_{in}}{R_S + Z_{in}}$  3. Emitter follower outputs:  $V_{amp} = A_V \times V_{in} = V_{in}$  4. Load receives:  $V_{load} = V_{amp} \times \frac{R_L}{Z_{out} + R_L}$   
With proper design ( $Z_{in} \gg R_S$  and  $Z_{out} \ll R_L$ ):

$$V_{load} \approx V_S$$

**Advantages of Emitter Follower:**

- Current gain:  $A_I = \beta$  (significant!)
- Power gain:  $A_P = A_V \times A_I = 1 \times \beta = \beta$
- Impedance transformation: High-Z to Low-Z
- No phase inversion
- Good linearity
- Simple circuit

**Typical Applications:**

- Buffer between stages in amplifiers
- Driving speakers or headphones from weak source
- Sensor interfacing (high-Z sensors)
- Output stage of audio amplifiers

- Impedance matching in RF circuits
- Level shifter (down by 0.7 V)

## Practical Example & Numerical

### Emitter Follower Buffering Demonstration

**Scenario:** MP3 player ( $R_S = 50 \text{ k}\Omega$ ,  $V_S = 1 \text{ V}$ ) driving headphones ( $R_L = 32 \text{ }\Omega$ )

**Without Buffer:**

$$V_{\text{headphones}} = 1 \text{ V} \times \frac{32}{50000 + 32} = 0.64 \text{ mV}$$

Result: Barely audible! 99.94% loss!

**With Emitter Follower Buffer:**

Assume:

- $Z_{in} = 50 \text{ k}\Omega$
- $Z_{out} = 50 \text{ }\Omega$

1. Input voltage to amplifier:

$$V_{in} = 1 \times \frac{50000}{50000 + 50000} = 0.5 \text{ V}$$

2. Amplifier output (unity gain):

$$V_{amp} = 0.5 \text{ V}$$

3. Voltage at headphones:

$$V_{\text{headphones}} = 0.5 \times \frac{32}{50 + 32} = 0.195 \text{ V} = 195 \text{ mV}$$

Result: 195 mV vs 0.64 mV = 305× improvement!

Still some loss at input, but dramatically better. With higher  $Z_{in}$ , even better performance.

**Optimized Design:**

Use Darlington configuration:  $Z_{in} = 500 \text{ k}\Omega$ ,  $Z_{out} = 10 \text{ }\Omega$

1. Input:

$$V_{in} = 1 \times \frac{500000}{50000 + 500000} = 0.909 \text{ V}$$

2. Output:

$$V_{\text{headphones}} = 0.909 \times \frac{32}{10 + 32} = 0.693 \text{ V}$$

Result: 693 mV vs 0.64 mV = 1083× improvement! Nearly full signal transfer.

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- Emitter follower provides impedance transformation
- High input impedance: Prevents source loading
- Low output impedance: Drives loads effectively
- Voltage gain  $\approx 1$ , but significant current and power gain
- Essential as buffer between high-Z source and low-Z load
- Output follows input (hence "follower")
- Design rule:  $Z_{in} \gg R_S$  and  $Z_{out} \ll R_L$
- Applications: Audio buffers, sensor interfaces, multi-stage amps

## Emitter Follower Input and Output Impedance - Part 2

### TL;DR (The Gist)

**TL;DR:** Input impedance of emitter follower is determined by bias resistors in parallel with base impedance. Output impedance is very low, determined by source resistance divided by  $\beta$  plus emitter junction resistance.

**Input Impedance:**  $Z_{in} = R_1 \parallel R_2 \parallel Z_{in(base)}$  where  $Z_{in(base)} = \beta(R_E \parallel R_L + r_e)$

**Output Impedance:**  $Z_{out} = \frac{R_S}{\beta} + r_e$  where  $r_e = \frac{26 \text{ mV}}{I_E}$

## Detailed Explanation

### 2. Detailed Explanation

#### Detailed Input Impedance Calculation

##### Circuit Configuration:

- Voltage divider bias:  $R_1$  (top),  $R_2$  (bottom)
- Emitter resistor:  $R_E$
- Load resistor:  $R_L$  (through output coupling capacitor)
- Input coupling capacitor:  $C_1$

##### AC Analysis Assumptions:

- Capacitors act as short circuits (at signal frequency)
- DC supply is AC ground
- Analyze small-signal behavior

##### Step 1: Find Equivalent Emitter Resistance

Looking from emitter, load is in parallel with emitter resistor:

$$R'_E = R_E \parallel R_L = \frac{R_E \times R_L}{R_E + R_L}$$

##### Step 2: Calculate Emitter Dynamic Resistance

The emitter PN junction has small-signal resistance:

$$r_e = \frac{26 \text{ mV}}{I_E}$$

Where:

- 26 mV is thermal voltage at room temperature (25°C)
- $I_E$  is DC emitter current in amperes

**Typical values:** For  $I_E = 1 \text{ mA}$ ,  $r_e = 26 \Omega$

##### Step 3: Calculate Base Input Impedance

Looking into the base, the transistor reflects emitter impedance multiplied by  $(\beta + 1)$ :

$$Z_{in(base)} = (\beta + 1)(R'_E + r_e) \approx \beta(R'_E + r_e)$$

Since  $\beta \gg 1$ , we approximate  $\beta + 1 \approx \beta$ .

Often  $R'_E \gg r_e$ , so:

$$Z_{in(base)} \approx \beta R'_E$$

##### Step 4: Include Bias Resistors

The bias resistors  $R_1$  and  $R_2$  are in parallel with base impedance:

$$R_{bias} = R_1 \parallel R_2 = \frac{R_1 \times R_2}{R_1 + R_2}$$

**Total input impedance:**

$$Z_{in} = R_{bias} \parallel Z_{in(base)}$$

##### Important Observation:

If  $R_{bias} \ll Z_{in(base)}$ :

$$Z_{in} \approx R_{bias}$$

The input impedance is limited by the bias network, not the transistor!

**Design Implication:** Use large bias resistors for high input impedance.

#### Detailed Output Impedance Calculation

##### Output Impedance Definition:

Looking back from the emitter into the circuit (with load removed).

##### Equivalent Circuit:

From emitter, we see:

- Emitter resistor  $R_E$  to supply (AC ground)
- Emitter junction resistance  $r_e$
- Source resistance  $R_S$  reflected through transistor

**Formula:**

$$Z_{out} = R_E \parallel \left( r_e + \frac{R_S \parallel R_{bias}}{\beta + 1} \right)$$

If  $R_E$  is large:

$$Z_{out} \approx r_e + \frac{R_S \parallel R_{bias}}{\beta}$$

Often  $R_S \ll R_{bias}$ :

$$Z_{out} \approx r_e + \frac{R_S}{\beta}$$

**Typical Values:**

- $r_e = 26 \, \Omega$  (for  $I_E = 1 \, \text{mA}$ )
- $\frac{R_S}{\beta} = \frac{10000}{100} = 100 \, \Omega$  (example)
- $Z_{out} \approx 26 + 100 = 126 \, \Omega$

**Key Insight:** Output impedance is very low compared to typical source impedances!

**Impedance with Load Connected:**

When load  $R_L$  is connected:

$$Z_{out(total)} = Z_{out} \parallel R_L$$

If  $R_L \gg Z_{out}$ :

$$Z_{out(total)} \approx Z_{out}$$

The load doesn't significantly change output impedance because  $Z_{out}$  is so low.

## Practical Example & Numerical

### Complete Impedance Calculation

**Given Circuit:**

- $V_{CC} = 12 \, \text{V}$
- $R_1 = 5.6 \, \text{k}\Omega$ ,  $R_2 = 6.8 \, \text{k}\Omega$
- $R_E = 4.7 \, \text{k}\Omega$
- $R_L = 10 \, \text{k}\Omega$
- $\beta = 100$
- Source:  $R_S = 50 \, \text{k}\Omega$

#### Step 1: Find DC Operating Point

Bias voltage:

$$V_B = 12 \times \frac{6.8}{5.6 + 6.8} = 6.58 \, \text{V}$$

Emitter voltage:

$$V_E = V_B - 0.7 = 5.88 \, \text{V}$$

Emitter current:

$$I_E = \frac{V_E}{R_E} = \frac{5.88}{4700} = 1.25 \, \text{mA}$$

#### Step 2: Calculate $r_e$

$$r_e = \frac{26 \, \text{mV}}{I_E} = \frac{0.026}{0.00125} = 20.8 \, \Omega \approx 21 \, \Omega$$

#### Step 3: Calculate Input Impedance

Equivalent emitter resistance:

$$R'_E = \frac{4.7 \times 10}{4.7 + 10} = 3.2 \, \text{k}\Omega$$

Base impedance:

$$Z_{in(base)} = 100 \times (3200 + 21) = 322 \, \text{k}\Omega$$

Bias resistance:

$$R_{bias} = \frac{5.6 \times 6.8}{5.6 + 6.8} = 3.07 \, \text{k}\Omega$$

Total input impedance:

$$Z_{in} = \frac{3070 \times 322000}{3070 + 322000} = 3.04 \, \text{k}\Omega \approx 3 \, \text{k}\Omega$$

**Observation:** Input impedance dominated by  $R_{bias}$ ! (3 k $\Omega$  vs 322 k $\Omega$ )

#### Step 4: Calculate Output Impedance

$$Z_{out} = r_e + \frac{R_S}{\beta} = 21 + \frac{50000}{100} = 21 + 500 = 521 \Omega$$

With load connected:

$$Z_{out(total)} = \frac{521 \times 10000}{521 + 10000} = 495 \Omega \approx 500 \Omega$$

#### Summary:

- $Z_{in} = 3 \text{ k}\Omega$  (limited by bias network)
- $Z_{out} = 500 \Omega$  (very low!)
- Impedance ratio:  $3000/500 = 6$  (modest transformation)
- For better performance: Increase  $R_1$  and  $R_2$  (but watch biasing)

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

- Input impedance:  $Z_{in} = R_{bias} \parallel \beta R'_E$
- Often limited by bias resistors, not transistor
- Emitter dynamic resistance:  $r_e = 26 \text{ mV}/I_E$
- Output impedance:  $Z_{out} = r_e + R_S/\beta$
- Typically very low (tens to hundreds of ohms)
- Higher  $I_E \rightarrow$  lower  $r_e \rightarrow$  lower  $Z_{out}$
- Larger bias resistors  $\rightarrow$  higher  $Z_{in}$
- Trade-off: Large bias resistors reduce current gain

## Capacitors in Amplifier Circuits

### Input and Output Coupling Capacitors

#### TL;DR (The Gist)

**TL;DR:** Coupling capacitors pass AC signals while blocking DC voltages, preventing DC bias levels from one stage affecting another. They form high-pass filters with circuit impedances.

**Purpose:** AC coupling while maintaining independent DC biasing

**Calculation:**  $C = \frac{1}{2\pi f_L Z}$  where  $f_L$  is cutoff frequency,  $Z$  is impedance

### Detailed Explanation

#### 2. Detailed Explanation

##### Purpose of Coupling Capacitors

##### What is Coupling:

Coupling means connecting the AC signal from one circuit element to another while isolating DC levels.

##### Why Needed:

##### Problem without coupling capacitors:

- DC bias voltage from one stage affects next stage
- Q-point (bias point) of amplifier disturbed
- Can push transistor out of active region
- Unpredictable operation
- Cannot optimize each stage independently

##### Solution with coupling capacitors:

- Block DC voltages between stages
- Pass AC signals freely
- Each stage maintains independent bias
- Stable, predictable operation

## How Capacitors Work for AC Coupling:

### DC Behavior:

- Capacitor blocks DC (infinite impedance)
- No DC current flows
- DC voltages isolated

### AC Behavior:

- Capacitor passes AC (low impedance at signal frequency)
- AC signal transferred
- Impedance:  $Z_C = \frac{1}{2\pi fC}$

### Applications:

#### 1. Audio Circuits:

- Microphone needs DC power (bias voltage)
- But output to speaker/recorder should be AC only
- Coupling capacitor blocks DC, passes audio signal

#### 2. Multi-Stage Amplifiers:

- Each stage optimally biased independently
- AC signal passes through coupling capacitors
- Overall gain:  $A_{total} = A_1 \times A_2 \times A_3 \times \dots$
- DC levels don't compound

#### 3. Emitter Follower:

- Input capacitor: Blocks external DC, preserves internal bias
- Output capacitor: Blocks DC offset, passes AC to load
- Load (e.g., speaker) receives pure AC

### Input Coupling Capacitor:

#### Function:

- Connects AC signal source to amplifier input
- Blocks DC component from source
- Preserves amplifier bias point

#### Forms high-pass filter with input impedance:

$$f_L = \frac{1}{2\pi(R_S + Z_{in})C_1}$$

Where:

- $f_L$  = lower cutoff frequency (3 dB point)
- $R_S$  = source resistance
- $Z_{in}$  = amplifier input impedance
- $C_1$  = input coupling capacitor

### Output Coupling Capacitor:

#### Function:

- Connects amplifier output to load
- Blocks DC bias voltage from reaching load
- Passes AC signal to load

#### Forms high-pass filter with output circuit:

$$f_L = \frac{1}{2\pi(Z_{out} + R_L)C_2}$$

Where:

- $Z_{out}$  = amplifier output impedance
- $R_L$  = load resistance
- $C_2$  = output coupling capacitor

### Design Procedure:

#### Step 1: Choose cutoff frequency $f_L$

- For audio: 20 Hz (or lower, like 2 Hz for safety margin)
- Should be decade below lowest signal frequency
- Example: For 20 Hz audio, use  $f_L = 2$  Hz

#### Step 2: Calculate input capacitor

$$C_1 = \frac{1}{2\pi f_L(R_S + Z_{in})}$$

#### Step 3: Calculate output capacitor

$$C_2 = \frac{1}{2\pi f_L(Z_{out} + R_L)}$$

**Step 4:** Select standard values (round up for safety)

**Important Notes:**

- Larger capacitor  $\rightarrow$  Lower cutoff  $\rightarrow$  Better bass response
- But larger capacitors cost more and take more space
- Electrolytic capacitors for large values ( $> 1 \mu\text{F}$ )
- Watch polarity on electrolytics!
- Film capacitors for better audio quality (if affordable)

## Practical Example & Numerical

### Coupling Capacitor Design for Audio Amplifier

**Given:**

- Audio range: 20 Hz - 20 kHz
- Source impedance:  $R_S = 50 \text{ k}\Omega$
- Input impedance:  $Z_{in} = 2.8 \text{ k}\Omega$
- Output impedance:  $Z_{out} = 50 \Omega$
- Load:  $R_L = 8 \Omega$  (speaker)
- Target cutoff:  $f_L = 2 \text{ Hz}$  (decade below 20 Hz)

**Input Capacitor Calculation:**

$$C_1 = \frac{1}{2\pi \times 2 \times (50000 + 2800)}$$
$$C_1 = \frac{1}{2\pi \times 2 \times 52800} = \frac{1}{663575} = 1.51 \mu\text{F}$$

Round up to standard value:  $C_1 = 2.2 \mu\text{F}$  or  $3.3 \mu\text{F}$

**Output Capacitor Calculation:**

$$C_2 = \frac{1}{2\pi \times 2 \times (50 + 8)}$$
$$C_2 = \frac{1}{2\pi \times 2 \times 58} = \frac{1}{728.5} = 1.37 \text{ mF} = 1370 \mu\text{F}$$

Round up to standard value:  $C_2 = 1500 \mu\text{F}$  or  $2200 \mu\text{F}$

**Verification:**

With  $C_1 = 3.3 \mu\text{F}$ :

$$f_L = \frac{1}{2\pi \times 52800 \times 3.3 \times 10^{-6}} = 0.91 \text{ Hz}$$

With  $C_2 = 2200 \mu\text{F}$ :

$$f_L = \frac{1}{2\pi \times 58 \times 2200 \times 10^{-6}} = 1.25 \text{ Hz}$$

Both well below 20 Hz ✓ Full audio bandwidth preserved ✓

**Component Selection:**

- $C_1 = 3.3 \mu\text{F}/25 \text{ V}$  electrolytic (+ towards amplifier input)
- $C_2 = 2200 \mu\text{F}/16 \text{ V}$  electrolytic (+ towards amplifier output)

**Effect Without Coupling Capacitors:**

Assume emitter at 5.8 V DC:

- Speaker would receive 5.8 V DC + AC signal
- DC current through  $8 \Omega$ :  $I = 5.8/8 = 725 \text{ mA}$
- Power wasted:  $P = 5.8 \times 0.725 = 4.2 \text{ W}$
- Speaker voice coil heats up
- Reduced dynamic range
- Potential speaker damage

With coupling capacitor:

- Speaker receives only AC signal
- No DC current
- No wasted power
- Full dynamic range
- Speaker operates optimally

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- Coupling capacitors pass AC, block DC
- Essential for isolating DC bias between stages
- Input capacitor:  $C_1 = \frac{1}{2\pi f_L(R_S + Z_{in})}$
- Output capacitor:  $C_2 = \frac{1}{2\pi f_L(Z_{out} + R_L)}$
- Choose  $f_L$  decade below lowest signal frequency
- Larger capacitor  $\rightarrow$  better low-frequency response
- Use electrolytic for large values, watch polarity
- Prevents DC from reaching loads (speakers, etc.)

## Bypass Capacitor in Common-Emitter Amplifiers - Part I

### TL;DR (The Gist)

**TL;DR:** Bypass capacitors shunt AC noise and ripple to ground while allowing DC to pass through resistors. In amplifiers, emitter bypass capacitors increase AC gain by shorting AC signal around the emitter resistor.

**Purpose:** Remove AC noise from DC supply; increase amplifier gain

**Function:** Low impedance path to ground for AC, high impedance for DC

### Detailed Explanation

## 2. Detailed Explanation

### What is a Bypass Capacitor?

#### Definition:

A capacitor placed in parallel with a circuit element to provide an alternate (low-impedance) path for AC signals to ground, bypassing the element.

#### Main Purposes:

##### 1. Power Supply Decoupling:

- Filters AC ripple from DC supply
- Removes 50/60 Hz AC noise
- Stabilizes supply voltage
- Placed close to IC power pins

##### 2. Emitter Degeneration Bypass:

- Shorts AC signal around emitter resistor
- Increases AC voltage gain
- Maintains DC bias stability
- Trade-off: DC stabilization vs AC gain

#### How Bypass Capacitors Work:

#### Frequency-Dependent Impedance:

$$Z_C = \frac{1}{2\pi fC}$$

#### At DC ( $f = 0$ ):

- $Z_C = \infty$  (open circuit)
- No DC current through capacitor
- DC follows normal circuit path

#### At AC (signal frequency):

- $Z_C$  very low (short circuit)
- AC takes path through capacitor
- AC bypassed to ground

#### Power Supply Noise Filtering:

#### Problem:

- DC power supplies often have AC ripple
- 50 Hz or 60 Hz from mains

- Switching noise from regulators
- This noise adds to signal (undesirable)

**Solution:**

- Place bypass capacitor from  $V_{CC}$  to ground
- Typical value: 0.1  $\mu\text{F}$  to 100  $\mu\text{F}$
- AC ripple shunted to ground
- Clean DC presented to circuit

**Path Selection:**

Current always takes path of least resistance.

**For DC:**

- Capacitor: Infinite resistance  $\rightarrow$  No DC flow
- Resistor: Finite resistance  $\rightarrow$  DC flows here

**For AC:**

- Capacitor: Low reactance  $\rightarrow$  AC flows here
- Resistor: Higher resistance  $\rightarrow$  AC avoids if possible

**Emitter Bypass Capacitor in Amplifiers:**

**Common-Emitter Without Bypass:**

- Emitter resistor  $R_E$  provides DC stability
- But also provides negative feedback for AC
- AC gain:  $A_V = \frac{R_C}{R_E + r_e}$  (reduced gain)
- Good stability, lower gain

**Common-Emitter With Bypass:**

- Capacitor in parallel with  $R_E$
- DC still flows through  $R_E$  (stability maintained)
- AC shorted around  $R_E$  (higher gain)
- AC gain:  $A_V = \frac{R_C}{r_e}$  (much higher!)
- Best of both worlds

**Typical Bypass Capacitor Values:**

**Power Supply Decoupling:**

- Digital ICs: 0.1  $\mu\text{F}$  ceramic (high frequency)
- Analog circuits: 10-100  $\mu\text{F}$  electrolytic (low frequency)
- Sometimes both in parallel (wide frequency range)

**Emitter Bypass:**

- Audio (20 Hz): 50-500  $\mu\text{F}$
- RF circuits: pF to nF range
- Rule: Reactance should be  $\leq 0.1 \times R_E$  at lowest frequency

**Placement Guidelines:**

- Mount as close as possible to relevant component
- Short leads minimize parasitic inductance
- For ICs: Bypass each supply pin
- Ground connection: Shortest path possible

## Practical Example & Numerical

### Power Supply Noise Filtering

**Problem:** DC supply has 50 Hz ripple

**Given:**

- Supply: 15 V DC with 1 V peak 50 Hz ripple
- Amplifier draws 10 mA
- Want to reduce ripple to  $\leq 0.1$  V

**Solution:** Add bypass capacitor

Choose capacitor reactance  $\leq 10 \Omega$  at 50 Hz:

$$X_C = \frac{1}{2\pi fC} \leq 10$$

$$C \geq \frac{1}{2\pi \times 50 \times 10} = \frac{1}{3141} = 318 \mu\text{F}$$

Use  $C = 470 \mu\text{F}$  (standard value)

**Verification:**

$$X_C = \frac{1}{2\pi \times 50 \times 470 \times 10^{-6}} = 6.77 \Omega$$

**Voltage divider effect:**

Assume supply impedance  $R_S = 100 \Omega$  (typical):

$$V_{ripple(out)} = 1 \text{ V} \times \frac{6.77}{100 + 6.77} = 0.063 \text{ V}$$

Ripple reduced from 1 V to 63 mV ✓ (i 0.1 V target achieved)

**Gain Increase with Emitter Bypass:**

**Circuit:** Common-emitter with  $R_C = 2.2 \text{ k}\Omega$ ,  $R_E = 470 \Omega$ ,  $r_e = 26 \Omega$

**Without bypass:**

$$A_V = \frac{R_C}{R_E + r_e} = \frac{2200}{470 + 26} = 4.4$$

**With bypass** (at signal frequency):

$$A_V = \frac{R_C}{r_e} = \frac{2200}{26} = 84.6$$

Gain increase:  $84.6/4.4 = 19.2\times!$

This demonstrates the dramatic effect of emitter bypass on gain.

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- Bypass capacitor provides low-impedance AC path to ground
- Blocks DC (infinite impedance), passes AC (low impedance)
- Power supply bypass: Removes ripple and noise
- Emitter bypass: Increases amplifier gain while maintaining DC stability
- Reactance formula:  $X_C = 1/(2\pi fC)$
- Design rule:  $X_C \leq 0.1 \times R$  at lowest frequency
- Place close to component for best performance
- Typical values: 0.1  $\mu\text{F}$  (digital), 10-100  $\mu\text{F}$  (analog)

## Bypass Capacitor in Common-Emitter Amplifiers - Part II

### TL;DR (The Gist)

**TL;DR:** Calculate emitter bypass capacitor value so its reactance is  $\leq 0.1 \times R_E$  at the lowest frequency to be bypassed. This ensures AC is effectively shorted to ground.

**Design Rule:**  $X_C = \frac{R_E}{10}$  at  $f_{low}$

**Formula:**  $C = \frac{10}{2\pi f_{low} R_E}$

## Detailed Explanation

### 2. Detailed Explanation

#### Bypass Capacitor Value Selection

**Design Criterion:**

The capacitor reactance at the lowest frequency should be much lower than the emitter resistance:

$$X_C \leq \frac{R_E}{10}$$

**Why one-tenth?**

This ensures the AC current divides 10:1 in favor of the capacitor path:

- 90% of AC current through capacitor (to ground)
- 10% of AC current through  $R_E$
- Effective AC bypass

**Derivation:**

Starting with reactance formula:

$$X_C = \frac{1}{2\pi fC}$$

Setting  $X_C = \frac{R_E}{10}$ :

$$\frac{1}{2\pi f_{low}C} = \frac{R_E}{10}$$

Solving for  $C$ :

$$C = \frac{10}{2\pi f_{low}R_E}$$

### Frequency Considerations:

Choosing  $f_{low}$ :

- Audio applications: 20 Hz (audible range)
- But 50/60 Hz AC ripple often problematic
- Safe choice: 50 Hz (covers both audio and AC noise)
- Lower frequency  $\rightarrow$  Larger capacitor required

### Frequency Response:

As frequency increases:

- $X_C$  decreases (better bypassing)
- At  $f = 10 \times f_{low}$ :  $X_C = \frac{R_E}{100}$  (99% bypass)
- At  $f = 100 \times f_{low}$ : Nearly perfect short

### Current Path Analysis:

DC Analysis ( $f = 0$ ):

- Capacitor: Open circuit
- All current through  $R_E$
- Emitter voltage:  $V_E = I_E \times R_E$
- Provides bias stability

AC Analysis (signal frequency):

- Capacitor: Low impedance ( $X_C \ll R_E$ )
- Most AC current through capacitor
- AC emitter voltage:  $v_e \approx 0$  (grounded for AC)
- High voltage gain achieved

### Parallel Impedance:

Total AC impedance at emitter:

$$Z_E = R_E \parallel X_C = \frac{R_E \times X_C}{R_E + X_C}$$

If  $X_C = R_E/10$ :

$$Z_E = \frac{R_E \times (R_E/10)}{R_E + (R_E/10)} = \frac{R_E^2/10}{11R_E/10} = \frac{R_E}{11}$$

Much lower than  $R_E$  alone!

### Practical Considerations:

#### Component Selection:

- Calculate exact value
- Round up to next standard value
- Electrolytic for large values ( $\geq 1 \mu\text{F}$ )
- Watch voltage rating:  $\geq V_E$  (typically  $\geq 16 \text{ V}$ )
- Polarity: + to emitter, - to ground

#### Trade-offs:

- Larger  $C \rightarrow$  Better low-frequency bypass
- But: Larger size, higher cost
- But: Slower turn-on transient
- Compromise based on application

### Multiple Bypass Capacitors:

For wide frequency range:

- Large electrolytic (low frequency):  $100 \mu\text{F}$
- Small ceramic (high frequency):  $0.1 \mu\text{F}$
- In parallel: Covers DC to MHz range

## Emitter Bypass Capacitor Design

Given:

- Emitter resistor:  $R_E = 470\ \Omega$
- Lowest frequency:  $f_{low} = 50\text{ Hz}$
- Want effective bypass

### Step 1: Calculate Required Reactance

$$X_C = \frac{R_E}{10} = \frac{470}{10} = 47\ \Omega$$

### Step 2: Calculate Capacitance

$$C = \frac{1}{2\pi f_{low} X_C} = \frac{1}{2\pi \times 50 \times 47}$$
$$C = \frac{1}{14760} = 67.8\ \mu\text{F}$$

### Step 3: Select Standard Value

Round up:  $C = 100\ \mu\text{F}$  (standard value, provides margin)

### Step 4: Verify Performance

At 50 Hz:

$$X_C = \frac{1}{2\pi \times 50 \times 100 \times 10^{-6}} = 31.8\ \Omega$$

Check ratio:

$$\frac{R_E}{X_C} = \frac{470}{31.8} = 14.8$$

Ratio  $\geq 10$  ✓ Excellent bypassing!

### Current Division:

At 50 Hz, AC current splits:

- Total impedance:  $Z_E = \frac{470 \times 31.8}{470 + 31.8} = 29.8\ \Omega$
- If 1 mA AC at emitter:
- Through  $R_E$ :  $\frac{31.8}{470 + 31.8} \times 1 = 0.063\text{ mA}$  (6.3%)
- Through  $C$ :  $\frac{470}{470 + 31.8} \times 1 = 0.937\text{ mA}$  (93.7%)

93.7% bypassed ✓

### Frequency Response:

At 20 Hz:

$$X_C = \frac{1}{2\pi \times 20 \times 100 \times 10^{-6}} = 79.6\ \Omega$$
$$\frac{R_E}{X_C} = \frac{470}{79.6} = 5.9$$

Still decent bypassing (85% through capacitor).

At 200 Hz:

$$X_C = \frac{1}{2\pi \times 200 \times 100 \times 10^{-6}} = 8\ \Omega$$
$$\frac{R_E}{X_C} = \frac{470}{8} = 58.8$$

Excellent bypassing (98.3% through capacitor)!

At 20 kHz:

$$X_C = \frac{1}{2\pi \times 20000 \times 100 \times 10^{-6}} = 0.08\ \Omega$$

Nearly perfect short for high frequencies.

### Component Specification:

- Value: 100  $\mu\text{F}$
- Type: Electrolytic
- Voltage rating: 25 V (for  $V_E < 10\text{ V}$ )
- Polarity: + to emitter, - to ground

## Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

- Design rule:  $X_C \leq R_E/10$  at lowest frequency
- Calculation:  $C = 10/(2\pi f_{low} R_E)$
- Choose  $f_{low} = 50$  Hz for audio (covers AC ripple too)
- Round up calculated value to standard capacitor size
- Larger capacitor = better low-frequency bypass
- Electrolytic capacitors for values  $\geq 1$   $\mu\text{F}$
- Watch polarity: + to emitter, - to ground
- Dramatically increases amplifier gain while maintaining DC stability

# Section 20 – Transistor Circuits

## Current Source Fundamentals

### Current Source - Introduction

#### TL;DR (The Gist)

A current source is a circuit element that maintains constant current flow regardless of the voltage developed across its terminals or the impedance it drives. Unlike voltage sources, ideal current sources have infinite internal resistance to ensure 100% power efficiency to the load.

#### Detailed Explanation

### 2. Detailed Explanation

#### Ideal vs. Real Current Sources

An ideal current source provides constant current with 100% efficiency, meaning if it's rated at 12 mA, the load receives the entire 12 mA without loss. The key difference between voltage and current sources lies in their internal resistance:

- **Voltage Source:** Zero internal resistance (series connection)
- **Current Source:** Infinite internal resistance (parallel connection)

#### Why Infinite Internal Resistance?

The internal impedance of a current source can be represented as a resistance in parallel with it. To supply 100% of power to the load, the source must have much higher resistance than the load. Current always takes the path of least resistance, so when the source has infinite resistance, current will flow out and take the lower resistance path through the load.

#### Current Division Analysis

For a real current source with finite internal resistance  $R_{int}$ , the current through the load  $R_L$  is calculated using current division:

$$I_L = I_{source} \times \frac{R_{int}}{R_{int} + R_L}$$

For example, with a 100 mA source,  $R_{int} = 10 \text{ k}\Omega$ , and  $R_L = 8 \text{ }\Omega$ :

$$I_L = 100 \text{ mA} \times \frac{10000}{10000 + 8} = 99.9992 \text{ mA}$$

This is 99.99% efficient, but not perfect. If  $R_{int}$  were lower, efficiency would decrease significantly.

#### Practical Example & Numerical

### Current Source Comparison

#### Current Source Comparison

##### Voltage Source Circuit:

- 5 V source with  $200 \text{ }\Omega$  total resistance:  $I = 5/200 = 25 \text{ mA}$
- Change load to  $5 \text{ k}\Omega$ :  $I = 5/5000 = 1 \text{ mA}$  (current changes!)

##### Current Source Circuit:

- 10 mA current source with multiple loads
- Switching between different resistor values
- Current remains constant at 10 mA regardless of load resistance
- Voltage across load adjusts to maintain constant current

This demonstrates the fundamental advantage: current sources maintain constant current delivery independent of load variations.

#### Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- Current source maintains constant current regardless of load impedance
- Ideal current source has infinite internal resistance for 100% efficiency

- Symbol: circle with arrow indicating current direction
- Current takes the path of least resistance
- Real current sources: high (but finite) internal resistance
- Output current remains steady despite load resistance fluctuations

## How to Design a Current Source

### TL;DR (The Gist)

A practical current source can be designed using a resistor with high supply voltage, or more effectively using a transistor configuration where emitter current  $I_E = (V_{base} - 0.6)/R_E$ . Adding a Zener diode stabilizes against supply voltage fluctuations, and using two transistors cancels the  $V_{BE}$  offset.

### Detailed Explanation

## 2. Detailed Explanation

### Simple Resistor Current Source

The most basic current source is a resistor connected to a high voltage supply. If the supply voltage  $V_{supply}$  is much higher than the load voltage  $V_{load}$ :

$$I \approx \frac{V_{supply}}{R}$$

This works when  $R_{load} \ll R$ . For example, with  $V_{supply} = 5 \text{ V}$  and  $R = 10 \text{ k}\Omega$ , desired current is  $500 \text{ }\mu\text{A}$ . Actual current depends on load resistance:

- Small  $R_{load}$ : error  $\approx 10 \text{ }\mu\text{A}$
- Medium  $R_{load}$ : error  $\approx 38 \text{ }\mu\text{A}$
- Large  $R_{load}$ : error  $\approx 200 \text{ }\mu\text{A}$  (problematic)

#### Drawbacks:

- Requires large voltages with significant power dissipation
- Current varies with load changes
- Not easily programmable

### Transistor-Based Current Source

A much better solution uses an NPN transistor:

$$I_C \approx I_E = \frac{V_{base} - 0.6}{R_E}$$

Since  $V_E = V_{base} - 0.6 \text{ V}$ , the collector current depends on the base voltage and emitter resistance, independent of supply voltage (as long as transistor isn't saturated).

#### Voltage Regulation with Zener Diode

To eliminate fluctuations from supply voltage changes, replace the voltage divider resistor with a Zener diode. If the Zener breakdown voltage is  $3.3 \text{ V}$ , the base voltage remains constant at  $3.3 \text{ V}$  regardless of supply variations, ensuring constant load current.

#### Two-Transistor Configuration for Offset Cancellation

The  $0.6 \text{ V } V_{BE}$  offset can be problematic. Using two transistors (Q1 and Q2) solves this:

- Q2 is the output stage with current set by emitter voltage
- Q1 is configured as a diode (base-collector shorted)
- Q1's  $V_{BE}$  drop compensates for Q2's  $V_{BE}$  drop
- Result:  $I_{out} \approx V_{in}/R_E$  (no offset!)

Note: This is first-order compensation since transistors may have different  $I_C$  and thus slightly different  $V_{BE}$ .

### Practical Example & Numerical

#### Transistor Current Source Design

**Given:** Design a  $1.9 \text{ mA}$  current source with  $20 \text{ V}$  supply

**Step 1:** Choose base voltage using voltage divider

- Design voltage divider for  $V_{base} = 2.5 \text{ V}$

- Use resistors to create stable bias point

**Step 2:** Calculate emitter voltage

$$V_E = V_{base} - 0.6 = 2.5 - 0.6 = 1.9 \text{ V}$$

**Step 3:** Calculate emitter resistance

$$R_E = \frac{V_E}{I_E} = \frac{1.9}{0.0019} = 1 \text{ k}\Omega$$

**Result:** Current through load = 1.9 mA, independent of load resistance

**With Zener Stabilization:**

- Replace voltage divider with 3.3 V Zener
- Supply voltage can fluctuate without affecting load current
- Current remains constant at design value

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- Simple resistor source:  $I \approx V_{supply}/R$  (poor regulation)
- Transistor source:  $I_C = (V_{base} - 0.6)/R_E$  (good regulation)
- Zener diode: stabilizes against supply voltage fluctuations
- Two-transistor config: cancels  $V_{BE}$  offset for accurate programming
- High input impedance: ideal for microcontroller DAC control
- Op-amps provide most accurate current sources (covered in advanced course)

## Amplifier Circuit Design

### How to Design a Common-Emitter Amplifier

#### TL;DR (The Gist)

A common-emitter amplifier provides voltage gain (not current gain like emitter follower). The voltage gain is  $A_v = R_C/R_E$ , the output is taken from the collector (180° phase shift), and DC biasing must place the transistor in the active region to prevent signal clipping.

#### Detailed Explanation

### 2. Detailed Explanation

#### Common Terminal Configurations

The terminal designated as "common" serves as ground/reference for both input and output:

- **Common Collector (Emitter Follower):** Base = input, Emitter = output, Collector = common (tied to supply)
- **Common Emitter:** Base = input, Collector = output, Emitter = common (tied to ground)
- **Common Base:** Emitter = input, Collector = output, Base = common

#### Emitter Follower Applications

Before studying common-emitter amplifiers, recall that emitter followers are used for:

- Current amplification without voltage gain
- Impedance matching (high input impedance, low output impedance)
- Buffer amplifiers for maximum power transfer

Example: Source with 120 k $\Omega$  output impedance driving 20  $\Omega$  load through emitter follower with 120 k $\Omega$  input impedance and 22  $\Omega$  output impedance.

#### Common-Emitter Amplifier Design Process

##### 1. Determine Gain Requirements

With supply voltage  $V_{CC} = 20 \text{ V}$  and input signal 500 mV, we can't amplify by  $\beta = 100$  (would require 50 V output). Choose realistic gain, e.g.,  $A_v = 10$  for 5 V output.

##### 2. Add Collector Resistor

Without  $R_C$ , collector voltage stays at  $V_{CC}$  (can't swing). The collector resistor enables voltage swing from 0 to  $V_{CC}$ . For maximum current of 2 mA:

$$R_C = \frac{V_{CC}}{I_{C,max}} = \frac{20}{0.002} = 10 \text{ k}\Omega$$

### 3. Set Voltage Gain with Emitter Resistor

The voltage gain (without considering intrinsic emitter resistance  $r_e$ ) is:

$$A_v = \frac{R_C}{R_E}$$

For  $A_v = 10$  with  $R_C = 10 \text{ k}\Omega$ :

$$R_E = \frac{R_C}{A_v} = \frac{10000}{10} = 1 \text{ k}\Omega$$

Note: Intrinsic emitter resistance  $r_e \approx 20 \text{ }\Omega$  can be significant. More accurate gain:

$$A_v = \frac{R_C}{R_E + r_e} \approx \frac{10000}{1000 + 20} \approx 9.8$$

### 4. DC Biasing

The transistor must be biased in the forward active region. A voltage divider sets base voltage around 1.6-1.7 V:

- Use resistors (e.g., 110 k $\Omega$  and 10 k $\Omega$ ) to create  $V_{base} \approx 1.6 \text{ V}$
- This places  $V_E \approx 1.0 \text{ V}$  and  $V_C \approx 10 \text{ V}$  (mid-supply for maximum swing)
- Avoids saturation ( $V_C \approx V_{base}$ ) and cutoff ( $V_{base} < 0.6 \text{ V}$ )

### 5. AC Coupling

Input and output coupling capacitors:

- Block DC, pass AC signals
- Prevent loading of signal source
- Allow independent DC biasing

### Important Note on Phase Inversion

Common-emitter configuration inverts the phase (180° shift). When input rises, output falls, and vice versa. This usually isn't a problem in most applications.

## Practical Example & Numerical

### Complete Design Example

#### Specifications:

- Input signal: 500 mV peak-to-peak
- Supply voltage: 20 V
- Load impedance: 1 M $\Omega$  (high-Z, doesn't need high current)
- Desired gain: 10

#### Component Selection:

1. **Collector resistor:**  $R_C = 10 \text{ k}\Omega$  (limits current to 2 mA max)
2. **Emitter resistor:**  $R_E = 1 \text{ k}\Omega$  (sets gain to 10)
3. **Bias resistors:** 110 k $\Omega$  and 10 k $\Omega$  (creates  $V_{base} = 1.6 \text{ V}$ )
4. **Coupling capacitors:** sized for desired low-frequency cutoff

#### Operating Point:

- $V_{base} = 1.6 \text{ V}$  (from voltage divider)
- $V_E = 1.0 \text{ V}$  ( $V_{base} - 0.6 \text{ V}$ )
- $I_E = V_E / R_E = 1.0 / 1000 = 1 \text{ mA}$
- $I_C \approx I_E = 1 \text{ mA}$
- $V_C = V_{CC} - I_C R_C = 20 - 10 = 10 \text{ V}$

#### Performance:

- Input: 500 mV peak-to-peak
- Output:  $\approx 4.8 \text{ V}$  peak-to-peak (gain  $\approx 9.6$ )
- Output centered at 10 V DC (optimal for maximum swing)
- Phase inverted relative to input

## Key Points (Interview Focus)

## 4. Key Points (Interview Focus)

- Common-emitter: voltage amplifier, emitter tied to ground
- Voltage gain:  $A_v = R_C/R_E$  (simplified) or  $A_v = R_C/(R_E + r_e)$  (accurate)
- Output from collector has 180° phase shift relative to input
- DC bias keeps transistor in active region:  $V_C > V_{base}$  (avoid saturation)
- Bias resistors set  $V_{base} > 0.6$  V (avoid cutoff)
- Collector resistor enables voltage swing from 0 to  $V_{CC}$
- Coupling capacitors block DC, pass AC signals
- Can cascade with emitter follower for current boosting

## Current Mirror Circuits

### Current Mirror

#### TL;DR (The Gist)

A current mirror copies the current from one branch to another, keeping output current constant regardless of loading. The basic configuration uses two matched transistors with bases connected, where one transistor (Q1) has base-collector shorted and acts as a diode to set the reference current that Q2 mirrors.

#### Detailed Explanation

## 2. Detailed Explanation

### Why "Current Mirror"?

The circuit gets its name because it copies or mirrors the current flowing in one active branch into another. Current mirroring is fundamental in integrated circuit design—from amplifiers to op-amps, nearly all ICs use at least one current mirror.

### Basic Two-Transistor Configuration

The simplest current mirror consists of:

- Q1: Base-collector shorted (acts as diode), sets reference
- Q2: Mirrors the current to the load
- Both bases connected together
- Both emitters connected to ground

### How It Works

The input "programming current" flows through Q1. Since Q1 has base and collector connected, it behaves like a diode with  $V_{BE} \approx 0.6$  V. This voltage also appears at Q2's base, turning it on with the same  $V_{BE}$ .

For matched transistors with same  $\beta$  and  $V_{BE}$ :

$$I_{C1} \approx I_{C2}$$

### Programming Current Calculation

Using Kirchhoff's voltage law on the input branch:

$$I_{prog} = \frac{V_{CC} - V_{BE}}{R}$$

More precisely, accounting for base currents of both transistors:

$$I_{prog} = I_{C1} + 2I_B$$

where both transistors draw base current through the programming resistor.

### Limitations of Basic Mirror

1. **Output voltage variations:** Slight  $V_{BE}$  variation with  $V_{CE}$  at constant  $I_C$  causes output current to vary slightly with output voltage.
2. **Transistor matching required:** Transistors must be on same substrate, manufactured together for accurate mirroring. In simulation, transistors are identical; in reality, slight differences exist.
3. **Base current error:** Both transistors draw base current, creating mismatch between programming and output current. Error is small for high- $\beta$  transistors but still present.

### Improved Three-Transistor Mirror

Adding Q3 as a buffer reduces base current error:

- Q3 provides base current for Q1 and Q2 via its emitter

- Only Q3's base current flows through programming resistor
- Reduces base current error by factor of  $(\beta + 1)$

New programming current equation:

$$I_{prog} = \frac{V_{CC} - 2V_{BE}}{R}$$

(accounts for two  $V_{BE}$  drops: Q3 and Q1)

### Emitter Degeneration

Adding emitter resistors provides negative feedback:

- Stabilizes mirror against temperature changes
- Improves matching between discrete transistors
- Reduces gain but improves performance in other aspects

### How Emitter Resistor Provides Negative Feedback:

If collector current tries to increase  $\rightarrow$  emitter current increases  $\rightarrow$  voltage drop across  $R_E$  increases  $\rightarrow V_{BE}$  decreases (since  $V_B$  is constant)  $\rightarrow$  transistor turns off slightly  $\rightarrow$  current increase is opposed.

This negative feedback provides:

- Temperature stability
- Better gain control
- Flatter frequency response
- Improved circuit predictability

In integrated circuits, emitter resistors are often omitted because neighboring transistors have negligible parameter differences and same temperature. For discrete designs, emitter resistors are beneficial.

### Wilson Current Mirror

A popular configuration that provides negative feedback without emitter resistors:

- Uses three transistors: Q1, Q2, and Q3
- Q3 provides inherent negative feedback
- Better stability than basic mirror

### How Wilson Mirror Works:

Small current through programming resistor  $\rightarrow$  Q3 base current  $\rightarrow$  Q3 conducts  $\rightarrow$  Q3 emitter current becomes programming current for Q1-Q2 mirror  $\rightarrow$  Q1 and Q2 collector currents equal  $\rightarrow$  Q3 collector current (output) mirrors input.

### Negative Feedback Mechanism:

If output current (Q3  $I_C$ ) tries to increase  $\rightarrow$  Q2  $I_C$  increases  $\rightarrow$  Q1  $I_C$  mirrors increase  $\rightarrow$  voltage drop across programming resistor increases  $\rightarrow$  Q3  $V_B$  decreases  $\rightarrow$  Q3 turns off slightly  $\rightarrow$  output current increase is opposed.

This self-regulating behavior provides better stability without emitter resistors.

## Practical Example & Numerical

### Basic Current Mirror Design

**Given:**  $V_{CC} = 5\text{ V}$ , desired mirror current =  $0.3\text{ mA}$ ,  $V_{BE} = 0.6\text{ V}$

**Step 1:** Calculate programming resistor

$$R = \frac{V_{CC} - V_{BE}}{I_{prog}} = \frac{5 - 0.6}{0.0003} = 14.67\text{ k}\Omega$$

Use standard value:  $15\text{ k}\Omega$

**Step 2:** Verify operation

- $I_{prog} = (5 - 0.6)/15000 = 0.293\text{ mA}$
- Q1 acts as diode with  $V_{BE} = 0.6\text{ V}$
- Q2 base voltage =  $0.6\text{ V}$  (same as Q1)
- Q2 collector current  $\approx 0.293\text{ mA}$  (mirrors Q1)

**Step 3:** Test with different loads

- Load =  $1\text{ k}\Omega$ : Output current =  $0.293\text{ mA}$
- Load =  $10\text{ k}\Omega$ : Output current =  $0.293\text{ mA}$
- Current remains constant regardless of load (within limits)

**Note:** In simulation with identical transistors, current is exactly  $0.3\text{ mA}$ . In practice, slight variations occur due to transistor mismatch.

## Key Points (Interview Focus)

## 4. Key Points (Interview Focus)

- Current mirror copies current from one branch to another
- Basic mirror: two transistors, bases connected, Q1 base-collector shorted
- Q1 acts as diode setting reference voltage for both transistors
- Output current independent of load (constant current sink/source)
- Limitations: transistor matching, base current error,  $V_{CE}$  variations
- Three-transistor mirror reduces base current error by  $(\beta + 1)$
- Emitter resistors provide negative feedback and temperature stability
- Wilson mirror provides feedback without emitter resistors
- Essential building block in all integrated circuit designs

# Differential Amplifier Analysis

## Differential Amplifier - Part 1

### TL;DR (The Gist)

A differential amplifier amplifies the difference between two input signals:  $V_o = A_d(V_1 - V_2)$ . This configuration is crucial for rejecting common-mode noise (signals appearing equally on both inputs) while amplifying differential signals. It's the fundamental building block of operational amplifiers.

### Detailed Explanation

## 2. Detailed Explanation

### Why Differential Amplifiers?

Differential amplifiers solve the critical problem of amplifying weak signals contaminated by noise. Applications include:

- Twisted pair cable transmission (Ethernet, digital signals)
- Audio signal processing
- Local area network signals
- Radio frequency communications
- Any application where noise rejection is essential

### Basic Principle

An amplifier that amplifies the difference between two input signals:

$$V_{out} = A_d(V_1 - V_2)$$

where  $A_d$  is the differential gain. The higher the difference between inputs, the higher the output voltage.

### Twisted Pair Cable Transmission

Consider Ethernet cable carrying data from router to computer:

- Two isolated copper wires twisted together
- Both wires carry the same information
- One wire has signal, other has inverted signal (180° out of phase)

### Signal Transmission:

- Wire 1: Original signal (e.g., sine wave at frequency  $f$ )
- Wire 2: Inverted signal (same frequency, opposite phase)

### Differential Amplification:

When both signals enter the differential amplifier:

$$V_{out} = A_d(V_1 - V_2)$$

If  $V_1 = +A \sin(\omega t)$  and  $V_2 = -A \sin(\omega t)$ :

$$V_{out} = A_d(A \sin(\omega t) - (-A \sin(\omega t))) = A_d \cdot 2A \sin(\omega t)$$

The signal is amplified by  $2A_d$ .

### Noise Rejection Principle

When noise is induced in the cable (electromagnetic interference):

- Noise appears on both wires equally (same phase and amplitude)
- Both wires are physically close, so noise is identical
- This is called "common-mode" noise

If noise  $V_n$  is added to both inputs:

- Wire 1: Signal + Noise =  $V_1 + V_n$
- Wire 2: Inverted Signal + Noise =  $V_2 + V_n$

Differential output:

$$V_{out} = A_d[(V_1 + V_n) - (V_2 + V_n)] = A_d(V_1 - V_2)$$

The noise cancels out! Only the signal difference is amplified.

### Two Types of Signals

#### 1. Differential Mode (Normal Mode):

- Inputs differ in magnitude or phase
- Example:  $V_1$  and  $V_2$  180° out of phase
- This is the desired signal to amplify
- Gain is  $A_d$  (differential gain)

#### 2. Common Mode:

- Both inputs identical in voltage and phase
- Example: Same noise on both inputs
- Should ideally not be amplified
- Gain is  $A_c$  (common-mode gain, should be  $\approx 0$ )

### Common-Mode Rejection Ratio (CMRR)

A metric quantifying the amplifier's ability to reject common-mode signals:

$$\text{CMRR} = 20 \log_{10} \left( \frac{A_d}{A_c} \right) \text{ [dB]}$$

where:

- $A_d$  = differential gain
- $A_c$  = common-mode gain

### Ideal vs. Practical CMRR:

- Ideal op-amp: CMRR =  $\infty$  dB ( $A_c = 0$ )
- Practical op-amps: CMRR = 80-100 dB
- Higher CMRR = better noise rejection

### Operational Amplifier Connection

Differential amplifiers are the main building blocks of operational amplifiers. Op-amps have differential input configuration:

- Non-inverting input (+)
- Inverting input (-)
- Output proportional to difference between inputs

## Practical Example & Numerical

### Twisted Pair Signal Transmission

**Scenario:** Transmitting 200 Hz signal with 100 mV amplitude over long cable

#### Transmitted Signals:

- Wire 1: 200 Hz, 100 mV (original phase)
- Wire 2: 200 Hz, 100 mV (inverted phase)

#### Noise Induced During Transmission:

- 60 Hz hum from power lines: 50 mV on both wires (same phase)
- Electromagnetic interference: various frequencies on both wires

#### At Receiver (Differential Amplifier):

- Input 1: 200 Hz signal + 60 Hz noise + other noise
- Input 2: Inverted 200 Hz signal + 60 Hz noise + other noise (same noise)

#### Differential Amplifier Processing:

$$V_{out} = A_d[(V_{signal1} + V_{noise}) - (V_{signal2} + V_{noise})]$$

$$V_{out} = A_d(V_{signal1} - V_{signal2})$$

**Result:**

- Clean 200 Hz signal amplified by  $A_d$
- All common-mode noise (60 Hz hum, interference) canceled
- Output contains only the desired information

**Real-World Application:** This is exactly how Ethernet works. Digital data transmitted differentially over twisted pair cables with excellent noise immunity over long distances (up to 100 meters for standard Ethernet).

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- Differential amplifier:  $V_{out} = A_d(V_1 - V_2)$
- Amplifies difference between inputs, rejects common signals
- Common mode: both inputs same voltage and phase (noise)
- Differential mode: inputs differ (desired signal)
- CMRR =  $20 \log_{10}(A_d/A_c)$  measures noise rejection ability
- Ideal CMRR =  $\infty$  dB, practical = 80-100 dB
- Twisted pair transmission: signal and inverted signal on two wires
- Noise appears equally on both wires, gets canceled by differential amp
- Foundation of operational amplifiers

## Differential Amplifier - Part 2

### TL;DR (The Gist)

A practical differential amplifier circuit uses two transistors with shared emitter resistor. Common-mode gain should ideally be zero (achieved by replacing emitter resistor with current source), while differential gain should be high. The output is taken from one collector, and the circuit exhibits excellent noise rejection when properly designed.

## Detailed Explanation

### 2. Detailed Explanation

#### Circuit Configuration

The differential amplifier consists of:

- Two NPN transistors (Q1, Q2) with bases as inputs
- Output taken from Q2 collector
- Collector resistors ( $R_C$ ) on both transistors
- Shared emitter resistor ( $R_E$ ) or current source
- Dual supply ( $\pm V_{CC}$ ) for maximum swing

#### Two Operating Modes

##### 1. Common-Mode Operation

Both inputs receive the same signal (same voltage and phase). This represents noise that should be rejected.

For basic circuit with emitter resistor  $R_E$ :

- Both inputs rise together
- More current flows through both transistors
- More current through large  $R_E$  creates large voltage drop
- Output change is small due to negative feedback from  $R_E$

Common-mode gain (with intrinsic emitter resistance  $r_e$ ):

$$A_c = \frac{R_C}{2R_E + r_e}$$

For ideal case where  $r_e \approx 0$ :

$$A_c = \frac{R_C}{2R_E}$$

**Example:** With  $R_C = 1 \text{ k}\Omega$  and  $R_E = 75 \text{ k}\Omega$ :

- Output still fluctuates (not ideal)
- Input: 2 V peak-to-peak

- Output: 1 V peak-to-peak
- $A_c = 0.5$  (should be closer to 0)

## 2. Differential-Mode Operation

Inputs receive opposite signals (one rises while other falls).

When input 1 rises and input 2 falls by same amount:

- More voltage across left  $R_C \rightarrow$  more current through Q1
- Less voltage across right  $R_C \rightarrow$  less current through Q2
- Total current through  $R_E$  stays approximately constant
- Output voltage rises (Q2 collector has less voltage drop)

When input 1 falls and input 2 rises:

- Q2 turns on more
- Output voltage falls
- Large voltage swing at output

Differential gain:

$$A_d = \frac{R_C}{r_e}$$

This is much larger than  $A_c$  because  $r_e \ll R_E$ .

## Common-Mode Rejection Ratio Calculation

For circuit with emitter resistor:

$$\text{CMRR} = \frac{A_d}{A_c} = \frac{R_C/r_e}{R_C/2R_E} = \frac{2R_E}{r_e}$$

Assuming  $r_e \approx 0$  for simplified analysis:

$$\text{CMRR} \approx \frac{R_E}{1 \text{ k}\Omega} \text{ (ratio form)}$$

With  $R_E = 75 \text{ k}\Omega$ :

$$\text{CMRR} = \frac{75000}{1000} = 75$$

This is decent but not excellent. We can do better!

## Improved Design with Current Source

Replace the large emitter resistor  $R_E$  with a current source:

- Current source has very high impedance (ideally infinite)
- Current source sinks constant current (e.g., 1.9 mA)
- Much better common-mode rejection

## Current Source Design for Differential Amp:

Using PNP transistor Q3 with voltage divider:

- Voltage divider sets Q3 base voltage (e.g.,  $-12.4 \text{ V}$  with  $\pm 15 \text{ V}$  supply)
- Q3 emitter voltage:  $V_E = V_B + 0.6 = -13 \text{ V}$
- Voltage across Q3 emitter resistor:  $(-15) - (-13) = 2 \text{ V}$
- Q3 emitter resistor value for 1.9 mA:  $R_E = 2/0.0019 \approx 1 \text{ k}\Omega$
- Q3 collector current  $\approx$  emitter current = 1.9 mA (constant)

## Performance with Current Source:

- Common-mode signal: output voltage doesn't change at all!
- Differential-mode signal: high gain, clean amplification
- CMRR is dramatically improved (approaches ideal)

New CMRR formula:

$$\text{CMRR} = \frac{2R_{\text{current\_source}}}{r_e}$$

Since  $R_{\text{current\_source}} \gg R_E$  (ideally infinite), CMRR is much higher.

## Collector Resistor Selection

Choose  $R_C$  to place quiescent collector voltage at half supply:

- Provides maximum dynamic range
- Allows largest voltage swing (excursion)
- Example: With  $\pm 15 \text{ V}$  supply, set  $V_C \approx 0 \text{ V}$  (midpoint)

## Real-World Signal Example

### Practical Application:

- Input 1: 60 Hz noise only

- Input 2: 200 Hz signal (100 mV) + 60 Hz noise (same as input 1)
- Output: Clean 200 Hz signal with no 60 Hz noise
- Demonstrates perfect common-mode (noise) rejection

Using pulse signals instead of sine waves:

- Pulses more sensitive to noise and distortion
- Better test of circuit quality
- Output pulses should be clean and sharp
- Low CMRR would show distorted pulses

### Differential vs. Common-Mode Summary

#### Differential Mode:

- Input 1 rises, Input 2 falls (or vice versa)
- Total current through current source constant
- Q1 and Q2 currents balance
- Large output voltage swing
- High gain

#### Common Mode:

- Both inputs rise or fall together
- Current source resists current change
- Emitter voltages rise to match input changes
- Collector currents unchanged
- Output voltage constant (ideally)
- Gain  $\approx 0$  (ideally)

## Practical Example & Numerical

### Complete Differential Amplifier Design

#### Specifications:

- Supply:  $\pm 15$  V
- Desired tail current: 1.9 mA
- High CMRR for noise rejection

#### Design Steps:

##### 1. Current Source Design

- Use voltage divider to set Q3 base:  $V_B = -12.4$  V
- Q3 emitter voltage:  $V_E = -12.4 + 0.6 = -13$  V
- Voltage across emitter resistor: 2 V
- Emitter resistor:  $R_E = 2/0.0019 = 1.05$  k $\Omega$  (use 1 k $\Omega$ )
- Tail current: 1.9 mA constant

##### 2. Collector Resistor Selection

- Each transistor carries  $\approx 1.9/2 = 0.95$  mA (quiescent)
- For  $V_C \approx 0$  V:  $R_C = 15/0.00095 \approx 15.8$  k $\Omega$
- Use standard value 15 k $\Omega$  or 16 k $\Omega$

##### 3. Performance Verification

#### Common-mode test (both inputs = 1 V, 60 Hz):

- With emitter resistor (75 k $\Omega$ ): Output fluctuates,  $A_c \approx 0.5$
- With current source: Output rock solid,  $A_c \approx 0$

#### Differential-mode test (Input 1 = +0.1 V, Input 2 = -0.1 V):

- Large output swing
- High differential gain ( $A_d \approx 130$  in example)
- Clean, undistorted output

#### Mixed signal test (Input 1 = 60 Hz noise, Input 2 = 200 Hz signal + 60 Hz noise):

- Output: Clean 200 Hz only
- 60 Hz completely removed
- Signal amplified by  $\approx 130$

## Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

- Two transistors with shared emitter connection
- Common-mode: both inputs same  $\rightarrow$  output unchanged (ideal)
- Differential-mode: inputs opposite  $\rightarrow$  large output swing
- $A_c = R_C / (2R_E + r_e)$  (should be  $\approx 0$ )
- $A_d = R_C / r_e$  (should be large)
- $\text{CMRR} = 2R_E / r_e$  with resistor, much higher with current source
- Replace emitter resistor with current source for best CMRR
- Current source has high impedance, sinks constant current
- Set  $V_C$  at mid-supply for maximum output swing
- Pulse signals better for testing than sine waves
- Practical CMRR with current source: approaches ideal ( $\gg 100$ )

# Section 21 – Audio Amplifier Classes

## Decibel and Power Measurements

### Decibel

#### TL;DR (The Gist)

The decibel (dB) is a logarithmic unit used to compare signal amplitudes or power levels. For voltage/amplitude:  $\text{dB} = 20 \log_{10}(A_2/A_1)$ . For power:  $\text{dB} = 10 \log_{10}(P_2/P_1)$ . This logarithmic scale makes it easier to work with ratios as large as millions.

#### Detailed Explanation

### 2. Detailed Explanation

#### Why Use Decibels?

When comparing amplitudes of two signals, you could say "Signal A is twice as large as Signal B," which is fine for small ratios. However, in electronics and audio, we often deal with ratios as large as millions. A logarithmic measure makes these comparisons more manageable and intuitive.

#### Decibel Definitions

##### For Power Ratios:

$$\text{dB} = 10 \log_{10} \left( \frac{P_2}{P_1} \right)$$

where  $P_1$  and  $P_2$  represent the power in two signals.

##### For Voltage/Amplitude Ratios:

$$\text{dB} = 20 \log_{10} \left( \frac{A_2}{A_1} \right)$$

where  $A_1$  and  $A_2$  are the two signal amplitudes.

#### Common Decibel Values

- **Double amplitude:**  $20 \log_{10}(2) = 20 \times 0.3 = 6 \text{ dB}$
- **10× amplitude:**  $20 \log_{10}(10) = 20 \times 1 = 20 \text{ dB}$
- **Half amplitude:**  $20 \log_{10}(0.5) = 20 \times (-0.3) = -6 \text{ dB}$
- **1000× amplitude:**  $20 \log_{10}(1000) = 60 \text{ dB}$

#### Why Factor of 20 vs. 10?

Power is proportional to voltage squared:  $P \propto V^2$ . When converting voltage ratios to power ratios:

$$\frac{P_2}{P_1} = \frac{V_2^2}{V_1^2} = \left( \frac{V_2}{V_1} \right)^2$$

Applying logarithm:

$$10 \log_{10} \left( \frac{P_2}{P_1} \right) = 10 \log_{10} \left[ \left( \frac{V_2}{V_1} \right)^2 \right] = 20 \log_{10} \left( \frac{V_2}{V_1} \right)$$

Hence, the factor of 20 for voltage/amplitude ratios.

#### Decibel in Audio Engineering

In audio systems, gain is commonly expressed in decibels rather than linear ratios:

- Easier to work with cascade gains (add dB instead of multiply ratios)
- More intuitive for large dynamic ranges
- Industry standard for specifications

#### Sound Pressure Levels

Decibels also measure sound loudness (SPL - Sound Pressure Level):

- 0 dB: Threshold of hearing (complete silence)
- 30 dB: Whisper
- 60 dB: Normal conversation
- 90 dB: Lawn mower
- 120 dB: Rock concert, threshold of pain
- 140 dB: Jet engine at close range

Microphone Preamplifier Calculation

Given:

- Microphone output: 1 mV
- Preamplifier gain: 60 dB
- Find output voltage

Solution:

From decibel table, 60 dB corresponds to linear ratio of 1000.

$$\text{Gain} = 10^{60/20} = 10^3 = 1000$$

Output voltage:

$$V_{out} = V_{in} \times \text{Gain} = 1 \text{ mV} \times 1000 = 1000 \text{ mV} = 1 \text{ V}$$

Verification:

$$\text{dB} = 20 \log_{10} \left( \frac{1000 \text{ mV}}{1 \text{ mV}} \right) = 20 \log_{10}(1000) = 20 \times 3 = 60 \text{ dB}$$

✓

Practical Insight:

Instead of saying "the output voltage is 1000 times greater than the input," we simply say "the amplifier has 60 dB gain." This is more concise and standard in audio engineering.

Cascaded Gains:

If two amplifiers are cascaded, each with 20 dB gain:

- Linear: Total gain =  $10 \times 10 = 100$
- Decibel: Total gain =  $20 + 20 = 40 \text{ dB}$

Adding decibels is simpler than multiplying ratios!

Key Points (Interview Focus)

4. Key Points (Interview Focus)

- Decibel: logarithmic unit for comparing signal levels
- Power ratio:  $\text{dB} = 10 \log_{10}(P_2/P_1)$
- Voltage ratio:  $\text{dB} = 20 \log_{10}(V_2/V_1)$
- 6 dB = double amplitude, 20 dB = 10× amplitude
- 60 dB = 1000× amplitude (common preamp gain)
- Cascaded gains: add dB values instead of multiplying ratios
- 0 dB SPL = threshold of hearing (silence)
- Logarithmic scale better for large dynamic ranges

Power Amplifier Fundamentals

Power Amplifier Classes - Introduction

TL;DR (The Gist)

Preamplifiers provide voltage gain with small current gain for signal processing, while power amplifiers provide high current gain to drive speakers. Power amplifier classes (A, B, AB, C, D) differ in topology, efficiency, and distortion characteristics. Efficiency = (useful power output / total power input) × 100%.

Detailed Explanation

## 2. Detailed Explanation

### Preamplifier vs. Power Amplifier

#### Preamplifier:

- Shapes and conditions the signal
- Provides significant voltage gain, small current gain
- Controls: gain, bass, mid, treble, volume, etc.
- Boosts weak signals to line level
- Good for recording and signal processing
- Low power consumption, minimal heat generation

#### Power Amplifier:

- Receives signal from preamplifier
- Outputs much larger version with high voltage and current
- Drives speakers (transducers converting electrical → sound)
- Must amplify current enough to power loudspeakers
- High power consumption, generates significant heat
- Requires heat management (heatsinks, cooling)

#### Why Separate Stages?

Preamplifiers are kept separate from power amplifiers to:

- Avoid noise from large power transistors
- Keep sensitive low-level circuitry away from high-power stages
- Prevent heat from power stage affecting preamp performance
- Allow modular design (swap components independently)

#### System Examples

##### Guitar Amplifier:

- Input: Guitar pickup signal
- Preamplifier: Shapes tone, controls gain/EQ
- Power amplifier: Drives speaker
- Combo amplifier: All stages in one cabinet

##### Audio Amplifier:

- Input: Microphone (very weak signal)
- Preamplifier: Boosts to line level
- Mixer/Processor: Combines with other signals
- Power amplifier: Drives loudspeakers

#### Amplifier Efficiency

Efficiency is the ratio of useful power delivered to the load versus total power consumed:

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

where:

- $P_{out}$  = useful power to speaker
- $P_{in}$  = total electrical power from supply
- Difference ( $P_{in} - P_{out}$ ) = wasted as heat

#### Example:

- 50% efficient amplifier delivering 50 W: draws 100 W (50 W wasted as heat)
- 80% efficient amplifier delivering 50 W: draws 62.5 W (12.5 W wasted)

#### Efficiency vs. Distortion Trade-off

- **Class A:** Most linear (least distortion), lowest efficiency ( $\approx 25\text{-}30\%$ )
- **Class B:** Better efficiency ( $\approx 60\text{-}70\%$ ), more distortion (crossover)
- **Class AB:** Compromise between A and B
- **Class D:** Highest efficiency ( $\approx 90\%$ ), switching design

#### Conduction Angle

The conduction angle describes how much of the input cycle the amplifying device conducts:

- **360°:** Device always on (Class A)
- **180°:** Device on for half cycle (Class B)
- **< 180°:** Device on for less than half (Class C)

Conduction angle is closely related to efficiency. Longer conduction means more power dissipation but better linearity.

### Amplifier Efficiency Comparison

**Scenario:** Need to deliver 100 W to speaker

#### Class A Amplifier (30% efficiency):

- Power from supply:  $P_{in} = 100/0.30 = 333 \text{ W}$
- Power wasted as heat:  $333 - 100 = 233 \text{ W}$
- Requires large heatsink
- Always drawing 333 W even with no signal!

#### Class AB Amplifier (60% efficiency):

- Power from supply:  $P_{in} = 100/0.60 = 167 \text{ W}$
- Power wasted as heat:  $167 - 100 = 67 \text{ W}$
- Moderate heatsink required
- More practical for medium power

#### Class D Amplifier (90% efficiency):

- Power from supply:  $P_{in} = 100/0.90 = 111 \text{ W}$
- Power wasted as heat:  $111 - 100 = 11 \text{ W}$
- Small heatsink or passive cooling
- Ideal for portable devices, subwoofers

#### Heat Dissipation Impact:

For continuous 100 W output:

- Class A: 233 W heat (like a space heater!)
- Class AB: 67 W heat (manageable)
- Class D: 11 W heat (minimal cooling needed)

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

- Preamp: voltage gain, signal shaping, low power
- Power amp: current gain, drives speakers, high power
- Separate stages prevent noise from power transistors affecting preamp
- Efficiency = (useful power / total power)  $\times 100\%$
- Class A: 25-30% efficiency, best linearity
- Class D:  $\approx 90\%$  efficiency, switching design
- Higher efficiency = less heat, smaller heatsinks
- Conduction angle:  $360^\circ$  (Class A),  $180^\circ$  (Class B),  $<180^\circ$  (Class C)

## Amplifier Class Theory

### Class A, B, AB, C, D - Theory

#### TL;DR (The Gist)

Class A: single device,  $360^\circ$  conduction, high linearity, 25-30% efficiency. Class B: two devices,  $180^\circ$  each, crossover distortion, 60% efficiency. Class AB: hybrid, slight bias to eliminate crossover, 50-60% efficiency. Class C:  $<180^\circ$ , RF applications, 60-80% efficiency. Class D: switching (PWM), 90% efficiency, minimal distortion with proper design.

### Detailed Explanation

#### 2. Detailed Explanation

##### Class A Amplifier

The Class A amplifier is essentially a common-emitter configuration we've studied before.

##### Characteristics:

- **Conduction angle:**  $360^\circ$  (always on)
- **Active elements:** Single transistor
- **Bias:** Constant, keeps transistor in active region

- **Linearity:** Excellent (minimal distortion)
- **Efficiency:** 25-30% (theoretical max 50% with inductive coupling)

#### Advantages:

- High linearity and low distortion
- Simple design (single device, minimal parts)
- Excellent high-frequency response
- Good feedback loop stability

#### Disadvantages:

- Very poor efficiency (wastes 70-75% as heat)
- High power loss even with no signal
- Requires large heatsinks
- Only suitable for low-power applications
- Continuous conduction → high heat generation

#### Class B Amplifier (Push-Pull)

Uses two complementary transistors (NPN and PNP), each conducting for half the cycle.

#### Characteristics:

- **Conduction angle:** 180° per device
- **Active elements:** Two transistors (complementary pair)
- **Bias:** Provided by input signal (no quiescent current)
- **Efficiency:** 60-70% (theoretical max 78.5%)

#### How It Works:

- NPN conducts positive half-cycle (input > 0.6 V)
- PNP conducts negative half-cycle (input < -0.6 V)
- Each transistor "pushes" or "pulls" current through load
- Combined output reconstructs full waveform

#### Advantages:

- Much better efficiency than Class A (60%+ vs. 25-30%)
- Minimal heat dissipation (smaller heatsinks)
- No quiescent current (zero power with no signal)
- Good for medium to high power applications

#### Disadvantages:

- **Crossover distortion:** Major problem!
- Mismatch where two halves join (dead zone near zero crossing)
- During 0 to 0.6 V transition, neither transistor conducts
- Output "glitches" when crossing ground
- Unacceptable for precision audio applications

#### Class AB Amplifier

Combination of Class A and Class B to eliminate crossover distortion while maintaining reasonable efficiency.

#### Characteristics:

- **Conduction angle:** > 180° per device (slight overlap)
- **Active elements:** Two transistors with bias network
- **Bias:** Small quiescent current keeps both slightly on
- **Efficiency:** 50-60% (compromise between A and B)

#### How It Works:

- Both transistors pre-biased to stay slightly in conduction
- Eliminates dead zone at crossover
- Each device conducts slightly into other's half-cycle
- Crossover distortion dramatically reduced

#### Bias Methods:

- **Diode bias:** Two diodes create  $\approx 1.4$  V between bases
- **Resistor network:** Voltage divider sets base voltages
- **Adjustable:** Potentiometer allows fine-tuning

#### Thermal Stability:

Diodes must be mounted on same heatsink as transistors:

- Transistor temp coefficient: positive ( $V_{BE}$  decreases with heat → more current)
- Diode temp coefficient: negative ( $V_f$  decreases with heat → less bias voltage)
- Compensation: diode heating reduces bias, counteracting transistor heating
- Prevents thermal runaway

**Trade-offs:**

- Lower quiescent current → higher efficiency, more distortion
- Higher quiescent current → lower efficiency, less distortion
- Typical: 1.4 V bias (both transistors barely on)

**Class C Amplifier**

Uses conduction angle  $< 180^\circ$  for RF applications.

**Characteristics:**

- **Conduction angle:**  $< 180^\circ$
- **Efficiency:** 60-80% (tuned mode)
- **Linearity:** Poor (untuned mode has huge distortion)
- **Applications:** RF oscillators, modulators, transmitters

**Why It Works:**

Output is highly nonlinear, but with tuned LC circuit at output:

- LC tank resonates at desired frequency
- Filters out harmonics and distortion
- Produces clean sinusoidal output at resonant frequency

**Not suitable for:**

- Audio amplification (too much distortion)
- Complex waveforms (only works with simple sinusoids)
- Linear amplification applications

**Class D Amplifier (Switching)**

Uses pulse-width modulation (PWM) instead of linear amplification.

**Characteristics:**

- **Topology:** Switching design (not analog)
- **Efficiency:** 90-95% (highest of all classes)
- **Devices:** MOSFETs (low on-resistance)
- **Modulation:** PWM encoding of audio signal

**How It Works:**

1. **Input encoding:** Analog signal compared with high-frequency triangle wave → PWM pulses
2. **Amplification:** PWM signal drives switching MOSFETs at high power
3. **Output filtering:** Low-pass filter reconstructs amplified analog signal

**PWM Principle:**

- Positive peak: 100% duty cycle (always on)
- Negative peak: 0% duty cycle (always off)
- Zero crossing: 50% duty cycle
- Triangle frequency  $\gg$  audio frequency (e.g., 200-500 kHz)

**Advantages:**

- Extremely high efficiency (90-95%)
- Minimal heat generation (small/no heatsink)
- No thermal runaway issues
- Compact design
- Ideal for portable devices, subwoofers

**Disadvantages:**

- High-frequency noise emission (requires shielding)
- Switching feed-through to output
- Difficulty achieving excellent linearity
- More complex than analog designs
- Requires proper dead-time management (prevent shoot-through)

**Applications:**

- Consumer audio (nearly universal now)
- Portable devices (battery-powered)
- High-power applications (PA systems, subwoofers)
- Increasingly used in high-end audio

## Practical Example & Numerical

## Class Comparison for 50 W Audio Amplifier

### Class A:

- Efficiency: 30%
- Input power: 167 W
- Heat dissipated: 117 W (continuously!)
- Heatsink: Very large
- Distortion:  $< 0.01\%$  (excellent)
- Best for: Audiophile applications, low power

### Class B:

- Efficiency: 65%
- Input power: 77 W
- Heat dissipated: 27 W
- Heatsink: Medium
- Distortion: 1-5% (crossover distortion)
- Best for: Not recommended (distortion issue)

### Class AB:

- Efficiency: 55%
- Input power: 91 W
- Heat dissipated: 41 W
- Heatsink: Medium
- Distortion:  $< 0.1\%$  (good)
- Best for: General audio, PA systems

### Class D:

- Efficiency: 90%
- Input power: 56 W
- Heat dissipated: 6 W
- Heatsink: Small or none
- Distortion:  $< 0.05\%$  (with good design)
- Best for: Portable, high-power, modern audio

### Selection Criteria:

- Ultimate sound quality: Class A
- General purpose: Class AB
- High power/efficiency: Class D
- RF transmitters: Class C

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- Class A: 360° conduction, 25-30% efficiency, best linearity
- Class B: 180° per device, 60-70% efficiency, crossover distortion
- Class AB:  $>180^\circ$  per device, 50-60% efficiency, eliminates crossover
- Class C:  $<180^\circ$ , RF only, 60-80% efficiency with tuned circuits
- Class D: PWM switching, 90-95% efficiency, minimal heat
- Thermal compensation: diodes on same heatsink as transistors
- Efficiency vs. distortion: fundamental trade-off
- Modern trend: Class D dominates consumer audio

## Practical Amplifier Simulations

### Simulation - Class A and Introduction to Class B

#### TL;DR (The Gist)

Class A common-emitter amplifier provides voltage gain ( $A_v = R_C/R_E$ ) but wastes power continuously with quiescent current flowing even without input signal. Efficiency  $< 30\%$  due to constant power dissipation. Maximum output swing achieved by biasing collector at mid-supply voltage.

## Detailed Explanation

### 2. Detailed Explanation

#### Class A Common-Emitter Amplifier Operation

##### Circuit Configuration:

- Input signal AC-coupled to base
- Voltage divider biases transistor in active region
- Collector resistor  $R_C$  sets voltage swing capability
- Emitter resistor  $R_E$  sets voltage gain
- Output from collector (voltage amplification)

##### Voltage Gain:

$$A_v = \frac{R_C}{R_E}$$

Example:  $R_C = 10\text{ k}\Omega$ ,  $R_E = 1\text{ k}\Omega \rightarrow A_v = 10$

##### Why Class A is Inefficient

The fundamental problem: transistor conducts continuously ( $360^\circ$ ), consuming power even with no input signal.

##### Quiescent Operating Point:

Setting collector voltage at mid-supply (e.g., 10 V with 20 V supply):

- Allows maximum voltage swing: 0 to 20 V
- Base voltage:  $\approx 1.6\text{ V}$  (from voltage divider)
- Emitter voltage:  $V_E = V_B - 0.6 = 1.0\text{ V}$
- Emitter current:  $I_E = V_E/R_E = 1.0/1000 = 1\text{ mA}$
- Collector current:  $I_C \approx I_E = 1\text{ mA}$
- Collector voltage:  $V_C = V_{CC} - I_C R_C = 20 - 10 = 10\text{ V}$

##### Power Dissipation (No Signal):

$$P_{\text{dissipated}} = V_{CE} \times I_C = 10\text{ V} \times 1\text{ mA} = 10\text{ mW}$$

This power is wasted as heat continuously, even when no music is playing!

##### Transistor as Switch vs. Amplifier

##### Saturation mode (switch ON):

- $V_{CE} \approx 0\text{ V}$  (minimum)
- $I_C = \text{maximum}$  (limited by resistors)
- Power dissipation:  $P = 0 \times I_{\text{max}} \approx 0$  (low)
- $I_C$  calculated by Ohm's Law, not  $\beta I_B$

##### Cutoff mode (switch OFF):

- $V_{CE} \approx V_{CC}$  (maximum)
- $I_C \approx 0$  (near zero)
- Power dissipation:  $P = V_{CC} \times 0 \approx 0$  (low)

##### Active mode (amplifier):

- $V_{CE}$  moderate (e.g., 10 V)
- $I_C$  moderate (e.g., 1 mA)
- Power dissipation:  $P = 10 \times 1 = 10\text{ mW}$  (high!)
- This is why amplifiers get hot while switches don't

##### Maximum Voltage Swing

For undistorted output, collector must swing between 0 V and  $V_{CC}$ :

- Too high quiescent  $V_C \rightarrow$  clipping at top
- Too low quiescent  $V_C \rightarrow$  clipping at bottom
- Optimal:  $V_C = V_{CC}/2$  (mid-supply)

##### Why Collector Resistor is Necessary

Without  $R_C$ :

- Collector voltage stays at  $V_{CC}$  (can't swing down)
- No voltage amplification possible

- Output is DC only

With  $R_C$ :

- When  $I_C$  increases  $\rightarrow$  voltage drop across  $R_C$  increases  $\rightarrow V_C$  decreases
- When  $I_C$  decreases  $\rightarrow$  voltage drop across  $R_C$  decreases  $\rightarrow V_C$  increases
- Output can swing from 0 to  $V_{CC}$

## Practical Example & Numerical

### Class A Amplifier Design and Analysis

#### Specifications:

- Supply voltage: 20 V
- Desired gain: 10
- Maximum collector current: 2 mA
- Input signal: 500 mV peak-to-peak

#### Component Selection:

1. **Collector resistor:**  $R_C = V_{CC}/I_{C,max} = 20/0.002 = 10 \text{ k}\Omega$
2. **Emitter resistor:**  $R_E = R_C/A_v = 10000/10 = 1 \text{ k}\Omega$
3. **Bias resistors:** Design for  $V_B = 1.6 \text{ V}$ 
  - Top resistor: 110 k $\Omega$
  - Bottom resistor: 10 k $\Omega$

#### Operating Point Verification:

$$V_B = 20 \times \frac{10}{110 + 10} = 1.67 \text{ V}$$

$$V_E = V_B - 0.6 = 1.07 \text{ V}$$

$$I_E = \frac{V_E}{R_E} = \frac{1.07}{1000} = 1.07 \text{ mA}$$

$$V_C = V_{CC} - I_C R_C = 20 - 1.07 \times 10 = 9.3 \text{ V}$$

(close to mid-supply ✓)

#### Performance:

- Input: 500 mV p-p
- Output:  $\approx 4.8 \text{ V}$  p-p (gain  $\approx 9.6$ , close to 10 ✓)
- Output centered at 9.3 V DC
- Can swing from  $\approx 2 \text{ V}$  to  $\approx 18 \text{ V}$  before clipping

#### Power Efficiency:

Quiescent power:  $P_Q = V_{CE} \times I_C = 10.7 \times 0.00107 = 11.4 \text{ mW}$

With signal, output power:  $P_{out} = V_{rms}^2/R_L$  (depends on load)

Efficiency typically  $< 30\%$  for Class A configuration.

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- Class A = common-emitter amplifier with continuous conduction
- Voltage gain:  $A_v = R_C/R_E$  (simplified formula)
- Quiescent point: bias collector at mid-supply for maximum swing
- Constant power dissipation even with no signal (inefficient!)
- Switching mode: low power (saturation:  $V_{CE} \approx 0$ , cutoff:  $I_C \approx 0$ )
- Active mode: moderate  $V_{CE}$  and  $I_C \rightarrow$  high power dissipation
- Collector resistor enables voltage swing (essential for amplification)
- Efficiency  $< 30\%$  due to continuous quiescent current

## Simulation - Class B and AB

## TL;DR (The Gist)

Class B push-pull uses complementary NPN/PNP transistors, each conducting one half-cycle. Crossover distortion occurs in dead zone ( $\pm 0.6$  V). Class AB pre-biases both transistors with  $\approx 1.4$  V between bases to eliminate crossover, trading some efficiency for much lower distortion. Thermal compensation prevents runaway.

## Detailed Explanation

### 2. Detailed Explanation

#### Class B Push-Pull Operation

##### Circuit Configuration:

- NPN transistor for positive half-cycle
- PNP transistor for negative half-cycle
- Emitters connected together to load
- Bases connected together to input signal
- Load referenced to ground (speaker)

##### How Each Transistor Conducts

##### Positive half-cycle (input $> 0.6$ V):

- NPN base-emitter forward biased  $\rightarrow$  NPN conducts
- PNP base-emitter reverse biased  $\rightarrow$  PNP off
- NPN "pushes" current through load
- Output follows input minus 0.6 V drop

##### Negative half-cycle (input $< -0.6$ V):

- NPN base-emitter reverse biased  $\rightarrow$  NPN off
- PNP base-emitter forward biased ( $V_E > V_B$  by 0.6 V)  $\rightarrow$  PNP conducts
- PNP "pulls" current through load
- Output follows input plus 0.6 V drop

##### Dead Zone ( $-0.6$ V $<$ input $<$ 0.6 V):

- Neither transistor conducts
- Output stuck at 0 V
- Creates "glitches" at zero crossing
- This is crossover distortion!

##### Why Class B is Efficient

With no input signal:

- Both transistors in cutoff
- No quiescent current flows
- Zero power dissipation (ideal)
- Huge improvement over Class A

With signal:

- Each transistor only conducts half the time
- Average power dissipation much lower
- Efficiency can exceed 60%

##### Current Amplification

Even though no voltage gain (emitter follower):

- Output current =  $\beta \times$  base current
- Typical  $\beta = 100 \rightarrow 100\times$  current gain
- Essential for driving low-impedance speakers

##### Class AB Solution to Crossover Distortion

##### Bias Network Design:

Insert voltage source ( $\approx 1.4$  V) between bases:

- Two diodes in series (most common)
- Two resistors with voltage divider
- Adjustable potentiometer for fine-tuning

##### How 1.4 V Bias Works:

With emitters at 0 V (through load):

- NPN base:  $+0.7$  V  $\rightarrow V_{BE} = 0.7$  V  $\rightarrow$  barely conducts
- PNP base:  $-0.7$  V  $\rightarrow V_{EB} = 0.7$  V  $\rightarrow$  barely conducts
- Both transistors slightly on simultaneously
- No dead zone at crossover!

**Quiescent Current Trade-off:**

Lower bias voltage (e.g., 1.0 V):

- Less quiescent current
- Higher efficiency
- More crossover distortion

Higher bias voltage (e.g., 2.0 V):

- More quiescent current
- Lower efficiency
- Less crossover distortion

Typical: 1.4 V (two diode drops) provides good compromise.

**Thermal Compensation with Diodes****The Problem: Thermal Runaway**

As transistors heat up:

- $V_{BE}$  decreases (negative temp coefficient)
- For same base voltage, more current flows
- More current  $\rightarrow$  more heat  $\rightarrow$  even more current
- Positive feedback  $\rightarrow$  thermal runaway  $\rightarrow$  destruction!

**The Solution: Matched Diode Bias**

Mount bias diodes on same heatsink as transistors:

- Diodes heat up with transistors
- Diode forward voltage decreases with temperature
- Lower  $V_f \rightarrow$  less bias voltage between bases
- Less bias  $\rightarrow$  less current  $\rightarrow$  compensates for transistor heating

**Temperature Coefficient Matching:**

- Transistor:  $V_{BE}$  decreases  $\approx -2 \text{ mV}/^\circ\text{C}$
- Diode:  $V_f$  decreases  $\approx -2 \text{ mV}/^\circ\text{C}$
- Two diodes: total  $-4 \text{ mV}/^\circ\text{C}$  (for two transistors)
- Perfect compensation when thermally coupled

**Practical Implementation:**

In integrated circuits (e.g., LM386 audio amplifier):

- Diodes and transistors on same silicon die
- Perfect thermal tracking
- Identical temperature curves
- Excellent stability over temperature

**Resistor Network Alternative**

Voltage divider from  $+V$  to  $-V$  with potentiometer:

- More adjustable than diodes
- Can tune for non-matched transistors
- Allows compensation for component variations
- No need for exact transistor matching

Disadvantage: No inherent thermal compensation (requires separate thermistor or diodes).

## Practical Example & Numerical

**Class B vs. Class AB Comparison****Class B Push-Pull (No Bias):**

Input: 5 V peak-to-peak sine wave

Output characteristics:

- Positive half: follows input minus 0.6 V
- Negative half: follows input plus 0.6 V
- Dead zone: -0.6 V to +0.6 V (1.2 V total)
- Visible "glitches" at zero crossings
- Distortion: 1-5% THD

Quiescent current: 0 mA (excellent efficiency)

**Class AB with Diode Bias:**

Same 5 V p-p input, with two diodes creating 1.4 V bias

Output characteristics:

- Smooth transition through zero
- No visible glitches
- Clean waveform reproduction
- Distortion:  $< 0.1\%$  THD

Quiescent current:  $\approx 2 \text{ mA}$  (small power dissipation)

Power dissipation:  $P_Q = V_{CE} \times I_Q = 10 \times 0.002 = 20 \text{ mW}$

Much better than Class A (which might dissipate 35 W!), but small penalty compared to pure Class B.

#### **Loudspeaker Example:**

8  $\Omega$  speaker, 2 W RMS rating:

Class A emitter follower:

- Can deliver 2 W to speaker ✓
- Quiescent dissipation: 35 W (!)
- Requires large heatsink
- Very inefficient

Class AB push-pull:

- Can deliver 2 W to speaker ✓
- Quiescent dissipation:  $\approx 2 \text{ W}$
- Moderate heatsink
- Much more practical

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

- Class B: NPN conducts positive, PNP conducts negative
- Crossover distortion in dead zone ( $\pm 0.6 \text{ V}$ )
- Zero quiescent current  $\rightarrow$  excellent efficiency (60%+)
- Class AB: 1.4 V bias keeps both transistors slightly on
- Eliminates crossover distortion at cost of small quiescent current
- Thermal compensation: diodes on same heatsink as transistors
- Diode  $V_f$  temperature coefficient matches transistor  $V_{BE}$
- Prevents thermal runaway (critical for reliability)
- Efficiency trade-off: lower bias = higher efficiency, more distortion

### Simulation - Class D

#### TL;DR (The Gist)

Class D uses PWM (pulse-width modulation) to encode analog signal as digital pulses. High-frequency switching MOSFETs amplify PWM signal with 90%+ efficiency. Low-pass filter (Butterworth) reconstructs analog output. Dead-time between switch transitions prevents shoot-through current. Requires comparator, MOSFET driver, and careful design for minimal distortion.

### Detailed Explanation

#### 2. Detailed Explanation

##### **Class D Operating Principle**

Instead of linear amplification, Class D uses switching:

- Transistors either fully ON or fully OFF (not in active region)
- ON state:  $V_{DS} \approx 0$ , high current  $\rightarrow$  power  $\approx 0$
- OFF state:  $V_{DS}$  high,  $I_D \approx 0 \rightarrow$  power  $\approx 0$
- Minimal power dissipation  $\rightarrow$  90-95% efficiency!

##### **PWM Encoding Process**

##### **Step 1: Generate Triangle Wave**

High-frequency triangle (carrier):

- Frequency: 200-500 kHz (10 $\times$  higher than 20 kHz audio limit)

- Amplitude: matches audio signal range
- Fixed frequency and amplitude

## Step 2: Compare with Audio Signal

Comparator (op-amp without feedback):

- (+) input: audio signal (low frequency)
- (-) input: triangle wave (high frequency)
- Output: digital (rail-to-rail)

### Comparator behavior:

- When audio > triangle: output HIGH
- When audio < triangle: output LOW
- Result: PWM pulses with duty cycle proportional to audio amplitude

### PWM Duty Cycle Encoding:

- Audio at positive peak: duty cycle  $\approx 100\%$  (always HIGH)
- Audio at zero: duty cycle = 50% (equal HIGH/LOW)
- Audio at negative peak: duty cycle  $\approx 0\%$  (always LOW)

## Step 3: Power Amplification

MOSFET switching stage:

- High-side MOSFET: connects load to  $+V_{supply}$
- Low-side MOSFET: connects load to ground
- PWM signal controls switching
- Both MOSFETs never on simultaneously (shoot-through prevention)

### Dead-Time Management

#### The Problem: Shoot-Through

MOSFETs don't switch instantaneously:

- Rise/fall times: 10-100 ns
- During transition, both MOSFETs briefly ON
- Creates low-impedance path:  $+V \rightarrow$  ground
- High current pulse  $\rightarrow$  MOSFET damage

#### The Solution: Dead-Time Insertion

Specialized MOSFET driver IC (e.g., IR2110):

- Adds delay between HIGH-side and LOW-side switching
- Dead-time: 50-200 ns (adjustable)
- Ensures one MOSFET fully off before other turns on
- Prevents shoot-through current

## Step 4: Output Filtering

Low-pass filter reconstructs analog signal:

- Removes high-frequency carrier (hundreds of kHz)
- Passes audio frequencies (20 Hz - 20 kHz)
- Extracts average voltage (which equals original audio!)

### Butterworth Filter

Preferred for audio applications:

- Maximally flat passband (no ripple in audio frequencies)
- Smooth frequency response
- Minimal signal attenuation in passband
- Sharp transition to stopband (rejects carrier)

Typical design:

- 2nd or 3rd order Butterworth
- Cutoff frequency: 30-50 kHz (above audio, below carrier)
- Inductor and capacitor values calculated for 8  $\Omega$  load

### Why MOSFETs Instead of BJTs?

#### MOSFET advantages for switching:

- Lower on-resistance ( $R_{DS(on)}$ ): 10-50 m $\Omega$  vs. 100+ m $\Omega$
- Faster switching: 10-50 ns vs. 100-500 ns
- Voltage-controlled (no base current waste)
- Better efficiency at high frequencies
- No storage time delay (BJT problem)

### High-Side Driver Challenge

Low-side MOSFET: easy to drive (source at ground)

High-side MOSFET: difficult (source floats at output voltage)

- Gate must be 10-15 V above source to turn on
- Source voltage varies with output
- Need bootstrap circuit or isolated supply

**Solution:** Integrated MOSFET driver IC

- Bootstrap capacitor creates floating supply
- Provides adequate gate drive for high-side
- Handles level-shifting automatically

#### Advantages of Class D

- Efficiency: 90-95% (vs. 25-30% for Class A)
- Heat: minimal (small/no heatsink)
- Size: compact (no large heatsink)
- Battery life: excellent for portable devices
- Power density: high power in small package

#### Disadvantages and Challenges

- EMI/RFI: high-frequency switching generates noise
- Requires shielding and filtering
- Switching artifacts can appear in output
- More complex than analog designs
- Requires specialized ICs (comparator, driver, MOSFETs)
- PCB layout critical (noise coupling, ground loops)

#### Modern Implementations

Today's Class D amplifiers often use:

- Delta-sigma modulation (alternative to PWM)
- Self-oscillating topology (no external triangle)
- Integrated Class D amplifier ICs (all-in-one solution)
- Digital input (no need for analog comparator)

## Practical Example & Numerical

### Class D Amplifier Design

#### Specifications:

- Audio input: 20 Hz - 20 kHz
- Output power: 50 W into 8  $\Omega$
- Supply:  $\pm 15$  V
- Switching frequency: 250 kHz

#### PWM Stage:

Triangle wave generator: 250 kHz,  $\pm 5$  V amplitude

Comparator (op-amp):

- Audio signal at (+) input
- Triangle at (-) input
- Output: PWM at 250 kHz, duty cycle 0-100%

#### Power Stage:

MOSFET selection:

- Voltage rating:  $> 30$  V ( $2\times$  supply for safety)
- Current rating:  $> 5$  A (peak current calculation)
- $R_{DS(on)}$ :  $< 50$  m $\Omega$  (low conduction loss)
- Switching speed:  $< 50$  ns (for 250 kHz operation)

Dead-time: 100 ns (prevents 5 A shoot-through current)

#### Output Filter (2nd-order Butterworth):

Cutoff frequency: 40 kHz (between audio and carrier)

For 8  $\Omega$  load:

- Inductor:  $L = 50$   $\mu$ H
- Capacitor:  $C = 10$   $\mu$ F
- Response: -3 dB at 40 kHz, -40 dB/decade rolloff

#### Performance:

Efficiency calculation:

- Output power: 50 W

- MOSFET losses:  $I_{rms}^2 \times R_{DS(on)} = 2.5^2 \times 0.05 = 0.31 \text{ W}$
- Switching losses:  $\approx 2 \text{ W}$  (estimated)
- Total input:  $52.3 \text{ W}$
- Efficiency:  $50/52.3 = 95.6\%$  ✓

Heat dissipation: Only  $2.3 \text{ W}$  (vs.  $116 \text{ W}$  for Class A!)

THD:  $< 0.1\%$  with proper design and filtering

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- Class D: switching amplifier using PWM encoding
- PWM: compare audio with high-frequency triangle wave
- Duty cycle encodes audio amplitude ( $50\% = \text{zero}$ ,  $100\% = \text{peak}$ )
- MOSFETs switch at hundreds of kHz (fully ON/OFF, not linear)
- Dead-time prevents shoot-through current (both MOSFETs ON)
- Low-pass filter (Butterworth) reconstructs analog from PWM
- Efficiency:  $90\text{-}95\%$  (minimal heat, small/no heatsink)
- MOSFETs preferred: low  $R_{DS(on)}$ , fast switching, voltage-controlled
- High-side driver requires bootstrap or isolated supply
- Dominant topology in modern audio (consumer, professional, portable)

# Section 22 – Other Circuits Using BJT

## Multivibrator Circuits

### Astable Multivibrator

#### TL;DR (The Gist)

An astable multivibrator is a free-running oscillator that continuously switches between two states without external trigger, generating a square wave output. Two transistors alternately switch between saturation and cutoff, with timing controlled by RC networks. Output frequency determined by resistor-capacitor time constants.

#### Detailed Explanation

### 2. Detailed Explanation

#### What is a Multivibrator?

Multivibrators are circuits used to implement two-state devices such as:

- Relaxation oscillators
- Timers
- Flip-flops

The two states refer to two voltage levels (e.g., 0 V and 5 V), often represented as logic HIGH and logic LOW.

#### Classification:

- **Astable:** No stable state, oscillates continuously
- **Monostable:** One stable state, temporarily switches when triggered
- **Bistable:** Two stable states, requires trigger to switch between them

#### Astable Multivibrator Operation

##### Circuit consists of:

- Two NPN transistors (Q1, Q2)
- Two coupling capacitors (C1, C2)
- Collector resistors and timing resistors
- Power supply ( $V_{CC}$ )

##### Operating Principle:

The circuit oscillates because the two transistors alternately switch between saturation (fully ON) and cutoff (fully OFF).

##### Starting Condition (power-on):

Initially, both transistors may briefly conduct, but due to slight component asymmetries, one will turn off first. Let's assume Q1 saturates and Q2 cuts off.

##### State 1: Q1 ON, Q2 OFF

- Q1 in saturation:  $V_{CE} \approx 0$  V, collector near ground
- C2 discharges through Q1 collector (which is at ground)
- Q2 base held negative by discharging C1 (from previous cycle)
- Q2 remains in cutoff
- C1 charging toward  $V_{CC}$  through R1

##### Transition from State 1 to State 2:

After time period determined by R1-C1 time constant:

- C1 fully discharges, begins charging in reverse direction
- Q2 base voltage rises above 0.6 V  $\rightarrow$  Q2 turns on
- Q2 collector drops to ground  $\rightarrow$  C2 discharges
- C2 discharge creates negative voltage at Q1 base  $\rightarrow$  Q1 turns off
- C2 begins charging toward  $V_{CC}$  through R2

##### State 2: Q1 OFF, Q2 ON

Now the roles are reversed:

- Q2 in saturation
- Q1 in cutoff (held off by C2 discharge)
- C2 charging through R2

##### Transition from State 2 to State 1:

After time determined by R2-C2 time constant, the cycle repeats.

### Key Mechanism: RC Time Constant

The frequency of oscillation is controlled by the RC networks:

- Larger R or C  $\rightarrow$  slower charging  $\rightarrow$  lower frequency
- Smaller R or C  $\rightarrow$  faster charging  $\rightarrow$  higher frequency

### Capacitor Polarity Reversal

Critical concept: When a transistor switches ON:

- Its collector drops from  $V_{CC}$  to  $\approx 0$  V suddenly
- Coupling capacitor was charged with one polarity
- Sudden voltage drop causes capacitor voltage to reverse
- This creates negative voltage at other transistor's base
- Negative base voltage keeps transistor OFF

Example: If C2 was charged to 5 V (right positive, left at  $V_{CC}$ ), and right side suddenly drops to 0 V, the left side goes to  $-5$  V relative to right side.

### Why It Oscillates Continuously

The circuit is inherently unstable in both states:

- Each state is temporary (determined by RC time constant)
- Capacitors continuously charge/discharge
- Each transition triggers the next transition
- No stable equilibrium exists
- Produces continuous square wave oscillation

### Output Waveform

Square wave taken from either collector:

- Amplitude: approximately  $V_{CC}$
- Frequency: determined by RC values
- Duty cycle: typically 50% (if  $R_1C_1 = R_2C_2$ )
- Asymmetric duty cycles possible with different RC values

## Practical Example & Numerical

### Astable Multivibrator Design

#### Design square wave generator:

- Supply voltage:  $V_{CC} = 5$  V
- Desired frequency: approximately 1 kHz
- Symmetric output (50% duty cycle)

#### Component Selection:

For 50% duty cycle, make both RC networks equal:  $R_1 = R_2$  and  $C_1 = C_2$

Time for each half-cycle:  $T/2 \approx 0.693 \times R \times C$

For 1 kHz frequency:  $T = 1/f = 1$  ms, so each half-cycle = 0.5 ms

$$0.5 \text{ ms} = 0.693 \times R \times C$$

Choose  $C = 0.1 \mu\text{F}$ :

$$R = \frac{0.5 \times 10^{-3}}{0.693 \times 0.1 \times 10^{-6}} = 7.2 \text{ k}\Omega$$

Use standard value:  $R = 6.8 \text{ k}\Omega$  or  $7.5 \text{ k}\Omega$

#### Complete Circuit:

- $R_1 = R_2 = 7.2 \text{ k}\Omega$  (timing resistors)
- $C_1 = C_2 = 0.1 \mu\text{F}$  (coupling capacitors)
- Collector resistors:  $1 \text{ k}\Omega$  (typical)
- Transistors: any general-purpose NPN (e.g., 2N2222)

#### Expected Performance:

- Frequency:  $\approx 1$  kHz
- Output: 0 to 5 V square wave
- Power consumption: continuous (circuit always active)
- Very stable oscillation with no external components needed

#### Asymmetric Duty Cycle Example:

For 70% HIGH, 30% LOW:

- Make  $R_1C_1$  larger (controls HIGH time)

- Make R2C2 smaller (controls LOW time)
- Ratio  $R1/R2 \approx 70/30 = 2.33$

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- Astable = no stable state, continuous oscillation
- Two transistors alternately saturate and cut off
- RC networks control timing (charge/discharge)
- Capacitor polarity reversal creates negative base voltage
- Frequency:  $f \approx 1/(1.4RC)$  for symmetric design
- Output: square wave with controllable frequency and duty cycle
- No external trigger needed (free-running oscillator)
- Simple DC to square wave converter with few components

## Monostable Multivibrator

### TL;DR (The Gist)

A monostable multivibrator has one stable state (OFF) and temporarily switches to unstable state (ON) when triggered. Output stays ON for time period  $T \approx R \times C$ , then returns to stable OFF state. Used for timers, pulse generators, and momentary activation circuits.

## Detailed Explanation

### 2. Detailed Explanation

#### Monostable Characteristics

##### Definition:

- One stable state (output normally OFF)
- One unstable state (output temporarily ON)
- Requires external trigger to switch states
- Automatically returns to stable state after time delay
- Also called "one-shot" multivibrator

#### Stable State (Before Trigger)

Q1 in cutoff, Q2 in saturation:

- Q2 collector near ground (saturated)
- Q1 base voltage very low (negative)  $\rightarrow$  Q1 OFF
- Capacitor C1 fully charged to  $V_{CC}$
- Circuit remains in this state indefinitely
- Output (from Q1 collector) = HIGH ( $\approx V_{CC}$ )

#### Why Q1 Stays OFF:

Q2 saturated means:

- Q2 collector  $\approx$  ground
- Q1 base connected through resistor to Q2 collector
- Q1 base voltage  $\approx 0$  V (insufficient to turn on)
- Even changing timing resistor won't help (all current goes through Q2 to ground)

#### Why Capacitor is Charged:

With Q2 saturated and Q1 OFF:

- Left side of C1: connected to  $V_{CC}$  through resistor
- Right side of C1: Q1 base at low voltage
- Voltage difference charges C1 to nearly  $V_{CC}$
- C1 holds this charge in stable state

#### Trigger Event

Push button or pulse applied to Q1 base:

- Positive pulse raises Q1 base above 0.6 V

- Q1 turns ON → Q1 collector drops to ground
- Q1 collector connected to Q2 base through resistor
- Q2 base voltage drops → Q2 turns OFF

#### Unstable State (After Trigger)

Q1 saturated, Q2 in cutoff:

- Q1 collector near ground
- Output (from Q1) = LOW (device turns ON)
- Q2 base held low by Q1 collector
- C1 begins discharging through circuit

#### Capacitor Discharge Phase

Critical mechanism for timing:

- C1 was charged to  $V_{CC}$  (left positive)
- Right side suddenly connected to ground via Q1
- C1 reverses polarity, creating negative voltage at Q2 base
- This keeps Q2 OFF during timing period
- C1 begins charging in reverse through timing resistor R

#### Return to Stable State

As C1 charges through R:

- Q2 base voltage rises (becomes less negative)
- When Q2 base reaches +0.6 V → Q2 turns ON
- Q2 collector drops to ground
- Q1 base pulled low → Q1 turns OFF
- Circuit returns to stable state
- Output returns to HIGH (device turns OFF)

#### Timing Calculation

Duration of unstable state (ON time):

$$T \approx R \times C$$

where:

- $R$  = timing resistor connected to Q2 base
- $C$  = coupling capacitor
- More precisely:  $T \approx 0.69 \times R \times C$

#### Component Roles

##### Timing resistor (R):

- Controls charging rate of capacitor
- Larger R → slower charging → longer ON time
- Smaller R → faster charging → shorter ON time

##### Collector resistor at output:

- Prevents base-emitter voltage drop from appearing at output
- Ensures output swings full range (0 to  $V_{CC}$ )
- Without it, output only reaches  $V_{CC} - V_{BE} \approx V_{CC} - 0.6 \text{ V}$

##### Base current limiting resistor:

- Prevents short circuit when trigger is applied
- Limits base current to safe levels
- Protects transistor and trigger source

#### Applications

- **Timers:** Turn device ON for specific duration
- **Pulse generators:** Create single pulse per trigger
- **Debouncing:** Clean up noisy switch contacts
- **Interactive exhibits:** Press button → demonstration runs once
- **Touch toys:** Press stomach → toy speaks once
- **Delay circuits:** Activate something after delay

## Practical Example & Numerical

### LED Timer Circuit

**Requirement:** Press button to turn LED ON for exactly 2 seconds

**Design:**

Choose capacitor:  $C = 100 \mu\text{F}$

Calculate resistor for  $T = 2 \text{ s}$ :

$$R = \frac{T}{C} = \frac{2}{100 \times 10^{-6}} = 20 \text{ k}\Omega$$

More precise calculation with 0.69 factor:

$$R = \frac{2}{0.69 \times 100 \times 10^{-6}} = 29 \text{ k}\Omega$$

Use standard value:  $R = 27 \text{ k}\Omega$  or  $30 \text{ k}\Omega$

#### Circuit Configuration:

- $V_{CC} = 10 \text{ V}$
- Q1, Q2: general-purpose NPN transistors
- Timing:  $R = 27 \text{ k}\Omega$ ,  $C = 100 \mu\text{F}$
- LED in series with collector resistor at Q1 collector
- Trigger: push button connected to Q1 base through  $1 \text{ k}\Omega$  resistor

#### Operation:

- Initially: LED OFF (stable state)
- Press button: LED turns ON
- Hold button or release: doesn't matter, LED stays ON
- After 2 seconds: LED automatically turns OFF
- Press again: LED turns ON for another 2 seconds

#### Verification in Simulation:

Measure time between trigger and return to stable state:

- Start time: when button pressed
- End time: when LED turns off
- Duration:  $\Delta t \approx 2 \text{ seconds}$  (may be  $\approx 1.8 \text{ s}$  depending on simulation accuracy)

#### Adjusting ON Time:

- For 5 seconds: increase  $R$  to  $72 \text{ k}\Omega$  (or  $C$  to  $250 \mu\text{F}$ )
- For 0.5 seconds: decrease  $R$  to  $7.2 \text{ k}\Omega$  (or  $C$  to  $25 \mu\text{F}$ )
- Easy to customize for specific applications

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

- Monostable = one stable state (normally OFF)
- Trigger switches to unstable state temporarily
- ON time duration:  $T \approx 0.69 \times R \times C$
- Automatically returns to stable state after timing period
- Capacitor discharge/recharge controls timing
- No need to hold trigger (one pulse sufficient)
- Similar to astable but with only one RC network
- Applications: timers, pulse generators, debouncing, delays

### Bistable Multivibrator

#### TL;DR (The Gist)

A bistable multivibrator has two stable states and requires two separate triggers (SET and RESET) to switch between them. Output remains in current state until opposite trigger is applied. Forms the basis of flip-flops and latches used in digital memory and storage elements.

#### Detailed Explanation

## 2. Detailed Explanation

### Bistable Characteristics

#### Definition:

- Two stable states (both can persist indefinitely)
- Requires trigger to change from one state to other
- Remains in new state until opposite trigger applied
- Also called "flip-flop" or "latch"
- Basic storage element in digital electronics

#### Key Difference from Other Multivibrators:

- **Astable:** 0 stable states (always oscillating)
- **Monostable:** 1 stable state (returns automatically)
- **Bistable:** 2 stable states (stays until triggered)

### Circuit Configuration

#### Differences from monostable:

- NO capacitors (capacitors made it unstable)
- Two trigger inputs instead of one
- SET trigger: switches output to HIGH
- RESET trigger: switches output to LOW

#### Logic Triggers:

Instead of push buttons, logic inputs used:

- Logic LOW (0): 0 V (acts like ground)
- Logic HIGH (1): 5 V (sends pulse to base)
- More intuitive for digital applications
- Can interface with digital circuits directly

#### State 1: Q2 ON, Q1 OFF (Output HIGH)

Initial stable condition:

- Q2 in saturation  $\rightarrow$  collector near ground
- Q1 in cutoff  $\rightarrow$  collector at  $V_{CC}$  (output HIGH)
- Q1 base connected to Q2 collector (through resistor)  $\rightarrow$  held LOW
- Q2 base receives current through resistor from Q1 collector  $\rightarrow$  stays ON
- This state persists indefinitely

#### Cross-Coupling Mechanism:

Each transistor's collector controls the other's base:

- Q1 collector  $\rightarrow$  Q2 base (through resistor)
- Q2 collector  $\rightarrow$  Q1 base (through resistor)
- Positive feedback: whichever is ON keeps other OFF
- Stable in either configuration

#### SET Operation (Output LOW $\rightarrow$ HIGH)

Apply positive pulse to Q1 base (SET input):

- SET trigger raises Q1 base above 0.6 V
- Q1 turns ON  $\rightarrow$  Q1 collector drops to ground
- Q1 collector connected to Q2 base
- Q2 base voltage drops  $\rightarrow$  Q2 turns OFF
- Q2 collector rises to  $V_{CC}$
- Q2 collector feeds back to Q1 base  $\rightarrow$  keeps Q1 ON
- New stable state established

#### State 2: Q1 ON, Q2 OFF (Output LOW)

Now the roles are reversed:

- Q1 in saturation  $\rightarrow$  collector near ground (output LOW)
- Q2 in cutoff  $\rightarrow$  collector at  $V_{CC}$
- Q2 base connected to Q1 collector  $\rightarrow$  held LOW
- Q1 base receives current from Q2 collector  $\rightarrow$  stays ON
- This state also persists indefinitely

#### RESET Operation (Output HIGH $\rightarrow$ LOW)

Apply positive pulse to Q2 base (RESET input):

- RESET trigger raises Q2 base above 0.6 V
- Q2 turns ON  $\rightarrow$  Q2 collector drops to ground
- Q2 collector connected to Q1 base

- Q1 base voltage drops → Q1 turns OFF
- Q1 collector rises to  $V_{CC}$  (output HIGH again)
- Q1 collector feeds back to Q2 base → keeps Q2 ON
- Returns to original stable state

### Base Current Limiting Resistors

Series resistors at trigger inputs are critical:

- Prevent short circuit: trigger HIGH (5 V) to ground (via saturated transistor)
- Without resistor: direct path from 5 V to 0 V
- Would draw excessive current, damage components
- Typical value: 100  $\Omega$  to 1 k $\Omega$

### Data Storage Application

Bistable circuit stores 1 bit of information:

- Output HIGH = binary 1 (data stored)
- Output LOW = binary 0 (data erased)
- SET pulse writes "1"
- RESET pulse writes "0"
- Data retained indefinitely (as long as power applied)

### Foundation of Digital Memory

Flip-flops and latches based on bistable circuits:

- **SR Latch:** Set-Reset latch (basic bistable)
- **D Flip-flop:** Data storage element
- **JK Flip-flop:** Toggle capability
- **T Flip-flop:** Toggle on clock

All digital memory (RAM, registers, counters) built from these elements!

### Practical Applications

- **Car alarm:** Door opens (SET) → alarm ON, owner presses button (RESET) → alarm OFF
- **Push-on/push-off switch:** First press ON, second press OFF
- **Digital counters:** Each flip-flop stores one bit
- **Computer memory:** Billions of bistable elements store data
- **State machines:** Control sequences in processors

## Practical Example & Numerical

### Bistable Circuit as Memory Element

**Circuit:**

- $V_{CC} = 5\text{ V}$
- Two NPN transistors (Q1, Q2)
- Collector resistors: 1 k $\Omega$  each
- Cross-coupling resistors: 10 k $\Omega$  each
- Trigger input resistors: 100  $\Omega$  each
- Output: LED at Q1 collector

**Initial State:**

- Q2 ON, Q1 OFF
- Output HIGH (LED OFF in this example with LED at Q1)
- Stored bit: "1"

**Operation Sequence:**

**Step 1:** Apply SET pulse (logic HIGH to Q1 base)

- Q1 turns ON
- Q2 turns OFF
- Output goes LOW (LED turns ON)
- Stored bit: "0"

**Step 2:** Release SET (back to logic LOW)

- Output remains LOW (LED stays ON)
- Bit "0" is retained
- No change without trigger

**Step 3:** Apply RESET pulse (logic HIGH to Q2 base)

- Q2 turns ON
- Q1 turns OFF
- Output goes HIGH (LED turns OFF)
- Stored bit: "1"

**Step 4:** Release RESET

- Output remains HIGH (LED stays OFF)
- Bit "1" is retained
- Waits for next SET pulse

**Current Flow Without Limiting Resistor:**

If 100  $\Omega$  resistor removed at SET input:

- SET = 5 V, Q2 collector = 0 V (ground)
- Direct short circuit: 5 V to ground
- Current: limited only by transistor  $R_{CE(sat)} \approx 1 \Omega$
- $I = 5/1 = 5 \text{ A}$  (would destroy circuit!)
- Limiting resistor:  $I = 5/100 = 50 \text{ mA}$  (safe)

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- Bistable = two stable states, both persist indefinitely
- SET trigger: output HIGH, RESET trigger: output LOW
- No capacitors (unlike astable and monostable)
- Cross-coupled transistors create positive feedback
- Stores 1 bit of information (digital memory element)
- Foundation of flip-flops and latches
- Basis of all digital memory (RAM, registers, counters)
- Current limiting resistors essential at trigger inputs

## Schmitt Trigger and Oscillators

### Schmitt Trigger

#### TL;DR (The Gist)

A Schmitt trigger is a comparator with hysteresis, providing two different threshold voltages for rising (upper threshold) and falling (lower threshold) edges. This prevents multiple output transitions caused by noisy input signals, converting slow or noisy inputs into clean digital outputs.

#### Detailed Explanation

### 2. Detailed Explanation

#### What is Hysteresis?

Hysteresis means the circuit has different switching thresholds depending on direction:

- **Upper threshold ( $V_{TH}$ ):** Input rising, output switches LOW  $\rightarrow$  HIGH
- **Lower threshold ( $V_{TL}$ ):** Input falling, output switches HIGH  $\rightarrow$  LOW
- **Hysteresis gap:**  $\Delta V = V_{TH} - V_{TL}$

#### Problem Without Hysteresis

Simple comparator with single threshold:

- Noise on input near threshold causes multiple output toggles
- Slow-rising input crosses threshold multiple times
- Output "chatters" or "bounces"
- Unreliable digital signal

Example: Noisy signal with 2 pulses but noise causes 6-7 output transitions at threshold crossings.

#### Solution With Schmitt Trigger

Two separate thresholds eliminate noise sensitivity:

- Input must rise above  $V_{TH}$  to switch output HIGH
  - Then input must fall below  $V_{TL}$  to switch output LOW
  - Noise between  $V_{TL}$  and  $V_{TH}$  has no effect
  - Clean, reliable output even with noisy input
- Example: Same noisy signal produces exactly 2 clean output pulses.

### Circuit Operation (BJT Implementation)

#### Initial State: Input LOW, Output LOW

- Input at 0 V (applied to Q1 base)
- Q1 in cutoff (base-emitter voltage negative)
- Q2 in saturation (receives base current from Q1 collector)
- Output (Q2 collector) near ground (LOW)
- Emitter resistor shared by both transistors

#### Emitter Resistor Creates Hysteresis:

Key mechanism:

- Both emitters connected to common resistor  $R_E$
- Current through  $R_E$  creates voltage at emitters
- This voltage affects threshold for both transistors
- Positive feedback: state change alters threshold

#### Input Rising (LOW $\rightarrow$ HIGH Transition):

As input rises from 0 V:

- Q1 base voltage increases
- Q1 emitter at  $\approx 0.9$  V (Q2 conducting sets this)
- Q1 needs  $V_{BE} \approx 0.6$  V to turn on
- Q1 turns ON when input reaches:  $V_{TH} = V_E + 0.6 \approx 1.5$  V

#### Upper Threshold ( $V_{TH}$ ):

$$V_{TH} = V_E + V_{BE} \approx 1.5 \text{ V}$$

When input exceeds  $V_{TH}$ :

- Q1 turns ON  $\rightarrow$  Q1 collector drops
- Q2 base voltage drops  $\rightarrow$  Q2 turns OFF
- Q2 collector rises to  $V_{CC}$  (output HIGH)
- Emitter voltage changes (now set by Q1)
- New threshold established for falling edge

#### Input Falling (HIGH $\rightarrow$ LOW Transition):

With output HIGH (Q1 ON, Q2 OFF):

- Q1 emitter at lower voltage (only Q1 current through  $R_E$ )
- Q2 needs base higher than emitter by 0.6 V to turn on
- But Q2 base tied to Q1 collector (near ground)
- Q1 must come out of saturation for Q2 to turn on

#### Lower Threshold ( $V_{TL}$ ):

$$V_{TL} = V_E + V_{BE} \approx 1.1 \text{ V}$$

When input falls below  $V_{TL}$ :

- Q1 current decreases, comes out of saturation
- Q1 collector voltage rises (enters active region)
- Q2 base voltage rises above emitter
- Q2 turns ON  $\rightarrow$  output goes LOW
- Cycle completes

#### Hysteresis Window

Gap between thresholds:

$$\Delta V = V_{TH} - V_{TL} \approx 1.5 - 1.1 = 0.4 \text{ V}$$

This gap provides noise immunity:

- Noise up to 0.4 V peak-to-peak won't cause false triggering
- Larger gap = more noise immunity, less sensitivity
- Smaller gap = more sensitivity, less noise immunity
- Adjustable by changing emitter resistor value

#### Applications

- **Wave shaping:** Convert slow/noisy signals to clean square waves
- **Sensor interfacing:** Light sensor, temperature sensor with noise
- **Debouncing:** Clean up mechanical switch contacts
- **Level detection:** Detect when signal crosses threshold
- **Oscillators:** Combined with RC network for relaxation oscillator
- **Advertising boards:** Light-dependent turn-on without flickering

#### Practical Example: Light-Activated Sign

Photodiode measures outdoor luminosity:

- As sun sets, voltage decreases
- At dusk, voltage crosses lower threshold
- Sign turns ON
- Without hysteresis: sign would flicker as clouds pass
- With hysteresis: sign stays ON until much brighter (morning)
- Upper threshold prevents premature turn-off

#### IC Implementations

Many ICs have built-in Schmitt trigger inputs:

- 74HC14: Hex Schmitt trigger inverter
- 555 timer: internal Schmitt trigger comparator
- Op-amp circuits: easy to add hysteresis with positive feedback

#### Transfer Characteristic

Plot output vs. input shows hysteresis loop:

- Input increasing: output switches at  $V_{TH}$
- Input decreasing: output switches at  $V_{TL}$
- Creates characteristic "loop" shape
- Width of loop = hysteresis amount

### Practical Example & Numerical

#### Schmitt Trigger for Noisy Signal Cleanup

##### Input Signal:

- 2 V sine wave (0 to 2 V)
- Plus 200 Hz noise ( $\pm 0.3$  V amplitude)
- Composite: slow rise/fall with significant noise

##### Circuit Parameters:

- $V_{CC} = 5$  V
- Upper threshold:  $V_{TH} \approx 1.5$  V
- Lower threshold:  $V_{TL} \approx 1.1$  V
- Hysteresis gap: 0.4 V

##### Operation:

##### Input rising from 0 V:

- Passes through 1.1 V: no change (below  $V_{TH}$ )
- Noise causes  $\pm 0.3$  V fluctuations around 1.1 V
- Output remains LOW (immune to noise)
- At 1.5 V: output switches to HIGH
- Clean transition despite noise

##### Input at peak (2 V):

- Output stays HIGH
- Noise doesn't bring input below 1.1 V threshold
- No false triggering

##### Input falling from 2 V:

- Passes through 1.5 V: no change (must reach  $V_{TL}$ )
- Noise around 1.5 V has no effect
- At 1.1 V: output switches to LOW
- Another clean transition

##### Result:

- Input: noisy 2 V sine wave

- Output: clean square wave, exactly 2 pulses
- No false triggering from noise
- Perfect for digital circuit interfacing

#### Without Schmitt Trigger (Simple Comparator):

- Single threshold at 1.3 V
- Input noise causes  $\pm 0.3$  V variation
- Near threshold: multiple crossings (1.0-1.6 V range)
- Output: 6-8 pulses instead of 2
- Unreliable, unusable signal

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

- Schmitt trigger: comparator with hysteresis (two thresholds)
- Upper threshold ( $V_{TH}$ ): input rising, output goes HIGH
- Lower threshold ( $V_{TL}$ ): input falling, output goes LOW
- Hysteresis gap:  $\Delta V = V_{TH} - V_{TL}$  provides noise immunity
- Shared emitter resistor creates positive feedback
- Prevents multiple transitions from noisy/slow inputs
- Converts analog signals to clean digital outputs
- Applications: wave shaping, debouncing, sensor interfacing

### Colpitts Oscillator (Positive Feedback Explained)

#### TL;DR (The Gist)

A Colpitts oscillator uses an LC tank circuit with capacitive voltage divider to create positive feedback, generating continuous sinusoidal oscillations. Frequency determined by  $f = 1/(2\pi\sqrt{LC_{total}})$  where  $C_{total} = C_1C_2/(C_1 + C_2)$ . Positive feedback from emitter (in-phase with input) sustains oscillations by compensating for losses.

### Detailed Explanation

#### 2. Detailed Explanation

##### What is an Oscillator?

An oscillator is an electronic circuit that produces periodically oscillating signals:

- Sine wave (analog oscillators)
- Square wave (digital oscillators)
- Triangle, sawtooth, etc.

##### Why Oscillators are Essential:

- Heartbeat of microcontrollers and processors
- Clock signals for digital circuits
- Radio frequency generation (transmitters, receivers)
- Signal generation for testing and measurement

Without oscillators, digital circuits would remain in "deep sleep"—no clock, no operation!

##### Types of Oscillators

- **RC oscillators:** Low frequency (audio range)
- **LC oscillators:** High frequency (RF applications)
- **Crystal oscillators:** Very stable, precise frequency
- **Op-amp based:** Adjustable, stable frequencies

##### Colpitts Oscillator Characteristics:

- Frequency range: 30 kHz to 300 MHz
- LC tank circuit (inductor + capacitors)
- High frequency sine wave generation
- Used in RF applications: radio receivers, transmitters, mobile communications
- Withstands temperature variations well

- Easy frequency adjustment (vary L or C)

### **Positive vs. Negative Feedback**

#### **Positive Feedback:**

- Output fed back to input in-phase
- Input and feedback add together
- Output increases (grows with time)
- Used to produce oscillations
- Unstable by design (desired for oscillators)

#### **Negative Feedback:**

- Output fed back to input out-of-phase ( $180^\circ$ )
- Feedback subtracts from input
- Output decreases (stabilizes)
- Used to stabilize amplifier gain
- Stable by design (desired for amplifiers)

### **Why Emitter Feedback is Positive**

NPN transistor phase relationships:

- Input: base voltage
- Collector output:  $180^\circ$  phase shift (inverted)
- Emitter output:  $0^\circ$  phase shift (in-phase with input)

For positive feedback:

- Must take feedback from emitter (in-phase)
- NOT from collector (would be negative feedback)
- Emitter signal adds to input  $\rightarrow$  positive feedback

### **LC Tank Circuit**

Heart of Colpitts oscillator:

- Inductor (L) in parallel with capacitors (C1, C2 in series)
- Natural resonant frequency
- Stores energy alternately in magnetic field (L) and electric field (C)
- Energy oscillates back and forth
- Creates sinusoidal voltage

#### **Tank Circuit Operation:**

##### **1. Capacitor charged:**

- Energy stored in electric field
- Begins discharging through inductor

##### **2. Current flows through inductor:**

- Energy transferred to magnetic field
- Current builds up

##### **3. Magnetic field collapses:**

- Inductor generates voltage (opposes change in current)
- Charges capacitor in opposite polarity

##### **4. Cycle repeats:**

- Energy oscillates between L and C
- Creates sinusoidal waveform

### **Problem: Damping**

Real components have resistance:

- Energy lost as heat in each cycle
- Oscillation amplitude decreases over time
- Eventually stops (damped oscillation)

### **Solution: Transistor Amplification**

Transistor compensates for losses:

- Amplifies weak oscillation
- Feeds energy back into tank circuit
- Maintains constant amplitude
- Continuous oscillation (undamped)

### **Colpitts Circuit Operation**

#### **Power-on sequence:**

##### **1. Initial charging:**

- Current flows from  $V_{CC}$  through bias resistor
- Charges capacitors C1 and C2

- Initially, capacitors have low impedance (act like short)
- Inductor has high impedance (opposes current change)
- Current prefers path through capacitors

## 2. Capacitors charge:

- C1 charges until voltage reaches 0.6-0.7 V
- C1 in parallel with base-emitter junction
- When  $V_{C1} \geq 0.6 \text{ V} \rightarrow$  transistor turns ON

## 3. Transistor turns ON:

- Large emitter current flows (limited by  $100 \Omega$  resistor)
- Emitter current splits: some through C1, some through C2
- Both capacitors begin discharging (charging in reverse)
- Collector voltage drops (transistor saturates)

## 4. Inductor responds:

- Current through inductor was building up
- Transistor saturation reduces current
- Magnetic field in inductor collapses
- Inductor generates voltage (opposes current change)
- This voltage charges C2 and discharges C1 further

## 5. Transistor turns OFF:

- C1 voltage drops below 0.6 V
- Base-emitter no longer forward biased
- Transistor enters cutoff
- Collector voltage rises back to  $\approx V_{CC}$

## 6. LC tank oscillates:

- Energy continues oscillating in LC circuit
- C1 charges back up through bias resistor
- When C1 reaches 0.6 V again  $\rightarrow$  transistor turns ON
- Cycle repeats

## Positive Feedback Mechanism

Critical for sustained oscillation:

- Emitter current flows when transistor ON
- This current goes through capacitive divider (C1, C2)
- Voltage across C1 fed directly to base
- Emitter voltage in-phase with base voltage
- Feedback adds to input  $\rightarrow$  positive feedback
- Compensates for LC tank losses

## Without positive feedback:

- Remove emitter connection
- Transistor still amplifies
- But weak input signal (no feedback boost)
- Insufficient to compensate losses
- Oscillation dies out quickly

## Frequency Calculation

Resonant frequency of LC tank:

$$f = \frac{1}{2\pi\sqrt{LC_{total}}}$$

where  $C_{total}$  is series combination of C1 and C2:

$$C_{total} = \frac{C_1 \cdot C_2}{C_1 + C_2}$$

For equal capacitors ( $C_1 = C_2 = C$ ):

$$C_{total} = \frac{C}{2}$$

$$f = \frac{1}{2\pi\sqrt{LC/2}} = \frac{1}{\pi\sqrt{2LC}}$$

**Example:**  $L = 1 \text{ mH}$ ,  $C_1 = C_2 = 100 \mu\text{F}$

$$C_{total} = \frac{100 \times 100}{100 + 100} = 50 \mu\text{F}$$

$$f = \frac{1}{2\pi\sqrt{10^{-3} \times 50 \times 10^{-6}}} = \frac{1}{2\pi\sqrt{5 \times 10^{-8}}} \approx 225 \text{ Hz}$$

### Frequency Adjustment

Easy to tune output frequency:

- Increase L or C → lower frequency
- Decrease L or C → higher frequency
- Variable capacitor → adjustable oscillator
- Variable inductor (rare) → coarse tuning

### Advantages of Colpitts Oscillator

- High frequency capability (up to 300 MHz)
- Good frequency stability
- Temperature resistant
- Simple circuit, few components
- Easy frequency adjustment
- Low cost

### Applications

- Radio frequency oscillators in receivers
- Local oscillators in transceivers
- Signal generators for testing
- Mobile communication devices
- RF transmitters

## Practical Example & Numerical

### Colpitts Oscillator Design for 217 Hz

#### Requirements:

- Output frequency: 217 Hz (from simulation)
- Sinusoidal waveform
- Low distortion

#### Component Selection:

Choose:  $C_1 = C_2 = 100 \mu\text{F}$  (equal values for symmetry)

Calculate total capacitance:

$$C_{total} = \frac{C_1 \cdot C_2}{C_1 + C_2} = \frac{100 \times 100}{200} = 50 \mu\text{F}$$

Calculate required inductance for  $f = 217 \text{ Hz}$ :

$$L = \frac{1}{(2\pi f)^2 C_{total}} = \frac{1}{(2\pi \times 217)^2 \times 50 \times 10^{-6}}$$

$$L = \frac{1}{1.864 \times 10^6 \times 50 \times 10^{-6}} = \frac{1}{93.2} \approx 10.7 \text{ mH}$$

Use:  $L = 10 \text{ mH}$  (close standard value)

#### Complete Circuit:

- Inductor: 10 mH
- Capacitors:  $C_1 = C_2 = 100 \mu\text{F}$
- Bias resistor: 1 k $\Omega$  (provides DC bias and limits current)
- Emitter resistor: 100  $\Omega$  (limits emitter current)
- Collector resistor: 100  $\Omega$  (sets output impedance)
- Transistor: general-purpose NPN (e.g., 2N2222)
- Supply:  $V_{CC} = 5 \text{ V}$

#### Performance:

Base voltage:  $\approx 100 \text{ mV}$  peak-to-peak (small signal)

Collector output:  $\approx 4.5 \text{ V}$  peak-to-peak (amplified)

Frequency: 217 Hz (as designed)

Waveform: Clean sinusoidal (low distortion)

**Positive Feedback Verification:**

With feedback connected: Large stable oscillation, 4.5 V amplitude

Without feedback (emitter disconnected): Tiny oscillation ( $< 10$  mV), rapidly decays

This proves positive feedback is essential for sustained oscillation!

**Frequency Tuning Example:**

To change to 500 Hz:

- Keep  $C_1 = C_2 = 100 \mu\text{F}$
- Calculate:  $L = 1/(2\pi \times 500)^2 \times 50 \times 10^{-6} = 2.03 \text{ mH}$
- Use  $L = 2.2 \text{ mH}$  (standard value)
- Actual frequency:  $\approx 480 \text{ Hz}$  (close enough)

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- Colpitts: LC oscillator with capacitive voltage divider
- Positive feedback from emitter (in-phase with input)
- Frequency:  $f = 1/(2\pi\sqrt{LC_{total}})$  where  $C_{total} = C_1C_2/(C_1 + C_2)$
- LC tank circuit oscillates naturally but decays (damped)
- Transistor amplifies and feeds energy back (undamped)
- Emitter output in-phase with base (positive feedback)
- Collector output  $180^\circ$  out-of-phase (negative feedback, not used)
- Range: 30 kHz - 300 MHz (RF applications)
- Easy frequency tuning by varying L or C
- Applications: RF oscillators, transmitters, receivers

# Section 23 – Linear Power Supply Design

This section covers the design of linear (regulated) power supplies, from understanding the fundamental building blocks to implementing complete adjustable voltage/current sources. We examine common design mistakes, learn proper regulation techniques using discrete components, and explore both single-rail and dual-rail (split) power supply configurations.

## Power Supply Fundamentals and Architecture

### Power Supply Introduction and Block Diagram

#### TL;DR (The Gist)

A linear power supply converts AC mains voltage to clean, regulated DC through four main stages: step-down transformer (voltage reduction), rectifier (AC to pulsating DC), filter (smoothing to clean DC), and voltage regulator (maintaining constant output despite load/input variations). Linear supplies are characterized by continuous conduction, simplicity, and low noise compared to switching supplies.

#### Detailed Explanation

### 2. Detailed Explanation

#### Power Supply Classifications:

Power supplies can be categorized by functional features:

- **Regulated:** Maintains constant output voltage/current despite variations in input voltage or load current. Essential for sensitive electronics.
- **Unregulated:** Output voltage varies significantly with input changes or load variations. Generally not suitable for precision applications.
- **Adjustable:** Output voltage/current can be programmed via mechanical controls (potentiometers) or control inputs.
- **Isolated:** Output is electrically independent of input, typically achieved with transformers. Provides safety barrier preventing dangerous voltages from passing through. Critical for switching supplies where grounds are separated.

#### Linear vs. Switching Power Supplies:

*Linear Power Supply:* Uses continuous conduction through transistors operating in their active region. The regulator acts as a variable resistor, dissipating excess power as heat. Advantages include simplicity, low noise, excellent regulation. Disadvantages are lower efficiency (typically 30-60%) and larger size/weight due to 50/60Hz transformer.

*Switching Mode Power Supply (SMPS):* Converts AC to DC via rectifier, then chops DC into high-frequency AC (tens to hundreds of kHz) using switching circuits. High-frequency transformer is much smaller (transformer size inversely proportional to frequency). Requires PWM driver controlling switching block. Advantages: high efficiency (70-95%), small size, light weight, low heat dissipation. Disadvantages: complex circuitry, electrical noise generation, higher component count.

#### Four Main Blocks of Linear Power Supply:

1. *Step-Down Transformer:* Reduces AC mains (e.g., 220V) to required lower voltage level. Turns ratio adjusted to obtain desired secondary voltage. For ideal transformer:  $P_{primary} = P_{secondary}$ , so  $V_1 I_1 = V_2 I_2$ . Step-down voltage transformation increases current proportionally.
2. *Rectifier:* Converts AC to unidirectional pulsating DC. Half-wave rectifier uses one diode (inefficient, high ripple). Full-wave bridge rectifier uses four diodes, conducts on both AC half-cycles, providing better DC utilization and lower ripple. Output is pulsating DC with voltage drops from conducting diodes (typically  $\approx 1.4V$  for two diodes in bridge).
3. *Filter:* Smooths pulsating DC to cleaner DC with minimal ripple. Capacitor filter most common for small supplies. Capacitor charges to peak voltage, then discharges slowly through load during AC dips. Large capacitance provides better smoothing. Other filters: LC filter,  $\pi$ -filter (CLC), choke input filter for higher current applications.
4. *Voltage Regulator:* Maintains constant output despite input voltage variations, load current changes, or temperature drift. Can be implemented with discrete components (transistors, Zener diodes) or integrated circuits (LM317 adjustable, 78xx fixed positive, 79xx fixed negative series). This is the most complex block to design properly.

#### Power Flow in Transformer:

Transformer action analogous to mechanical gears: primary side like large gear (high torque/voltage, low speed/current), secondary side like small gear (low torque/voltage, high speed/current). Step-down transformer reduces voltage but increases current to maintain power balance (minus losses).

#### Practical Example & Numerical

### Transformer Current Relationship:

Consider a step-down transformer: primary 220V AC with 0.5A fuse, secondary outputs 53V AC.

For ideal transformer (no losses):

$$P_{\text{primary}} = P_{\text{secondary}} \implies V_1 I_1 = V_2 I_2$$
$$220\text{V} \times 0.5\text{A} = 53\text{V} \times I_2 \implies I_2 = \frac{110}{53} \approx 2.08\text{A}$$

If secondary load draws more than 2.08A, primary current exceeds 0.5A fuse rating, causing fuse to blow and protect circuit.

### IC Voltage Regulators:

Common fixed regulators use simple naming convention:

- 78xx series: Positive voltage, where xx = output voltage (7805 = +5V, 7812 = +12V)
- 79xx series: Negative voltage, where xx = output voltage (7912 = -12V, 7905 = -5V)

For adjustable output, LM317 (positive) or LM337 (negative) provide voltage programming via external resistor network.

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- Linear power supplies comprise four essential blocks: transformer, rectifier, filter, and regulator
- Regulated supplies maintain constant output; unregulated supplies exhibit significant voltage variation with load
- Transformer power relationship:  $P_{in} = P_{out}$  (ideal), so step-down voltage transformation increases current
- Full-wave bridge rectifier superior to half-wave: better DC utilization, lower ripple, higher efficiency
- Capacitor filter: charges to peak, discharges through load, larger capacitance = better smoothing
- Switching supplies achieve higher efficiency and smaller size via high-frequency operation, but add complexity and noise
- Isolation (transformer-based) provides safety barrier, essential for many applications
- IC regulators (78xx, 79xx, LM317) simplify design but discrete designs teach fundamental regulation principles

## Common Power Supply Design Mistakes

### TL;DR (The Gist)

Naive power supply designs using simple voltage dividers or Zener diodes alone suffer from poor load regulation (output voltage drops significantly when load current increases), excessive power dissipation in series components, and inability to provide adequate current. These designs illustrate why proper active regulation with transistors is necessary for functional power supplies.

## Detailed Explanation

### 2. Detailed Explanation

#### Design Mistake 1: Resistive Voltage Divider

Attempting to create 10V output from 50V DC source using voltage divider (e.g., 4kΩ and 1kΩ resistors) fails when load is connected. Load resistance appears in parallel with bottom divider resistor, changing the division ratio.

For unloaded divider:  $V_{out} = V_{in} \frac{R_2}{R_1 + R_2} = 50 \frac{1k}{5k} = 10\text{V}$ .

With 1kΩ load connected, equivalent resistance:  $R_{eq} = R_2 \parallel R_{load} = \frac{1k \times 1k}{1k + 1k} = 500\Omega$ .

New output:  $V_{out} = 50 \frac{500}{4000 + 500} \approx 5.6\text{V}$ . Output voltage collapses with load.

#### Design Mistake 2: Zener Diode Only

Using Zener diode with series current-limiting resistor improves regulation. Zener operated in reverse breakdown maintains constant voltage across its terminals. Series resistor (e.g., 500Ω) limits current to safe level.

**Advantages:** Output voltage stable at Zener breakdown voltage ( $V_Z$ ) even with moderate load variations. Much better than resistive divider.

**Critical Problems:**

- **Low current capability:** If load draws too much current, Zener current drops below minimum Zener current ( $I_{Z,min}$ ), losing regulation. Voltage collapses (e.g., with 100Ω load drawing 100mA, regulation fails).
- **High power dissipation:** Under no-load or high-impedance load conditions, all circuit current flows through

Zener, causing maximum power dissipation:  $P_Z = V_Z \times I_Z$ . Can easily exceed Zener power rating, destroying device.

- **Series resistor compromise:** Small resistance allows adequate load current but causes excessive Zener dissipation at no-load. Large resistance protects Zener but limits available load current. No good compromise exists.
- **Electrical noise:** Zener diodes can generate electrical noise on DC output as breakdown mechanism stabilizes voltage. Large capacitor across Zener (e.g.,  $100\mu\text{F}$ ) helps filter noise.

#### Series Resistor Trade-off:

Series resistor value must balance conflicting requirements:

- Too high: Reduces load current capability, output voltage drops under load
- Too low: Excessive Zener current at no-load, high power dissipation (e.g., 3W requiring power resistor), potential Zener destruction

For 10V Zener with  $1\text{k}\Omega$  load (10mA), if series resistor is  $500\Omega$ : current from 50V source =  $(50-10)/500 = 80\text{mA}$ . Under load, 10mA goes to load, 70mA through Zener. Power in Zener:  $10 \times 0.07 = 0.7\text{W}$ . Power in resistor:  $(50-10) \times 0.08 = 3.2\text{W}$ . Very inefficient.

#### Need for Active Regulation:

These passive designs demonstrate why active regulation using transistors is essential. Transistors provide:

- Current amplification (high load current from small control current)
- Low power dissipation in reference element (Zener)
- Better load regulation (output voltage stable across wide load current range)
- Efficient power delivery to load

### Practical Example & Numerical

#### Voltage Divider Failure Calculation:

50V source, voltage divider  $4\text{k}\Omega + 1\text{k}\Omega$ , desired 10V output.

No load:  $V_{out} = 50 \times \frac{1000}{5000} = 10\text{V}$ . ✓

With  $1\text{k}\Omega$  load:

$$R_{parallel} = \frac{1k \times 1k}{1k + 1k} = 500\Omega$$

$$V_{out} = 50 \times \frac{500}{4000 + 500} = 50 \times 0.111 = 5.56\text{V}$$

Output dropped 44% from desired value. Unacceptable for any real application.

#### Zener Regulation Limits:

10V Zener with  $500\Omega$  series resistor, 50V input.

No load condition:

$$I_{total} = \frac{50 - 10}{500} = 80\text{mA} \text{ (all through Zener)}$$

$$P_{Zener} = 10 \times 0.08 = 0.8\text{W}$$

With  $100\Omega$  load: Load requires  $10/100 = 100\text{mA}$ . But total circuit current only 80mA. Impossible to supply. Zener current goes to zero, regulation lost, output voltage collapses to  $\approx 8.3\text{V}$ .

Zener alone cannot provide adequate current for low-resistance loads.

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

- Resistive voltage dividers fail as power supplies: output voltage varies drastically with load resistance
- Load resistance in parallel with divider bottom resistor changes division ratio, collapsing output voltage
- Zener-only regulation provides voltage reference but cannot deliver significant current
- Zener requires series current-limiting resistor, creating power dissipation trade-off
- Small series resistor: excessive Zener dissipation at no-load; large series resistor: insufficient load current
- Zener power dissipation highest at no-load (all current through Zener), can exceed ratings
- Minimum Zener current ( $I_{Z,min}$ ) must be maintained for regulation; heavy loads drop Zener current below minimum
- Zener diodes can generate electrical noise; add large capacitor across Zener for filtering
- These failures motivate need for active regulation using transistors (current gain, efficient power delivery)

# Transistor-Based Voltage Regulation

## Emitter Follower Regulation with Darlington Configuration

TL;DR (The Gist)

Adding an NPN transistor (emitter follower configuration) to Zener reference solves power dissipation problem: Zener provides voltage reference with minimal current, transistor amplifies current for load. Darlington pair (two transistors cascaded) further increases current gain ( $\beta_{total} = \beta_1 \times \beta_2$ ), enabling high output current with minimal base current. This approach allows high series resistance (protecting Zener) while maintaining excellent load current capability.

### Detailed Explanation

## 2. Detailed Explanation

### Single Transistor Emitter Follower:

Circuit configuration: Zener diode connected to transistor base, transistor emitter connected to load, series resistor limits Zener current. Transistor operates as emitter follower (common collector configuration).

*Operating Principle:*

- Zener provides stable voltage reference  $V_Z$  at transistor base
- Transistor emitter voltage:  $V_{out} = V_Z - V_{BE}$  (one diode drop lower, typically 0.7V)
- Load current flows through collector-emitter,  $I_C \approx \beta \times I_B$
- Base current very small due to current gain, leaving most series resistor current for Zener

*Advantages over Zener-only:*

- High input impedance at base reduces base current to microamps
- Series resistor can be large (protecting Zener) without compromising load current
- Zener power dissipation dramatically reduced (e.g., from 700mW to 40mW)
- Load current capability increased by factor of  $\beta$  (e.g., 100× improvement)

*Limitations:*

- Output voltage fixed at  $V_Z - 0.7V$  (one diode drop loss)
- Minimum output voltage limited to  $\approx 0.7V$  (cannot reach near-zero)
- For very low load resistance, single transistor may have insufficient current gain

### Darlington Pair Configuration:

Two transistors cascaded: Q1 collector connected to Q2 collector, Q1 emitter connected to Q2 base. Acts as single transistor with greatly increased gain.

*Current Gain:*

$$\beta_{total} = \beta_1 \times \beta_2$$

For two transistors each with  $\beta = 100$ :  $\beta_{total} = 10,000$ . Extremely high current amplification.

*Voltage Relationships:*

Output voltage two diode drops below Zener reference:

$$V_{out} = V_Z - V_{BE1} - V_{BE2} \approx V_Z - 1.4V$$

To compensate, increase Zener voltage by 1.4V. For 10V desired output, use 11.4V Zener.

*Input Impedance:*

Emitter follower input impedance:  $Z_{in} \approx \beta(r_e + R_{load})$ . For Darlington:  $Z_{in} \approx \beta_1\beta_2(r_e + R_{load})$ . Extremely high, meaning negligible base current drawn from Zener reference.

*Benefits for Power Supply:*

- Base current reduced to  $I_C/\beta_{total}$ , e.g., 1A load with  $\beta_{total} = 1000$  requires only 1mA base current
- Ample current remains for Zener, ensuring operation above  $I_{Z,min}$  even under heavy load
- First transistor (Q1) must be power transistor handling high collector current
- Second transistor (Q2) can be small signal type (minimal current)
- Heat sink required for Q1 due to power dissipation:  $P = V_{CE} \times I_C$

### Noise Filtering:

Capacitor (e.g., 100 $\mu$ F) across Zener diode filters electrical noise generated during breakdown operation. Zener noise can appear as ripple on DC output; capacitor smooths this to clean DC.

### Design Considerations:

*Series Resistor Sizing:* Total current through series resistor = Zener current + base current. With Darlington, base current negligible, so  $I_{series} \approx I_Z$ . Choose  $R_{series}$  to provide 5-10mA Zener current at minimum input voltage.

*Current Limitations:* Despite high gain, output current ultimately limited by:

- Power transistor maximum collector current rating

- Power dissipation in transistor:  $P = (V_{in} - V_{out}) \times I_{out}$
- Heat sinking capability for power transistor

## Practical Example & Numerical

### Darlington Pair Current Amplification:

Design for 10V output, 1A maximum load current. Use 11.4V Zener (compensate for two  $V_{BE}$  drops), Darlington pair with  $\beta_1 = \beta_2 = 100$ .

Total current gain:  $\beta_{total} = 100 \times 100 = 10,000$ .

For 1A load current:

$$I_{base} = \frac{I_C}{\beta_{total}} = \frac{1A}{10,000} = 0.1mA = 100\mu A$$

With 10mA Zener current (ensuring good regulation), series resistor current:  $10mA + 0.1mA \approx 10mA$ .

For 50V input:

$$R_{series} = \frac{V_{in} - V_Z}{I_{series}} = \frac{50 - 11.4}{0.01} = 3.86k\Omega \approx 3.9k\Omega$$

Power in series resistor:

$$P_R = I^2 R = (0.01)^2 \times 3900 = 0.39W \text{ (use 0.5W or 1W resistor)}$$

Zener power:  $P_Z = 11.4 \times 0.01 = 0.114W$  (much less than before).

### Output Voltage Calculation:

With 11.4V Zener, output voltage:

$$V_{out} = V_Z - V_{BE1} - V_{BE2} = 11.4 - 0.7 - 0.7 = 10.0V$$

At  $10\Omega$  load:  $I_{load} = 10/10 = 1A$ . Circuit successfully delivers 1A at 10V.

For single transistor ( $\beta = 100$ ) at same load: base current would be  $1/100 = 10mA$ . With only 10mA total from series resistor, Zener would be starved. Darlington solves this problem.

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- Emitter follower (common collector) configuration: Zener at base, load at emitter, provides current gain
- Single transistor: output  $V_Z - V_{BE}$ , current gain  $\beta$ , reduces Zener dissipation dramatically
- Darlington pair: two transistors cascaded, total gain  $\beta_{total} = \beta_1 \times \beta_2$  (typically 1,000-10,000)
- Darlington output voltage:  $V_Z - 2V_{BE} \approx V_Z - 1.4V$ , compensate by increasing Zener voltage
- Extremely high input impedance reduces base current to microamps, even for ampere-level loads
- Series resistor can be large (3-10k $\Omega$ ), protecting Zener while maintaining load current capability
- First transistor must be power type (handles high  $I_C$ ), second can be small signal
- Heat sink essential for power transistor: dissipation  $P = (V_{in} - V_{out})I_{out}$
- Capacitor across Zener (100 $\mu F$ ) filters noise for clean DC output
- Limitation: output voltage not adjustable, fixed by Zener value minus diode drops

## Fully Adjustable Transistor Power Supply (1.3V - 50V, 10A)

### TL;DR (The Gist)

A complete adjustable linear power supply uses feedback control: potentiometer samples output voltage, Darlington pair compares to setpoint and controls pass transistors. Circuit topology: parallel power transistors (Q4, Q5) driven by control transistor (Q3), with feedback network (Q1, Q2 Darlington) pulling Q3 base low when output exceeds setpoint. Enables wide voltage range (1.3-50V) and high current (up to 10A) with voltage adjustment via single potentiometer.

## Detailed Explanation

## 2. Detailed Explanation

### Circuit Architecture:

*Input Stage:* AC mains (220V) → fuse (0.5A) → step-down transformer (220V:53V) → bridge rectifier (4 diodes) → large filter capacitor (C1, e.g., 10,000μF) → clean 52V DC.

Fuse rating calculation: Transformer power balance  $P_1 = P_2$ , so  $220 \times 0.5 = 53 \times I_2$ , giving  $I_2 \approx 2.08\text{A}$  secondary current maximum. Higher secondary current would require higher primary current, blowing fuse.

*Power Stage:* Two NPN power transistors (Q4, Q5) in parallel provide high output current capability. Parallel connection: emitters tied together to output, collectors tied to supply rail, bases driven together by control transistor Q3.

*Control Stage:* NPN transistor Q3 drives Q4/Q5 bases. Q3 collector connects to supply rail through diode D1, Q3 base receives control signal from feedback network. Diode D1 ensures Q3 operates in forward-active mode ( $V_C > V_B > V_E$ ) by creating voltage drop.

*Feedback Network:* Darlington pair (Q1, Q2) samples output voltage via potentiometer (R\_pot). When output voltage increases, voltage at Q2 base increases, turning Q2-Q1 on harder, pulling Q3 base toward ground. Lower Q3 base voltage reduces Q3 collector current, reducing Q4/Q5 base drive, lowering output voltage. This negative feedback stabilizes output.

### Detailed Operating Principle:

*Voltage Adjustment Mechanism:*

Potentiometer forms voltage divider across output:  $V_{Q2,base} = V_{out} \frac{R_2}{R_1 + R_2}$  where R1 and R2 are potentiometer segments.

- **Maximum output (50V):** Potentiometer set so Q2 base at minimum voltage ( $\approx 250\text{mV}$ ), Q1-Q2 barely conducting, Q3 base high (near supply rail minus D1 drop), Q3 drives Q4-Q5 hard, maximum output.
- **Minimum output (1.3V):** Potentiometer rotated so Q2 base at 1.3V, Q1-Q2 conduct heavily, pulling Q3 base near ground, Q3 barely conducts, Q4-Q5 barely on, 1.3V output.

Minimum voltage limit (1.3V) determined by Q3 operating requirements: if Q3 emitter (following output) drops below  $\approx 1.3\text{V}$ , Q3 base-emitter junction insufficiently forward biased, Q3 turns off, feedback loop broken.

*Current Flow Path:*

Supply (52V) → D1 → Q3 collector/base junction → Q3 emitter → Q4/Q5 bases → Q4/Q5 emitters → output load → ground. Current divides: portion through R1-R2 to limit Q3 current, majority through Q4-Q5 to load.

*Power Transistor Balancing:*

Transistors Q4 and Q5 never perfectly matched even if same part number. Without balancing, one transistor may conduct more current, leading to uneven heating and potential thermal runaway.

Small resistors (R4, R5, e.g., 0.1-0.5Ω, 5W) in series with each emitter balance current. If Q4 tries to conduct more current, larger voltage drop across R4 reduces Q4  $V_{BE}$ , throttling Q4 current. Self-balancing action distributes current evenly.

Resistor values kept very low to minimize voltage drop (wasted voltage reducing maximum output capability). Power rating must handle:  $P = I^2 R$ , e.g., 5A through 0.2Ω gives  $P = 25 \times 0.2 = 5\text{W}$ .

### Component Functions:

*R1, R2 (series with Q3 collector):* Limits current through Q3. Prevents excessive Q3 collector current when Q3 fully on. Typical values 100-470Ω.

*D1 (in Q3 collector path):* Creates 0.7V drop ensuring  $V_{C,Q3} > V_{B,Q3}$  for forward-active operation. Without D1, Q3 may saturate, losing linear control.

*C2 (across output):* Large capacitor (1000-10,000μF) smooths output voltage during rapid load current changes. If load suddenly demands high current, capacitor supplies energy while feedback loop adjusts. Without C2, output voltage may exhibit transient spikes/dips.

*R\_discharge (parallel with C2):* When power supply unplugged and no load connected, C2 remains charged to last set voltage (potentially 50V). R\_discharge (e.g., 330Ω, 5W) slowly discharges C2, preventing dangerous voltage at output terminals. Time constant:  $\tau = RC$ , e.g.,  $330 \times 0.01 = 3.3\text{s}$  for 10,000μF. Voltage decays to safe level in  $\approx 5\tau = 16.5\text{s}$ . Without R\_discharge: connecting new load rated for 10V to output still charged at 50V would destroy load.

### Current Limiting and Protection:

Circuit shown does not include current limiting. Real power supplies add current sense resistor in output path and comparator/transistor to limit maximum current. Without limiting, short circuit or overload can destroy pass transistors.

Maximum current determined by:

- Transformer secondary current capability (limited by primary fuse)
- Q4/Q5 maximum collector current ratings (check datasheet)
- Heat dissipation capability of transistors/heat sinks

For 10A output capability, Q4 and Q5 must each handle 5A continuous (with balancing). Power dissipation in each transistor:

$$P_{Q4} = (V_{in} - V_{out}) \times I_{Q4}$$

Worst case:  $V_{in} = 52\text{V}$ ,  $V_{out} = 1.3\text{V}$ ,  $I_{Q4} = 5\text{A}$ :  $P = 50.7 \times 5 = 253.5\text{W}$  per transistor! Requires substantial heat sinking or forced air cooling. At higher output voltages, dissipation lower.

### Feedback Loop Stability:

Negative feedback system can oscillate if loop gain too high or phase margin insufficient. C2 provides frequency compensation, reducing high-frequency gain and stabilizing loop. Value chosen empirically for stable operation across load range.

## Practical Example & Numerical

### Voltage Adjustment Calculation:

Potentiometer total resistance  $10k\Omega$ , output voltage  $50V$ .

For maximum output (Q2 base at  $250mV$  to keep Q1-Q2 barely on):

$$V_{Q2,base} = V_{out} \frac{R_2}{R_1 + R_2} = 50 \times \frac{50}{10000} = 0.25V$$

This means potentiometer set with  $R_1 = 9.95k\Omega$ ,  $R_2 = 50\Omega$ .

For minimum output (Q2 base at  $1.3V$  for full conduction):

$$1.3 = V_{out} \frac{R_2}{10k} \implies V_{out} = \frac{1.3 \times 10k}{R_2}$$

When output is  $1.3V$  and potentiometer adjusted so  $R_2 = 10k\Omega$  (fully rotated), feedback maintains  $1.3V$  output.

### Current Distribution in Parallel Transistors:

Q4 and Q5 each with  $\beta = 100$ , Q3 providing base drive.

For  $10A$  total output current ( $5A$  per transistor ideally):

$$I_{B,Q4} = I_{B,Q5} = \frac{5A}{100} = 50mA \text{ each}$$

Total base current from Q3:  $100mA$ . If Q3 has  $\beta = 100$ :

$$I_{B,Q3} = \frac{100mA}{100} = 1mA$$

Very small control current from feedback network controls high output current via cascaded gain.

### Power Dissipation Example:

Output set to  $10V$ , load draws  $5A$  ( $2.5A$  per transistor), input  $52V$ .

Voltage drop per transistor:  $V_{CE} = 52 - 10 = 42V$ .

Power per transistor:

$$P = V_{CE} \times I_C = 42 \times 2.5 = 105W$$

Total dissipation in both transistors:  $210W$ ! Linear regulation inherently inefficient at large voltage differences. Requires large heat sinks or active cooling.

Efficiency:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{10 \times 5}{52 \times 5} = \frac{50}{260} = 19.2\%$$

Majority of input power wasted as heat. Switching supplies achieve 80-95% efficiency in same scenario.

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- Fully adjustable supply uses negative feedback: output sampled by potentiometer, compared via Darlington pair
- Feedback controls pass transistors (Q4, Q5) via driver (Q3), stabilizing output voltage
- Input stage: fuse  $\rightarrow$  transformer  $\rightarrow$  bridge rectifier  $\rightarrow$  filter capacitor produces clean DC rail
- Fuse rating limits maximum output current via transformer power balance:  $V_1 I_1 = V_2 I_2$
- Parallel power transistors (Q4, Q5) increase current capability, require emitter resistors for current balancing
- Balancing resistors (R4, R5) small value ( $0.1-0.5\Omega$ ), high power ( $5W$ ), equalize transistor currents
- Diode D1 in Q3 collector ensures forward-active operation, prevents saturation
- Output capacitor C2 (large value) stabilizes voltage during transient load changes, provides frequency compensation
- Discharge resistor prevents C2 remaining charged when power removed, safety feature
- Minimum output voltage ( $1.3V$ ) limited by Q3 operating requirements, cannot reach near-zero
- Power dissipation worst at low output voltage, high current:  $P = (V_{in} - V_{out})I_{out}$

- Requires substantial heat sinking for power transistors, especially at low output voltages
- Linear regulation efficiency poor for large input-output voltage differences:  $\eta = V_{out}/V_{in}$
- Circuit as shown lacks current limiting; real designs add current sense and limit circuitry

## Split (Dual) Power Supply Design

### Dual-Rail Power Supply (+12V / -12V)

#### TL;DR (The Gist)

Split (dual) power supplies provide both positive and negative voltage rails with common ground, essential for circuits like op-amps requiring bipolar operation. Achieved using center-tapped transformer (two equal secondary windings with grounded center tap), two separate rectifier/filter stages, and positive/negative voltage regulators (78xx and 79xx series). Single transformer produces both rails simultaneously.

#### Detailed Explanation

### 2. Detailed Explanation

#### Center-Tapped Transformer:

Center-tapped transformer has primary winding and secondary with three terminals: two outer terminals and center tap.

*Voltage Relationship:* If total secondary voltage (across outer terminals) is  $V_{total}$ , then voltage from each outer tap to center =  $V_{total}/2$ , and these two voltages are  $180^\circ$  out of phase (opposite polarity).

Example: 24V center-tapped secondary measures 24V across outer taps, +12V AC from top tap to center, -12V AC from bottom tap to center (referenced to center tap at any instant).

*Physical Construction:* Primary typically has two wire leads, secondary has three wire leads where middle lead is center tap. Total turns on secondary split equally: if 240 turns total, 120 turns from top-to-center, 120 turns from center-to-bottom.

*Advantage:* Single transformer provides both positive and negative AC voltages for dual supply. Eliminates need for two separate transformers.

#### Dual Rectification and Filtering:

Each secondary half connected to separate full-bridge rectifier. Top secondary half → rectifier 1 → positive DC. Bottom secondary half → rectifier 2 → negative DC. Center tap connected to ground.

*Rectifier Configuration:* Two options:

- Two full-bridge rectifiers (4 diodes each, 8 diodes total): each half of secondary feeds bridge independently
- Single center-tap rectifier (2 diodes total): simpler but gives half-wave rectification on each rail, higher ripple

Full-bridge approach (shown in typical  $\pm 12V$  supply): 4 diodes for +12V rail, 4 diodes for -12V rail.

*Filter Capacitors:* Large electrolytic capacitors (e.g.,  $2200\mu F$ , 25V rating) smooth rectified voltage on each rail.

Connection: Positive capacitor between +DC and ground (positive terminal to +DC). Negative capacitor between ground and -DC (positive terminal to ground, negative terminal to -DC).

Both capacitors charge to approximately peak secondary voltage minus diode drops:  $V_{cap} \approx V_{rms} \times \sqrt{2} - 1.4V$ .

For 12V AC RMS secondary half:  $V_{cap} \approx 12 \times 1.414 - 1.4 \approx 15.6V$ . After filtering, unregulated  $\pm 16V$  DC approximately.

#### Voltage Regulation:

Unregulated DC varies with mains voltage and load current. Linear regulators maintain constant output.

*78xx Series (Positive Regulators):*

- Three-terminal IC: input, ground, output
- Naming: 78xx where xx = output voltage (7812 = +12V, 7805 = +5V, 7815 = +15V)
- Requires input voltage  $\geq$  output + 2-3V for dropout specification
- Example: 7812 requires  $\geq 14 - 15V$  input for +12V regulated output

*79xx Series (Negative Regulators):*

- Three-terminal IC: input, ground, output (ground is common reference)
- Naming: 79xx where xx = output voltage (7912 = -12V, 7905 = -5V)
- Input voltage must be more negative than output by 2-3V
- Example: 7912 requires  $\leq -14V$  input for -12V regulated output

*Regulation Action:* Both ICs maintain constant output voltage despite:

- Input voltage variations (mains fluctuations)
- Load current changes (voltage divider effect in unregulated supply)
- Temperature changes (internal compensation)

### Applications Requiring Dual Supplies:

*Operational Amplifiers:* Op-amps must amplify both positive and negative portions of AC signals. With single positive supply, output cannot swing below ground, clipping negative half of signal. Dual supply allows output to swing positive (toward +rail) and negative (toward -rail), preserving entire signal waveform.

*DC Motor Reversing:* Motor connected between +12V and -12V terminals (not ground). Applying +12V to one terminal, -12V to other gives 24V across motor in one polarity (clockwise rotation). Reversing connections gives opposite polarity, reversing motor direction (counterclockwise). Used in robotics, toys, bidirectional actuation.

*Audio Circuits:* Audio signals are AC (bipolar). Dual supplies allow biasing signal at ground (0V) and amplifying positive/negative excursions symmetrically without coupling capacitors.

### Safety and Grounding:

Center tap of transformer grounded establishes 0V reference. Both +12V and -12V measured with respect to this ground. Critical for safety: ground connection often bonded to chassis/earth for shock protection.

Without proper grounding, floating supply can develop dangerous voltages relative to earth ground, creating shock hazard.

### Power Ratings:

Diode ratings: Each diode must handle peak secondary current plus safety margin. For 2A output capability, use diodes rated  $\geq 6A$ , 400V (provides safety factor and handles surge currents during capacitor charging).

Capacitor ratings: Voltage rating must exceed peak rectified voltage. For  $\pm 12V$  supply with  $\approx 16V$  unregulated, use capacitors rated  $\geq 25V$  for safety margin.

Regulator IC ratings: 78xx/79xx series typically handle 1-1.5A continuous. For higher currents, use paralleling techniques or higher-current regulators (e.g., LM338 for 5A).

## Practical Example & Numerical

### Center-Tapped Transformer Voltage Calculation:

Transformer: 220V AC primary, 24V AC center-tapped secondary.

Voltage across outer taps: 24V AC RMS.

Voltage from top tap to center:  $24/2 = 12V$  AC RMS.

Voltage from bottom tap to center:  $24/2 = 12V$  AC RMS.

At any instant, if top tap is +12V relative to center, bottom tap is -12V relative to center ( $180^\circ$  phase difference).

After rectification and filtering: approximately  $12 \times \sqrt{2} - 1.4 = 15.6V$  DC on each rail.

### Dual Supply Output Calculation:

Unregulated rails: +16V and -16V DC (after capacitor filter).

Regulators: 7812 (+12V) and 7912 (-12V).

Regulated outputs:

- Positive rail: +12V DC relative to ground
- Negative rail: -12V DC relative to ground
- Voltage between positive and negative rails:  $12 - (-12) = 24V$  DC

Op-amp powered from  $\pm 12V$  supply can output signals ranging from approximately -11V to +11V (within rail limits), preserving bipolar waveforms.

### Motor Voltage Differential:

DC motor rated 12V, connected between +12V and -12V terminals (bypassing ground).

Voltage across motor:  $V_+ - V_- = 12 - (-12) = 24V$  DC.

Motor sees 24V, rotates clockwise (assuming polarity).

Reversing connections: motor positive to -12V rail, motor negative to +12V rail.

New voltage:  $-12 - 12 = -24V$  DC, motor rotates counterclockwise.

Caution: Motor must be rated for 24V operation, or use lower voltage dual supply (e.g.,  $\pm 6V$  for 12V motor).

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- Dual (split) power supply provides positive and negative voltage rails with common ground
- Center-tapped transformer produces two equal AC voltages  $180^\circ$  out of phase from single secondary
- Voltage from each outer tap to center tap = (total secondary voltage) / 2
- Two separate rectifier/filter stages process each secondary half independently
- Filter capacitors: positive cap between +DC and ground, negative cap between ground and -DC
- 78xx series ICs regulate positive voltages (7805 = +5V, 7812 = +12V, 7815 = +15V)
- 79xx series ICs regulate negative voltages (7905 = -5V, 7912 = -12V, 7915 = -15V)
- Voltage regulators maintain constant output despite input variations, load changes, temperature drift

- Op-amps require dual supplies to amplify bipolar signals without clipping negative excursions
- DC motors can reverse direction using dual supplies (swap terminal connections to reverse polarity)
- Center tap grounded for safety, establishes 0V reference for both positive and negative rails
- Diode current rating must include safety margin for surge currents during capacitor charging
- Capacitor voltage rating must exceed peak rectified voltage:  $V_{peak} \approx V_{rms} \times 1.414 - 1.4$
- For higher output currents, use paralleled regulators or higher-current regulator ICs (LM338, etc.)

# Section 24 – Operational Amplifier (Op-Amp) - Fundamentals

This section introduces the operational amplifier (op-amp), one of the most essential analog building blocks in electronics. We cover op-amp operation principles, the two golden rules for circuit analysis, fundamental configurations (comparator, buffer, non-inverting and inverting amplifiers), and practical limitations including gain-bandwidth product. Understanding these fundamentals enables design of amplifiers, filters, signal conditioners, and mathematical operation circuits.

## Op-Amp Basics and Buffer Configurations

### Op-Amp Introduction and Comparator Operation

#### TL;DR (The Gist)

An operational amplifier (op-amp) is a high-gain DC differential amplifier with two inputs (inverting  $-$  and non-inverting  $+$ ) and one output. Open-loop gain is extremely large ( $10^5$  to  $10^6$ ), making direct use impractical. In open-loop configuration without feedback, op-amp acts as comparator: output swings to positive rail when  $V_+ > V_-$ , negative rail when  $V_- > V_+$ . Requires dual power supply ( $\pm V_{CC}$ ) for bipolar operation.

#### Detailed Explanation

### 2. Detailed Explanation

#### Historical Context and Naming:

Operational amplifiers developed originally for analog computers performing mathematical operations (addition, subtraction, integration, differentiation, calculus) in hardware before digital computers existed. Name derives from this operational capability. While modern systems use digital computation, op-amps remain essential for analog signal processing, amplification, and mathematical operations in hardware.

#### Basic Structure and Terminology:

Op-amp has differential input stage with two input terminals:

- **Non-inverting input ( $+$ ):** Positive input terminal, output in-phase with this input
- **Inverting input ( $-$ ):** Negative input terminal, output out-of-phase (inverted) relative to this input
- **Output:** Single-ended output terminal
- **Power supply pins ( $V_+$ ,  $V_-$ ):** Dual supply required (e.g.,  $\pm 15V$ ), often omitted from schematics for clarity but always necessary in actual circuits

Internal architecture: Differential amplifier input stage (transistor pair Q1, Q2) followed by emitter follower output stage (Q3) providing low output impedance. Practical op-amp circuits (e.g., 741) contain complex circuitry with many transistors, resistors, compensation networks. Simplified models sufficient for circuit analysis using golden rules.

#### Open-Loop Gain:

Open-loop gain ( $A_{OL}$ ) is natural internal gain without feedback, enormously large: typically  $10^5$  to  $10^6$  or higher. Datasheets often don't specify exact value because it varies widely with temperature, supply voltage, manufacturing variations. Safe to assume infinite for analysis purposes.

Fundamental voltage relationship (open-loop):

$$V_{out} = A_{OL}(V_+ - V_-)$$

Where  $V_+$  is voltage at non-inverting input,  $V_-$  is voltage at inverting input. Due to massive gain, even millivolt differences between inputs drive output to saturation (rail limits).

#### Comparator Operation (Open-Loop Configuration):

Without feedback loop (open-loop), op-amp compares two input voltages and outputs digital-like signal:

Case 1:  $V_+ > V_-$  (non-inverting input higher):

$$V_{out} = +V_{sat} \approx +V_{CC}$$

Output swings to positive supply rail (e.g.,  $+15V$  for  $\pm 15V$  supply).

Case 2:  $V_- > V_+$  (inverting input higher):

$$V_{out} = -V_{sat} \approx -V_{CC}$$

Output swings to negative supply rail (e.g.,  $-15V$ ).

Case 3:  $V_+ = V_-$  (inputs equal):

$$V_{out} = A_{OL} \times 0 = 0V \text{ (ideally)}$$

In practice, output near zero but slight offset voltage may exist.

Small input differences rapidly drive output to maximum/minimum due to enormous gain. Example: With  $A_{OL} = 100,000$  and  $V_+ - V_- = 0.1\text{mV}$ :

$$V_{out} = 100,000 \times 0.0001 = 10\text{V}$$

If rails are  $\pm 15\text{V}$ , output achieves 10V. If difference were 1mV, calculated output would be 100V, but actual output saturates at rail voltage (15V).

#### Comparator Limitations:

Op-amps can function as comparators but aren't optimal. Dedicated comparator ICs designed specifically for comparison offer:

- Faster switching speeds (op-amps not optimized for saturated operation)
- Better-defined output levels compatible with digital logic
- No phase compensation (intentionally fast switching)
- Open-collector or push-pull outputs suitable for various applications

Op-amps used as comparators acceptable in non-critical applications but proper comparator ICs preferred for precision threshold detection, fast digital interfacing, or high-speed applications.

#### Power Supply Requirements:

Most op-amps require dual (split) power supply: positive rail ( $+V_{CC}$ , e.g.,  $+15\text{V}$ ) and negative rail ( $-V_{CC}$ , e.g.,  $-15\text{V}$ ) relative to ground. This allows:

- Output swing through zero (both positive and negative voltages)
- Amplification of AC signals without clipping
- Bipolar operation essential for many applications

Single-supply op-amps exist (discussed in later topics) where negative rail connected to ground, requiring biasing techniques for AC signals.

#### Why Open-Loop Impractical:

Enormous open-loop gain makes op-amp unusable as standalone amplifier. Gain unstable (varies with temperature, supply voltage, device-to-device), output saturates with tiniest input differences, no control over amplification factor. Solution: negative feedback, transforming op-amp into controlled, stable, predictable amplifier.

### Practical Example & Numerical

#### Comparator Output Calculation:

Op-amp with open-loop gain  $A_{OL} = 100,000$ , powered by  $\pm 15\text{V}$  supply.

*Scenario 1:*  $V_+ = 3\text{V}$ ,  $V_- = 4\text{V}$ .

Difference:  $V_+ - V_- = 3 - 4 = -1\text{V}$ .

Calculated output:  $V_{out} = 100,000 \times (-1) = -100,000\text{V}$ .

Actual output:  $V_{out} = -15\text{V}$  (saturated at negative rail, cannot exceed supply).

*Scenario 2:*  $V_+ = 2.001\text{V}$ ,  $V_- = 2.000\text{V}$ .

Difference:  $0.001\text{V} = 1\text{mV}$ .

Calculated output:  $V_{out} = 100,000 \times 0.001 = 100\text{V}$ .

Actual output:  $V_{out} = +15\text{V}$  (saturated at positive rail).

Even 1mV difference produces saturation. This demonstrates why open-loop gain makes op-amp function as comparator: output binary (at one rail or the other) for almost any input difference.

#### Threshold Detection Application:

Temperature sensor outputs 0-5V ( $0\text{V} = 0^\circ\text{C}$ ,  $5\text{V} = 100^\circ\text{C}$ ). Want LED to turn on when temperature exceeds  $50^\circ\text{C}$  (2.5V).

Circuit: Sensor voltage to  $V_+$ , reference 2.5V (from voltage divider) to  $V_-$ . Output drives LED (through current-limiting resistor).

When  $T < 50^\circ\text{C}$ : sensor voltage  $< 2.5\text{V}$ , so  $V_+ < V_-$ , output at  $-15\text{V}$  (LED off).

When  $T > 50^\circ\text{C}$ : sensor voltage  $> 2.5\text{V}$ , so  $V_+ > V_-$ , output at  $+15\text{V}$  (LED on).

Simple threshold detector using op-amp as comparator.

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

- Op-amp is high-gain differential amplifier:  $V_{out} = A_{OL}(V_+ - V_-)$
- Two inputs: non-inverting (+) and inverting (-); output in-phase with non-inverting input
- Open-loop gain enormous ( $10^5$  to  $10^6$ ), varies widely, considered infinite for analysis
- Requires dual power supply ( $\pm V_{CC}$ ) for bipolar output swing

- Open-loop configuration (no feedback): op-amp functions as comparator
- Comparator output saturates at supply rails:  $+V_{CC}$  when  $V_+ > V_-$ ,  $-V_{CC}$  when  $V_- > V_+$
- Op-amp internal structure: differential input stage, high-gain amplifier, emitter follower output
- Direct use as amplifier impractical due to unstable, uncontrolled massive gain
- Named "operational amplifier" for historical role in analog computers performing math operations
- Dedicated comparator ICs superior to op-amps for comparison applications (faster, better output levels)

## Voltage Follower (Buffer) and Current Boosting

### TL;DR (The Gist)

Op-amp buffer (voltage follower) configured with output directly connected to inverting input, signal applied to non-inverting input. Output equals input ( $V_{out} = V_{in}$ , unity gain) but provides impedance transformation: extremely high input impedance (minimal loading on source) and low output impedance (can drive loads). Essential for interfacing high-impedance sources to low-impedance loads. Current capacity increased by adding emitter follower transistor in feedback loop.

### Detailed Explanation

## 2. Detailed Explanation

### The Two Golden Rules of Op-Amps:

These rules enable analysis of virtually any op-amp circuit operating in linear region:

*Rule 1: No current flows into or out of the inputs.*

Op-amp input impedance extremely high (megohms to teraohms), so input currents negligible (picoamps to nanoamps).

For analysis purposes, assume zero input current:

$$I_{in+} = I_{in-} = 0$$

This rule applies to ALL op-amp configurations (open-loop, closed-loop, inverting, non-inverting).

*Rule 2: Op-amp adjusts output to make both inputs equal voltage.*

When negative feedback present (closed-loop configuration), op-amp drives output voltage to whatever value necessary to equalize voltages at two inputs:

$$V_+ = V_-$$

Critical: Rule 2 ONLY applies with negative feedback (closed-loop). Does NOT apply to open-loop (comparator) configuration where inputs can differ.

These two simple rules sufficient to analyze gain, impedance, behavior of most op-amp circuits without complex internal analysis.

### Buffer (Voltage Follower) Configuration:

Simplest closed-loop configuration: output connected directly to inverting input (wire connection,  $R_f = 0$ ), signal applied to non-inverting input.

*Circuit Analysis Using Golden Rules:*

Given: Input voltage  $V_{in}$  applied to  $V_+$  terminal.

From Rule 2 (negative feedback present):  $V_- = V_+$ , so  $V_- = V_{in}$ .

Since output directly connected to inverting input:  $V_{out} = V_-$ .

Therefore:

$$V_{out} = V_{in}$$

Unity gain: output voltage exactly follows input voltage. Hence names "voltage follower" or "buffer".

From Rule 1: No current flows into either input. Input impedance appears infinite to source. Source not loaded.

Output impedance very low (ohms), can source/sink tens of milliamps. Can drive low-impedance loads without voltage drop.

### Purpose and Applications of Buffering:

*Impedance Transformation Problem:*

Voltage divider example: Two  $10k\Omega$  resistors divide 10V to produce 5V at junction. When  $100\Omega$  load connected:

Parallel combination:  $R_{eq} = \frac{10k \times 100}{10k + 100} \approx 99\Omega$  (bottom resistor in parallel with load).

New divider ratio:  $V_{out} = 10 \times \frac{99}{10000 + 99} \approx 0.098V$ .

Output collapses from 5V to 98mV! Voltage divider cannot supply current without severe voltage drop.

*Buffer Solution:*

Insert op-amp buffer between voltage divider and load. Op-amp input draws zero current (Rule 1), so divider sees no load, maintains 5V. Op-amp output drives  $100\Omega$  load with 5V, sourcing required 50mA from power supply (not from divider).

Load receives full 5V despite low impedance, source not perturbed.

### Input and Output Impedance Characteristics:

*Input Impedance:* Extremely high, typically:

- BJT input op-amps:  $10^6$  to  $10^9\Omega$  (megohms to gigohms)
- FET input op-amps:  $10^{12}$  to  $10^{14}\Omega$  (teraohms)

Input current negligible: nanoamps (nA) for BJT types, picoamps (pA) for FET types. Source not loaded.

*Output Impedance:* Very low, typically  $10\text{-}100\Omega$  in open-loop, approaching zero with feedback. Can drive loads of hundreds of ohms to kilohms without significant voltage drop.

### Current Sourcing Limitations:

Typical op-amp output current: 20-40mA continuous. Some op-amps handle up to 100mA, others limited to 10mA. Check datasheet for maximum output current specification.

If load requires more current than op-amp can provide, op-amp enters current limiting or may be damaged. Output voltage sags if current demand exceeds capability.

### Increasing Buffer Current with Transistor:

For loads requiring hundreds of milliamps or amps, add NPN power transistor to buffer circuit:

*Configuration:* Op-amp output drives transistor base, transistor collector connects to positive supply, emitter provides output to load. Feedback taken from emitter back to op-amp inverting input.

*Operation:* Op-amp provides small base current (few milliamps), transistor amplifies by  $\beta$  (typically 50-200), emitter sources large load current (hundreds of mA to amps). Load current supplied from power supply via transistor, not from op-amp.

*Base-Emitter Drop Compensation:* Without feedback from emitter, output voltage  $V_{out} = V_{in} - V_{BE} \approx V_{in} - 0.7V$ . Fixed voltage drop error.

With feedback from emitter to inverting input: Rule 2 forces  $V_- = V_+$ . Since  $V_-$  = emitter voltage and  $V_+ = V_{in}$ , emitter voltage equals  $V_{in}$ . Op-amp automatically increases its output (base voltage) to  $V_{in} + 0.7V$  to compensate for  $V_{BE}$  drop. Result:  $V_{out} = V_{in}$  accurately.

Transistor must be power type to handle high currents, requires heat sinking for power dissipation:  $P = (V_{CC} - V_{out}) \times I_{load}$ .

## Practical Example & Numerical

### Voltage Divider Loading Problem:

Two  $10k\Omega$  resistors divide 10V supply. Unloaded output:  $V_{out} = 10 \times \frac{10k}{20k} = 5V$ .

Load impedance  $100\Omega$  connected to output.

Effective bottom resistance:  $R_{parallel} = \frac{10k \times 100}{10k + 100} = \frac{1,000,000}{10,100} = 99.01\Omega$ .

Loaded output:

$$V_{out} = 10 \times \frac{99.01}{10,000 + 99.01} = 10 \times 0.0098 = 0.098V = 98mV$$

Output drops 98% from desired value! Load current:  $I = 0.098/100 = 0.98mA$ .

For load to receive 5V at  $100\Omega$ : requires 50mA current. Divider cannot provide without massive voltage drop.

### Buffer Solution:

Insert op-amp buffer: divider output to non-inverting input, load to op-amp output.

Op-amp input current: 0A (Rule 1). Divider maintains 5V (no loading).

Op-amp output: 5V (Rule 2,  $V_{out} = V_{in}$ ).

Load current:  $5/100 = 50mA$ , sourced from op-amp output.

Op-amp draws 50mA from power supply, delivers to load. Divider unperturbed, load receives full 5V.

### Current-Boosted Buffer Calculation:

Load requires 500mA at 5V (e.g.,  $10\Omega$  load). Op-amp maximum output 40mA (insufficient).

Add NPN transistor:  $\beta = 100$ ,  $V_{BE} = 0.8V$ . Feedback from emitter to op-amp inverting input.

For 500mA emitter current: base current  $I_B = 500/100 = 5mA$  (within op-amp capability).

Without feedback compensation: emitter voltage =  $5 - 0.8 = 4.2V$  (error).

With feedback: Rule 2 forces emitter at 5V. Op-amp output (base) automatically rises to  $5 + 0.8 = 5.8V$ . Transistor emitter delivers 5V precisely, load receives 500mA.

Power dissipation in transistor (assuming 12V supply):  $P = (12 - 5) \times 0.5 = 3.5W$ . Requires heat sink.

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- Golden Rule 1: No current flows into or out of op-amp inputs ( $I_{in} = 0$ ), applies to all configurations
- Golden Rule 2: Op-amp makes both inputs equal voltage ( $V_+ = V_-$ ), applies ONLY with negative feedback

- Buffer configuration: output connected to inverting input, signal to non-inverting input
- Buffer provides unity gain:  $V_{out} = V_{in}$ , voltage follower action
- Input impedance extremely high (gigohms to teraohms), output impedance very low (ohms)
- Buffer isolates high-impedance sources from low-impedance loads, prevents source loading
- Typical op-amp output current: 20-40mA, some up to 100mA, check datasheet for limits
- Current-booster buffer: add power transistor, feedback from emitter compensates  $V_{BE}$  drop
- Transistor feedback ensures  $V_{out} = V_{in}$  despite base-emitter voltage drop
- Applications: sensor interfacing, driving loads from voltage dividers, impedance matching, signal isolation

## Amplifier Configurations

### Non-Inverting Amplifier

#### TL;DR (The Gist)

Non-inverting amplifier applies input signal to non-inverting input, uses voltage divider (feedback resistor  $R_f$  and ground resistor  $R_1$ ) in feedback path to inverting input. Output in-phase with input. Voltage gain:  $A_v = 1 + R_f/R_1$ . Always gain  $\geq 1$ . High input impedance (like buffer), suitable for AC or DC signals. Feedback reduces enormous open-loop gain to stable, predictable closed-loop gain.

#### Detailed Explanation

### 2. Detailed Explanation

#### Circuit Configuration:

Non-inverting amplifier topology:

- Input signal applied to non-inverting input ( $V_+$ )
- Feedback resistor  $R_f$  connects output to inverting input ( $V_-$ )
- Resistor  $R_1$  connects inverting input to ground
- $R_f$  and  $R_1$  form voltage divider sampling fraction of output voltage

#### Gain Derivation Using Golden Rules:

Voltage divider at inverting input creates:

$$V_- = V_{out} \frac{R_1}{R_1 + R_f}$$

From Rule 2 (negative feedback):  $V_- = V_+$ , and input applied to  $V_+$ , so:

$$V_{in} = V_{out} \frac{R_1}{R_1 + R_f}$$

Solving for  $V_{out}/V_{in}$ :

$$\frac{V_{out}}{V_{in}} = \frac{R_1 + R_f}{R_1} = 1 + \frac{R_f}{R_1}$$

Non-inverting amplifier voltage gain:

$$A_v = 1 + \frac{R_f}{R_1}$$

Note the +1 term (absent in inverting amplifier formula). Minimum gain is 1 (when  $R_f = 0$ , unity-gain buffer).

#### Example Calculation:

$R_f = 9k\Omega$ ,  $R_1 = 1k\Omega$ :

$$A_v = 1 + \frac{9k}{1k} = 1 + 9 = 10$$

For  $V_{in} = 1V$ :  $V_{out} = 10 \times 1 = 10V$ .

For  $V_{in} = -1V$  (with dual supply):  $V_{out} = 10 \times (-1) = -10V$ .

#### Why "Non-Inverting":

Output signal in-phase with input signal ( $0^\circ$  phase shift). Positive input produces positive output, negative input produces negative output. Signal not inverted.

For AC signals: input and output waveforms aligned in time, peaks and troughs coincide. Contrasts with inverting amplifier ( $180^\circ$  phase shift).

#### Characteristics and Advantages:

**Input Impedance:** Extremely high (like buffer). Input current negligible due to Rule 1. Suitable for high-impedance sources (sensors, microphones, pickups) that cannot supply significant current.

**Output Impedance:** Very low (ohms). Can drive low-impedance loads.

**Gain Range:** Always  $\geq 1$ . Cannot provide attenuation (gain  $< 1$ ). For gain exactly 1, use buffer ( $R_f = 0$  or short).

**Common-Mode Rejection:** Non-inverting input referenced to ground through source impedance. Good common-mode rejection ratio (CMRR) rejects noise on both inputs.

**Stability:** Negative feedback via voltage divider stabilizes gain, reduces sensitivity to open-loop gain variations, temperature drift, supply voltage changes. Closed-loop gain determined almost entirely by external resistors (precision, stable).

#### AC and DC Compatibility:

Op-amp is DC-coupled: can amplify both DC and AC signals without modification. For AC signals with dual supply ( $\pm V_{CC}$ ), no biasing required. AC waveform swings positive and negative around ground, output follows with gain applied.

For single-supply operation (covered in later topic), AC signals require biasing to mid-supply to prevent clipping.

#### Resistor Selection:

Choose  $R_1$  typically  $1k\Omega$  to  $100k\Omega$ . Too low wastes current (output sources more current through divider). Too high increases noise sensitivity and input bias current errors.

$R_f$  calculated from desired gain:  $R_f = R_1(A_v - 1)$ .

Use precision resistors (1% or better) for accurate, stable gain.

### Practical Example & Numerical

#### Non-Inverting Amplifier Design:

Design amplifier with gain of 5 for audio application.

Gain formula:  $A_v = 1 + R_f/R_1 = 5$ .

Solving:  $R_f/R_1 = 4$ , so  $R_f = 4R_1$ .

Choose  $R_1 = 10k\Omega$  (reasonable value for audio):

$$R_f = 4 \times 10k = 40k\Omega$$

Use standard value  $R_f = 39k\Omega$  (closest), actual gain:

$$A_v = 1 + \frac{39k}{10k} = 1 + 3.9 = 4.9$$

Slightly lower than target but acceptable. For precision, use  $40k\Omega$  exactly (may require series/parallel combination or trim pot).

#### AC Signal Amplification:

Input: 1V peak-to-peak sine wave, 1kHz. Gain = 10 ( $R_f = 9k$ ,  $R_1 = 1k$ ).

Output: 10V peak-to-peak sine wave, 1kHz.

Input swings  $\pm 0.5V$  around ground. Output swings  $\pm 5V$  around ground. Waveforms in-phase.

With  $\pm 15V$  supply, output easily accommodates  $\pm 5V$  swing (well within rails).

#### Buffer as Special Case:

Buffer is non-inverting amplifier with  $R_f = 0$  (short circuit),  $R_1 = \infty$  (open circuit, or absent).

Gain:  $A_v = 1 + 0/\infty = 1 + 0 = 1$ . Unity gain confirmed by formula.

Alternatively, direct connection (wire) from output to inverting input means  $R_f = 0$ :  $A_v = 1 + 0/R_1 = 1$  regardless of  $R_1$  value.

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

- Non-inverting amplifier: input to non-inverting terminal, feedback to inverting terminal via voltage divider
- Voltage gain:  $A_v = 1 + R_f/R_1$ , always  $\geq 1$  (minimum unity gain)
- Output in-phase with input ( $0^\circ$  phase shift), hence "non-inverting"
- High input impedance (megohms to gigohms), suitable for high-impedance sources
- Low output impedance (ohms), can drive low-impedance loads
- Stable gain determined by external resistor ratio, independent of open-loop gain variations
- Buffer is special case:  $R_f = 0$ , gain = 1
- Can amplify AC or DC signals without modification (DC-coupled)
- Negative feedback reduces gain from enormous open-loop value to controlled closed-loop value

- Resistor selection:  $R_1$  typically 1k-100k $\Omega$ ,  $R_f = R_1(A_v - 1)$  for desired gain

## Inverting Amplifier and Single-Supply Operation

### TL;DR (The Gist)

Inverting amplifier applies input signal through resistor  $R_{in}$  to inverting input, non-inverting input grounded. Output inverted (180° phase shift) relative to input. Voltage gain:  $A_v = -R_f/R_{in}$  (negative sign indicates inversion). Virtual ground at inverting input node: appears at ground potential but no current flows to ground. For single-supply operation, bias non-inverting input to mid-supply via voltage divider, adds DC offset to output.

### Detailed Explanation

## 2. Detailed Explanation

### Circuit Configuration:

Inverting amplifier topology:

- Input signal applied through resistor  $R_{in}$  to inverting input ( $V_-$ )
- Non-inverting input ( $V_+$ ) connected to ground (or bias voltage for single supply)
- Feedback resistor  $R_f$  connects output to inverting input
- Input resistor  $R_{in}$  and feedback resistor  $R_f$  determine gain

### Virtual Ground Concept:

Critical concept for inverting amplifier analysis. Non-inverting input grounded (0V). From Rule 2 (negative feedback), op-amp forces inverting input to equal non-inverting input:

$$V_- = V_+ = 0V$$

Inverting input node at 0V (ground potential) BUT from Rule 1, no current flows into inverting input pin. Current cannot flow to ground through this node. Node called "virtual ground": at ground voltage but not actually connected to ground, no current path to ground.

Confusing initially: measuring inverting input node with voltmeter shows 0V, yet input signal "disappears" across  $R_{in}$ . Signal voltage dropped entirely across  $R_{in}$  because far end at virtual ground (0V).

### Gain Derivation Using Golden Rules:

Input voltage  $V_{in}$  applied through  $R_{in}$ . Virtual ground at inverting input (0V).

Voltage across  $R_{in}$ :  $V_{in} - 0 = V_{in}$ .

Current through  $R_{in}$  (by Ohm's law):

$$I_{in} = \frac{V_{in}}{R_{in}}$$

From Rule 1: No current flows into inverting input pin. From Kirchhoff's current law: current through  $R_{in}$  must continue through  $R_f$  (nowhere else to go).

So:  $I_f = I_{in} = V_{in}/R_{in}$ .

Voltage across  $R_f$ :  $V_f = I_f \times R_f = \frac{V_{in}}{R_{in}} \times R_f$ .

One end of  $R_f$  at virtual ground (0V), other end at output. Voltage across  $R_f$  from ground to output:

$$V_{out} - 0 = -V_f$$

(Negative because current flows from output toward virtual ground, making output negative when input positive.)

Therefore:

$$V_{out} = -\frac{R_f}{R_{in}} V_{in}$$

Inverting amplifier voltage gain:

$$A_v = -\frac{R_f}{R_{in}}$$

Negative sign indicates inversion. Note: no +1 term (unlike non-inverting). Gain magnitude can be less than, equal to, or greater than 1.

### Phase Inversion:

Output 180° out of phase with input. Positive input produces negative output, negative input produces positive output.

For AC signals: when input at positive peak, output at negative peak. When input at zero crossing rising, output at zero crossing falling. Complete inversion.

Example:  $V_{in} = +1V$ ,  $R_{in} = 1k$ ,  $R_f = 10k$ .

$$V_{out} = -\frac{10k}{1k} \times 1 = -10V$$

Input positive, output negative. Gain magnitude 10, sign indicates inversion.

#### Input Impedance Difference:

Unlike non-inverting amplifier, inverting amplifier input impedance NOT extremely high. Input impedance approximately equal to  $R_{in}$  because input applied to virtual ground (low impedance point).

For  $R_{in} = 1k\Omega$ , input impedance  $\approx 1k\Omega$ . Source must be able to drive this impedance. Not suitable for high-impedance sources without buffering.

Trade-off: Gain can be less than 1 (attenuation possible), but input impedance lower.

#### Single-Supply Operation:

Inverting amplifier with dual supply ( $\pm V_{CC}$ ): non-inverting input grounded, output swings positive and negative around ground.

With single supply (e.g.,  $+V_{CC}$ , ground): negative rail at ground (0V). Output cannot swing below ground. AC signals clipped at negative half-cycle.

*Solution: Bias Non-Inverting Input to Mid-Supply*

Connect non-inverting input to  $V_{CC}/2$  via voltage divider (two equal resistors from  $V_{CC}$  to ground).

From Rule 2: Virtual ground becomes  $V_{CC}/2$  instead of 0V.

Output biased to  $V_{CC}/2$  with no input signal. AC input signal adds to this bias, output swings symmetrically above and below  $V_{CC}/2$ .

Example:  $+12V$  single supply. Bias non-inverting input to 6V. With AC input signal  $\pm 1V$  and gain of 3, output swings  $6 \pm 3V$  (3V to 9V range), staying within 0-12V rails.

*DC Blocking Capacitor:*

Input AC signal coupled through capacitor in series with  $R_{in}$ . Capacitor blocks DC component, passes AC. Prevents DC input from shifting bias point.

Output may require DC blocking capacitor to following stage to remove  $V_{CC}/2$  offset, passing only AC component.

Capacitor values chosen based on lowest frequency of interest:  $C \geq 1/(2\pi f_{low} R_{in})$  for input coupling.

### Practical Example & Numerical

#### Inverting Amplifier Calculation:

$R_{in} = 1k\Omega$ ,  $R_f = 3k\Omega$ ,  $V_{in} = +2V$ .

Gain:  $A_v = -R_f/R_{in} = -3k/1k = -3$ .

Output:  $V_{out} = -3 \times 2 = -6V$ .

Current through  $R_{in}$ :  $I = 2/1k = 2mA$ .

Current through  $R_f$ : same 2mA (Rule 1, no current into op-amp).

Voltage across  $R_f$ :  $V = 2mA \times 3k = 6V$ .

Since inverting input at virtual ground (0V) and output side of  $R_f$  must drop 6V, output at  $-6V$ . Confirms calculation.

#### Single-Supply AC Amplifier:

Design inverting amplifier for audio, gain = -5, single  $+12V$  supply.

Bias: Non-inverting input to  $12/2 = 6V$  via two  $10k\Omega$  resistors (voltage divider).

Virtual ground now at 6V. Output biased to 6V with no input.

Gain:  $R_f/R_{in} = 5$ . Choose  $R_{in} = 10k$ ,  $R_f = 50k$ .

Input: 1V peak AC signal (0.5V amplitude,  $\pm 0.5V$  swing) coupled through capacitor.

AC output:  $0.5 \times (-5) = -2.5V$  amplitude swing around 6V bias.

Output voltage range:  $6 - 2.5 = 3.5V$  (negative peak) to  $6 + 2.5 = 8.5V$  (positive peak).

Stays within 0-12V rails, no clipping. AC signal inverted ( $180^\circ$  phase shift) and amplified.

Input coupling capacitor (for 20Hz audio):  $C \geq 1/(2\pi \times 20 \times 10k) \approx 0.8\mu F$ . Use  $1\mu F$  or  $10\mu F$ .

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

- Inverting amplifier: input via  $R_{in}$  to inverting terminal, non-inverting terminal grounded (or biased)
- Voltage gain:  $A_v = -R_f/R_{in}$ , negative sign indicates  $180^\circ$  phase inversion
- Gain magnitude can be  $< 1$ ,  $= 1$ , or  $> 1$  (attenuation, unity, or amplification)
- Virtual ground: inverting input at ground potential (or bias voltage) but no current flows to ground
- Input impedance approximately  $R_{in}$ , not extremely high like non-inverting configuration
- Current through  $R_{in}$  equals current through  $R_f$  (Rule 1: no current into op-amp input)

- Output inverted: positive input  $\rightarrow$  negative output, negative input  $\rightarrow$  positive output
- Single-supply operation requires biasing non-inverting input to mid-supply ( $V_{CC}/2$ )
- DC blocking capacitors required for AC coupling in single-supply circuits
- Output in single-supply has DC offset ( $V_{CC}/2$ ), AC component superimposed on bias

## Bandwidth and Frequency Limitations

### Gain-Bandwidth Product and Frequency Response

#### TL;DR (The Gist)

Practical op-amps have limited bandwidth: gain decreases at higher frequencies due to internal frequency compensation (stabilizes op-amp against oscillation). Gain-Bandwidth Product (GBW or GBWP) is constant: product of closed-loop gain and bandwidth frequency.  $GBW$  = frequency where open-loop gain becomes unity (gain = 1). For closed-loop amplifier:  $BW = GBW/A_v$ . Higher gain reduces bandwidth; lower gain increases bandwidth. Trade-off between gain and frequency response.

#### Detailed Explanation

### 2. Detailed Explanation

#### Ideal vs. Practical Frequency Response:

Ideal op-amp: infinite bandwidth, amplifies all frequencies from DC to arbitrarily high frequencies with constant gain. Frequency-independent.

Practical op-amp: Bandwidth limited. Open-loop gain constant only at very low frequencies (typically below 10Hz), then decreases linearly (20dB/decade) as frequency increases. Frequency compensation built into most op-amps ensures stability but limits bandwidth.

#### Open-Loop Frequency Response:

Open-loop gain vs. frequency (Bode plot):

- Low frequencies (DC to  $\approx 10\text{Hz}$ ): Gain constant at maximum ( $A_{OL} \approx 10^5$  to  $10^6$ )
- Above breakpoint frequency: Gain decreases at 20dB/decade (factor of 10 per decade of frequency)
- Unity-gain frequency ( $f_t$  or  $f_{GBW}$ ): Frequency where open-loop gain = 1 (0dB)

For popular 741 op-amp:  $A_{OL} \approx 100,000$  at DC, unity-gain frequency  $\approx 1\text{MHz}$ .

At 100kHz: gain dropped to  $\approx 10$ . At 1MHz: gain = 1.

#### Gain-Bandwidth Product Definition:

GBW (or GBWP) is constant for a given op-amp, equal to unity-gain frequency:

$$GBW = A_v \times BW$$

Where  $A_v$  is closed-loop voltage gain (magnitude),  $BW$  is -3dB bandwidth (frequency where gain drops to 70.7% of maximum, or -3dB).

GBW also called unity-gain bandwidth, gain-bandwidth product, or  $f_t$  (transition frequency).

#### Bandwidth Calculation:

For closed-loop amplifier with gain  $A_v$ , bandwidth:

$$BW = \frac{GBW}{A_v}$$

Higher gain  $\rightarrow$  lower bandwidth. Lower gain  $\rightarrow$  higher bandwidth.

Example: Op-amp with  $GBW = 1\text{MHz}$ .

- Gain = 1 (buffer):  $BW = 1\text{MHz}/1 = 1\text{MHz}$  (full bandwidth)
- Gain = 10:  $BW = 1\text{MHz}/10 = 100\text{kHz}$
- Gain = 100:  $BW = 1\text{MHz}/100 = 10\text{kHz}$

At frequencies above bandwidth, gain decreases. For gain 100 amplifier, signals above 10kHz have reduced gain. At 100kHz, actual gain might be only 10 instead of 100.

#### Why Frequency Compensation Limits Bandwidth:

Early op-amps prone to oscillation due to phase shifts in high-gain feedback loops. Internal frequency compensation (typically single dominant pole created by internal capacitor) rolls off gain at low frequency, ensuring phase margin sufficient for stability under all feedback conditions.

Trade-off: Guaranteed stability at cost of reduced bandwidth. Uncompensated op-amps have wider bandwidth but require external compensation components and careful design to prevent oscillation.

### Datasheet Specification:

Op-amp datasheets list "gain-bandwidth product", "unity-gain bandwidth", or "transition frequency" (all same parameter). Sometimes listed as "bandwidth" but actually refers to unity-gain frequency.

Example: 741 datasheet shows "bandwidth" or "GBW"  $\approx 1\text{MHz}$  (typical),  $\approx 1.5\text{MHz}$  (some versions).

When designing amplifier, always check GBW and calculate bandwidth for intended gain to ensure adequate frequency response for application.

### Slew Rate vs. Bandwidth:

Separate limitation: Slew rate (maximum rate of output voltage change,  $\text{V}/\mu\text{s}$ ) limits large-signal bandwidth. For small signals, GBW dominates. For large-amplitude signals, slew rate may further limit frequency response. Both parameters important for complete frequency characterization.

## Practical Example & Numerical

### Bandwidth Calculation Example:

Op-amp:  $\text{GBW} = 1\text{MHz}$ . Design non-inverting amplifier with gain = 10.

Bandwidth:  $BW = \text{GBW}/A_v = 1\text{MHz}/10 = 100\text{kHz}$ .

Input signal:  $50\text{kHz}$  sine wave. Well within  $100\text{kHz}$  bandwidth, gain accurately 10.

Input signal:  $200\text{kHz}$  sine wave. Exceeds bandwidth. Actual gain reduced. At  $200\text{kHz}$ , gain approximately  $1\text{MHz}/200\text{kHz} = 5$  (half the intended gain). Output amplitude only half expected value.

### Gain Trade-off Analysis:

Need to amplify  $50\text{kHz}$  signal with op-amp  $\text{GBW} = 1\text{MHz}$ . What maximum gain maintains full bandwidth at  $50\text{kHz}$ ?

Required:  $BW \geq 50\text{kHz}$  for signal to pass unattenuated.

From  $BW = \text{GBW}/A_v$ :

$$A_v = \frac{\text{GBW}}{BW} = \frac{1\text{MHz}}{50\text{kHz}} = 20$$

Maximum gain = 20 to maintain full amplitude at  $50\text{kHz}$ . If gain set to 100, bandwidth only  $10\text{kHz}$ , and  $50\text{kHz}$  signal attenuated by factor of  $\approx 5$ .

### Audio Amplifier Design:

Audio range:  $20\text{Hz}$  to  $20\text{kHz}$ . Need gain = 40 (32dB) across entire audio range.

Required GBW:  $\text{GBW} \geq A_v \times BW = 40 \times 20\text{kHz} = 800\text{kHz}$ .

Select op-amp with  $\text{GBW} \geq 800\text{kHz}$ . Using 741 ( $\text{GBW} \approx 1\text{MHz}$ ) provides margin:  $BW = 1\text{MHz}/40 = 25\text{kHz}$ , covers entire audio range.

Using lower-bandwidth op-amp ( $\text{GBW} = 100\text{kHz}$ ) gives  $BW = 100\text{kHz}/40 = 2.5\text{kHz}$ , inadequate (rolls off well below  $20\text{kHz}$  audio limit).

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- Practical op-amps have limited bandwidth; gain decreases with increasing frequency
- Gain-Bandwidth Product (GBW): constant for given op-amp,  $\text{GBW} = A_v \times BW$
- GBW equals unity-gain frequency (frequency where open-loop gain = 1)
- Closed-loop bandwidth:  $BW = \text{GBW}/A_v$ , higher gain reduces bandwidth
- Internal frequency compensation stabilizes op-amp but limits bandwidth (dominant pole)
- Open-loop gain decreases 20dB/decade above breakpoint frequency (typically  $\approx 10\text{Hz}$ )
- Buffer (gain = 1) has maximum bandwidth equal to GBW
- High-gain amplifiers have reduced bandwidth; signals above BW are attenuated
- Always check datasheet GBW and calculate bandwidth for intended gain
- Common op-amps: 741 ( $\text{GBW} \approx 1\text{MHz}$ ), LM358 ( $\approx 1\text{MHz}$ ), TL071 ( $\approx 3\text{MHz}$ ), high-speed types (tens to hundreds of MHz)

## Cascading Op-Amps to Increase Bandwidth

### TL;DR (The Gist)

Cascading (series connection) of multiple op-amp stages with distributed gain increases overall bandwidth compared to single high-gain stage. Total gain is product of individual stage gains. Total bandwidth calculated:  $BW_{total} =$

$BW_{stage} \times \sqrt{2^{1/n} - 1}$  where  $n$  = number of stages, all stages identical gain. Diminishing returns beyond 2-3 stages. Two-stage design with gain  $\sqrt{A_{total}}$  per stage provides  $\approx 0.64 \times BW_{single}$  improvement.

## Detailed Explanation

### 2. Detailed Explanation

#### Bandwidth Limitation Problem:

Single-stage amplifier with high gain has narrow bandwidth. Example:  $GBW = 1\text{MHz}$ , desired gain = 100.

Single stage:  $BW = 1\text{MHz}/100 = 10\text{kHz}$ . If signal frequency 50kHz (above 10kHz bandwidth), gain reduced, output attenuated.

Cannot simply increase GBW (op-amp parameter, fixed). Solution: Distribute gain across multiple stages.

#### Cascading Principle:

Connect output of first op-amp stage to input of second stage. Each stage provides portion of total gain. Output of last stage delivers total gain to load.

*Total Gain:* Product of individual stage gains:

$$A_{total} = A_1 \times A_2 \times A_3 \times \cdots \times A_n$$

For  $n$  identical stages each with gain  $A$ :

$$A_{total} = A^n$$

Conversely, for total gain  $A_{total}$  distributed equally across  $n$  stages:

$$A_{stage} = \sqrt[n]{A_{total}} = A_{total}^{1/n}$$

#### Bandwidth Improvement Calculation:

Each individual stage has bandwidth:

$$BW_{stage} = \frac{GBW}{A_{stage}}$$

Total system bandwidth (for  $n$  identical stages):

$$BW_{total} = BW_{stage} \times \sqrt{2^{1/n} - 1}$$

This formula accounts for cumulative -3dB points of cascaded stages. Simple multiplication ( $BW_{total} = n \times BW_{stage}$ ) incorrect; bandwidths combine geometrically, not linearly.

#### Two-Stage Example (Most Common):

Desired:  $A_{total} = 100$ ,  $GBW = 1\text{MHz}$ .

Single stage:  $BW = 1\text{MHz}/100 = 10\text{kHz}$ .

Two stages: Each stage gain  $A_{stage} = \sqrt{100} = 10$ .

Each stage bandwidth:  $BW_{stage} = 1\text{MHz}/10 = 100\text{kHz}$ .

Total system bandwidth:

$$BW_{total} = 100\text{kHz} \times \sqrt{2^{1/2} - 1} = 100\text{kHz} \times \sqrt{1.414 - 1} = 100\text{kHz} \times \sqrt{0.414}$$

$$BW_{total} = 100\text{kHz} \times 0.6436 = 64.36\text{kHz}$$

Improved from 10kHz (single stage) to 64.36kHz (two stages). Factor of 6.4 improvement!

#### Three-Stage Example:

Same total gain 100, three stages.

Each stage gain:  $A_{stage} = \sqrt[3]{100} = 4.642$ .

Each stage bandwidth:  $BW_{stage} = 1\text{MHz}/4.642 = 215.44\text{kHz}$ .

Total bandwidth:

$$BW_{total} = 215.44\text{kHz} \times \sqrt{2^{1/3} - 1} = 215.44\text{kHz} \times \sqrt{1.26 - 1}$$

$$BW_{total} = 215.44\text{kHz} \times 0.51 = 109.87\text{kHz}$$

Improved further to  $\approx 110\text{kHz}$ . Compared to two stages (64kHz): additional improvement factor only 1.7. Diminishing returns.

#### Diminishing Returns:

- 1 stage  $\rightarrow$  2 stages:  $6.4\times$  bandwidth improvement
- 2 stages  $\rightarrow$  3 stages:  $1.7\times$  bandwidth improvement
- 3 stages  $\rightarrow$  4 stages:  $1.4\times$  bandwidth improvement (approximate)

Beyond 3-4 stages, minimal bandwidth gain. Additional complexity (more components, power consumption, noise, cost) not justified. Practical designs typically use 2-3 stages maximum.

#### Design Trade-offs:

*Advantages of Cascading:*

- Significant bandwidth increase for given total gain
- Lower gain per stage reduces distortion, improves linearity
- Each stage operates within comfortable GBW margin

*Disadvantages:*

- More components, higher cost
- Increased power consumption (multiple op-amps)
- More PCB space required
- Cumulative noise from multiple stages
- Stability considerations for each stage

#### Practical Application:

Use cascaded stages when:

- High gain required at high frequency (beyond single-stage GBW limit)
- Bandwidth-critical application (e.g., video, RF, high-speed data)
- Distortion reduction important (lower gain per stage = better linearity)

Use single stage when:

- Bandwidth adequate for application frequency
- Simplicity, low cost, low power critical
- Moderate gain requirement

### Practical Example & Numerical

#### Design Problem: High-Gain Wideband Amplifier

Requirement: Amplify 50kHz signal with gain = 100. Op-amp GBW = 1MHz.

*Single-stage analysis:*

Gain = 100,  $BW = 1\text{MHz}/100 = 10\text{kHz}$ .

Signal at 50kHz well above 10kHz bandwidth. Gain at 50kHz approximately  $1\text{MHz}/50\text{kHz} = 20$  (factor of 5 below target). Unacceptable.

*Two-stage design:*

Each stage gain:  $\sqrt{100} = 10$ .

Each stage bandwidth:  $1\text{MHz}/10 = 100\text{kHz}$ .

Total bandwidth:  $100\text{kHz} \times \sqrt{2^{0.5} - 1} = 64.36\text{kHz}$ .

Signal at 50kHz within 64kHz bandwidth, gain accurately 100. Success!

Configuration: First stage non-inverting amplifier with gain 10 ( $R_f = 9\text{k}$ ,  $R_1 = 1\text{k}$ ). Second stage identical. Output of first stage to input of second stage.

#### Comparison Table:

Stages	Gain/Stage	BW/Stage	Total BW
1	100	10 kHz	10 kHz
2	10	100 kHz	64 kHz
3	4.64	215 kHz	110 kHz
4	3.16	316 kHz	143 kHz

Diminishing returns evident: 2→3 stages adds 46kHz, 3→4 stages adds only 33kHz.

#### Practical Limit Demonstration:

For gain 1000, GBW = 1MHz:

Single stage:  $BW = 1\text{kHz}$ .

Two stages (gain 31.6 each):  $BW = 20.3\text{kHz}$  (20× improvement).

Three stages (gain 10 each):  $BW = 51\text{kHz}$  (51× improvement over single, 2.5× over two stages).

Two-stage design provides excellent compromise: substantial bandwidth improvement with reasonable complexity.

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

- Cascading multiple op-amp stages distributes total gain, increases bandwidth
- Total gain: product of individual stage gains,  $A_{total} = A_1 \times A_2 \times \dots \times A_n$
- For  $n$  identical stages:  $A_{stage} = \sqrt[n]{A_{total}}$  distributes gain equally
- Total bandwidth:  $BW_{total} = BW_{stage} \times \sqrt{2^{1/n} - 1}$  for  $n$  identical stages
- Two-stage design most common:  $\approx 6\times$  bandwidth improvement over single high-gain stage

- Three stages: additional  $\approx 1.7\times$  improvement, diminishing returns evident
- Beyond 3-4 stages: minimal bandwidth gain, added complexity not justified
- Each stage operates at lower gain: better linearity, lower distortion
- Trade-offs: improved bandwidth vs. added components, power, cost, noise
- Formula assumes identical stages (same gain, same GBW); different stages require modified calculation

# Section 25 – Op-Amp Arithmetic Circuits

This section explores operational amplifier circuits configured to perform mathematical operations in analog hardware: addition (summing amplifiers), subtraction (differential amplifiers), integration, and differentiation. These circuits formed the foundation of analog computers and remain essential for signal processing, sensor conditioning, waveform generation, and data conversion applications. Understanding arithmetic op-amp circuits enables design of mixers, averagers, D/A converters, signal conditioners, and mathematical function generators.

## Summing Amplifiers

### Inverting Summing Amplifier

#### TL;DR (The Gist)

Inverting summing amplifier combines multiple input signals into single inverted output. Multiple input resistors ( $R_1, R_2, R_3, \dots$ ) connect to inverting input (virtual ground node), feedback resistor  $R_f$  provides gain control. Output voltage is weighted sum of all inputs with inversion:  $V_{out} = -(R_f/R_1)V_1 - (R_f/R_2)V_2 - \dots$ . Equal input resistors produce simple sum with gain determined by  $R_f$ . Applications: audio mixing, D/A conversion, signal combining.

#### Detailed Explanation

### 2. Detailed Explanation

#### Historical Context:

Operational amplifiers originally developed (Carlos Swartzel, 1940s-1960s era) for analog computers performing mathematical operations in hardware before digital computers became practical. Addition, subtraction, integration, differentiation implemented using op-amp circuits with passive components. Named "operational" amplifier for this operational/mathematical capability.

#### Circuit Configuration:

Multiple input voltages ( $V_1, V_2, V_3, \dots, V_n$ ) applied through individual resistors ( $R_1, R_2, R_3, \dots, R_n$ ) to common inverting input node. Non-inverting input grounded. Feedback resistor  $R_f$  connects output to inverting input. All inputs share virtual ground summing junction.

#### Topology:

- Each input through its own resistor to summing junction (virtual ground)
- Non-inverting input tied to ground (0V)
- Feedback resistor  $R_f$  from output to summing junction
- Summing junction is virtual ground (0V potential, Rule 2)

#### Operation Analysis Using Golden Rules:

From Rule 2: Non-inverting input at ground (0V), so inverting input (summing junction) also at 0V (virtual ground). Each input resistor sees voltage drop equal to input voltage:

$$I_1 = \frac{V_1 - 0}{R_1} = \frac{V_1}{R_1}, \quad I_2 = \frac{V_2}{R_2}, \quad I_3 = \frac{V_3}{R_3}, \text{ etc.}$$

From Kirchhoff's current law at summing junction (currents in = currents out):

$$I_1 + I_2 + I_3 + \dots + I_n = I_f$$

From Rule 1: No current flows into op-amp input. All input currents sum and flow through feedback resistor  $R_f$ . Current through  $R_f$  (from summing junction at 0V to output):

$$I_f = \frac{0 - V_{out}}{R_f} = -\frac{V_{out}}{R_f}$$

(Negative because current flows from virtual ground toward negative output voltage when inputs positive.)

Combining:

$$\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} + \dots = -\frac{V_{out}}{R_f}$$

Solving for output voltage:

$$V_{out} = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3 + \dots\right)$$

Negative sign indicates inversion (inverting amplifier configuration).

### Weighted Summing:

Each input has independent gain (weight) determined by ratio  $R_f/R_i$ . Different input resistors create weighted sum.

*Example: Different weights*

$R_f = 10\text{k}\Omega$ ,  $R_1 = 10\text{k}\Omega$ ,  $R_2 = 5\text{k}\Omega$ ,  $R_3 = 2\text{k}\Omega$ .

Weights:  $R_f/R_1 = 1$ ,  $R_f/R_2 = 2$ ,  $R_f/R_3 = 5$ .

Output:  $V_{out} = -(1 \times V_1 + 2 \times V_2 + 5 \times V_3)$ .

Input 2 has twice the influence of input 1, input 3 has five times the influence.

### Equal Resistor Case:

If all input resistors equal ( $R_1 = R_2 = R_3 = \dots = R_{in}$ ):

$$V_{out} = -\frac{R_f}{R_{in}}(V_1 + V_2 + V_3 + \dots)$$

Simple sum of inputs with overall gain  $R_f/R_{in}$ .

For unity-gain sum ( $R_f = R_{in}$ ):

$$V_{out} = -(V_1 + V_2 + V_3 + \dots)$$

Output equals negative of algebraic sum of inputs.

### AC Signal Summing:

Op-amp is DC-coupled, works equally well with DC and AC signals. Multiple AC waveforms combined into composite signal.

Example: 5V AC (200Hz) + 2V square wave (20Hz) with equal resistors produces output combining both waveforms with inversion. Useful for audio mixing, signal synthesis, modulation.

### Input Impedance:

Unlike non-inverting amplifier, each input sees impedance approximately equal to its input resistor (connected to virtual ground). Not extremely high impedance. Source must drive  $R_{in}$  resistance.

For high-impedance sources, add buffer (voltage follower) before each input.

### Virtual Ground Summing Junction:

Critical concept: Summing junction physically at 0V (virtual ground) but electrically isolated from actual ground (no current path to ground). All input currents converge at this node, sum algebraically, flow through feedback path.

Op-amp output adjusts to maintain 0V at summing junction (Rule 2).

## Practical Example & Numerical

### Three-Input Summing Amplifier:

Inputs:  $V_1 = 2\text{V DC}$ ,  $V_2 = 3\text{V DC}$ ,  $V_3 = 1\text{V DC}$ .

All resistors equal:  $R_1 = R_2 = R_3 = R_f = 10\text{k}\Omega$ .

Currents:

$$I_1 = \frac{2}{10k} = 0.2\text{mA}, \quad I_2 = \frac{3}{10k} = 0.3\text{mA}, \quad I_3 = \frac{1}{10k} = 0.1\text{mA}$$

Total current into summing junction:  $I_{total} = 0.2 + 0.3 + 0.1 = 0.6\text{mA}$ .

This current flows through  $R_f$ , creating voltage drop:

$$V_{drop} = 0.6\text{mA} \times 10k = 6\text{V}$$

Since summing junction at 0V and current flows toward output:  $V_{out} = -6\text{V}$ .

Verification using formula:

$$V_{out} = -\frac{10k}{10k}(2 + 3 + 1) = -1 \times 6 = -6\text{V}$$

### Weighted Sum Example:

Design 3-bit digital-to-analog converter (DAC) with  $V_{ref} = 5\text{V}$ .

Binary weights: MSB (most significant bit) has weight 4, middle bit weight 2, LSB (least significant bit) weight 1.

Choose:  $R_f = 10\text{k}\Omega$ . For weights 4:2:1, use  $R_{MSB} = 10k/4 = 2.5\text{k}\Omega$ ,  $R_{mid} = 10k/2 = 5\text{k}\Omega$ ,  $R_{LSB} = 10k/1 = 10\text{k}\Omega$ .

Binary input 101 (5 in decimal): MSB = 5V, middle = 0V, LSB = 5V.

Output:

$$\begin{aligned} V_{out} &= -\left(\frac{10k}{2.5k} \times 5 + \frac{10k}{5k} \times 0 + \frac{10k}{10k} \times 5\right) \\ &= -(4 \times 5 + 2 \times 0 + 1 \times 5) = -(20 + 0 + 5) = -25\text{V} \end{aligned}$$

For binary 000:  $V_{out} = 0\text{V}$ . For binary 111:  $V_{out} = -(20 + 10 + 5) = -35\text{V}$ .

Output range 0 to -35V for 3-bit input 0-7. Add inverting amplifier stage to remove negative sign if needed.

## 4. Key Points (Interview Focus)

- Inverting summing amplifier combines multiple inputs into single inverted output
- Circuit: multiple input resistors to common summing junction (virtual ground), feedback resistor sets gain
- Output formula:  $V_{out} = -\sum (R_f/R_i)V_i$ , each input independently weighted
- Equal input resistors:  $V_{out} = -(R_f/R_{in})(V_1 + V_2 + \dots)$ , simple sum with overall gain
- Summing junction is virtual ground: 0V potential, no current to ground, all currents sum through  $R_f$
- Works with DC and AC signals, useful for audio mixing, signal combining, waveform synthesis
- Input impedance approximately  $R_{in}$  (not high), source must drive input resistor
- Applications: audio mixers, D/A converters, analog computers, multi-source signal combiners
- Weighted summing by choosing different input resistor values creates programmable gains per input
- Negative sign from inverting configuration; add second inverter for non-inverted sum if needed

## Non-Inverting Summing Amplifier and Applications

### TL;DR (The Gist)

Non-inverting summing amplifier produces positive sum of input voltages. Input resistors ( $R_1, R_2, \dots$ ) connect inputs to common node, voltage divider averaging inputs applied to non-inverting input. Feedback resistor network ( $R_a, R_b$ ) sets gain. For  $n$  equal-value inputs and gain =  $n$ , output equals positive sum:  $V_{out} = V_1 + V_2 + \dots$ . Higher input impedance than inverting version. Applications: audio mixing, averaging circuits, offset addition, sensor combining, multi-channel data acquisition.

### Detailed Explanation

## 2. Detailed Explanation

### Circuit Configuration and Advantage:

Non-inverting summing amplifier based on non-inverting amplifier topology. Input resistors form voltage divider network, averaged voltage applied to non-inverting input. Feedback network ( $R_a$  ground to inverting input,  $R_b$  inverting input to output) sets gain.

*Key Advantage:* Much higher input impedance than inverting summing amplifier. Inputs not connected to virtual ground, less loading on sources. No current flows into non-inverting input (Rule 1), minimal loading.

Input impedance approximately equal to input resistor values (for sources) but op-amp input stage presents very high impedance, so overall much less source loading.

### Analysis for Two Equal Inputs:

Two inputs  $V_1$  and  $V_2$ , equal input resistors  $R_1 = R_2 = R$ .

Voltage divider at non-inverting input:

$$V_+ = \frac{V_1 + V_2}{2}$$

(Average of two inputs if resistors equal.)

Non-inverting amplifier gain:

$$A_v = 1 + \frac{R_b}{R_a}$$

Output voltage:

$$V_{out} = A_v \times V_+ = \left(1 + \frac{R_b}{R_a}\right) \frac{V_1 + V_2}{2}$$

For output to equal exact sum ( $V_1 + V_2$ ), set gain = 2:

$$1 + \frac{R_b}{R_a} = 2 \implies \frac{R_b}{R_a} = 1 \implies R_b = R_a$$

With  $R_a = R_b$ :

$$V_{out} = 2 \times \frac{V_1 + V_2}{2} = V_1 + V_2$$

Perfect non-inverted sum.

**General  $n$ -Input Case:**

For  $n$  inputs with equal input resistors, voltage at non-inverting input:

$$V_+ = \frac{V_1 + V_2 + \dots + V_n}{n}$$

(Average of all inputs.)

To make output equal sum of all inputs:

$$V_{out} = V_1 + V_2 + \dots + V_n$$

Requires:

$$A_v \times \frac{V_1 + V_2 + \dots + V_n}{n} = V_1 + V_2 + \dots + V_n$$

Therefore:  $A_v = n$ .

Gain relationship:  $1 + R_b/R_a = n$ , so  $R_b/R_a = n - 1$ , giving  $R_b = (n - 1)R_a$ .

*Examples:*

- 2 inputs: gain = 2,  $R_b = R_a$
- 3 inputs: gain = 3,  $R_b = 2R_a$
- 4 inputs: gain = 4,  $R_b = 3R_a$

#### Unity-Gain Buffer Case:

If feedback removed ( $R_b = 0$ , direct connection output to inverting input,  $R_a = \infty$  or omitted), circuit becomes unity-gain buffer.

Gain = 1. Output:

$$V_{out} = 1 \times \frac{V_1 + V_2 + \dots + V_n}{n} = \text{average of inputs}$$

Useful for averaging multiple voltage sources or sensor readings.

#### Design Complexity:

More complex than inverting summing amplifier. Requires careful resistor selection, especially for unequal input weights. With equal inputs and proper gain setting, achieves straightforward positive sum.

Advantage: Higher input impedance outweighs complexity in high-impedance source applications.

#### Applications:

*Audio Mixing:* Combining multiple audio channels without loading sources. Potentiometers on input resistors enable individual channel volume control. Output in-phase with inputs (no inversion). Used in mixing consoles, multi-microphone setups.

*Offset Addition:* Adding negative offset voltage to sensor output to zero reading at specific point. Example: Temperature sensor outputs 0-5V (0°C to 100°C). Add negative offset to make output 0V at freezing point (0°C).

*Digital-to-Analog Conversion:* Weighted resistor DAC using non-inverting configuration. Binary-weighted input resistors (doubling sequence: R, 2R, 4R, 8R, ...) create digital-to-analog conversion. Accuracy depends on resistor precision and consistent logic level voltages.

Challenges: Resistor tolerance errors accumulate, logic level variations cause inaccuracies. Commercial DAC ICs use precision internal resistor networks (laser-trimmed) for superior accuracy.

*Signal Averaging:* Multiple sensor readings averaged to reduce noise. Unity-gain buffer configuration produces average voltage. Improves signal-to-noise ratio by  $\sqrt{n}$  for  $n$  uncorrelated noise sources.

*Multi-Source Combining:* Combining signals from different sources (instruments, sensors, generators) into composite waveform for analysis, processing, transmission.

## Practical Example & Numerical

### Two-Input Non-Inverting Summer:

Inputs:  $V_1 = 3V$ ,  $V_2 = 2V$ . Equal input resistors  $R_1 = R_2 = 10k\Omega$ .

Voltage at non-inverting input:

$$V_+ = \frac{3 + 2}{2} = 2.5V$$

For output  $= V_1 + V_2 = 5V$ , need gain = 2.

Set  $R_a = R_b = 10k\Omega$  (gain =  $1 + 10k/10k = 2$ ).

Output:

$$V_{out} = 2 \times 2.5 = 5V$$

Correct sum achieved.

### Three-Input Averaging Circuit:

Three sensor voltages:  $V_1 = 4V$ ,  $V_2 = 5V$ ,  $V_3 = 3V$ . Equal input resistors  $R = 10k\Omega$ .

Unity-gain buffer (output connected directly to inverting input):

Voltage at non-inverting input:

$$V_+ = \frac{4 + 5 + 3}{3} = 4\text{V}$$

Output (gain = 1):

$$V_{out} = 1 \times 4 = 4\text{V}$$

Average of three sensors = 4V. Useful for noise reduction, redundant sensor averaging.

#### Audio Mixer Design:

Four audio channels, each 0-1V peak. Want output = sum of all channels (0-4V peak).

Equal input resistors  $R_{in} = 10\text{k}\Omega$  for all channels.

Voltage at non-inverting input (four channels all at 1V peak):

$$V_+ = \frac{1 + 1 + 1 + 1}{4} = 1\text{V}$$

Need gain = 4 for output = 4V.

Gain =  $1 + R_b/R_a = 4$ , so  $R_b = 3R_a$ .

Choose  $R_a = 10\text{k}\Omega$ ,  $R_b = 30\text{k}\Omega$ .

Output (all channels at 1V):

$$V_{out} = 4 \times 1 = 4\text{V}$$

With individual channels varying, output = sum of all channel voltages, in-phase (no inversion).

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

- Non-inverting summing amplifier: input resistors form voltage divider to non-inverting input
- Output is non-inverted sum:  $V_{out} = V_1 + V_2 + \dots$  (with proper gain setting)
- For  $n$  equal inputs, set gain =  $n$  to achieve exact sum:  $R_b = (n - 1)R_a$
- Higher input impedance than inverting summer, less source loading
- Unity-gain configuration produces average of inputs:  $V_{out} = (V_1 + V_2 + \dots)/n$
- More complex resistor selection compared to inverting summer, especially for weighted sums
- Applications: audio mixing (in-phase sum), offset addition, signal averaging, multi-sensor combining
- DAC implementation possible with weighted resistors but commercial ICs more accurate
- Potentiometers on input resistors enable individual channel gain control (mixer application)
- Averaging reduces noise by factor  $\sqrt{n}$  for  $n$  independent noise sources

## Differential Amplifier

### Differential Amplifier and Common-Mode Rejection

#### TL;DR (The Gist)

Differential amplifier outputs difference between two inputs:  $V_{out} = A_d(V_2 - V_1)$  where  $A_d$  is differential gain. For equal resistors ( $R_1 = R_2$ ,  $R_3 = R_4$ ), unity differential gain:  $V_{out} = V_2 - V_1$ . For adjustable gain with symmetry:  $R_1 = R_2$  and  $R_3 = R_4$ , giving  $V_{out} = (R_3/R_1)(V_2 - V_1)$ . Rejects common-mode signals (noise appearing equally on both inputs). Essential for differential signaling (USB, Ethernet), noise rejection, sensor interfacing, instrumentation.

#### Detailed Explanation

#### 2. Detailed Explanation

##### Circuit Configuration:

Input  $V_1$  applied through resistor  $R_1$  to inverting input. Input  $V_2$  applied to voltage divider ( $R_2$  and  $R_4$ ), junction connected to non-inverting input. Feedback resistor  $R_3$  from output to inverting input.

Symmetric design:  $R_1 = R_2$  (input resistors equal),  $R_3 = R_4$  (feedback/divider resistors equal).

##### Unity-Gain Differential Amplifier:

All resistors equal:  $R_1 = R_2 = R_3 = R_4 = R$ .

Analysis:

Voltage at non-inverting input (voltage divider  $R_2$  and  $R_4$ ):

$$V_+ = V_2 \frac{R_4}{R_2 + R_4} = V_2 \frac{R}{R + R} = \frac{V_2}{2}$$

From Rule 2:  $V_- = V_+$  (both inputs at same voltage in linear operation).

So:  $V_- = V_2/2$ .

Inverting input is junction of  $R_1$  (from  $V_1$ ) and  $R_3$  (from  $V_{out}$ ). Using virtual ground principle and current balance:

Current through  $R_1$ :  $I_1 = (V_1 - V_-)/R_1 = (V_1 - V_2/2)/R$ .

Current through  $R_3$ :  $I_3 = (V_- - V_{out})/R_3 = (V_2/2 - V_{out})/R$ .

From Rule 1:  $I_1 = I_3$  (no current into op-amp input).

Equating:

$$\frac{V_1 - V_2/2}{R} = \frac{V_2/2 - V_{out}}{R}$$

Simplifying:

$$\begin{aligned} V_1 - \frac{V_2}{2} &= \frac{V_2}{2} - V_{out} \\ V_{out} &= \frac{V_2}{2} - V_1 + \frac{V_2}{2} = V_2 - V_1 \end{aligned}$$

Unity-gain differential output:

$$V_{out} = V_2 - V_1$$

Output equals difference between two inputs. If  $V_2 > V_1$ : positive output. If  $V_1 > V_2$ : negative output.

### Adjustable-Gain Differential Amplifier:

For differential gain  $A_d \neq 1$ , maintain symmetry:  $R_1 = R_2$  and  $R_3 = R_4$ , but allow  $R_3/R_1 \neq 1$ .

General formula with symmetry:

$$V_{out} = \frac{R_3}{R_1}(V_2 - V_1)$$

Differential gain:  $A_d = R_3/R_1$ .

Example:  $R_1 = R_2 = 10\text{k}\Omega$ ,  $R_3 = R_4 = 30\text{k}\Omega$ .

Gain:  $A_d = 30\text{k}/10\text{k} = 3$ .

For  $V_2 = 8\text{V}$ ,  $V_1 = 5\text{V}$ :  $V_{out} = 3 \times (8 - 5) = 9\text{V}$ .

### Common-Mode Rejection:

*Common-Mode Signal*: Signal appearing equally on both inputs (same voltage, same phase). Example: 60Hz noise induced on both signal wires from power line interference.

*Differential-Mode Signal*: Desired signal appearing as difference between inputs. Example:  $V_2 = +1\text{V}$ ,  $V_1 = -1\text{V}$  (differential =  $2\text{V}$ ).

Differential amplifier amplifies differential-mode signal, rejects (cancels) common-mode signal.

Example:  $V_1 = 60\text{Hz} + \text{desired signal}$ ,  $V_2 = 60\text{Hz} + \text{desired signal}$  (noise equal on both).

Output:  $V_{out} = (V_2 - V_1) = (\text{desired}_2 - \text{desired}_1)$ . 60Hz cancels (common to both).

Common-Mode Rejection Ratio (CMRR): Measure of differential amplifier's ability to reject common-mode signals. High CMRR = excellent common-mode rejection.

### Input Impedance Issue and Buffer Solution:

Standard differential amplifier has moderate input impedance (approximately  $R_1$  and  $R_2$  values). For high-impedance sources, input loading can be problematic.

*Solution*: Add unity-gain buffers (voltage followers) to each input. Buffer outputs drive differential amplifier. Extremely high input impedance presented to sources ( $V_1$  and  $V_2$ ), buffers provide current to drive differential amplifier resistors.

Buffered differential amplifier: Superior input characteristics, prevents source loading, maintains differential and common-mode rejection properties.

### Applications - Differential Signaling:

*USB (Universal Serial Bus)*: Uses differential signaling on D+ and D- data lines. Same digital data transmitted as complementary signals (one inverted relative to other). Receiver uses differential amplifier to extract data:  $V_{out} = V_{D+} - V_{D-}$ . Electromagnetic interference (EMI) induced equally on both twisted-pair wires, canceled at receiver. Robust data transmission even in noisy environments.

*Ethernet*: Twisted-pair Ethernet (10BASE-T, 100BASE-TX, 1000BASE-T) uses differential signaling. Each pair carries complementary signals, differential receiver extracts data while rejecting common-mode noise.

*Other Differential Interfaces*: RS-422, RS-485 (industrial communications), HDMI, DisplayPort (video), CAN bus (automotive), I<sup>2</sup>S (audio).

### Twisted Pair and EMI Rejection:

Twisted pair cabling: Two wires twisted together. When EMI couples into cable, induced voltage approximately equal on both wires (due to proximity and twisting). Differential receiver subtracts wires: EMI cancels, desired signal (which is differential) passes through.

Twisting ensures both wires exposed to same electromagnetic environment, maximizing common-mode EMI coupling and thus maximizing rejection.

**Unity-Gain Differential Amplifier:**

All resistors  $10\text{k}\Omega$ . Inputs:  $V_1 = 5\text{V}$ ,  $V_2 = 8\text{V}$ .

Output:  $V_{out} = V_2 - V_1 = 8 - 5 = 3\text{V}$ .

Inputs:  $V_1 = 3\text{V}$ ,  $V_2 = 1\text{V}$ .

Output:  $V_{out} = 1 - 3 = -2\text{V}$  (negative because  $V_1 > V_2$ ).

**Gain = 3 Differential Amplifier:**

$R_1 = R_2 = 10\text{k}\Omega$ ,  $R_3 = R_4 = 30\text{k}\Omega$ . Gain =  $30\text{k}/10\text{k} = 3$ .

Inputs:  $V_1 = 2\text{V}$ ,  $V_2 = 3\text{V}$ .

Difference:  $V_2 - V_1 = 1\text{V}$ .

Output:  $V_{out} = 3 \times 1 = 3\text{V}$ .

**Common-Mode Rejection Demonstration:**

Unity-gain differential amplifier. Both inputs have 60Hz noise (5V peak) plus differential signal.

$V_1 = 60\text{Hz}$  (5V peak) + 2V DC = varies  $2\text{V} \pm 5\text{V}$ .

$V_2 = 60\text{Hz}$  (5V peak) + 4V DC = varies  $4\text{V} \pm 5\text{V}$ .

Common-mode component: 60Hz noise (equal on both).

Differential component:  $4 - 2 = 2\text{V}$  DC.

Output:  $V_{out} = V_2 - V_1 = (60\text{Hz} + 4) - (60\text{Hz} + 2) = 2\text{V}$  DC.

60Hz completely canceled (common-mode rejection). Only differential signal (2V DC difference) appears at output.

**Differential Signaling Application:**

USB data transmission: Logic HIGH = D+ at 3.3V, D- at 0V (difference = +3.3V). Logic LOW = D+ at 0V, D- at 3.3V (difference = -3.3V).

EMI noise (e.g., 1V peak, 100kHz) couples equally into both D+ and D-:

D+ = signal + 1V noise, D- = signal + 1V noise.

Differential receiver:  $V_{out} = V_{D+} - V_{D-} = (\text{signal} + \text{noise}) - (\text{signal} + \text{noise}) = \text{signal}$  (differential component only).

Noise canceled, clean data recovered. Without differential signaling, 1V noise on single-ended signal would corrupt data.

Key Points (Interview Focus)

4. Key Points (Interview Focus)

- Differential amplifier outputs difference between two inputs:  $V_{out} = A_d(V_2 - V_1)$
- Unity gain (all resistors equal):  $V_{out} = V_2 - V_1$
- Adjustable gain with symmetry ( $R_1 = R_2$ ,  $R_3 = R_4$ ):  $V_{out} = (R_3/R_1)(V_2 - V_1)$
- Common-mode signals (equal on both inputs) canceled, differential signals amplified
- High Common-Mode Rejection Ratio (CMRR) essential for noise immunity
- Input impedance moderate ( $\approx R_1, R_2$ ); add buffers for high-impedance sources
- Applications: differential signaling (USB, Ethernet, RS-485), sensor interfacing, noise rejection
- Twisted-pair cables maximize common-mode EMI coupling for better rejection
- Differential signaling robust in noisy environments (industrial, automotive, long-distance communications)
- Symmetry critical:  $R_1 = R_2$  and  $R_3 = R_4$  ensures proper common-mode rejection and gain accuracy

## Calculus Operations: Integration and Differentiation

Op-Amp Integrator Circuit

TL;DR (The Gist)

Op-amp integrator performs mathematical integration: output voltage proportional to integral (accumulated sum) of input voltage over time. Circuit: input resistor  $R$  to inverting input, feedback capacitor  $C$  (replacing feedback resistor). Output:  $V_{out}(t) = -\frac{1}{RC} \int V_{in}(t) dt$ . Constant input produces linear ramp output. Square wave input produces triangular wave output. Sine wave input produces cosine wave (90° phase shift). Applications: waveform generation (triangle from square), analog computers, ADCs, signal averaging, timing circuits.

Detailed Explanation

## 2. Detailed Explanation

### Circuit Configuration:

Input resistor  $R$  connects input voltage to inverting input (virtual ground). Feedback capacitor  $C$  connects output to inverting input (replaces feedback resistor in standard inverting amplifier). Non-inverting input grounded. Key difference from standard inverting amplifier: Capacitor in feedback path instead of resistor.

### Operation and Integration Principle:

Inverting input at virtual ground (0V, Rule 2). Input voltage  $V_{in}$  across resistor  $R$  creates current:

$$I_{in} = \frac{V_{in}}{R}$$

From Rule 1: No current into op-amp input. All current through  $R$  flows into capacitor  $C$ .

Capacitor current-voltage relationship:

$$I_C = C \frac{dV_C}{dt}$$

Where  $V_C$  is voltage across capacitor. Since one side of capacitor at virtual ground (0V), other side (output) has:

$$V_C = 0 - V_{out} = -V_{out}$$

Therefore:

$$I_C = -C \frac{dV_{out}}{dt}$$

Equating capacitor current to input current:

$$\frac{V_{in}}{R} = -C \frac{dV_{out}}{dt}$$

Rearranging:

$$\frac{dV_{out}}{dt} = -\frac{1}{RC} V_{in}$$

Integrating both sides with respect to time:

$$V_{out}(t) = -\frac{1}{RC} \int_0^t V_{in}(\tau) d\tau + V_{out}(0)$$

Where  $V_{out}(0)$  is initial output voltage (capacitor initial charge).

Output voltage proportional to integral of input voltage. Negative sign from inverting configuration.

### Time Constant and Integration Rate:

Time constant  $\tau = RC$  determines integration rate. Larger  $RC$ : slower integration (gentler ramp). Smaller  $RC$ : faster integration (steeper ramp).

For constant input voltage  $V_{in} = V_0$ :

$$V_{out}(t) = -\frac{1}{RC} V_0 t + V_{out}(0)$$

Linear ramp with slope  $-V_0/(RC)$ .

### Waveform Transformations:

*Step Input*  $\rightarrow$  *Ramp Output*:

Constant DC input (step function) produces linearly increasing/decreasing ramp output. Output rises until op-amp saturates at supply rail.

Example:  $V_{in} = +1V$  (constant),  $R = 10k\Omega$ ,  $C = 1\mu F$ ,  $\tau = RC = 10ms$ .

Output:  $V_{out}(t) = -\frac{1}{0.01} \times 1 \times t = -100t$  (volts). Ramps at  $-100V/s$  until hitting negative rail.

*Square Wave Input*  $\rightarrow$  *Triangular Wave Output*:

Square wave alternates between positive and negative constant values. During positive phase, output ramps negatively (integrating positive constant). During negative phase, output ramps positively (integrating negative constant). Result: triangular waveform.

Frequency relationship: Triangle frequency = square wave frequency. Useful for waveform generation.

*Sine Wave Input*  $\rightarrow$  *Cosine Wave Output*:

Mathematical relationship:  $\int \sin(\omega t) dt = -\frac{1}{\omega} \cos(\omega t) + \text{const.}$

Integrator produces cosine wave from sine wave input,  $90^\circ$  phase shift. Output amplitude scaled by  $1/(\omega RC)$ . At higher frequencies, output amplitude decreases (integrator acts as low-pass filter).

### Saturation and Reset:

With DC or low-frequency input, integrator output eventually saturates at supply rail (cannot integrate indefinitely). Capacitor charges fully, output stuck at rail.

*Reset Mechanism*: Parallel resistor across capacitor or switch to discharge capacitor between integration cycles. Common in ADCs and timing circuits.

### Low-Pass Filter Behavior:

For AC signals, integrator behaves as active low-pass filter. Gain decreases with frequency:  $A_v(\omega) = -\frac{1}{j\omega RC}$ .

Magnitude:  $|A_v| = 1/(\omega RC)$ , inversely proportional to frequency.  
Cutoff frequency (corner frequency):

$$f_c = \frac{1}{2\pi RC}$$

Below  $f_c$ : integration behavior dominant. Above  $f_c$ : attenuation increases at 20dB/decade. Passes low frequencies, attenuates high frequencies.

#### Applications:

*Waveform Generation:* Converting square wave (from oscillator, microcontroller PWM) to triangle wave. Used in function generators, synthesizers, test equipment.

*Analog Computers:* Solving differential equations in analog hardware. Integration fundamental operation. Historical use in analog computers (aerospace, simulation).

*Analog-to-Digital Converters (ADCs):* Dual-slope ADC uses integrator. Input voltage integrated for fixed time, then reference voltage integrated until integrator returns to zero. Time ratio gives digital representation.

*Signal Averaging:* Integrating signal over time period and dividing by time gives average value. Noise averaging, DC component extraction.

*Sensor Signal Conditioning:* Some sensors (e.g., accelerometers measuring acceleration) require integration to obtain velocity or displacement.

### Practical Example & Numerical

#### Constant Input Integration:

$V_{in} = 2V$  (constant),  $R = 100k\Omega$ ,  $C = 10\mu F$ .

Time constant:  $RC = 100k \times 10\mu = 1s$ .

Input current:  $I = 2/100k = 20\mu A$ .

Output voltage (starting from  $V_{out}(0) = 0$ ):

$$V_{out}(t) = -\frac{1}{1} \times 2 \times t = -2t \text{ (volts)}$$

At  $t = 1s$ :  $V_{out} = -2V$ . At  $t = 5s$ :  $V_{out} = -10V$ .

Linear ramp at  $-2V/s$ . Continues until hitting negative supply rail (e.g.,  $-15V$  at  $t = 7.5s$ ).

#### Square Wave to Triangle Wave:

Input:  $1kHz$  square wave,  $\pm 1V$  amplitude.  $R = 10k\Omega$ ,  $C = 0.1\mu F$ ,  $RC = 1ms$ .

Square wave period:  $T = 1ms$  ( $1kHz$ ).

During positive half-cycle ( $+1V$ ,  $0.5ms$ ):

$$\Delta V_{out} = -\frac{1}{1ms} \times 1 \times 0.5ms = -0.5V$$

Output ramps down  $0.5V$ .

During negative half-cycle ( $-1V$ ,  $0.5ms$ ):

$$\Delta V_{out} = -\frac{1}{1ms} \times (-1) \times 0.5ms = +0.5V$$

Output ramps up  $0.5V$ .

Result: Triangular wave,  $1kHz$ ,  $\pm 0.5V$  amplitude (peak-to-peak =  $1V$ ),  $90^\circ$  phase-shifted relative to square wave.

#### Sine Wave Integration:

Input:  $V_{in}(t) = \sin(2\pi \times 100t)$  ( $100Hz$  sine wave,  $1V$  amplitude).

$R = 10k\Omega$ ,  $C = 1\mu F$ ,  $RC = 10ms$ .

Angular frequency:  $\omega = 2\pi \times 100 = 628.3 \text{ rad/s}$ .

Output:

$$\begin{aligned} V_{out}(t) &= -\frac{1}{RC} \int \sin(\omega t) dt = -\frac{1}{10ms} \times \left( -\frac{1}{628.3} \cos(\omega t) \right) \\ &= \frac{100}{628.3} \cos(2\pi \times 100t) = 0.159 \cos(2\pi \times 100t) \end{aligned}$$

Cosine wave ( $90^\circ$  phase shift),  $100Hz$ , amplitude  $0.159V$  (reduced by factor  $1/(\omega RC) = 1/(628.3 \times 0.01) \approx 0.159$ ).

### Key Points (Interview Focus)

## 4. Key Points (Interview Focus)

- Op-amp integrator: input resistor  $R$ , feedback capacitor  $C$ , performs mathematical integration
- Output formula:  $V_{out}(t) = -(1/RC) \int V_{in}(t) dt$ , proportional to integral of input
- Time constant  $RC$  sets integration rate: larger  $RC$  = slower integration
- Constant input produces linear ramp output:  $V_{out} = -(V_{in}/RC) \times t$
- Square wave input  $\rightarrow$  triangular wave output (waveform generation application)
- Sine wave input  $\rightarrow$  cosine wave output ( $90^\circ$  phase shift, amplitude scaled by  $1/\omega RC$ )
- Behaves as low-pass filter for AC signals: cutoff frequency  $f_c = 1/(2\pi RC)$
- Output saturates at supply rail for DC/low-frequency inputs; requires reset mechanism
- Applications: triangle wave generation, analog computers, ADCs, signal averaging, sensor conditioning
- Initial capacitor voltage sets integration constant ( $V_{out}(0)$ ), affects DC offset

## Op-Amp Differentiator Circuit

### TL;DR (The Gist)

Op-amp differentiator computes mathematical derivative (rate of change) of input voltage. Circuit: input capacitor  $C$  to inverting input, feedback resistor  $R$ . Output:  $V_{out}(t) = -RC dV_{in}/dt$ , proportional to rate of input voltage change. Triangular wave input produces square wave output. Sine wave input produces cosine wave ( $90^\circ$  lead, opposite phase shift from integrator). Tends toward instability at high frequencies; often requires frequency compensation. Applications: edge detection, rate-of-change measurement, frequency emphasis (high-pass filter), waveform shaping.

### Detailed Explanation

## 2. Detailed Explanation

### Circuit Configuration:

Input capacitor  $C$  connects input voltage to inverting input (virtual ground). Feedback resistor  $R$  connects output to inverting input. Non-inverting input grounded.

Key difference from integrator: Capacitor at input, resistor in feedback (opposite positions).

### Operation and Differentiation Principle:

*Capacitance Reactance Concept:*

Capacitor opposes voltage changes by creating current. Greater capacitance = greater opposition to voltage change, larger charge/discharge current for given rate of change.

Capacitor current-voltage relationship:

$$I_C = C \frac{dV_C}{dt}$$

Current proportional to rate of voltage change across capacitor ( $dV/dt$ ).

*Circuit Analysis:*

Inverting input at virtual ground (0V). Voltage across input capacitor:

$$V_C = V_{in} - 0 = V_{in}$$

Current through capacitor:

$$I_C = C \frac{dV_{in}}{dt}$$

From Rule 1: No current into op-amp. All capacitor current flows through feedback resistor  $R$ .

Voltage across  $R$  (from virtual ground to output):

$$V_R = I_C \times R = RC \frac{dV_{in}}{dt}$$

Since virtual ground at 0V and current flows from 0V toward output:

$$V_{out} = 0 - V_R = -RC \frac{dV_{in}}{dt}$$

Differentiator output:

$$V_{out}(t) = -RC \frac{dV_{in}(t)}{dt}$$

Output proportional to derivative (rate of change) of input. Negative sign from inverting configuration.

### Waveform Transformations:

*Ramp (Triangular) Input → Square Wave Output:*

Linear ramp has constant slope:  $dV/dt = \text{constant}$ . Differentiator produces constant output (square wave level). Positive slope → negative constant output. Negative slope → positive constant output. Result: Square wave from triangular input.

*Square Wave Input → Spike Output:*

Square wave has instantaneous transitions (ideally infinite  $dV/dt$  at edges). Differentiator produces sharp spikes at rising and falling edges.

Rising edge (positive  $dV/dt$ ) → negative spike. Falling edge (negative  $dV/dt$ ) → positive spike. Between transitions (constant voltage,  $dV/dt = 0$ ) → zero output.

Practical circuits: Spikes have finite width determined by edge slew rate and circuit bandwidth.

*Sine Wave Input → Cosine Wave Output (Phase Lead):*

Mathematical relationship:  $d(\sin \omega t)/dt = \omega \cos(\omega t)$ .

Differentiator produces cosine from sine input,  $90^\circ$  phase lead (opposite of integrator's  $90^\circ$  lag). Output amplitude scaled by  $\omega RC$ : higher frequencies amplified more.

### High-Pass Filter Behavior:

For AC signals, differentiator behaves as active high-pass filter. Gain increases with frequency:  $A_v(\omega) = -j\omega RC$ .

Magnitude:  $|A_v| = \omega RC$ , directly proportional to frequency.

Low frequencies attenuated, high frequencies amplified. Gain increases at +20dB/decade above corner frequency.

Corner frequency:

$$f_c = \frac{1}{2\pi RC}$$

### Stability Issues and Compensation:

Differentiator inherently prone to instability, especially at high frequencies. Combination of capacitive input and high-frequency gain increase can cause oscillation.

Noise amplification: High-frequency noise amplified more than signal (due to  $\omega RC$  gain). Differentiator can become noisy oscillator.

*Frequency Compensation:*

Add small capacitor  $C_f$  in parallel with feedback resistor  $R$ . Creates low-pass filter in feedback path, limits high-frequency gain.

Alternatively: Add small resistor  $R_s$  in series with input capacitor. Limits high-frequency gain, improves stability. Differentiator becomes band-pass filter (high-pass from differentiator action, low-pass from compensation).

Properly compensated differentiator maintains differentiation at frequencies of interest while preventing high-frequency instability.

### Comparison: Integrator vs. Differentiator:

- Integrator: Capacitor in feedback, resistor at input. Computes integral. Low-pass behavior. Generally stable.
- Differentiator: Capacitor at input, resistor in feedback. Computes derivative. High-pass behavior. Prone to instability.
- Phase: Integrator gives  $-90^\circ$  (lag), differentiator gives  $+90^\circ$  (lead) for sine waves
- Inverse operations: Integration and differentiation are mathematical inverses

### Applications:

*Edge Detection:* Detecting rapid voltage changes (edges) in signals. Pulse detection, event timing, zero-crossing detection.

*Rate-of-Change Measurement:* Measuring how fast signal changes. Velocity from position sensor, acceleration from velocity.

*Frequency Emphasis:* Emphasizing high-frequency components in signal. Audio applications (treble boost), noise enhancement for certain detection schemes.

*Waveform Shaping:* Converting triangular wave to square wave (opposite of integrator). Function generators, signal synthesizers.

*High-Pass Filtering:* Active high-pass filter with gain. Pre-emphasis in communication systems, AC coupling with gain.

Limited use compared to integrator due to noise and stability concerns. Often replaced by digital differentiation in modern systems.

## Practical Example & Numerical

### Triangular Wave to Square Wave:

Input: 1kHz triangular wave, 1V peak-to-peak, symmetric around 0V.

Triangle wave equation (approximation):  $V_{in}(t)$  ramps from -0.5V to +0.5V in 0.5ms (rising), then +0.5V to -0.5V in 0.5ms (falling).

$C = 0.1\mu\text{F}$ ,  $R = 10\text{k}\Omega$ ,  $RC = 1\text{ms}$ .

Rising edge slope:  $dV/dt = (0.5 - (-0.5))/0.0005 = 2000 \text{ V/s}$ .

Output during rising edge:

$$V_{out} = -RC \frac{dV}{dt} = -0.001 \times 2000 = -2\text{V}$$

Falling edge slope:  $dV/dt = (-0.5 - 0.5)/0.0005 = -2000 \text{ V/s}$ .

Output during falling edge:

$$V_{out} = -0.001 \times (-2000) = +2\text{V}$$

Result: Square wave,  $\pm 2\text{V}$ ,  $1\text{kHz}$ , inverted phase relative to triangle wave.

#### Sine Wave Differentiation:

Input:  $V_{in}(t) = \sin(2\pi \times 100t)$  ( $100\text{Hz}$ ,  $1\text{V}$  amplitude).

$C = 1\mu\text{F}$ ,  $R = 10\text{k}\Omega$ ,  $RC = 10\text{ms}$ .

Angular frequency:  $\omega = 2\pi \times 100 = 628.3 \text{ rad/s}$ .

Derivative:  $dV_{in}/dt = \omega \cos(\omega t) = 628.3 \cos(2\pi \times 100t)$ .

Output:

$$\begin{aligned} V_{out}(t) &= -RC \frac{dV_{in}}{dt} = -0.01 \times 628.3 \cos(2\pi \times 100t) \\ &= -6.28 \cos(2\pi \times 100t) \end{aligned}$$

Cosine wave ( $90^\circ$  phase lead relative to input sine),  $100\text{Hz}$ ,  $6.28\text{V}$  amplitude (amplified by factor  $\omega RC = 6.28$ ).

Higher frequencies would be amplified even more, demonstrating high-pass nature and potential noise/stability issues.

#### Square Wave Edge Detection:

Input:  $1\text{kHz}$  square wave,  $0$  to  $5\text{V}$  transitions.

Rising edge: Voltage jumps from  $0\text{V}$  to  $5\text{V}$ . Ideally instantaneous, but practical slew rate limited (e.g.,  $10\text{V}/\mu\text{s}$ ).

$C = 0.01\mu\text{F}$ ,  $R = 10\text{k}\Omega$ .

During rising edge ( $dV/dt = 10 \text{ V}/\mu\text{s} = 10 \times 10^6 \text{ V/s}$ ):

$$V_{out} = -RC \frac{dV}{dt} = -0.0001 \times 10^7 = -1000\text{V (theoretical)}$$

Actual output saturates at negative rail (e.g.,  $-15\text{V}$ ). Short negative spike.

Between edges (constant voltage,  $dV/dt = 0$ ):  $V_{out} = 0\text{V}$ .

Falling edge: Positive spike (symmetrical).

Result: Sharp spikes at each edge, zero between edges. Edge detection achieved.

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

- Op-amp differentiator: input capacitor  $C$ , feedback resistor  $R$ , computes derivative
- Output formula:  $V_{out}(t) = -RC dV_{in}/dt$ , proportional to rate of input voltage change
- Capacitor current proportional to  $dV/dt$ :  $I_C = C dV_{in}/dt$
- Triangular wave input  $\rightarrow$  square wave output (opposite of integrator)
- Square wave input  $\rightarrow$  spike output at edges (edge detection)
- Sine wave input  $\rightarrow$  cosine wave output ( $90^\circ$  phase lead, amplitude  $\times \omega RC$ )
- Behaves as high-pass filter: gain increases with frequency, amplifies noise
- Prone to instability and oscillation at high frequencies
- Compensation required: small capacitor across  $R$  or small resistor in series with  $C$
- Applications: edge detection, rate measurement, frequency emphasis, waveform shaping, high-pass filtering
- Less commonly used than integrator due to noise amplification and stability issues
- Inverse of integrator:  $d(\int f dt)/dt = f$  (differentiation undoes integration)

# Section 26 – Op-Amp Based Precision Rectifiers

This section explores precision rectifier circuits utilizing operational amplifiers to overcome fundamental limitations of passive diode rectifiers. Traditional diode rectifiers suffer from forward voltage drop (typically 0.7V for silicon diodes), making them unsuitable for low-amplitude signal processing. Precision rectifiers (active rectifiers) employ op-amp feedback to eliminate diode voltage drop, enabling accurate rectification of signals well below diode threshold voltage. These circuits provide controlled gain, extremely low output impedance, high input impedance, and near-ideal diode behavior essential for instrumentation, signal processing, and measurement applications.

## Precision Rectifier Fundamentals

### Comparison: Passive vs Active Rectification

#### TL;DR (The Gist)

Traditional passive rectifiers (diode-based) convert AC to DC but suffer 0.7V voltage drop per diode, limiting minimum signal amplitude. Half-wave rectifier: output = input – 0.7V (one diode drop). Full-wave rectifier: output = input – 1.4V (two diode drops). Precision rectifiers use op-amps with diodes in feedback loop to eliminate voltage drop through negative feedback compensation. Advantages: (1) No voltage drop (rectify signals < 0.7V), (2) Amplification capability, (3) Very low output impedance, (4) High input impedance, (5) Near-ideal diode characteristics. Essential for low-level signal processing.

#### Detailed Explanation

### 2. Detailed Explanation

#### Passive Rectifier Review:

*Rectification Concept:* Converting alternating current (AC) to direct current (DC). Current flows in one direction only (may be pulsating, but unidirectional). Output maintains same polarity regardless of input polarity changes.

*Half-Wave Rectifier:* Converts only one half-cycle (positive or negative) of AC input to DC. Other half-cycle blocked. Output frequency equals input frequency. Single diode implementation. Efficiency approximately 40.6%.

*Full-Wave Rectifier:* Converts both positive and negative half-cycles to DC (same polarity). Output frequency doubles (120Hz from 60Hz input). Bridge rectifier uses four diodes, center-tap transformer uses two diodes. Efficiency approximately 81.2%. Provides twice the average output voltage compared to half-wave.

#### Fundamental Limitation: Diode Voltage Drop

Silicon diode forward voltage drop:  $V_f \approx 0.7V$  (depends on current, temperature, diode type). Schottky diode:  $V_f \approx 0.3V$  (lower but still significant for small signals).

#### Half-Wave Passive Rectifier:

One diode in series with signal path. Output voltage:

$$V_{out} = V_{in} - V_f \approx V_{in} - 0.7V$$

For  $V_{in} = 5V$  peak AC:  $V_{out} = 4.3V$  peak DC (acceptable loss).

For  $V_{in} = 0.5V$  peak AC: Diode barely conducts, severe distortion, output  $\approx 0V$  (unusable).

Cannot rectify signals smaller than diode threshold voltage.

#### Full-Wave Passive Rectifier (Bridge):

Two diodes conduct simultaneously (series path through signal). Output voltage:

$$V_{out} = V_{in} - 2V_f \approx V_{in} - 1.4V$$

Double voltage drop compounds small-signal problem.

#### Precision Rectifier Solution: Op-Amp Compensation

Operational amplifier drives diode(s) in feedback loop. Negative feedback ensures op-amp output compensates for diode voltage drop automatically.

*Key Principle:* Op-amp Golden Rule 2 (negative feedback forces inputs to same voltage). Feedback sampled after diode, so op-amp increases output voltage by exactly one diode drop to maintain input voltage equality. Diode drop absorbed internally, external circuit sees no voltage loss.

#### Advantages of Precision Rectifiers:

##### 1. Zero Effective Voltage Drop:

Op-amp compensates diode forward voltage. Output voltage equals input voltage (during conduction half-cycle). Can rectify signals much smaller than 0.7V—millivolt-level signals accurately processed. No threshold voltage limitation.

Example: 50mV AC signal perfectly rectified (impossible with passive diode rectifier).

## 2. Amplification Capability:

Precision rectifier core typically based on inverting or non-inverting amplifier configuration. Gain easily adjustable by resistor ratios:  $A_v = R_f/R_{in}$  (inverting) or  $A_v = 1 + R_f/R_{in}$  (non-inverting).

Single circuit performs rectification and amplification simultaneously. Reduces component count, simplifies signal conditioning chains.

Example: Rectify and amplify 10mV sensor signal to 1V for ADC input (gain = 100).

## 3. Very Low Output Impedance:

Op-amp output impedance typically  $< 100\Omega$  (often  $< 10\Omega$  for low-power op-amps,  $< 1\Omega$  for power op-amps). Load variations minimally affect output voltage. Can drive low-impedance loads without voltage drop or distortion.

Contrast: Passive rectifier output impedance includes diode dynamic resistance plus source impedance (can be high).

## 4. High Input Impedance:

Non-inverting configurations: Input impedance approaches op-amp input impedance ( $10^{12}\Omega$  for FET-input op-amps,  $10^9\Omega$  for BJT-input). Minimal source loading, preserves signal integrity.

Inverting configurations: Input impedance =  $R_{in}$  (input resistor value), still controllable and predictable.

## 5. Near-Ideal Diode Behavior:

Ideal diode characteristics: Zero forward voltage drop, infinite reverse resistance, zero forward resistance, instantaneous switching. Precision rectifier closely approximates ideal diode through active compensation. Limited only by op-amp slew rate and bandwidth (typically adequate for audio and instrumentation frequencies).

## Applications Requiring Precision Rectification:

- *Low-Level Signal Processing:* Sensor outputs (thermocouples, strain gauges, photodiodes), biomedical signals (ECG, EEG—microvolt to millivolt range)
- *Instrumentation:* RMS-to-DC converters, AC voltmeters, true RMS meters, peak detectors
- *Signal Conditioning:* Envelope detection, amplitude demodulation (AM radio), absolute value circuits
- *Measurement:* Precision diode replacement in test equipment, oscilloscope peak hold, waveform analysis
- *Audio Processing:* Compressor/limiter circuits, VU meters, audio level detection
- *Power Electronics:* Low-voltage energy harvesting, battery charging control, solar panel MPPT

## Trade-offs and Limitations:

Increased complexity compared to passive rectifiers. Requires power supply for op-amp (often dual supply for bipolar signals). Bandwidth limited by op-amp specifications (slew rate, gain-bandwidth product). Small-signal rectification at high frequencies challenging. Cost higher than simple diode rectifier. For high-voltage, high-current applications, passive rectifiers often more practical.

## Practical Example & Numerical

### Voltage Drop Comparison:

Input signal: 1V peak AC sine wave.

#### Passive Half-Wave Rectifier:

Silicon diode ( $V_f = 0.7V$ ). Output peak:  $V_{out} = 1 - 0.7 = 0.3V$ . Voltage loss: 70%. Unacceptable for precision applications.

#### Precision Half-Wave Rectifier:

Op-amp with diode in feedback. Op-amp output:  $V_{op} = V_{in} + V_f = 1 + 0.7 = 1.7V$ . After diode:  $V_{out} = V_{op} - V_f = 1.7 - 0.7 = 1V$ . Output equals input, zero effective drop.

### Small Signal Rectification:

Input: 100mV peak AC (typical sensor signal).

#### Passive Rectifier:

100mV  $<$  700mV diode threshold. Diode barely conducts, severe non-linearity. Output  $\approx 0V$  (signal lost).

#### Precision Rectifier:

Op-amp compensates automatically. Output: 100mV peak DC. Perfect rectification maintained even at millivolt levels.

### Amplification Example:

Input: 20mV AC sensor signal. Requirement: Rectify and amplify to 2V DC for ADC (gain = 100).

#### Passive Approach (fails):

Rectifier cannot process 20mV. Even if amplified first, requires separate amplifier stage plus rectifier (two circuits, complexity).

#### Precision Rectifier with Gain:

Single precision rectifier with  $R_f/R_{in} = 100$ . Input: 20mV AC. Output: 2V rectified DC. Single stage achieves both functions.

## Key Points (Interview Focus)

## 4. Key Points (Interview Focus)

- Passive rectifiers: voltage drop 0.7V (half-wave) or 1.4V (full-wave bridge), limits small signal processing
- Precision rectifiers: op-amp compensates diode drop through negative feedback, zero effective voltage loss
- Can rectify signals well below 0.7V threshold (millivolt-level signals accurately processed)
- Advantages: no voltage drop, gain capability, low output impedance, high input impedance, ideal diode behavior
- Op-amp Golden Rule 2 forces compensation: output = input +  $V_f$  so feedback point = input voltage
- Applications: instrumentation, low-level sensors, biomedical signals, RMS conversion, peak detection
- Trade-offs: complexity, power supply required, bandwidth limitations, cost
- Essential for precision measurement and signal conditioning in modern electronics
- Full-wave precision rectifiers provide both half-cycles rectified with same zero-drop advantage
- Gain adjustable by resistor ratios: single circuit performs rectification and amplification

## Half-Wave Precision Rectifier Circuits

### Basic Non-Inverting Half-Wave Precision Rectifier

#### TL;DR (The Gist)

Basic precision half-wave rectifier: op-amp in non-inverting configuration with diode in feedback path. Input to non-inverting input, feedback sampled after diode. Op-amp compensates diode drop by outputting  $V_{out} = V_{in} + V_f$  so feedback point matches input (Rule 2). Positive input half-cycle passes with zero effective drop. Negative half-cycle blocked (op-amp saturates low, diode reverse-biased, output = 0V). Can operate with single positive supply (no negative rail needed for this configuration). Rectifies signals well below 0.7V accurately.

#### Detailed Explanation

### 2. Detailed Explanation

#### Circuit Configuration:

Input signal applied to non-inverting input ( $V_+$ ). Op-amp output connected to diode anode. Diode cathode connected to: (1) output terminal, (2) negative feedback path back to inverting input ( $V_-$ ). Inverting input has no other connections (feedback only). Load resistor typically at output node (diode cathode).

*Key Topology Feature:* Feedback sampled *after* diode (at cathode), not before. This placement critical for compensation mechanism.

#### Single Supply Operation:

Unlike many op-amp circuits requiring dual supply ( $\pm 15V$ ), basic precision rectifier can operate with single positive supply.

Reasoning: Input signal positive half-cycle requires op-amp output positive (to forward-bias diode). Negative half-cycle: op-amp output goes to 0V (or slightly above ground), diode reverse-biased, output 0V. Op-amp never needs to output negative voltage for this half-wave rectification.

Power connections:  $V_{CC}$  = positive supply (e.g., +15V, +12V, +5V—choose based on input signal amplitude + headroom),  $V_{EE}$  or  $V_-$  = ground (0V).

Supply voltage selection: Must exceed maximum input voltage plus diode drop plus op-amp headroom. Example: For 5V peak input signal, use  $V_{CC} \geq 7V$  (5V + 0.7V diode + 1.3V op-amp headroom).

#### Operation During Positive Half-Cycle:

Input voltage positive:  $V_{in} = +V$  (where  $0 < V < V_{CC}$ ).

Op-amp Golden Rule 2: Negative feedback forces  $V_- = V_+$ . Since  $V_+ = V_{in}$ , op-amp must make  $V_- = V_{in}$ .

Inverting input connected to diode cathode (output). To achieve  $V_{cathode} = V_{in}$ , and knowing diode voltage drop:

$$V_{cathode} = V_{anode} - V_f$$

Therefore:

$$V_{in} = V_{op-amp\ output} - V_f$$

Solving for op-amp output:

$$V_{op-amp\ output} = V_{in} + V_f$$

Op-amp automatically outputs voltage higher by exactly one diode drop than input voltage.

Output voltage (at cathode, after diode):

$$V_{out} = V_{op-amp\ output} - V_f = (V_{in} + V_f) - V_f = V_{in}$$

Perfect transfer: Output equals input during positive half-cycle. Zero effective voltage drop.

#### Example Calculation:

Input:  $V_{in} = +0.5V$ . Diode forward voltage:  $V_f = 0.7V$  (typical silicon diode at low current).

Op-amp output:  $V_{op} = 0.5 + 0.7 = 1.2V$ .

After diode:  $V_{out} = 1.2 - 0.7 = 0.5V$ .

Output perfectly matches input, even though signal well below diode threshold.

#### Small Signal Capability:

For  $V_{in} = 50mV$  (50 millivolts):

Op-amp outputs:  $V_{op} = 0.05 + V_f$ . Diode conducts (op-amp provides forward voltage). Output:  $V_{out} = 0.05V$ .

Passive diode rectifier would fail completely at 50mV (far below 0.7V threshold). Precision rectifier works flawlessly.

#### Operation During Negative Half-Cycle:

Input voltage negative:  $V_{in} = -V$  (negative value).

Op-amp attempts to force  $V_- = V_+ = -V$  (negative voltage at inverting input). To make cathode negative, anode must be even more negative (by  $V_f$ ). Op-amp tries to output negative voltage.

With single positive supply (ground at negative rail), op-amp cannot output negative voltage. Output saturates at ground potential (0V, or slightly above—typically tens of millivolts).

Diode anode at 0V, cathode at 0V (connected to inverting input via feedback). Diode reverse-biased or zero-biased (not conducting). No current flows. Output voltage:  $V_{out} = 0V$ .

Result: Negative half-cycle completely blocked. Output remains at 0V throughout negative input excursion.

#### Half-Wave Rectification Achieved:

Positive half-cycle:  $V_{out} = V_{in}$  (passes with zero drop). Negative half-cycle:  $V_{out} = 0V$  (blocked). Classic half-wave rectification characteristic without passive diode voltage drop penalty.

#### Waveform Transformation:

Input: Sine wave AC,  $\pm V_{pk}$  amplitude, centered at 0V.

Output: Pulsating DC, 0 to  $+V_{pk}$  (positive peaks preserved, negative portions clipped to 0V). Frequency equals input frequency. Average DC value:  $V_{avg} = V_{pk}/\pi \approx 0.318 \times V_{pk}$  (same as passive half-wave rectifier).

#### Diode Selection and Forward Voltage:

Diode type affects compensation accuracy. Silicon diode:  $V_f \approx 0.6$  to  $0.7V$  (current-dependent). Schottky diode:  $V_f \approx 0.3$  to  $0.4V$  (lower drop, faster switching). Germanium diode:  $V_f \approx 0.3V$  (rare in modern designs).

Op-amp compensates regardless of diode type. Works with any forward voltage. Even LED could theoretically be used ( $V_f \approx 2V$ —op-amp compensates, though impractical).

Current affects  $V_f$ : Higher current increases forward voltage slightly. Op-amp tracks this variation automatically through feedback.

#### Practical Considerations:

*Speed and Slew Rate:* Op-amp must respond quickly to input changes. Slew rate ( $V/\mu s$ ) limits maximum frequency. For sine wave  $V_{pk}$  amplitude at frequency  $f$ : required slew rate  $\geq 2\pi f V_{pk}$ . Low slew rate causes distortion at high frequencies.

Example: 10V peak, 10kHz sine requires  $SR \geq 2\pi \times 10k \times 10 \approx 0.63 V/\mu s$ . Most general-purpose op-amps adequate.

*Output Current:* Op-amp drives diode and load. Output current capability must exceed load requirements. Typical op-amp: 20-30mA max. For higher currents, use buffer stage or power op-amp.

*Accuracy:* Op-amp offset voltage and bias current introduce small errors. Precision op-amps (low offset) recommended for accurate low-level rectification.

## Practical Example & Numerical

#### 500mV Sine Wave Rectification:

Input: 500mV peak sine wave (1kHz). Op-amp: Powered with +15V and 0V (single supply). Diode: General-purpose silicon (e.g., 1N4148),  $V_f = 0.5V$  at low current.

*Positive Peak (+500mV):*

Op-amp output:  $V_{op} = 500mV + 500mV = 1V$  (1 volt).

After diode:  $V_{out} = 1V - 0.5V = 500mV$ .

Output matches input exactly.

*Negative Peak (-500mV):*

Op-amp attempts negative output, saturates at 0V (ground rail). Diode reverse-biased. Output:  $V_{out} = 0V$ .

*Result:* Half-wave rectified signal, 0 to 500mV, no voltage drop. Passive diode rectifier would fail ( $500mV < 700mV$  threshold).

#### Verification of Op-Amp Compensation:

Simulator measurement at positive peak:

- Input (non-inverting pin): +500mV
- Op-amp output (diode anode): +1.0V
- Output (diode cathode, feedback point): +500mV

Voltage across diode:  $1.0 - 0.5 = 0.5\text{V} = V_f$ . Op-amp increased output by exactly diode drop amount. Feedback point equals input (Rule 2 satisfied). Compensation mechanism verified.

**Extremely Small Signal (50mV):**

Input: 50mV peak. Diode  $V_f \approx 0.5\text{V}$  (depends on current, approximately constant at low currents).

Op-amp output:  $50\text{mV} + 500\text{mV} = 550\text{mV}$ .

Output:  $550 - 500 = 50\text{mV}$ .

Perfect rectification at 1/10th of diode threshold voltage. Demonstrates precision rectifier capability impossible with passive circuits.

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- Basic precision half-wave: input to non-inverting pin, diode in feedback (after diode to inverting pin)
- Op-amp compensates diode drop: outputs  $V_{in} + V_f$  so feedback point =  $V_{in}$  (Rule 2)
- Positive half-cycle:  $V_{out} = V_{in}$  (zero effective voltage drop)
- Negative half-cycle: op-amp saturates at 0V, diode reverse-biased,  $V_{out} = 0\text{V}$  (blocked)
- Single positive supply operation sufficient (op-amp never outputs negative voltage in this config)
- Rectifies signals well below diode threshold (millivolt-level signals accurately processed)
- Feedback sampled after diode (critical for compensation mechanism)
- Op-amp automatically tracks diode  $V_f$  variations (current, temperature, diode type)
- Speed limited by op-amp slew rate:  $\text{SR} \geq 2\pi f V_{pk}$  for sine waves
- Output current limited by op-amp capability (typically 20-30mA)
- Works with any diode type: silicon, Schottky, germanium—op-amp compensates any  $V_f$
- Applications: low-level signal rectification, peak detection, envelope detection, instrumentation

## Inverting Precision Half-Wave Rectifier with Gain

### TL;DR (The Gist)

Inverting precision half-wave rectifier with gain: input to inverting input through  $R_{in}$ , dual-diode feedback network with  $R_f$ . Rectifies and amplifies simultaneously. Gain:  $A_v = -R_f/R_{in}$  (inverting amplifier formula). Negative input half-cycle passes (becomes positive output after inversion). Positive input blocked. Dual supply required (op-amp outputs negative voltage during blocking cycle). Voltage divider ( $R_{in}$ ,  $R_f$ ) maintains virtual ground at inverting input (Rule 2). One diode conducts during pass cycle, other conducts during block cycle (steering output current path). Single-stage rectification and amplification ideal for low-level sensor signal conditioning.

### Detailed Explanation

### 2. Detailed Explanation

**Circuit Configuration:**

Input signal applied through input resistor  $R_{in}$  to inverting input. Non-inverting input grounded (0V). Two diodes in feedback network:

- Diode D1: Anode to op-amp output, cathode to inverting input (through feedback resistor  $R_f$ )
- Diode D2: Cathode to op-amp output, anode to inverting input (through  $R_f$ )—reverse direction relative to D1

Feedback resistor  $R_f$  connects diode network to inverting input. Output taken from diode cathode (D1) or op-amp output depending on design variation.

*Core Topology:* Inverting amplifier with diode-steering feedback network. Two diodes conduct alternately depending on input polarity, creating rectification while maintaining amplifier gain.

**Fundamental Principle: Virtual Ground Maintenance**

Op-amp Golden Rule 2: Inverting input (virtual ground) maintained at 0V (since non-inverting input grounded). Regardless of input signal polarity or amplitude, op-amp adjusts output voltage to keep inverting input at 0V.

Voltage divider formed by  $R_{in}$  (input to virtual ground) and  $R_f$  (virtual ground to output via diode). For virtual ground to remain at 0V with one end at  $V_{in}$  and other end at  $V_{out}$ :

$$\frac{V_{in}}{R_{in}} + \frac{V_{out}}{R_f} = 0 \quad (\text{current balance at virtual ground})$$

Solving for output:

$$V_{out} = -\frac{R_f}{R_{in}} V_{in}$$

Standard inverting amplifier gain relationship, but implemented with diode steering for rectification.

**Operation During Negative Input Half-Cycle (Pass Cycle):**

Input voltage negative:  $V_{in} = -V$  (negative value, e.g., -0.5V).

To maintain virtual ground at 0V, and given voltage divider with  $V_{in}$  negative on one end, output must be positive on other end.

Calculation: If  $V_{in} = -0.5V$  and  $R_f = R_{in}$  (unity gain magnitude):

Virtual ground at 0V requires:  $V_{out} = -(-0.5) = +0.5V$  (after inversion and rectification).

Actually, output becomes positive:  $V_{out} = (R_f/R_{in}) \times |V_{in}|$ .

Op-amp output goes positive (e.g., +0.5V plus diode drop). Diode D1 conducts (forward-biased). Current path: Input  $\rightarrow R_{in} \rightarrow$  virtual ground  $\rightarrow R_f \rightarrow$  D1  $\rightarrow$  output. Diode D2 reverse-biased (off).

Output voltage (at D1 cathode): Positive value, proportional to negative input, inverted and rectified.

**Operation During Positive Input Half-Cycle (Block Cycle):**

Input voltage positive:  $V_{in} = +V$  (positive value, e.g., +0.5V).

To maintain virtual ground at 0V with positive voltage on input side, output side of divider must be negative.

Op-amp output goes negative. Diode D2 conducts (forward-biased—cathode at negative op-amp output, anode toward virtual ground). Diode D1 reverse-biased (off).

Current path: Input  $\rightarrow R_{in} \rightarrow$  virtual ground, but instead of going to output through  $R_f$  and D1 (blocked), current diverts through D2 back to op-amp output.

Output voltage (at D1 cathode): Remains at or near 0V (D1 not conducting, no forward current path). Positive input blocked from output.

Op-amp output: Negative voltage approximately equal to negative diode drop (to turn on D2). Typically around -0.4V to -0.7V.

**Dual Supply Requirement:**

Unlike basic non-inverting precision rectifier (single supply), inverting version requires dual supply (e.g.,  $\pm 15V$ ,  $\pm 12V$ ,  $\pm 5V$ ).

Reason: During positive input (block cycle), op-amp outputs negative voltage (to conduct D2 and shunt current). Negative supply rail necessary for op-amp to output negative voltage.

Power connections:  $V_{CC}$  = positive supply,  $V_{EE}$  or  $V_-$  = negative supply (equal magnitude or asymmetric based on signal range).

**Gain Control and Amplification:**

Gain determined by resistor ratio (standard inverting amplifier):

$$A_v = -\frac{R_f}{R_{in}}$$

Negative sign indicates inversion (negative input produces positive output). Magnitude of gain sets amplification.

For  $R_f = R_{in}$ :  $|A_v| = 1$  (unity gain, rectification without amplification).

For  $R_f = 2 \times R_{in}$ :  $|A_v| = 2$  (double amplitude, gain of 2).

For  $R_f = 10 \times R_{in}$ :  $|A_v| = 10$  (tenfold amplification).

**Example: Unity Gain Configuration**

$R_{in} = 10k\Omega$ ,  $R_f = 10k\Omega$ . Gain magnitude = 1.

Input: -0.5V (negative). Output: +0.5V (positive, inverted, rectified).

Input: +0.5V (positive). Output: 0V (blocked).

**Example: Gain = 2 Configuration**

$R_{in} = 10k\Omega$ ,  $R_f = 20k\Omega$ . Gain magnitude = 2.

Input: -0.5V (negative). Output:  $+2 \times 0.5 = +1V$  (amplified).

Input: +0.5V (positive). Output: 0V (blocked).

Output amplitude doubled compared to input (rectification with  $2\times$  gain).

**Current Flow Analysis:**

*Negative Input (D1 Conducting):*

Input current:  $I_{in} = V_{in}/R_{in}$  (flows from input to virtual ground).

Feedback current:  $I_f = I_{in}$  (Rule 1: no current into op-amp, so input current equals feedback current).

Feedback current through  $R_f$  and D1 to output.

Output sources current:  $I_{out} = I_f = V_{in}/R_{in}$ .

*Positive Input (D2 Conducting):*

Input current:  $I_{in} = V_{in}/R_{in}$  (flows from input toward virtual ground).

This current diverts through D2 back to op-amp output (not to external output node). D1 blocked, so no current to output terminal. Output current:  $I_{out} = 0$ .

**Diode Roles:**

D1: Output diode—conducts during pass cycle, delivers rectified signal to output.

D2: Shunt diode—conducts during block cycle, provides low-impedance path for input current to op-amp output, prevents D1 conduction, keeps output at 0V.

Both diodes essential for proper half-wave precision rectification with gain.

#### Applications:

Low-level sensor signals requiring both rectification and amplification. Example: 10mV AC sensor output needs rectification and  $100\times$  gain (1V DC output). Single precision rectifier stage achieves both.

Signal conditioning chains: Reduces component count (eliminates separate amplifier and rectifier stages). Photodiode signal processing (light intensity detection). Audio envelope detection (amplitude modulation demodulation).

Instrumentation amplifiers with rectified output.

### Practical Example & Numerical

#### Unity Gain Rectifier Analysis:

Circuit:  $R_{in} = 10k\Omega$ ,  $R_f = 10k\Omega$ , gain = 1. Input: 500mV peak AC sine wave (negative and positive half-cycles). Dual supply:  $\pm 15V$ .

*Negative Half-Cycle (Input = -500mV):*

Virtual ground maintained at 0V. Voltage divider:  $V_{in} = -0.5V$  on one end, output on other end, center at 0V. For symmetry: Output = +0.5V.

Op-amp output: +0.5V + diode drop (e.g., +1.0V assuming  $V_f = 0.5V$ ). D1 conducts. Output after D1: +0.5V. Perfect inversion and rectification without voltage drop.

*Positive Half-Cycle (Input = +500mV):*

Op-amp output goes negative (approximately -0.5V to -0.7V) to conduct D2. D2 shunts input current back to op-amp. D1 reverse-biased, blocks. Output: 0V.

*Result:* Negative half-cycles become positive output (inverted, rectified). Positive half-cycles blocked (output = 0V). Half-wave rectification with inversion.

#### Gain = 2 Amplification:

Circuit:  $R_{in} = 10k\Omega$ ,  $R_f = 20k\Omega$ , gain = 2. Input: 500mV peak AC.

*Negative Input (-500mV):*

Gain =  $R_f/R_{in} = 20k/10k = 2$ . Output:  $2 \times 0.5 = 1V$  (positive, amplified).

Op-amp output: 1V + diode drop  $\approx 1.5V$ . D1 conducts. Output: 1V.

*Positive Input (+500mV):*

D2 conducts, output blocked. Output: 0V.

*Result:* Output amplitude 1V (doubled from 500mV input). Simultaneous rectification and amplification in single stage.

#### Small Signal with High Gain:

Application: Thermocouple output 10mV, need 1V rectified DC (gain = 100).

Circuit:  $R_{in} = 1k\Omega$ ,  $R_f = 100k\Omega$ , gain = 100.

Input: 10mV AC (small thermocouple signal).

Negative input (-10mV): Output =  $100 \times 10mV = 1V$  (rectified, amplified).

Positive input (+10mV): Output = 0V (blocked).

Single precision rectifier achieves  $100\times$  gain and rectification—ideal for low-level sensor interfacing.

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

- Inverting precision half-wave rectifier: input to inverting pin via  $R_{in}$ , dual-diode feedback network
- Gain controllable:  $A_v = -R_f/R_{in}$  (standard inverting amplifier formula)
- Negative input half-cycle passes, becomes positive output (inversion + rectification)
- Positive input half-cycle blocked (output = 0V)
- Dual supply required: op-amp outputs negative voltage during block cycle
- Virtual ground at inverting input (0V) maintained by voltage divider ( $R_{in}$ ,  $R_f$ )
- Diode D1: conducts during pass cycle, delivers rectified signal to output
- Diode D2: conducts during block cycle, shunts input current, prevents output conduction
- Single stage performs rectification and amplification simultaneously
- Applications: low-level sensor conditioning, photodiode amplification, envelope detection
- For unity gain:  $R_f = R_{in}$ ; for gain = 10:  $R_f = 10 \times R_{in}$
- Ideal for signals requiring both rectification and significant amplification (eliminates separate stages)

# Section 27 – Common Op-Amp Based Circuits

This bonus section examines three essential op-amp circuit configurations frequently encountered in signal processing, measurement, and control applications: peak detector (captures and holds maximum signal voltage), current-to-voltage converter (transduces current into proportional voltage for sensor interfacing), and Schmitt trigger (comparator with hysteresis providing noise immunity). These circuits demonstrate op-amp versatility beyond basic amplification, enabling critical functions in instrumentation, data acquisition, photodiode signal processing, and reliable digital signal generation from noisy analog inputs.

## Peak Detection and Signal Capture

### Op-Amp Peak Detector with Hold Capability

#### TL;DR (The Gist)

Peak detector circuit captures and stores maximum (peak) value of time-varying input signal. Configuration: precision half-wave rectifier with hold capacitor. Op-amp in non-inverting mode drives diode, capacitor at diode cathode stores peak voltage. When input rises above stored voltage, op-amp forward-biases diode, charging capacitor to new peak. When input falls below stored voltage, diode reverse-biases, isolating capacitor (holds peak voltage indefinitely). Output buffer (voltage follower) prevents load from discharging capacitor. Manual reset via switch/resistor across capacitor. Applications: AC voltmeter peak reading, envelope detection, signal analysis, maximum value measurement of non-sinusoidal waveforms.

#### Detailed Explanation

### 2. Detailed Explanation

#### Purpose and Advantages Over Multimeter:

Peak detector outputs DC voltage equal to peak (maximum) value of applied AC or pulsating signal. Maintains peak value until manually reset or new higher peak occurs.

*Multimeter Limitation:* AC voltmeters measure RMS (root-mean-square) value. For sine wave:  $V_{RMS} = V_{peak}/\sqrt{2} \approx 0.707 \times V_{peak}$ . To find peak:  $V_{peak} = \sqrt{2} \times V_{RMS} \approx 1.414 \times V_{RMS}$ . This conversion only valid for pure sinusoidal waveforms. Complex waveforms (distorted, pulsed, irregular) cannot be accurately measured by standard AC meters using RMS-to-peak conversion.

*Peak Detector Advantage:* Directly measures actual peak voltage of any waveform shape. No assumptions about signal shape required. Essential for non-sinusoidal signals: pulse trains, modulated signals, complex waveforms, transient spikes.

#### Circuit Configuration:

Core components: Op-amp (non-inverting configuration), diode (charging path), hold capacitor (stores peak), output buffer (optional but recommended).

#### Topology:

- Input signal to non-inverting input ( $V_+$ )
- Op-amp output to diode anode
- Diode cathode to: (1) inverting input ( $V_-$ , feedback), (2) hold capacitor (to ground), (3) output node
- Capacitor stores voltage, provides output
- Voltage follower buffer isolates capacitor from load

Similar to precision half-wave rectifier, but with critical addition of hold capacitor at output node.

#### Operation During Rising Input (Capacitor Charging):

Initial state: Capacitor uncharged ( $V_C = 0V$ ). Input signal applied, increases from 0V.

Op-amp Golden Rule 2: Attempts to keep  $V_- = V_+$ . Since  $V_+ = V_{in}$  (input signal) and  $V_-$  connected to capacitor voltage ( $V_C$ ), op-amp drives output to make  $V_C = V_{in}$ .

Op-amp output:  $V_{op} = V_{in} + V_f$  (input plus diode forward voltage, compensating diode drop—precision rectifier principle).

Diode forward-biased (anode at  $V_{op}$ , cathode at lower voltage  $V_C$ ). Current flows through diode, charging capacitor. Capacitor voltage rises:  $V_C \rightarrow V_{in}$ .

When  $V_C$  reaches  $V_{in}$ : Inputs equalized ( $V_- = V_+$ ), Rule 2 satisfied. Charging current reduces to zero (equilibrium).

*Key Point:* Capacitor charged to input voltage during rising edge, tracking input as it increases.

#### Operation During Falling Input (Capacitor Holding):

Input signal decreases from peak value. Capacitor voltage  $V_C$  remains at previous peak (capacitor cannot discharge instantly without current path).

Voltage comparison:  $V_+ = V_{in}$  (now lower),  $V_- = V_C$  (still at peak). Inverting input higher than non-inverting input ( $V_- > V_+$ ).

Op-amp response: Attempts to reduce  $V_-$  to match  $V_+$ . To lower inverting input voltage, op-amp output goes negative (if dual supply) or to ground (if single supply). Tries to pull capacitor voltage down.

Diode behavior: Op-amp output negative (or low), diode cathode at higher voltage  $V_C$  (positive). Diode reverse-biased (cathode positive relative to anode). No current flows through diode.

Critical mechanism: Reverse-biased diode blocks discharge path. Capacitor isolated from op-amp output. Capacitor retains charge, voltage  $V_C$  stays at peak value.

*Op-Amp Comparator Mode:* During hold phase, op-amp essentially operates as comparator (output saturates negative because  $V_- > V_+$ ), despite negative feedback connection. Feedback path blocked by reverse-biased diode, breaking typical negative feedback operation.

#### Detection of New Higher Peak:

If input signal later rises above stored peak:  $V_{in} > V_C$  (non-inverting input exceeds inverting input).

Op-amp output goes positive again:  $V_{op} = V_{in} + V_f$ . Diode forward-biases. Current flows, charging capacitor to new higher peak. Process repeats: capacitor updated to new maximum value.

Result: Capacitor always retains highest peak encountered since last reset.

#### Hold Capacitor Selection:

Larger capacitance: Longer hold time (less voltage droop from leakage), slower charging (affects response to fast transients). Typical:  $1\mu\text{F}$  to  $100\mu\text{F}$ .

Smaller capacitance: Faster response to peaks, shorter hold time (more droop from leakage currents).

Low-leakage capacitor types preferred: Polypropylene, polyester, tantalum. Minimize self-discharge.

#### Output Buffer Stage (Voltage Follower):

*Problem Without Buffer:* Connecting load directly to capacitor provides discharge path. Load current drains capacitor:  $V_C$  drops, losing peak information. Even high-impedance loads (ADC inputs, multimeter) draw small current, causing voltage decay.

*Buffer Solution:* Unity-gain voltage follower after hold capacitor. Buffer input (non-inverting pin) connected to capacitor. Buffer output drives load.

Advantages:

- Extremely high input impedance ( $10^{12}\Omega$  FET-input op-amp): Negligible current drawn from capacitor
- Low output impedance ( $< 100\Omega$ ): Can drive low-impedance loads without voltage drop
- Unity gain: Output voltage equals capacitor voltage accurately
- Isolation: Capacitor voltage preserved regardless of load variations

#### Reset Mechanism:

Capacitor must be discharged to measure new peak values (reset circuit). Two common methods:

##### 1. Manual Reset (Switch and Resistor):

Resistor (e.g.,  $100\Omega$  to  $1\text{k}\Omega$ ) and normally-open switch in parallel with capacitor. Pressing switch connects resistor across capacitor, discharging through  $R$ . Discharge time constant:  $\tau = RC$ . Smaller  $R$ : faster reset (but higher discharge current spike).

Example:  $C = 10\mu\text{F}$ ,  $R = 100\Omega$ ,  $\tau = 1\text{ms}$  (rapid discharge).

##### 2. Automatic Reset (Transistor Control):

Transistor (BJT or MOSFET) across capacitor, controlled by microcontroller or timer. Logic HIGH: transistor saturates, shorts capacitor (discharge). Logic LOW: transistor off, normal peak detection. Enables programmed reset cycles, automatic periodic measurements.

#### Applications:

- *AC Voltmeter (Peak Reading):* Measure true peak voltage of AC signals, especially non-sinusoidal waveforms
- *Envelope Detection:* Extract amplitude envelope from modulated signals (AM radio, RF communications)
- *Signal Analysis:* Determine maximum voltage excursions in complex waveforms
- *Transient Capture:* Capture brief voltage spikes or glitches for diagnostic purposes
- *Data Acquisition:* Hold peak value for slow ADC conversion
- *Test Equipment:* Oscilloscope peak hold function, automatic test systems

## Practical Example & Numerical

### Peak Detection of Complex Waveform:

Input: Two sine generators in series creating complex waveform. First generator: 5V peak, 50Hz. Second generator: 2V peak, 200Hz. Combined peak: approximately 7V (when both peaks align constructively).

Circuit: Op-amp peak detector with  $10\mu\text{F}$  capacitor, voltage follower buffer.

*Operation:*

Initial state: Capacitor at 0V. Input waveform starts, reaches first peak (e.g., 6V). Op-amp charges capacitor to 6V. Input falls, diode blocks, capacitor holds 6V.

Later cycle: Input reaches higher peak (7V) due to constructive phase alignment. Op-amp detects  $V_{in}$  (7V) >  $V_C$  (6V). Diode conducts, capacitor charges to 7V. New peak stored.

Output (after buffer): Steady 7V DC, representing maximum peak voltage of complex waveform.

*Result:* True peak measured directly, independent of waveform shape or RMS calculations.

#### Multimeter Comparison:

Same complex waveform, AC multimeter (RMS mode) measures:  $V_{RMS} \approx 4.5V$  (hypothetical).

Using sine wave conversion:  $V_{peak} = 1.414 \times 4.5 \approx 6.36V$  (incorrect estimate).

Peak detector output: 7V (accurate actual peak).

Demonstrates peak detector advantage for non-sinusoidal signals.

#### Capacitor Discharge Time:

Capacitor:  $10\mu F$ , charged to 10V. No load, only op-amp input leakage (1nA typical).

Discharge current:  $I_{leak} = 1nA$ . Voltage drop rate:  $dV/dt = I/C = 10^{-9}/10^{-5} = 10^{-4} V/s = 0.1mV/s$ .

Time to drop 1V:  $t = 1/(0.0001) = 10,000s \approx 2.8$  hours.

Excellent hold time for practical measurements (minutes to hours before significant droop).

With buffer: Hold time extended indefinitely (leakage reduced to femtoampere range).

#### Reset Mechanism Example:

Reset resistor:  $R = 220\Omega$ . Capacitor:  $C = 10\mu F$ . Time constant:  $\tau = 220 \times 10^{-5} = 2.2ms$ .

Discharge to 1% of initial voltage:  $t = 5\tau = 11ms$  (rapid reset when button pressed).

Brief button press (100ms) fully discharges capacitor, ready for new peak measurement cycle.

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

- Peak detector: captures and holds maximum voltage of time-varying signal
- Circuit: op-amp non-inverting config, diode, hold capacitor, output buffer (voltage follower)
- Rising input: diode conducts, capacitor charges to input voltage (tracking mode)
- Falling input: diode reverse-biased, capacitor isolated, holds peak voltage (hold mode)
- Op-amp compensates diode drop (precision rectifier principle):  $V_{op} = V_{in} + V_f$
- Capacitor always retains highest peak since last reset
- Buffer essential: isolates capacitor from load, prevents discharge, enables measurement
- Reset mechanism: switch/resistor (manual) or transistor (automatic) discharges capacitor
- Advantages over multimeter: measures true peak of non-sinusoidal waveforms, no RMS conversion needed
- Applications: AC voltmeter, envelope detection, transient capture, signal analysis, data acquisition
- Capacitor selection: larger = longer hold, smaller = faster response; low-leakage types preferred
- Hold time: hours typical with proper capacitor and buffer (minimal leakage current)

## Current-to-Voltage Conversion

### Current-to-Voltage Converter (Transimpedance Amplifier)

#### TL;DR (The Gist)

Current-to-voltage (I-V) converter, also called transimpedance amplifier, converts input current to proportional output voltage. Configuration: current source to inverting input, non-inverting input grounded, feedback resistor  $R_f$  from output to inverting input. Virtual ground at inverting input forces all input current through  $R_f$ . Output voltage:  $V_{out} = -I_{in} \times R_f$  (Ohm's law applied to feedback resistor). Gain is  $R_f$  (units: ohms, transimpedance). Negative sign from inverting topology. Superior to simple resistor: virtual ground prevents voltage buildup at input, maintains constant input impedance, provides gain control. Essential for photodiode amplification, current sensor readout, precision current measurement. Linear current response better than voltage response for many sensors.

#### Detailed Explanation

## 2. Detailed Explanation

### Amplifier Gain Concept with Different Units:

Traditional amplifier: Voltage input, voltage output. Gain  $A_v = V_{out}/V_{in}$  (dimensionless ratio). Example: 10mV input, 100mV output, gain = 10.

Current-to-voltage amplifier: Current input, voltage output. "Gain" has units (ohms,  $\Omega$ ), called transimpedance. Output amplitude = input current  $\times$  transimpedance.

Example: 5mA input current, 5V output voltage. Transimpedance:  $5V/5mA = 1k\Omega$ .

*Analogy to Resistor:* Ohm's law:  $V = I \times R$ . Resistor converts current to voltage with "gain" = resistance. I-V converter performs same function but with op-amp advantages (virtual ground, low output impedance, controlled gain).

### Current Source Fundamentals:

*Definition:* Circuit element maintaining constant current flow regardless of load voltage or impedance. Complementary to voltage source (maintains constant voltage regardless of load current).

*Ideal Current Source Characteristics:*

- Provides specified current (rating: e.g., 5mA, 100 $\mu$ A, 10A)
- Current independent of load resistance
- Adjusts output voltage as needed to maintain current
- Infinite output impedance (theoretical)

*Symbol:* Circle with arrow indicating current direction (corresponds to voltage polarity—current flows from positive terminal).

*Practical Operation:* Current source varies output voltage to compensate for load resistance changes, maintaining constant current. Higher load resistance: higher voltage. Lower load resistance: lower voltage.

Example: 10mA current source driving variable load. Load = 100 $\Omega$ : voltage = 1V. Load = 1k $\Omega$ : voltage = 10V. Current remains 10mA.

### Simple Resistor as I-V Converter (Baseline):

Resistor  $R$  connected to current source. Voltage developed:  $V = I \times R$  (Ohm's law).

Current source: 10mA. Resistor: 1k $\Omega$ . Output voltage:  $V = 10mA \times 1k\Omega = 10V$ .

Changing current: 20mA. Output voltage: 20V. Linear current-to-voltage conversion.

*Limitations:* Input node voltage rises with current (not virtual ground). Source must handle voltage variation. No isolation between input and output. Limited gain control (single resistor).

### Op-Amp I-V Converter Circuit Configuration:

Input current source connected to inverting input ( $V_-$ ). Non-inverting input grounded ( $V_+ = 0V$ ). Feedback resistor  $R_f$  from output to inverting input. No other components.

*Topology Simplicity:* Minimal component count. Single feedback resistor sets transimpedance gain. Op-amp provides active conversion with virtual ground advantage.

### Analysis Using Op-Amp Golden Rules:

*Rule 1:* No current flows into op-amp inputs. All input current must flow somewhere else.

*Rule 2:* Negative feedback forces inverting input voltage equal to non-inverting input voltage. Since  $V_+ = 0$  (grounded),  $V_- = 0$  (virtual ground).

*Current Flow Path:*

Input current  $I_{in}$  flows into inverting input node. Cannot flow into op-amp (Rule 1). Must flow through feedback resistor  $R_f$  to output. Therefore:  $I_{R_f} = I_{in}$  (all input current through feedback resistor).

*Voltage Calculation:*

Voltage across  $R_f$ : Left terminal at virtual ground (0V), right terminal at  $V_{out}$ .

Ohm's law across  $R_f$ :

$$V_{R_f} = I_{R_f} \times R_f = I_{in} \times R_f$$

Polarity: Current flows from virtual ground (0V) toward output. If current flows left-to-right (into circuit), output terminal at lower potential (negative voltage).

Output voltage:

$$V_{out} = 0 - V_{R_f} = -I_{in} \times R_f$$

### I-V Converter Equation:

$$\boxed{V_{out} = -I_{in} \times R_f}$$

Negative sign: Inverting topology. Current flowing into circuit produces negative output voltage. Current flowing out produces positive output.

Transimpedance gain:  $Z_{trans} = R_f$  (units: ohms).

### Polarity Relationship:

Current into circuit (positive  $I_{in}$ ): Negative output voltage. Current out of circuit (negative  $I_{in}$ ): Positive output voltage.

Example:  $I_{in} = +5mA$  (into circuit),  $R_f = 1k\Omega$ .  $V_{out} = -5mA \times 1k\Omega = -5V$ .

Reverse current direction:  $I_{in} = -5mA$  (out).  $V_{out} = -(-5mA) \times 1k\Omega = +5V$ .

### Advantages Over Simple Resistor Conversion:

#### 1. Virtual Ground Input:

Inverting input maintained at 0V (virtual ground). Input node voltage constant regardless of current magnitude. Simplifies current source design (source sees fixed voltage, not varying load).

#### 2. Low Output Impedance:

Op-amp output impedance typically  $< 100\Omega$ . Can drive low-impedance loads without voltage drop or distortion. Output voltage stable under varying load conditions.

#### 3. Controlled Gain:

Transimpedance set by single resistor  $R_f$ . Easy gain adjustment (change resistor value). Wide gain range:  $100\Omega$  to  $10M\Omega$  typical.

#### 4. Signal Isolation:

Input current source isolated from output voltage load. No direct electrical connection. Prevents loading effects, improves measurement accuracy.

### Photodiode Application (Primary Use Case):

#### Photodiode Characteristics:

Photodiode in reverse-bias mode generates current proportional to incident light intensity. Current response highly linear (better than 1% linearity over wide light range). Voltage response non-linear (affected by diode junction characteristics).

For accurate light measurement: Use current output (linear) rather than voltage output (non-linear).

#### I-V Converter Integration:

Photodiode connected to I-V converter input. Photodiode generates current  $I_{photo}$  proportional to light. I-V converter produces voltage  $V_{out} = -I_{photo} \times R_f$ . Output voltage linearly proportional to light intensity.

Further processing: Output voltage to ADC, microcontroller, display, or additional signal conditioning circuits.

#### Transimpedance Selection:

Bright light (high photocurrent): Smaller  $R_f$  (e.g.,  $1k\Omega$  to  $10k\Omega$ ) prevents output saturation.

Low light (small photocurrent): Larger  $R_f$  (e.g.,  $100k\Omega$  to  $10M\Omega$ ) provides higher sensitivity, larger output voltage.

### Other Applications:

Current sensors (Hall effect, current transformers). Precision current measurement instruments. Ionization chamber readout (radiation detection). Photomultiplier tube signal conditioning. Piezoelectric sensor amplification (charge-to-voltage conversion with capacitor feedback).

## Practical Example & Numerical

### Basic I-V Conversion:

Current source:  $I_{in} = 10\text{mA}$ . Feedback resistor:  $R_f = 1k\Omega$ .

Output voltage:

$$V_{out} = -I_{in} \times R_f = -10\text{mA} \times 1k\Omega = -10V$$

Current into circuit produces negative output voltage.

#### Reversed Current:

Reverse current source polarity:  $I_{in} = -10\text{mA}$  (current flows out).

Output voltage:

$$V_{out} = -(-10\text{mA}) \times 1k\Omega = +10V$$

Positive output voltage for reversed current.

### Photodiode Light Measurement:

Photodiode specifications:  $1\mu\text{A}$  per lux (light intensity unit). Maximum photocurrent:  $100\mu\text{A}$  (bright sunlight).

Transimpedance resistor:  $R_f = 100k\Omega$  (high gain for sensitivity).

#### Low Light (1 lux):

Photocurrent:  $1\mu\text{A}$ . Output voltage:  $V_{out} = -1\mu\text{A} \times 100k\Omega = -0.1V = -100\text{mV}$ .

Measurable voltage for dim light.

#### Bright Light (100 lux):

Photocurrent:  $100\mu\text{A}$ . Output voltage:  $V_{out} = -100\mu\text{A} \times 100k\Omega = -10V$ .

Linear response maintained across 100:1 light intensity range.

### Gain Adjustment for Different Ranges:

Application: Light meter with auto-ranging capability.

Low light range:  $R_f = 1M\Omega$  (high sensitivity). Photocurrent  $1\mu\text{A}$ : output =  $-1V$  (easily measured).

Bright light range:  $R_f = 10k\Omega$  (lower gain). Photocurrent  $100\mu\text{A}$ : output =  $-1V$  (prevents saturation).

Microcontroller switches  $R_f$  values (relay or analog switch) for optimal range.

### Comparison: Resistor vs I-V Converter:

Current:  $5\text{mA}$ . Resistor:  $1k\Omega$ .

#### Simple Resistor:

Voltage:  $V = 5\text{mA} \times 1k\Omega = 5V$  (across resistor). Input node at  $5V$  (not virtual ground). Current source must handle  $5V$  compliance voltage.

#### *I-V Converter:*

Output:  $V_{out} = -5\text{mA} \times 1\text{k}\Omega = -5\text{V}$  (at op-amp output). Input node: 0V (virtual ground). Current source operates at 0V (simplified drive requirements).

I-V converter provides virtual ground advantage, reducing current source design complexity.

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

- Current-to-voltage converter (I-V, transimpedance amplifier): converts current to voltage
- Circuit: current source to inverting input, non-inverting grounded, feedback resistor  $R_f$
- Output equation:  $V_{out} = -I_{in} \times R_f$  (negative sign from inverting topology)
- Transimpedance gain:  $R_f$  (units: ohms), sets current-to-voltage conversion ratio
- Virtual ground at input: inverting input at 0V regardless of current magnitude
- All input current flows through  $R_f$  (Rule 1: no current into op-amp)
- Advantages: virtual ground input, low output impedance, controlled gain, signal isolation
- Superior to simple resistor: constant input voltage, better load driving, easier gain control
- Primary application: photodiode amplification (linear current response to light)
- Photodiode current response more linear than voltage response (better than 1% linearity)
- Transimpedance selection: high  $R_f$  (100k $\Omega$ -10M $\Omega$ ) for low light, low  $R_f$  (1k $\Omega$ -10k $\Omega$ ) for bright light
- Other uses: current sensors, precision current measurement, radiation detection, charge amplification

## Comparator with Hysteresis

### Op-Amp Schmitt Trigger (Non-Inverting Comparator with Hysteresis)

#### TL;DR (The Gist)

Schmitt trigger: comparator circuit with hysteresis (different switching thresholds for rising vs falling transitions), providing noise immunity. Op-amp configuration: positive feedback (output to non-inverting input via voltage divider), input to inverting input. Two threshold voltages: upper threshold  $V_{TH}$  (output switches HIGH to LOW when input rises above), lower threshold  $V_{TL}$  (output switches LOW to HIGH when input falls below). Hysteresis voltage:  $V_{hyst} = V_{TH} - V_{TL}$ . Prevents multiple output transitions from noisy input near single threshold. Voltage divider ( $R_1$  to  $V_{CC}$ ,  $R_2$  to ground,  $R_3$  from output—positive feedback) sets thresholds dynamically based on output state. Essential for clean digital signal generation from noisy analog sources, debouncing, oscillator circuits, noise-immune switching.

#### Detailed Explanation

#### 2. Detailed Explanation

##### **Hysteresis Concept and Necessity:**

*Hysteresis Definition:* Circuit characteristic where switching thresholds differ depending on transition direction. Rising input crosses upper threshold to change state. Falling input must cross lower threshold (not same point) to restore original state. Creates "dead band" between thresholds.

*Problem Without Hysteresis (Simple Comparator):*

Single threshold voltage  $V_{th}$ . Input signal slowly approaches threshold. Noise superimposed on signal (real-world condition). As input nears threshold, noise causes input to cross threshold multiple times (oscillates above/below).

Result: Output toggles rapidly, generating multiple unwanted transitions. Called "chattering" or "ringing." Causes false triggering, unreliable operation, potential damage to downstream circuits (relays, counters, logic).

*Solution: Hysteresis (Schmitt Trigger):*

Two thresholds:  $V_{TH}$  (upper) and  $V_{TL}$  (lower), separated by hysteresis voltage  $V_{hyst}$ .

Rising input: Output switches when input crosses  $V_{TH}$  (going up). Falling input: Output switches when input crosses  $V_{TL}$  (going down). Between  $V_{TL}$  and  $V_{TH}$ : Output state unchanged (immune to noise within this range).

Noise immunity: If noise amplitude  $< V_{hyst}$ , no false triggering occurs. Output switches cleanly, once per intended transition.

##### **Application Example: Temperature Control**

Sensor monitors room temperature, outputs voltage proportional to temperature (e.g., 10mV/ $^{\circ}\text{C}$ ). Target: Turn on fan at 25 $^{\circ}\text{C}$ , turn off at 22 $^{\circ}\text{C}$  (3 $^{\circ}\text{C}$  hysteresis).

*Without Hysteresis (Single Threshold at 23.5°C):*

Temperature fluctuates naturally: 23.4°C, 23.6°C, 23.5°C, 23.7°C (random variations, drafts, sensor noise). Fan toggles repeatedly: ON, OFF, ON, OFF (unnecessary wear, annoying cycling).

*With Hysteresis (Upper 25°C, Lower 22°C):*

Temperature rises to 25°C: Fan turns ON. Temperature drifts: 24.8°C, 24.5°C, 23.9°C (fan stays ON—still above 22°C lower threshold). Temperature falls to 22°C: Fan turns OFF. Temperature drifts: 22.5°C, 23°C, 23.5°C (fan stays OFF—still below 25°C upper threshold).

Clean operation: Fan switches only when temperature definitively crosses wide boundaries. No chattering from minor fluctuations.

### Op-Amp Schmitt Trigger Circuit Configuration:

*Key Difference from Standard Comparator:* Positive feedback instead of negative feedback (or no feedback).

Standard comparator: No feedback, or negative feedback (for linear operation). Schmitt trigger: Positive feedback from output to non-inverting input via resistor  $R_3$ .

*Component Topology:*

- Input signal to inverting input ( $V_-$ )
- Non-inverting input ( $V_+$ ) connected to voltage divider:  $R_1$  from  $V_{CC}$  (positive supply),  $R_2$  to ground,  $R_3$  from output
- Output: Two states (HIGH  $\approx V_{CC}$ , LOW  $\approx 0V$  or  $-V_{EE}$ )

Voltage divider with three resistors:  $R_1$  and  $R_2$  set baseline reference,  $R_3$  (positive feedback) modifies reference based on output state.

### Threshold Voltage Calculation:

Non-inverting input voltage (threshold voltage) determined by superposition of two voltage sources:  $V_{CC}$  via  $R_1$ ,  $V_{out}$  via  $R_3$ .

*When Output HIGH ( $V_{out} = V_{CC}$ , e.g., +15V):*

All resistors effectively in series/parallel combination. Simplified analysis: Non-inverting input voltage rises above baseline.

Upper threshold  $V_{TH}$ : Higher voltage at non-inverting input when output HIGH. Input must exceed this to switch output LOW.

*When Output LOW ( $V_{out} = 0V$  or  $-V_{EE}$ , e.g., 0V or -15V):*

Non-inverting input voltage drops below baseline. Lower threshold  $V_{TL}$ : Lower voltage at non-inverting input when output LOW. Input must fall below this to switch output HIGH.

*Example with Equal Resistors:*

$R_1 = R_2 = R_3 = R$ . Supply:  $\pm 15V$ .

Without input signal, output state arbitrary (assume HIGH initially). Output HIGH (+15V): Non-inverting input (voltage divider between +15V via  $R_1$ , +15V via  $R_3$ , ground via  $R_2$ ). Calculation:  $V_+ \approx +7.5V$  (upper threshold  $V_{TH}$ ).

When input exceeds +7.5V: Output switches to LOW (-15V or 0V). Output LOW (0V single supply, or -15V dual supply): Non-inverting input (voltage divider between +15V via  $R_1$ , 0V/-15V via  $R_3$ , ground via  $R_2$ ). Calculation:  $V_+ \approx +2.5V$  (lower threshold  $V_{TL}$ , single supply example).

Hysteresis:  $V_{hyst} = V_{TH} - V_{TL} = 7.5 - 2.5 = 5V$  (example values).

### Detailed Operation (Assuming Initial Output HIGH):

*State 1: Output HIGH, Input Below  $V_{TH}$*

Output:  $V_{out} = +V_{CC}$  (e.g., +15V). Non-inverting input:  $V_+ = V_{TH}$  (upper threshold, e.g., +7.5V). Inverting input:  $V_- = V_{in}$  (signal input). Condition:  $V_{in} < V_{TH}$  (input below threshold).

Comparator state:  $V_+ > V_-$ , output remains HIGH (stable state).

*Transition 1: Input Rises Above  $V_{TH}$*

Input signal increases:  $V_{in}$  crosses  $V_{TH}$  (e.g.,  $V_{in} = +8V > +7.5V$ ). Now:  $V_- > V_+$ , comparator switches output to LOW.

Output:  $V_{out} \rightarrow 0V$  (or  $-V_{EE}$ ). Threshold changes: Positive feedback via  $R_3$  now applies low voltage, pulling non-inverting input down to  $V_{TL}$  (lower threshold).

*State 2: Output LOW, Input Above  $V_{TL}$*

Output:  $V_{out} = 0V$  (or  $-V_{EE}$ ). Non-inverting input:  $V_+ = V_{TL}$  (lower threshold, e.g., +2.5V). Inverting input:  $V_- = V_{in}$  (still high from previous transition). Condition:  $V_{in} > V_{TL}$  (input above lower threshold).

Comparator state:  $V_- > V_+$ , output remains LOW (stable state).

*Transition 2: Input Falls Below  $V_{TL}$*

Input signal decreases:  $V_{in}$  crosses  $V_{TL}$  (e.g.,  $V_{in} = +2V < +2.5V$ ). Now:  $V_+ > V_-$ , comparator switches output to HIGH.

Output:  $V_{out} \rightarrow +V_{CC}$ . Threshold changes: Positive feedback applies high voltage, raising non-inverting input back to  $V_{TH}$ .

Cycle repeats.

### Positive Feedback Mechanism:

Resistor  $R_3$  from output to non-inverting input creates positive feedback loop. When output changes state, feedback immediately changes threshold voltage at non-inverting input. Reinforces output state change (positive feedback).

accelerates transition, prevents intermediate states).

Result: Clean, fast transitions. No oscillation or ambiguity. Output "snaps" between HIGH and LOW states.

#### Design Considerations:

Hysteresis voltage selection: Must exceed expected noise amplitude. Too small: Insufficient noise immunity. Too large: Reduced sensitivity, delayed response.

Resistor ratios: Determine threshold voltages and hysteresis. Calculated from supply voltage and desired  $V_{TH}$ ,  $V_{TL}$  using voltage divider equations.

Supply voltage: Dual supply ( $\pm V$ ) provides symmetric thresholds around ground. Single supply (0 to  $+V$ ) requires threshold adjustment for positive-only signals.

#### Applications:

- *Noise-Immune Switching*: Convert slow, noisy analog signals to clean digital outputs
- *Debouncing*: Eliminate contact bounce in mechanical switches
- *Zero-Crossing Detector*: Detect AC signal zero crossings without false triggers from noise
- *Oscillators*: Relaxation oscillators, square wave generators (with RC timing network)
- *Level Detection*: Battery level monitoring, over-voltage/under-voltage protection
- *Sensor Interfacing*: Temperature, light, pressure sensors with noisy outputs

### Practical Example & Numerical

#### Schmitt Trigger Threshold Calculation:

Circuit:  $R_1 = R_2 = R_3 = 10\text{k}\Omega$  (equal resistors). Dual supply:  $\pm 15\text{V}$ .

Output HIGH ( $+15\text{V}$ ):

Non-inverting input voltage divider: Three  $10\text{k}\Omega$  resistors.  $R_1$  from  $+15\text{V}$ ,  $R_2$  to ground ( $0\text{V}$ ),  $R_3$  from  $+15\text{V}$  (output). Equivalent: Two  $10\text{k}\Omega$  resistors in parallel ( $+15\text{V}$  sources via  $R_1$  and  $R_3$ ) =  $5\text{k}\Omega$ , in series with  $10\text{k}\Omega$  ( $R_2$  to ground).

$$V_+ = +15 \times \frac{10\text{k}}{5\text{k} + 10\text{k}} = +15 \times \frac{10}{15} = +10\text{V}.$$

Upper threshold:  $V_{TH} = +10\text{V}$ .

Output LOW ( $0\text{V}$ , single supply assumption):

$R_1$  from  $+15\text{V}$ ,  $R_2$  to ground,  $R_3$  from  $0\text{V}$  (output).

Voltage divider:  $V_+ = +15 \times \frac{10\text{k}}{20\text{k}} = +7.5\text{V}$  (simplified calculation).

Lower threshold:  $V_{TL} = +7.5\text{V}$  (example; actual depends on  $R_3$  contribution).

Hysteresis:  $V_{hyst} = 10 - 7.5 = 2.5\text{V}$ .

#### Noisy Signal Application:

Input: Slowly rising sine wave (0 to  $10\text{V}$ ,  $0.1\text{Hz}$ ) with superimposed  $1\text{kHz}$  noise ( $0.5\text{V}$  peak-to-peak amplitude).

Simple comparator (no hysteresis, threshold  $5\text{V}$ ): As input crosses  $5\text{V}$ , noise causes input to oscillate around threshold ( $4.75\text{V}$  to  $5.25\text{V}$ ). Output toggles multiple times (10-20 transitions during crossing period). Unreliable digital output.

Schmitt trigger (thresholds  $4\text{V}$  and  $6\text{V}$ ,  $2\text{V}$  hysteresis): Input rises, crosses  $6\text{V}$  (upper threshold): output switches HIGH (single clean transition). Noise amplitude ( $0.5\text{V}$ ) much smaller than hysteresis ( $2\text{V}$ ): no false triggers. Input falls, crosses  $4\text{V}$  (lower threshold): output switches LOW (single clean transition). Clean digital output, two transitions total (one per intended edge).

#### Temperature Control Example:

Sensor:  $10\text{mV}/^\circ\text{C}$ . Target: Fan ON at  $25^\circ\text{C}$ , OFF at  $22^\circ\text{C}$ .

Upper threshold voltage:  $V_{TH} = 25 \times 10\text{mV} = 250\text{mV}$ . Lower threshold voltage:  $V_{TL} = 22 \times 10\text{mV} = 220\text{mV}$ .

Hysteresis:  $V_{hyst} = 250 - 220 = 30\text{mV}$  ( $3^\circ\text{C}$ ).

Design resistors to create  $220\text{mV}$  and  $250\text{mV}$  thresholds with chosen supply voltage (e.g.,  $+5\text{V}$  single supply). Temperature rises to  $25^\circ\text{C}$  ( $250\text{mV}$ ): output HIGH, fan ON. Temperature fluctuates  $23\text{--}24^\circ\text{C}$  ( $230\text{--}240\text{mV}$ , within hysteresis band): fan stays ON. Temperature drops to  $22^\circ\text{C}$  ( $220\text{mV}$ ): output LOW, fan OFF. Temperature fluctuates  $23\text{--}24^\circ\text{C}$ : fan stays OFF.

No chattering, clean fan control despite temperature variations.

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

- Schmitt trigger: comparator with hysteresis, two different switching thresholds
- Upper threshold  $V_{TH}$ : input rising, output switches HIGH to LOW
- Lower threshold  $V_{TL}$ : input falling, output switches LOW to HIGH
- Hysteresis voltage:  $V_{hyst} = V_{TH} - V_{TL}$ , provides noise immunity
- Positive feedback: output to non-inverting input via  $R_3$ , changes threshold based on output state
- Voltage divider ( $R_1$ ,  $R_2$ ,  $R_3$ ) sets threshold voltages dynamically

- Prevents chattering: noise smaller than hysteresis does not cause false triggers
- Clean transitions: output "snaps" between states, no oscillation near threshold
- Applications: noise-immune switching, debouncing, zero-crossing detection, oscillators, level detection
- Design: hysteresis must exceed noise amplitude; resistor ratios determine thresholds
- Dual supply: symmetric thresholds; single supply: positive-only thresholds
- Essential for converting noisy analog signals to reliable digital outputs

# Section 28 – Linear Voltage Regulator

This section explores linear voltage regulation techniques and integrated circuit regulators essential for stable DC power supply design. Linear regulators maintain constant output voltage despite variations in input voltage (line regulation) or load current (load regulation) through continuous adjustment of series pass element resistance. Coverage includes voltage regulator IC families (78xx fixed positive, 79xx fixed negative, LM317 adjustable), LM317 adjustable regulator design and applications, datasheet interpretation for practical circuits, and discrete op-amp-based regulator implementation. Understanding linear regulators critical for power supply design, embedded systems, instrumentation, and any application requiring stable, low-noise DC voltage despite input variations or load changes.

## Voltage Regulator IC Families

### Fixed and Adjustable Voltage Regulator ICs

#### TL;DR (The Gist)

Linear voltage regulator ICs provide stable DC output voltage from higher, potentially noisy input voltage. Three main types: (1) Fixed positive (78xx series: 7805 = +5V, 7812 = +12V, 7815 = +15V), (2) Fixed negative (79xx series: 7905 = -5V, 7912 = -12V, 7915 = -15V), (3) Adjustable (LM317 positive: 1.25V to 37V adjustable, 1.5A max; LM337 negative adjustable). Advantages over discrete zener+transistor circuits: adjustable output voltage, built-in thermal shutdown, short-circuit protection, surge protection, no base-emitter voltage drop compensation needed. Minimal external components (input/output capacitors). Essential for reliable power supply design in embedded systems, instrumentation, consumer electronics.

#### Detailed Explanation

### 2. Detailed Explanation

#### Evolution from Discrete Regulators:

##### *Zener Diode Regulator (Basic):*

Zener diode in reverse breakdown provides voltage reference. Series current-limiting resistor from input. Load in parallel with zener. Major drawbacks: (1) High power dissipation in series resistor (in series with load current path), (2) Resistor must be sized for compromise between sufficient zener current and load current capability, (3) Poor line and load regulation, (4) Fixed output voltage (zener  $V_Z$  value).

##### *Zener + Transistor Regulator (Improved):*

Emitter follower (common collector) transistor driven by zener reference. Zener provides base voltage, transistor emitter outputs regulated voltage. Advantages: Current-limiting resistor carries only base current (much smaller), load driven by transistor (higher current capability). Drawbacks: (1) Output voltage still fixed by zener  $V_Z$ , (2) Base-emitter voltage drop ( $V_{BE} \approx 0.6\text{--}0.7\text{V}$ ) reduces output:  $V_{out} = V_Z - V_{BE}$ , (3) No overcurrent protection (transistor can be destroyed by excessive load current), (4) No thermal protection.

Example: Zener  $V_Z = 5.6\text{V}$ , output  $V_{out} = 5.6 - 0.7 = 4.9\text{V}$  (not exactly 5V).

##### *Need for Integrated Regulators:*

Discrete circuits lack: adjustable output, protection features, temperature compensation, precision. Integrated circuit regulators solve these issues with complete regulator system on single chip.

#### Voltage Regulator IC Advantages:

- **Built-in Protection:** Thermal shutdown (overtemperature), current limiting (short-circuit protection), safe operating area protection
- **Adjustable Output:** LM317/LM337 adjustable regulators provide wide voltage range with external resistors
- **No  $V_{BE}$  Drop Compensation:** Internal circuitry compensates, output voltage accurate
- **Excellent Regulation:** Line regulation (input voltage variation rejection) typically  $< 0.1\%$ , load regulation (output voltage variation with load current) typically  $< 0.5\%$
- **Temperature Compensation:** Output voltage stable over temperature range
- **Minimal External Components:** Only input/output capacitors typically needed
- **Ease of Use:** Simple three-terminal devices (IN, OUT, GND or ADJ)

#### 78xx Series: Fixed Positive Voltage Regulators

**Naming Convention:** 78xx where xx = output voltage in volts. Examples: 7805 (+5V), 7806 (+6V), 7808 (+8V), 7809 (+9V), 7812 (+12V), 7815 (+15V), 7818 (+18V), 7824 (+24V).

##### *Common Specifications (78xx):*

- **Output voltage:** Fixed positive (5V, 12V, 15V typical)
- **Output current:** Up to 1A (with heatsink), typically 100mA without heatsink

- Input voltage: Must be 2-3V higher than output (dropout voltage requirement)
- Package: TO-220 (through-hole, 3 pins), TO-252 (surface-mount) common
- Thermal shutdown: Typically 150°C
- Current limiting: Built-in, typically 2A maximum

*Pin Configuration (78xx, TO-220 package):*

Looking at front (metal tab side), pins left-to-right: (1) Input (IN), (2) Ground (GND), (3) Output (OUT).

*Basic Application Circuit:*

Input capacitor (0.33μF ceramic) close to input pin: Prevents oscillations, filters high-frequency noise from input supply (especially important if regulator far from main power supply filter capacitor). Optional but recommended.

Output capacitor (0.1μF to 1μF ceramic): Improves transient response (fast load current changes), reduces output voltage spikes, stabilizes feedback loop. Recommended for clean output.

Example: 7812 regulator, input 15-20V unregulated, output 12V regulated, 500mA load.  $C_{in} = 0.33\mu\text{F}$ ,  $C_{out} = 0.1\mu\text{F}$ .

### **79xx Series: Fixed Negative Voltage Regulators**

*Naming Convention:* 79xx where xx = magnitude of negative output voltage. Examples: 7905 (-5V), 7912 (-12V), 7915 (-15V).

*Application:* Dual-supply systems (e.g., ±12V for op-amps, audio circuits). Negative rail generation.

*Pin Configuration (79xx, TO-220):*

Different from 78xx! Looking at front, pins left-to-right: (1) Ground (GND), (2) Input (IN), (3) Output (OUT).

*Capacitor Placement:* Same purpose as 78xx (input capacitor for oscillation prevention, output capacitor for transient response). Values similar (0.33μF input, 0.1-1μF output).

### **LM317: Adjustable Positive Voltage Regulator**

Most popular adjustable regulator. Three-terminal device: IN (input), OUT (output), ADJ (adjust).

*Specifications:*

- Output voltage range: 1.25V to 37V (adjustable via external resistors)
- Output current: Up to 1.5A (with adequate heatsinking)
- Input-output differential: Minimum 3V (dropout voltage)
- Internal reference voltage:  $V_{ref} = 1.25\text{V}$  (between OUT and ADJ pins)
- Load regulation: Typically 0.1%
- Line regulation: Typically 0.01%/V
- Temperature stability: Typically 1%

*Pin Configuration (TO-220):*

Looking at front, pins left-to-right: (1) ADJ (adjust), (2) OUT (output), (3) IN (input).

*Key Operating Principle:*

Internal reference maintains 1.25V between OUT and ADJ pins. Resistor divider from OUT to GND sets output voltage. Current through resistor divider determines ADJ pin voltage, which controls output voltage via internal feedback loop.

### **LM337: Adjustable Negative Voltage Regulator**

Negative equivalent of LM317. Output range: -1.25V to -37V. Pin configuration and external component selection similar to LM317 but for negative voltages. Used with LM317 for adjustable dual supplies.

### **Low Dropout (LDO) Regulators:**

Advanced regulators with very low dropout voltage (input-output differential). Standard regulators (78xx, LM317): Dropout 2-3V. LDO regulators: Dropout 0.1-0.5V (some ultra-LDO: < 100mV).

Advantages: Operate with input voltage very close to output (efficient for battery applications), less heat dissipation, suitable for low-voltage systems (3.3V, 1.8V logic).

Examples: LM1117 (1V dropout, 800mA), MCP1700 (178mV dropout, 250mA), ADP150 (60mV dropout, 200mA).

Application: Battery-powered devices where maximizing usable battery voltage range critical, voltage conversion from 3.7V Li-Ion to 3.3V logic with minimal loss.

## **Practical Example & Numerical**

### **7805 Fixed Regulator Application:**

Input: 9V battery (nominal, 7-10V range under load/charge). Output requirement: Stable 5V for microcontroller.

Circuit: 7805 voltage regulator.  $C_{in} = 0.33\mu\text{F}$  (input),  $C_{out} = 0.1\mu\text{F}$  (output). Load: 200mA (microcontroller + peripherals).

Input voltage range: 7V (depleted battery) to 10V (fresh battery). Output: 5V ± 0.1V (stable despite 3V input variation). Load current: 0-200mA (varies with microcontroller activity). Output voltage droop: < 25mV (excellent load regulation).

Dropout check: Minimum input 7V, output 5V, differential = 2V. Adequate for 7805 (typical dropout 2V at 200mA). Heat dissipation: Power  $P = (V_{in} - V_{out}) \times I = (9 - 5) \times 0.2 = 0.8\text{W}$  (modest, small heatsink or TO-220 alone sufficient for this current).

### Dual Supply with 7812 and 7912:

Input:  $\pm 18\text{V}$  unregulated (from transformer with center-tap rectifier). Output requirement:  $\pm 12\text{V}$  regulated for audio op-amp circuit.

Positive rail: 7812 regulator, input  $+18\text{V}$ , output  $+12\text{V}$ . Negative rail: 7912 regulator, input  $-18\text{V}$ , output  $-12\text{V}$ . Capacitors:  $0.33\mu\text{F}$  input,  $0.1\mu\text{F}$  output on each regulator.

Load:  $100\text{mA}$  per rail (op-amp audio stages). Total regulation:  $\pm 12\text{V} \pm 0.05\text{V}$  despite input variations ( $\pm 15\text{V}$  to  $\pm 20\text{V}$ ).

### Comparison: Discrete vs IC Regulator:

Discrete zener+transistor: Zener  $5.6\text{V}$ , transistor  $V_{BE} = 0.7\text{V}$ . Output:  $4.9\text{V}$  (not standard  $5\text{V}$ ). Load current capability: Limited by transistor power rating, no protection. Component count: 3 (zener, transistor, resistor) minimum.

7805 IC regulator: Output:  $5.0\text{V}$  (precise). Load current:  $1\text{A}$  max (with heatsink). Protection: Thermal shutdown, current limiting built-in. Component count: 1 IC + 2 capacitors.

IC regulator clearly superior: accuracy, current capability, protection, ease of use.

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- Voltage regulator ICs: integrated linear regulators with built-in protection and precision
- Three types: fixed positive (78xx), fixed negative (79xx), adjustable (LM317/LM337)
- 78xx series: 7805 =  $+5\text{V}$ , 7812 =  $+12\text{V}$ , 7815 =  $+15\text{V}$  (xx = output voltage)
- 79xx series: 7905 =  $-5\text{V}$ , 7912 =  $-12\text{V}$ , 7915 =  $-15\text{V}$  (negative outputs)
- LM317: adjustable  $1.25\text{V}$  to  $37\text{V}$ ,  $1.5\text{A}$  max,  $V_{ref} = 1.25\text{V}$  internal reference
- Advantages: thermal shutdown, short-circuit protection, no  $V_{BE}$  drop, excellent regulation
- External capacitors: input ( $0.33\mu\text{F}$ , prevents oscillation), output ( $0.1\mu\text{F}$ , transient response)
- Dropout voltage: 78xx/79xx typically  $2\text{--}3\text{V}$ , LDO regulators  $0.1\text{--}0.5\text{V}$  (input must exceed output by dropout)
- Pin configs differ: 78xx (IN-GND-OUT), 79xx (GND-IN-OUT), LM317 (ADJ-OUT-IN)
- Superior to discrete circuits: adjustable, protected, temperature compensated, easy to use
- Applications: embedded systems, audio, instrumentation, any stable DC voltage requirement
- Heat dissipation:  $P = (V_{in} - V_{out}) \times I_{load}$ , heatsink often required

## LM317 Adjustable Regulator Design

### LM317 Design Equations and Practical Circuits

#### TL;DR (The Gist)

LM317 adjustable regulator uses external resistor divider ( $R_1$ ,  $R_2$ ) to set output voltage. Internal  $1.25\text{V}$  reference between OUT and ADJ pins drives constant current ( $I_{ADJ} \approx 50\mu\text{A}$ , negligible) through  $R_1$  (typically  $240\Omega$ ). Output voltage formula:  $V_{out} = 1.25 \times (1 + R_2/R_1) + I_{ADJ} \times R_2 \approx 1.25(1 + R_2/R_1)$ . Simplified:  $V_{out} = V_{ref}(R_1 + R_2)/R_1$ . Input capacitor ( $0.1\mu\text{F}$ ) prevents oscillation if far from supply filter. Output capacitor ( $1\text{--}10\mu\text{F}$ ) improves transient response. Optional: ADJ pin capacitor ( $10\mu\text{F}$ ) for enhanced ripple rejection. Applications: variable bench power supply, battery charger (constant current mode with sense resistor), current limiter, high-current output with external pass transistor. Datasheet provides circuit examples and component selection guidance.

## Detailed Explanation

### 2. Detailed Explanation

#### Internal Architecture and Operating Principle:

LM317 contains: bandgap voltage reference ( $1.25\text{V}$ ), error amplifier (op-amp comparing reference to feedback), series pass transistor (Darlington pair for high current), protection circuits (thermal shutdown, current limiting, safe operating area).

#### Functional Block Diagram:

Voltage reference generates stable  $1.25\text{V}$ . Error amplifier compares reference ( $1.25\text{V}$ ) to voltage between OUT and ADJ pins. Amplifier output drives series pass transistor base. Pass transistor adjusts to maintain  $1.25\text{V}$  across  $R_1$  (between OUT and ADJ). Feedback loop: Output voltage changes  $\rightarrow$  ADJ pin voltage changes  $\rightarrow$  error amplifier corrects  $\rightarrow$  pass transistor adjusts.

#### Key Internal Characteristic:

LM317 regulates to maintain exactly 1.25V between OUT and ADJ terminals (internal reference voltage  $V_{ref} = 1.25V$ ). This voltage appears across  $R_1$  (connected OUT to ADJ).

**Output Voltage Calculation:**

*Resistor Divider Configuration:*

$R_1$ : Connected between OUT and ADJ pins (240 $\Omega$  typical, recommended in datasheet).  $R_2$ : Connected between ADJ and GND. Voltage divider formed by  $R_1$  and  $R_2$ .

*Current Flow Analysis:*

Voltage across  $R_1$ :  $V_{R_1} = V_{ref} = 1.25V$  (maintained by internal regulation).

Current through  $R_1$ :

$$I_{R_1} = \frac{V_{ref}}{R_1} = \frac{1.25}{R_1}$$

Adjust pin current  $I_{ADJ}$ : Typically 50 $\mu A$  (specified in datasheet). Flows out of ADJ pin into  $R_2$ . Often negligible in calculations.

Current through  $R_2$ :  $I_{R_2} = I_{R_1} + I_{ADJ} \approx I_{R_1}$  (if  $I_{ADJ}$  neglected).

Voltage across  $R_2$ :

$$V_{R_2} = I_{R_2} \times R_2 \approx \frac{V_{ref}}{R_1} \times R_2 = 1.25 \times \frac{R_2}{R_1}$$

Output voltage (voltage divider):

$$V_{out} = V_{R_1} + V_{R_2} = 1.25 + 1.25 \times \frac{R_2}{R_1}$$

**LM317 Output Voltage Formula:**

$$V_{out} = 1.25 \times \left( 1 + \frac{R_2}{R_1} \right)$$

Or equivalently:

$$V_{out} = V_{ref} \times \frac{R_1 + R_2}{R_1}$$

Including  $I_{ADJ}$  (precise calculation):

$$V_{out} = 1.25 \times \left( 1 + \frac{R_2}{R_1} \right) + I_{ADJ} \times R_2$$

For most applications,  $I_{ADJ} \times R_2$  term negligible (typically < 10mV).

**Resistor Value Selection:**

$R_1$  Value (Typical 240 $\Omega$ ):

Datasheet recommends 240 $\Omega$  for optimal performance. Current through  $R_1$ :  $I_{R_1} = 1.25/240 \approx 5.2mA$  (quiescent current through divider). Larger  $R_1$ : Lower quiescent current (better efficiency), but increased sensitivity to  $I_{ADJ}$  variations and noise. Smaller  $R_1$ : Higher quiescent current (worse efficiency), better immunity to noise, less  $I_{ADJ}$  effect.

Common range: 120 $\Omega$  to 1k $\Omega$  (240 $\Omega$  good compromise).

$R_2$  Calculation for Desired Output:

Rearrange formula:

$$\begin{aligned} \frac{R_2}{R_1} &= \frac{V_{out}}{1.25} - 1 \\ R_2 &= R_1 \left( \frac{V_{out}}{1.25} - 1 \right) \end{aligned}$$

Example:  $V_{out} = 5V$ ,  $R_1 = 240\Omega$ .

$$R_2 = 240 \times \left( \frac{5}{1.25} - 1 \right) = 240 \times (4 - 1) = 240 \times 3 = 720\Omega$$

Standard resistor: Use 720 $\Omega$  (if available) or 680 $\Omega$  + 39 $\Omega$  series, or potentiometer for adjustment.

**Capacitor Requirements:**

*Input Capacitor ( $C_{in}$ , 0.1 $\mu F$ ):*

Purpose: Prevent oscillations, especially if LM317 located far from main power supply filter capacitor. Placement: Directly at IN pin to GND, close proximity (<1 inch). Type: Ceramic (low ESR, high-frequency response). Mandatory if regulator not adjacent to power supply filter.

*Output Capacitor ( $C_{out}$ , 1-10 $\mu F$ ):*

Purpose: Improve transient response to rapid load current changes. When load current suddenly increases, output capacitor supplies immediate charge before regulator responds. Reduces output voltage dips during load transients. Typical: 1 $\mu F$  ceramic or 10 $\mu F$  electrolytic. Optional but highly recommended for stable operation.

*ADJ Pin Capacitor ( $C_{ADJ}$ , 10 $\mu F$ , optional):*

Capacitor from ADJ pin to GND. Purpose: Enhanced ripple rejection (filters AC ripple from input, improves output smoothness). Improves transient response (datasheet mentions this). Creates time constant with  $R_2$ , slowing ADJ pin voltage changes. Drawback: Can cause output voltage overshoot during turn-on or shutdown (capacitor charges/discharges through  $R_2$ ). Protection diodes recommended if using ADJ capacitor.

*Protection Diodes (Optional):*

Diode from OUT to IN (cathode to IN, anode to OUT): Protects regulator if output shorted to ground while input still energized. Diode from OUT to ADJ (cathode to OUT, anode to ADJ): Discharges ADJ capacitor if output shorted, prevents damage from reverse current.

### **Transient Response and Stability:**

*Transient Response Definition:*

Circuit response to sudden change from steady state. Examples: Input voltage step change, load current step change, turn-on/turn-off.

In regulators: Sudden load current increase causes temporary output voltage dip. Well-designed regulator: Small dip ( $< 100\text{mV}$ ), quick recovery ( $< 50\mu\text{s}$ ). Poor transient response: Large voltage excursion, ringing (oscillation before settling), slow recovery.

*Causes of Poor Transient Response:*

Insufficient output capacitance. Long PCB traces (high inductance) between regulator and load. Inadequate input capacitance (input voltage sags during transient).

*Improvement Methods:*

Increase  $C_{out}$  ( $1\text{-}10\mu\text{F}$  or more). Use low-ESR capacitors (ceramic, tantalum). Add ADJ pin capacitor ( $10\mu\text{F}$ ) for enhanced ripple rejection. Short, wide PCB traces for high-current paths.

### **Dropout Voltage and Minimum Input:**

Dropout voltage: Minimum input-output differential for regulation. LM317 dropout: Typically 2-3V (depends on load current).

Minimum input voltage:

$$V_{in(min)} = V_{out} + V_{dropout}$$

Example:  $V_{out} = 5\text{V}$ ,  $V_{dropout} = 2\text{V}$  (at 1A),  $V_{in(min)} = 7\text{V}$ .

Input voltage must exceed this minimum for proper regulation. Below minimum: Regulator operates in dropout (output voltage drops, poor regulation).

### **Adjustable Power Supply Design:**

Replace fixed  $R_2$  with potentiometer. Typical:  $5\text{k}\Omega$  potentiometer (variable 0 to  $5\text{k}\Omega$ ).

Output voltage range: Minimum (potentiometer at  $0\Omega$ ):  $V_{out} = 1.25 \times (1 + 0/240) = 1.25\text{V}$ . Maximum (potentiometer at  $5\text{k}\Omega$ ):  $V_{out} = 1.25 \times (1 + 5000/240) \approx 27\text{V}$ .

For finer control: Add fixed resistor in series with potentiometer to set minimum output above 1.25V. Example:  $240\Omega$  fixed +  $2.5\text{k}\Omega$  pot: Range 1.25V to 14V approximately.

### **Datasheet Application Circuits:**

Datasheet contains valuable circuit examples: 0-30V adjustable regulator (using negative supply to achieve output below 1.25V), high-current regulator (external pass transistor for  $> 1.5\text{A}$ ), precision current limiter (sense resistor in series), battery charger (constant voltage/constant current mode), improved ripple rejection circuit (ADJ capacitor + protection diodes).

Studying datasheet recommended: Component values optimized by manufacturer, protection circuits detailed, PCB layout guidelines provided.

## **Practical Example & Numerical**

### **5V Fixed Output Design:**

Requirement: 5V output from 7-9V input, 500mA load.

$R_1 = 240\Omega$  (standard). Calculate  $R_2$ :

$$R_2 = 240 \times \left( \frac{5}{1.25} - 1 \right) = 240 \times 3 = 720\Omega$$

Use  $720\Omega$  resistor (or  $680\Omega + 39\Omega$  series =  $719\Omega$ , close enough).

Capacitors:  $C_{in} = 0.1\mu\text{F}$  ceramic,  $C_{out} = 10\mu\text{F}$  electrolytic.

Dropout check:  $V_{in(min)} = 5 + 2 = 7\text{V}$ . Input range 7-9V adequate.

Output verification:

$$V_{out} = 1.25 \times \left( 1 + \frac{720}{240} \right) = 1.25 \times 4 = 5.0\text{V}$$

### **12V Adjustable (Variable) Supply:**

Input: 15-20V unregulated. Output: 1.25V to 12V adjustable, 1A max.

$R_1 = 240\Omega$  fixed.  $R_2 = 5\text{k}\Omega$  potentiometer.

Maximum output (pot at 5kΩ):

$$V_{out(max)} = 1.25 \times \left(1 + \frac{5000}{240}\right) = 1.25 \times 21.83 \approx 27V$$

But input only 20V max, so output limited by input minus dropout:  $V_{out(max)} \approx 20 - 2 = 18V$  practical.

To achieve exactly 12V max:  $R_2 = 240 \times (12/1.25 - 1) = 240 \times 8.6 = 2064\Omega$ . Use 2kΩ or 2.2kΩ potentiometer.

Adjusted:  $R_2 = 2k\Omega$  pot.

$$V_{out(max)} = 1.25 \times \left(1 + \frac{2000}{240}\right) = 1.25 \times 9.33 \approx 11.67V$$

Close to 12V, acceptable.

#### Current Calculation Through Divider:

$R_1 = 240\Omega$ ,  $V_{ref} = 1.25V$ .

$$I_{R_1} = \frac{1.25}{240} \approx 5.2mA$$

Quiescent current (wasted current through divider): 5.2mA. Power dissipation in divider:  $P = 1.25 \times 5.2mA \approx 6.5mW$  (negligible for most applications).

#### Heat Dissipation Calculation:

Input: 15V. Output: 5V. Load current: 1A.

Power dissipation in LM317:

$$P = (V_{in} - V_{out}) \times I_{load} = (15 - 5) \times 1 = 10W$$

Thermal management critical: TO-220 package thermal resistance  $\theta_{JA} \approx 50C/W$  (no heatsink). Temperature rise:  $\Delta T = P \times \theta_{JA} = 10 \times 50 = 500C$  (would destroy IC!).

With heatsink ( $\theta_{JA} \approx 5C/W$ ):  $\Delta T = 10 \times 5 = 50C$  (manageable, IC junction at ambient + 50°C).

Conclusion: Heatsink mandatory for this application.

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

- LM317: adjustable 1.25V-37V regulator, 1.5A max, three terminals (IN, OUT, ADJ)
- Internal  $V_{ref} = 1.25V$  maintained between OUT and ADJ pins
- Output voltage formula:  $V_{out} = 1.25(1 + R_2/R_1)$  where  $R_1$  = OUT to ADJ,  $R_2$  = ADJ to GND
- Standard  $R_1 = 240\Omega$  (datasheet recommendation),  $R_2$  calculated for desired output
- $R_2$  calculation:  $R_2 = R_1(V_{out}/1.25 - 1)$
- Capacitors:  $C_{in} = 0.1\mu F$  (oscillation prevention),  $C_{out} = 1 - 10\mu F$  (transient response)
- Optional ADJ capacitor (10μF) improves ripple rejection but needs protection diodes
- Variable supply: replace  $R_2$  with potentiometer for adjustable output
- Dropout voltage: 2-3V typical, input must exceed output by this amount
- Transient response: output voltage behavior during sudden load/input changes
- Heat dissipation:  $P = (V_{in} - V_{out}) \times I_{load}$ , heatsink often required
- Datasheet circuits: battery charger, current limiter, high-current design, 0V minimum output

## Discrete Op-Amp Linear Regulator

### Op-Amp and Transistor Linear Regulator Design

#### TL;DR (The Gist)

Discrete linear regulator using op-amp provides adjustable, low-noise regulated voltage with excellent line/load regulation. Components: op-amp, zener diode (voltage reference), series pass transistor (NPN emitter follower), resistor divider (sets output voltage), current-limiting resistor (overcurrent protection). Zener (e.g., 6V) biases op-amp non-inverting input (reference). Voltage divider samples output, feeds op-amp inverting input (feedback). Op-amp compares reference to feedback, drives transistor base. Transistor adjusts to maintain output = reference  $\times$  (divider ratio). Output voltage:  $V_{out} = V_Z \times (R_1 + R_2)/R_2$  where  $V_Z$  = zener voltage. Potentiometer in divider enables adjustable output. Transistor provides high current (op-amp alone limited to 20-30mA). Major drawback: inefficiency—power dissipated as heat  $P = (V_{in} - V_{out}) \times I_{load}$ . Efficiency =  $V_{out}/V_{in}$ . Requires heatsink for moderate/high currents. Suitable for low-power precision applications, educational understanding of regulator principles.

## 2. Detailed Explanation

### Circuit Topology and Component Roles:

#### Zener Diode (Voltage Reference):

Provides stable voltage reference for op-amp non-inverting input. Reverse-biased at breakdown voltage (e.g., 6V zener). Biasing resistor from higher input voltage ensures sufficient zener current (5-10mA typical for stable operation).

Reference stability critical: Zener voltage sets baseline for output voltage. Temperature-compensated zeners (e.g., 1N829) provide better stability. Reference voltage determines minimum output voltage (cannot be lower than zener voltage with standard configuration).

#### Operational Amplifier (Error Amplifier):

Compares reference voltage (non-inverting input, from zener) to feedback voltage (inverting input, from output divider). Amplifies error signal. Drives series pass transistor base to correct output voltage deviations.

Op-amp Golden Rules applied: Rule 1 (no input current): Minimal loading on zener and divider. Rule 2 (inputs equal with feedback):  $V_+ = V_-$ , so divider voltage forced equal to zener voltage, establishing regulated output.

#### Series Pass Transistor (NPN Emitter Follower):

High-current element delivering load current. Op-amp provides base current (small, typically  $< 10\text{mA}$ ). Transistor amplifies to collector-emitter current:  $I_C = \beta \times I_B$  (current gain  $\beta$  typically 50-200).

Emitter follower configuration: Base driven by op-amp, collector to high input voltage, emitter to output load. Voltage relationship:  $V_{emitter} = V_{base} - V_{BE}$  (base-emitter drop  $\approx 0.7\text{V}$ ). Op-amp compensates for  $V_{BE}$  drop automatically through feedback.

Power transistor selection essential: Must handle full load current. Power dissipation:  $P = (V_{in} - V_{out}) \times I_C$ . Choose transistor with adequate power rating and mount on heatsink.

#### Voltage Divider (Feedback Network):

Two resistors ( $R_1$  above,  $R_2$  below) sample output voltage. Divider output (junction of  $R_1$  and  $R_2$ ) connected to op-amp inverting input. Establishes feedback loop for regulation.

Divider ratio sets output voltage multiplication factor. For equal resistors: Output voltage =  $2 \times$  zener voltage.

#### Current-Limiting Resistor (Overcurrent Protection):

Series resistor between transistor emitter and output terminal. Limits maximum current during short circuit or overload. Maximum current:  $I_{max} \approx V_{in}/R_{limit}$  (approximate, assumes output shorted to ground).

Example:  $V_{in} = 16\text{V}$ ,  $R_{limit} = 10\Omega$ ,  $I_{max} \approx 1.6\text{A}$ . Prevents transistor destruction during fault conditions. Power dissipation in resistor during fault significant, must be rated accordingly.

### Operation and Feedback Mechanism:

#### Steady-State Operation:

Op-amp maintains  $V_+ = V_-$  (Rule 2).  $V_+ = V_Z$  (zener voltage, e.g., 6V).  $V_- =$  divider output =  $V_{out} \times R_2 / (R_1 + R_2)$ . Setting equal:

$$V_Z = V_{out} \times \frac{R_2}{R_1 + R_2}$$

Solving for output voltage:

$$V_{out} = V_Z \times \frac{R_1 + R_2}{R_2}$$

Example:  $V_Z = 6\text{V}$ ,  $R_1 = R_2 = R$  (equal resistors).

$$V_{out} = 6 \times \frac{2R}{R} = 12\text{V}$$

Output voltage =  $2 \times$  reference voltage (divider ratio = 2).

#### Regulation Mechanism (Load Increase):

Load current increases  $\rightarrow$  Output voltage tends to drop (due to transistor/circuit resistance). Divider voltage ( $V_-$ ) decreases below zener reference ( $V_+$ ). Op-amp detects  $V_+ > V_-$ , output goes more positive. Increased op-amp output drives transistor base higher. Transistor conducts more current, raising output voltage back up. Equilibrium restored:  $V_- = V_+ = V_Z$ , output regulated.

#### Regulation Mechanism (Input Voltage Increase):

Input voltage increases  $\rightarrow$  More voltage across transistor, tends to increase output. Output voltage rises slightly. Divider voltage ( $V_-$ ) increases above reference ( $V_+$ ). Op-amp detects  $V_- > V_+$ , output goes less positive (or negative if dual supply). Decreased op-amp output reduces transistor base drive. Transistor conducts less (higher  $V_{CE}$ ), absorbing extra input voltage. Output voltage returns to setpoint:  $V_- = V_+ = V_Z$ .

Negative feedback loop maintains stable output despite input and load variations.

### Adjustable Output Voltage:

Replace fixed resistors  $R_1$  and/or  $R_2$  with potentiometer. Typical: Potentiometer for  $R_1$ , fixed resistor for  $R_2$  (sets minimum voltage).

Output voltage range:

$$V_{out(min)} = V_Z \times \frac{0 + R_2}{R_2} = V_Z$$

(Potentiometer at minimum,  $R_1 = 0$ .)

$$V_{out(max)} = V_Z \times \frac{R_{1(max)} + R_2}{R_2}$$

(Potentiometer at maximum.)

Example:  $V_Z = 6V$ ,  $R_2 = 1k\Omega$  fixed,  $R_1 = 10k\Omega$  potentiometer.

Minimum:  $V_{out(min)} = 6V$ . Maximum:  $V_{out(max)} = 6 \times (10k + 1k)/1k = 6 \times 11 = 66V$  (theoretical, limited by input voltage and transistor ratings).

Practical maximum determined by input voltage minus dropout: If  $V_{in} = 20V$ ,  $V_{out(max)} \approx 18V$  (allowing 2V dropout).

### Efficiency and Heat Dissipation:

*Linear Regulator Inefficiency:*

Voltage difference ( $V_{in} - V_{out}$ ) dropped across series pass transistor. Power dissipated as heat:  $P_{transistor} = (V_{in} - V_{out}) \times I_{load}$ .

Efficiency:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{V_{out} \times I_{load}}{V_{in} \times I_{load}} = \frac{V_{out}}{V_{in}}$$

Example:  $V_{in} = 16V$ ,  $V_{out} = 6V$ ,  $I_{load} = 1A$ .

Efficiency:  $\eta = 6/16 = 0.375 = 37.5\%$ . Power dissipated:  $P = (16 - 6) \times 1 = 10W$ . Energy wasted: 62.5% (10W heat, only 6W to load).

Low efficiency characteristic of all linear regulators (not specific to this design). Switching regulators (buck converters) achieve 80-95% efficiency for same application.

*Thermal Management:*

High power dissipation requires heatsinking. Transistor junction temperature:  $T_J = T_{ambient} + P \times \theta_{JA}$  where  $\theta_{JA}$  = thermal resistance junction-to-ambient.

Without heatsink:  $\theta_{JA} \approx 50 - 100C/W$  (TO-220 package). With heatsink:  $\theta_{JA} \approx 2 - 10C/W$  (depends on heatsink size, airflow).

Example:  $P = 10W$ ,  $T_{ambient} = 25C$ , heatsink  $\theta_{JA} = 5C/W$ .  $T_J = 25 + 10 \times 5 = 75C$  (safe for most transistors, max typically 150°C).

Without heatsink:  $T_J = 25 + 10 \times 50 = 525C$  (instant destruction!).

Heatsink mandatory for power dissipation  $> 1W$ .

### Ripple Rejection and Output Noise:

Op-amp-based regulator provides excellent ripple rejection. Input ripple (AC component on DC input) attenuated by regulator loop gain. Op-amp gain (typically  $10^5$ ) reduces input ripple by same factor at low frequencies.

Output noise primarily from: Zener diode noise (inherent), op-amp noise (input-referred voltage noise), resistor thermal noise (Johnson noise).

For low-noise applications: Use low-noise zener (voltage reference IC like TL431 superior), low-noise op-amp (e.g., OP07, OPA2134), large capacitor across zener (filters noise).

### Advantages and Disadvantages vs IC Regulators:

*Advantages:*

Adjustable output voltage (wide range). Educational value (understand regulator operation). Customizable (can add features: precision reference, faster op-amp). Low output noise (with proper component selection). Fast transient response (op-amp bandwidth).

*Disadvantages:*

Higher component count (vs single IC regulator). No built-in protection (must add current limiting, thermal shutdown manually). Lower efficiency (same as IC linear regulators, inherent to topology). More complex design (vs LM317 two-resistor setup). Larger PCB area.

Practical use: Niche applications requiring customization. Educational purposes. Otherwise, IC regulators (LM317, 78xx) preferred for simplicity, reliability, built-in protection.

## Practical Example & Numerical

### 12V Output Regulator Design:

Specifications: Input 16V, output 12V, load current 500mA.

*Component Selection:*

Zener diode: 6V (e.g., 1N4735A, 1W rated). Op-amp: LM358 (dual supply not needed, single 16V supply adequate).

Transistor: TIP31C (NPN, 3A max, 40W max, TO-220). Voltage divider:  $R_2 = 1k\Omega$ , calculate  $R_1$  for 12V output.

Output voltage equation:  $V_{out} = V_Z \times (R_1 + R_2)/R_2$ .

Rearrange:  $R_1 = R_2 \times (V_{out}/V_Z - 1) = 1k \times (12/6 - 1) = 1k \times 1 = 1k\Omega$ .

Divider:  $R_1 = R_2 = 1k\Omega$ .

Current limiting:  $R_{limit} = 10\Omega$ , 5W rated (limits short-circuit current to  $\approx 16/10 = 1.6A$ ).

*Power Dissipation:*

Transistor:  $P = (16 - 12) \times 0.5 = 2\text{W}$ . Heatsink with  $\theta_{JA} = 10\text{C/W}$ :  $\Delta T = 2 \times 10 = 20\text{C}$  rise. Junction temperature:  $25 + 20 = 45\text{C}$  (safe, well below  $150\text{C}$  max).

Zener biasing resistor: Choose for 10mA zener current.  $R_{bias} = (V_{in} - V_Z)/I_Z = (16 - 6)/0.01 = 1\text{k}\Omega$ . Power:  $P = 10\text{mA} \times 10\text{V} = 100\text{mW}$  (1/4W resistor adequate).

*Efficiency:*

$\eta = 12/16 = 0.75 = 75\%$ . Better than previous example (smaller voltage drop), but still significant heat (2W dissipated).

#### **Variable 6-18V Power Supply:**

Input: 20V unregulated. Output: 6-18V adjustable, 300mA max.

Zener: 6V. Divider:  $R_2 = 1\text{k}\Omega$  fixed,  $R_1 = 10\text{k}\Omega$  potentiometer.

Output range: Minimum (pot at  $0\Omega$ ):  $V_{out} = 6\text{V}$ . Maximum (pot at  $10\text{k}\Omega$ ):  $V_{out} = 6 \times (10\text{k} + 1\text{k})/1\text{k} = 66\text{V}$  (theoretical, limited by 20V input). Practical max:  $20 - 2 = 18\text{V}$  (allowing 2V dropout).

Adjust potentiometer for desired output voltage anywhere in 6-18V range.

Power dissipation (worst case, maximum  $V_{in} - V_{out}$ ): Input 20V, output 6V, current 300mA.  $P = (20 - 6) \times 0.3 = 4.2\text{W}$ . Heatsink required.

#### **Ripple Rejection Example:**

Input: 16V DC with 1V peak-to-peak ripple (15.5-16.5V variation). Op-amp loop gain at ripple frequency (120Hz):  $A_{loop} \approx 10^4$  (typical for LM358 at low frequency).

Ripple attenuation: Output ripple  $\approx$  input ripple /  $A_{loop} = 1\text{V}/10^4 = 0.1\text{mV}$  peak-to-peak. Excellent ripple rejection, clean DC output suitable for sensitive circuits.

### **Key Points (Interview Focus)**

#### **4. Key Points (Interview Focus)**

- Discrete linear regulator: op-amp + zener reference + series pass transistor + divider
- Zener diode: voltage reference for op-amp non-inverting input (e.g., 6V)
- Op-amp: error amplifier comparing reference to feedback, drives transistor base
- NPN transistor: emitter follower providing high current (op-amp alone limited to 20-30mA)
- Voltage divider: feedback network sampling output, inverting input to op-amp
- Output voltage:  $V_{out} = V_Z \times (R_1 + R_2)/R_2$  where  $V_Z$  = zener voltage
- Adjustable output: potentiometer in divider enables variable voltage
- Current limiting: series resistor limits fault current, prevents transistor damage
- Op-amp Golden Rule 2: maintains  $V_+ = V_-$ , so divider voltage = zener voltage
- Efficiency:  $\eta = V_{out}/V_{in}$  (inherently low for linear regulators)
- Power dissipation:  $P = (V_{in} - V_{out}) \times I_{load}$ , dissipated as heat in transistor
- Heatsink mandatory: for  $P > 1\text{W}$ , prevents thermal destruction
- Advantages: adjustable, educational, low noise, fast transient response
- Disadvantages: inefficient, no built-in protection, higher component count vs IC regulators
- Practical use: educational, custom designs; IC regulators (LM317, 78xx) preferred for production

# Section 29 – MOSFETs

## Transistor Classification and Types

### TL;DR (The Gist)

Transistors are classified into two main categories: Bipolar Junction Transistors (BJT) and Field Effect Transistors (FET). FETs include JFETs and MOSFETs, with MOSFETs further divided into enhancement-mode and depletion-mode types. Each transistor type has distinct circuit symbols and operational characteristics, making them suitable for different applications in switching and amplification.

### Detailed Explanation

## 2. Detailed Explanation

### Fundamental Transistor Functions:

Transistors perform two critical functions in electronic circuits:

- **Switching:** Controlling current flow on/off enables complex circuit implementations. Applications include telephone switching systems (connecting millions of users via 10-digit dialing), internet routing (accessing websites across continents), computers, traffic lights, and electric power grids.
- **Amplification:** Boosting weak electrical signals to useful levels. Radio receivers amplify tiny radio wave signals to drive speakers, converting low-energy voltage signals into higher voltage or current outputs.

### Transistor Classification Hierarchy:

#### 1. Bipolar Junction Transistors (BJT):

- NPN transistors (current flows collector to emitter when base is positive)
- PNP transistors (current flows emitter to collector when base is negative)
- Three terminals: Emitter, Base, Collector
- Made of solid semiconductor material with three connection terminals

#### 2. Field Effect Transistors (FET):

##### 2a. Junction FET (JFET):

- N-channel JFET
- P-channel JFET

##### 2b. Metal-Oxide-Semiconductor FET (MOSFET):

###### Depletion Mode:

- N-channel depletion MOSFET (conducts with zero gate voltage, depleted by negative gate)
- P-channel depletion MOSFET (conducts with zero gate voltage, depleted by positive gate)

###### Enhancement Mode:

- N-channel enhancement MOSFET (requires positive gate voltage to conduct)
- P-channel enhancement MOSFET (requires negative gate voltage to conduct)

### Circuit Symbol Identification:

Each transistor type has a unique schematic symbol for circuit representation. The differences in symbols reflect fundamental operational differences. Memorizing these symbols is essential for reading circuit diagrams and understanding device behavior. The arrow direction, terminal configurations, and additional elements (like the substrate connection in MOSFETs) distinguish between types.

From the late 1960s onward, MOSFET technology became widespread as semiconductor materials and processing improved (early development struggled with insulating oxide layer fabrication). Today, MOSFETs are one of the most widely used semiconductor techniques and a principal element in integrated circuit technology.

### Practical Example & Numerical

## 

### Transistor Classification Example:

Consider identifying transistors in a power supply circuit:

- **BJT (NPN):** Used in discrete linear regulators with emitter-follower configuration for high current capability. Symbol shows arrow pointing outward from emitter.
- **Enhancement N-channel MOSFET:** Used in switching power supplies (DC-DC converters) for high-efficiency on/off control. Symbol shows broken channel line indicating no conduction at zero gate voltage.
- **Depletion N-channel MOSFET:** Used in constant-current sources or analog switches. Symbol shows solid

channel line indicating conduction at zero gate voltage.

The circuit designer selects transistor type based on application requirements: BJTs for linear amplification with moderate input impedance, enhancement MOSFETs for efficient switching with very high input impedance, depletion MOSFETs for normally-on operation with voltage control.

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

- Transistors perform two fundamental functions: switching (controlling current flow) and amplification (boosting signal levels)
- Two main transistor families: Bipolar Junction Transistors (BJT) and Field Effect Transistors (FET)
- BJTs classified as NPN or PNP with terminals: emitter, base, collector
- FETs divided into JFETs and MOSFETs
- MOSFETs categorized by mode: enhancement (requires gate voltage to conduct) vs depletion (conducts at zero gate voltage)
- Each transistor type has unique circuit symbol reflecting operational characteristics
- MOSFET technology became widespread in late 1960s and is now fundamental to integrated circuits
- Proper transistor type selection depends on application requirements (switching vs amplification, input impedance, efficiency)

# MOSFET Fundamentals and Voltage Control

## TL;DR (The Gist)

MOSFETs (Metal-Oxide-Semiconductor Field Effect Transistors) are voltage-controlled devices with three terminals: Source, Gate, and Drain. Unlike BJTs where base current controls collector current, MOSFETs have virtually no gate current due to an insulating oxide layer, resulting in extremely high input impedance. The gate voltage controls channel conductivity through an electric field across the insulating dielectric, making MOSFETs ideal for low-power control applications.

## Detailed Explanation

### 2. Detailed Explanation

#### MOSFET Terminal Configuration:

MOSFETs have three terminals with different names from BJT equivalents:

- **Source (S):** Similar to BJT emitter, current entry/exit point for channel
- **Gate (G):** Similar to BJT base, control terminal (but with no current flow)
- **Drain (D):** Similar to BJT collector, current exit/entry point for channel

A fourth terminal, the **substrate (bulk)**, is often internally connected to the source or brought out separately. Circuit symbols indicate substrate with an arrow showing the bulk material type (N-type or P-type).

#### Voltage Control vs Current Control:

##### BJT Operation (Current-Controlled):

$$I_C = \beta \times I_B$$

Bipolar transistors require base current to control collector current. The base-emitter junction must be forward-biased (typically  $\sim 0.7\text{ V}$  for silicon), and the base current directly determines the collector current through the current gain  $\beta$  (typically 100-300).

##### MOSFET Operation (Voltage-Controlled):

MOSFETs have almost zero gate current ( $I_G \approx 0\text{ A}$ ) because the gate is physically isolated from the channel by a thin oxide insulating layer (typically silicon dioxide,  $\text{SiO}_2$ ). This dielectric prevents DC current flow while allowing electric field penetration.

The gate voltage  $V_{GS}$  controls channel conductivity through capacitive coupling:

- Electric field induced across the insulating oxide layer
- Field modulates charge carrier density in the channel
- Channel conductivity varies with carrier concentration
- Drain current  $I_D$  controlled by  $V_{GS}$  without requiring gate current

##### Input Impedance Comparison:

The negligible gate current results in extremely high input impedance:

$$Z_{in, \text{MOSFET}} \gg Z_{in, \text{BJT}}$$

Typical values:

- BJT input impedance:  $1\text{ k}\Omega$  to  $100\text{ k}\Omega$  (varies with operating point)
- MOSFET input impedance:  $10^{12}\text{ }\Omega$  to  $10^{15}\text{ }\Omega$  (essentially infinite for DC analysis)

##### Operational Amplifier Application:

Op-amps use MOSFETs in their input stages to achieve very high input impedance, ensuring virtually zero current draw from the signal source. This high input impedance:

- Prevents loading the signal source
- Enables accurate voltage measurement without current drain
- Allows op-amp to convert low-energy voltage signals to higher voltage/current outputs
- Avoids dangerous high-current draw in low-impedance circuits

##### MOSFET Circuit Symbol Variations:

Enhancement mode symbols show a broken channel line (no conduction at  $V_{GS} = 0$ ), while depletion mode symbols show a solid channel line (conduction at  $V_{GS} = 0$ ). The substrate arrow indicates channel type: arrow pointing toward channel = N-channel (NMOS), arrow pointing away = P-channel (PMOS).

##### Structure Difference:

The key structural difference between enhancement and depletion mode MOSFETs lies in the fabrication of the channel region. Enhancement mode has no physical channel at zero gate voltage (must be induced), while depletion mode has a pre-existing doped channel that can be enhanced or depleted by gate voltage.

## Practical Example & Numerical

### Voltage Control Demonstration:

Consider controlling a 10 mA load current:

#### Using BJT (NPN):

- Required collector current:  $I_C = 10 \text{ mA}$
- Transistor current gain:  $\beta = 100$
- Required base current:  $I_B = I_C / \beta = 10 \text{ mA} / 100 = 0.1 \text{ mA} = 100 \mu\text{A}$
- Base-emitter voltage:  $V_{BE} \approx 0.7 \text{ V}$
- Input power to base:  $P_{in} = V_{BE} \times I_B = 0.7 \times 0.1 \text{ mA} = 0.07 \text{ mW}$

#### Using N-channel Enhancement MOSFET:

- Required drain current:  $I_D = 10 \text{ mA}$
- Gate-source voltage:  $V_{GS} = 3 \text{ V}$  (above threshold)
- Gate current:  $I_G \approx 0 \text{ A}$  (typically  $< 1 \text{ pA}$ )
- Input power to gate:  $P_{in} = V_{GS} \times I_G \approx 0 \text{ W}$

The MOSFET requires essentially zero input power for control, making it ideal for:

- Battery-powered devices (minimal control power consumption)
- High-frequency switching (no base charge storage delays)
- Interfacing with logic circuits (CMOS outputs have limited current capability)
- Precision instrumentation (no current drawn from measurement source)

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

- MOSFETs have three main terminals: Source (S), Gate (G), Drain (D), plus substrate connection
- **Critical difference from BJT:** MOSFETs are voltage-controlled ( $I_D$  controlled by  $V_{GS}$ ), BJTs are current-controlled ( $I_C$  controlled by  $I_B$ )
- Gate has virtually zero current ( $I_G \approx 0$ ) due to thin oxide insulating layer separating gate from channel
- Gate voltage controls channel conductivity through electric field induced capacitively across oxide dielectric
- MOSFET input impedance ( $10^{12}$ - $10^{15} \Omega$ ) vastly exceeds BJT input impedance ( $1$ - $100 \text{ k}\Omega$ )
- Op-amps use MOSFET input stages to achieve high input impedance and zero current draw
- Enhancement mode: broken channel symbol, no conduction at  $V_{GS} = 0$
- Depletion mode: solid channel symbol, conduction at  $V_{GS} = 0$
- Zero gate current enables low-power control and prevents signal source loading

# N-Channel Enhancement MOSFET Operation

## TL;DR (The Gist)

N-channel enhancement MOSFETs require a positive gate-source voltage above a threshold voltage ( $V_{TH}$ ) to conduct current. Below  $V_{TH}$ , the MOSFET remains off with no drain current. Once  $V_{GS} > V_{TH}$ , drain current increases with gate voltage. The drain-source voltage ( $V_{DS}$ ) affects current only when below a critical value, similar to BJT saturation, defining two operating regions: linear (ohmic) and saturation (active).

## Detailed Explanation

### 2. Detailed Explanation

#### Threshold Voltage Concept:

The threshold voltage  $V_{TH}$  (also denoted  $V_{GS(th)}$  or  $V_T$ ) is the minimum gate-source voltage required to form a conductive channel between source and drain.

#### Channel Formation:

- $V_{GS} < V_{TH}$ : No channel exists, MOSFET is OFF,  $I_D = 0$  A (similar to BJT cutoff region with  $V_{BE} < 0.7$  V)
- $V_{GS} = V_{TH}$ : Channel begins to form, minimal current flows (threshold condition)
- $V_{GS} > V_{TH}$ : Conductive channel established, drain current flows and increases with higher  $V_{GS}$

Typical threshold voltage values:  $V_{TH} = 1\text{--}4$  V for enhancement N-channel MOSFETs (varies by device, specified in datasheet). The example MOSFET has  $V_{TH} = 1.5$  V.

#### Gate Voltage Control Behavior:

As gate voltage increases above threshold:

$$V_{GS} \uparrow \Rightarrow \text{Channel conductivity} \uparrow \Rightarrow I_D \uparrow$$

The electric field from the positive gate voltage attracts electrons (in N-channel) to the channel region beneath the gate oxide, forming a conductive path. Higher  $V_{GS}$  creates stronger field, attracts more electrons, increases conductivity, and allows greater drain current.

#### Operating Regions - Drain Voltage Effect:

Similar to BJT active and saturation regions, MOSFETs have distinct operating regions based on drain voltage:

##### 1. Cutoff Region:

$$V_{GS} < V_{TH} \Rightarrow I_D = 0 \text{ A}$$

No channel exists regardless of drain voltage.

##### 2. Linear (Ohmic/Triode) Region:

$$V_{GS} > V_{TH} \text{ and } V_{DS} < (V_{GS} - V_{TH})$$

In this region, drain current is approximately proportional to drain voltage (MOSFET acts like voltage-controlled resistor):

$$I_D \propto V_{DS} \text{ (approximately linear relationship)}$$

As  $V_{DS}$  decreases,  $I_D$  decreases nearly linearly. This is analogous to BJT saturation where  $V_{CE}$  is small and limits current flow.

##### 3. Saturation (Active) Region:

$$V_{GS} > V_{TH} \text{ and } V_{DS} \geq (V_{GS} - V_{TH})$$

In this region, drain current is nearly independent of drain voltage:

$$I_D \approx \text{constant (determined primarily by } V_{GS}\text{)}$$

Changing  $V_{DS}$  (as long as it remains above the critical value) does not significantly affect  $I_D$ . This is analogous to BJT active region where  $I_C = \beta I_B$  regardless of  $V_{CE}$  (as long as  $V_{CE}$  is sufficiently large).

The critical drain voltage separating regions is:

$$V_{DS,crit} = V_{GS} - V_{TH}$$

For the example with  $V_{GS} = 3$  V and  $V_{TH} = 1.5$  V:

$$V_{DS,crit} = 3 - 1.5 = 1.5 \text{ V}$$

However, the observation showed critical voltage  $\approx 2$  V, which accounts for additional device characteristics and non-ideal effects.

#### Analogy to BJT Behavior:

##### BJT Active Region:

- $V_{BE} > 0.7\text{ V}$  (transistor ON)
- $I_C = \beta I_B$  (independent of  $V_{CE}$  when  $V_{CE}$  is sufficient)
- Changing  $V_{CE}$  (in active region) does not change  $I_C$

#### MOSFET Saturation Region:

- $V_{GS} > V_{TH}$  (transistor ON)
- $I_D$  determined by  $V_{GS}$  (independent of  $V_{DS}$  when  $V_{DS}$  is sufficient)
- Changing  $V_{DS}$  (in saturation region) does not change  $I_D$

#### Key Observation from Simulation:

The drain current  $I_D$  is determined by gate voltage  $V_{GS}$  when operating in the saturation region. Changes in drain voltage  $V_{DS}$  do not affect drain current as long as  $V_{DS}$  remains above the critical value. Once  $V_{DS}$  falls below this threshold (entering linear region), drain current begins decreasing with decreasing drain voltage.

This behavior is essential for amplifier design (operate in saturation region for constant-current source behavior) and switch design (operate in linear region for low on-resistance, cutoff for zero current).

### Practical Example & Numerical

#### N-Channel Enhancement MOSFET Operating Points:

Consider an N-channel enhancement MOSFET with  $V_{TH} = 1.5\text{ V}$ :

##### Case 1: Cutoff Region

- Gate-source voltage:  $V_{GS} = 1.0\text{ V}$
- Drain-source voltage:  $V_{DS} = 10\text{ V}$
- Analysis:  $V_{GS} = 1.0\text{ V} < V_{TH} = 1.5\text{ V}$
- Result:  $I_D = 0\text{ A}$  (no channel, MOSFET OFF)

##### Case 2: Saturation Region (Active)

- Gate-source voltage:  $V_{GS} = 3.0\text{ V}$
- Drain-source voltage:  $V_{DS} = 5.0\text{ V}$
- Analysis:  $V_{GS} = 3.0\text{ V} > V_{TH} = 1.5\text{ V}$  (ON)
- Critical voltage:  $V_{DS,crit} = V_{GS} - V_{TH} = 3.0 - 1.5 = 1.5\text{ V}$
- Check:  $V_{DS} = 5.0\text{ V} > 1.5\text{ V}$  (saturation region)
- Result:  $I_D$  determined by  $V_{GS}$ , independent of  $V_{DS}$
- Use case: Current source, amplifier active region

##### Case 3: Linear Region (Ohmic)

- Gate-source voltage:  $V_{GS} = 3.0\text{ V}$
- Drain-source voltage:  $V_{DS} = 1.0\text{ V}$
- Analysis:  $V_{GS} = 3.0\text{ V} > V_{TH} = 1.5\text{ V}$  (ON)
- Critical voltage:  $V_{DS,crit} = 1.5\text{ V}$
- Check:  $V_{DS} = 1.0\text{ V} < 1.5\text{ V}$  (linear region)
- Result:  $I_D$  proportional to  $V_{DS}$ , acts as resistor
- Use case: Analog switch, low on-resistance switching

##### Case 4: Region Boundary

- Gate-source voltage:  $V_{GS} = 3.0\text{ V}$
- Drain-source voltage:  $V_{DS} = 1.5\text{ V}$
- Analysis:  $V_{DS} = V_{GS} - V_{TH}$  (boundary condition)
- Result: Transition between linear and saturation regions
- Note: Exact boundary varies with device characteristics

These operating regions determine circuit design choices: amplifiers use saturation region for constant transconductance, switches use linear region (ON state) and cutoff region (OFF state) for minimal power dissipation.

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

- N-channel enhancement MOSFET requires  $V_{GS} > V_{TH}$  to conduct current
- Threshold voltage  $V_{TH}$  (typically 1-4 V) is minimum gate voltage to form conductive channel
- Below threshold ( $V_{GS} < V_{TH}$ ): MOSFET OFF,  $I_D = 0\text{ A}$  (cutoff region, similar to BJT with  $V_{BE} < 0.7\text{ V}$ )
- Above threshold ( $V_{GS} > V_{TH}$ ): MOSFET ON, higher  $V_{GS}$  increases  $I_D$

- **Saturation region:**  $V_{DS} \geq (V_{GS} - V_{TH})$ , drain current  $I_D$  independent of  $V_{DS}$ , determined by  $V_{GS}$  alone (similar to BJT active region)
- **Linear region:**  $V_{DS} < (V_{GS} - V_{TH})$ , drain current proportional to  $V_{DS}$ , MOSFET acts as voltage-controlled resistor
- Critical drain voltage:  $V_{DS,crit} = V_{GS} - V_{TH}$  separates linear and saturation regions
- Amplifier applications use saturation region (constant-current source behavior)
- Switch applications use linear region (low on-resistance) and cutoff region (zero current)
- Voltage control (zero gate current) enables efficient interfacing with logic circuits and low-power operation

# Section 30 – N-channel MOSFET Characteristic Curve

## Cutoff Region

TL;DR (The Gist)

The cutoff region is the MOSFET OFF state where gate-source voltage is below the threshold voltage ( $V_{GS} < V_{TH}$ ). No conductive channel exists between drain and source, resulting in zero drain current ( $I_D = 0\text{ A}$ ). The MOSFET acts as an open circuit, similar to a BJT in cutoff. This region is used for the OFF state in switching applications.

## Detailed Explanation

### 2. Detailed Explanation

#### Cutoff Region Definition:

The cutoff region occurs when the gate-source voltage is insufficient to create a conductive channel:

$$V_{GS} < V_{TH} \Rightarrow I_D = 0\text{ A}$$

#### Threshold Voltage Comparison - BJT vs MOSFET:

##### BJT Threshold Voltage ( $\sim 0.6\text{--}0.7\text{ V}$ ):

- Determined by base-emitter diode forward voltage drop
- Silicon PN junction requires  $\sim 0.7\text{ V}$  to conduct
- Relatively consistent across different BJT devices (temperature-dependent)
- Above threshold: collector current appears and increases rapidly in forward active region
- Below threshold: transistor shuts down, enters cutoff, no collector current flows

##### MOSFET Threshold Voltage ( $V_{TH}$ varies by device):

- Not determined by diode junction (different physical mechanism)
- Varies significantly between different MOSFET types and manufacturers
- Typical range for enhancement N-channel:  $1\text{--}4\text{ V}$  (can be higher or lower)
- Defined as minimum gate-source voltage to create conducting path between source and drain
- Different construction leads to different threshold voltages

#### Physical Mechanism:

In N-channel enhancement MOSFETs, a conductive channel does not exist naturally between source and drain. A positive gate-source voltage creates an electric field that attracts electrons to the region beneath the gate oxide, forming an inversion layer (N-type channel in P-type substrate). This requires a minimum voltage (threshold voltage) to induce sufficient charge.

#### Cutoff Region Characteristics:

When  $V_{GS} < V_{TH}$ :

- No conductive channel formed
- MOSFET is turned OFF
- No conduction between drain and source ( $I_D = 0\text{ A}$  in ideal case)
- MOSFET acts as open circuit (extremely high drain-source resistance)
- Changing drain voltage has no effect on drain current (remains zero)

#### Transition Behavior:

As gate voltage approaches threshold from below:

- $V_{GS} < V_{TH}$ : MOSFET remains in cutoff
- $V_{GS} = V_{TH}$ : Transition point, channel begins forming
- $V_{GS} > V_{TH}$ : MOSFET enters conduction (ohmic or saturation region depending on  $V_{DS}$ )

In practice, the transition is not instantaneous. There's a gradual increase in drain current as gate voltage crosses the threshold, though the transition is relatively sharp. Subthreshold conduction (weak inversion) causes small leakage current below threshold, but this is typically negligible for most applications.

#### Practical Considerations:

- Threshold voltage specified in datasheet (often as range, e.g.,  $0.8\text{--}3.0\text{ V}$ )
- Manufacturing variations cause threshold voltage spread
- Temperature affects threshold voltage (typically decreases with increasing temperature)
- To ensure reliable OFF state, keep  $V_{GS}$  well below  $V_{TH}$  (safety margin)

- In digital switching applications, gate voltage transitions between well-defined low (cutoff) and high (saturation) states

#### Application in Switching:

The cutoff region provides the OFF state for MOSFET switches. To turn off an N-channel enhancement MOSFET:

- Reduce gate voltage below threshold:  $V_{GS} < V_{TH}$
- Channel disappears, drain current ceases
- MOSFET presents open circuit between drain and source
- Minimal power dissipation in OFF state (only leakage current)

### Practical Example & Numerical

#### Cutoff Region Operation Example:

Consider an N-channel enhancement MOSFET with  $V_{TH} = 1.5 \text{ V}$  used as a switch:

##### Case 1: Gate Voltage Below Threshold

- Gate-source voltage:  $V_{GS} = 1.4 \text{ V}$
- Analysis:  $V_{GS} = 1.4 \text{ V} < V_{TH} = 1.5 \text{ V}$
- Result: MOSFET in cutoff region
- Drain current:  $I_D = 0 \text{ A}$  (ideal),  $< 1 \mu\text{A}$  (practical leakage)
- Behavior: Acts as open circuit regardless of drain voltage
- Application: Switch in OFF state

##### Case 2: Reducing Gate Voltage to Turn Off

- Initial state:  $V_{GS} = 3.0 \text{ V}$ , MOSFET conducting in saturation region
- Action: Reduce gate voltage to  $V_{GS} = 0 \text{ V}$
- Analysis:  $V_{GS} = 0 \text{ V} < V_{TH} = 1.5 \text{ V}$
- Result: Conduction stops, MOSFET enters cutoff
- Drain current: Transitions from operating current to zero
- Note: Lowering gate voltage beyond threshold (e.g., to  $0 \text{ V}$ ,  $-5 \text{ V}$ ) does not change cutoff behavior—drain current remains zero

##### Case 3: Threshold Voltage Variation

- MOSFET A:  $V_{TH} = 2.0 \text{ V}$  (higher threshold)
- MOSFET B:  $V_{TH} = 1.0 \text{ V}$  (lower threshold)
- Gate voltage applied:  $V_{GS} = 1.5 \text{ V}$
- MOSFET A:  $1.5 \text{ V} < 2.0 \text{ V} \rightarrow \text{Cutoff, } I_D = 0$
- MOSFET B:  $1.5 \text{ V} > 1.0 \text{ V} \rightarrow \text{Conducting (ohmic/saturation depending on } V_{DS})$
- Lesson: Threshold voltage varies between devices; consult datasheet for specific MOSFET

#### Comparison with BJT Cutoff:

For BJT with  $V_{BE, \text{threshold}} \approx 0.7 \text{ V}$ :

- $V_{BE} = 0.5 \text{ V} < 0.7 \text{ V} \rightarrow \text{Cutoff, } I_C = 0$
- Acts as open circuit between collector and emitter
- Similar behavior to MOSFET cutoff but different voltage levels and physical mechanisms

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

- **Cutoff condition:**  $V_{GS} < V_{TH}$  results in  $I_D = 0 \text{ A}$
- MOSFET acts as open circuit in cutoff region (no conduction between drain and source)
- Similar to BJT cutoff but different threshold voltage values
- BJT threshold:  $\sim 0.7 \text{ V}$  (silicon diode drop), MOSFET threshold: varies by device (typically 1-4 V for enhancement mode)
- Threshold voltage is minimum gate-source voltage needed to create conductive channel
- Enhancement N-channel MOSFETs have no natural channel; positive  $V_{GS}$  creates inversion layer
- Threshold voltage varies between devices (manufacturing, design), specified in datasheet as range
- Changing drain voltage in cutoff region has no effect on drain current (remains zero)
- Cutoff region provides OFF state for switching applications with minimal power dissipation
- Temperature and manufacturing variations affect threshold voltage

# Ohmic (Linear) Region

## TL;DR (The Gist)

The ohmic region (also called linear or triode region) is where the MOSFET acts as a voltage-controlled resistor. Drain current varies nearly linearly with drain-source voltage, following Ohm's Law behavior. This region occurs when  $V_{GS} > V_{TH}$  and  $V_{DS} < (V_{GS} - V_{TH})$ . The MOSFET channel behaves like a resistor whose resistance is controlled by gate voltage, used in analog switches and variable resistor applications.

## Detailed Explanation

### 2. Detailed Explanation

#### Ohmic Region Definition and Conditions:

The ohmic (linear) region occurs when:

$$V_{GS} > V_{TH} \quad \text{and} \quad V_{DS} < (V_{GS} - V_{TH})$$

In this region, the drain current has an approximately linear relationship with drain-source voltage:

$$I_D \propto V_{DS} \quad (\text{linear response mimicking Ohm's Law})$$

#### Physical Behavior:

When  $V_{DS}$  is small:

- Conductive channel exists along entire length from source to drain
- Channel depth relatively uniform (minimal voltage drop along channel)
- MOSFET acts as voltage-controlled resistor
- Resistance controlled by gate voltage: higher  $V_{GS} \rightarrow$  lower channel resistance  $\rightarrow$  higher current for given  $V_{DS}$

#### Characteristic Curve Analysis:

On the MOSFET characteristic curve (drain current  $I_D$  vs drain-source voltage  $V_{DS}$ ):

- Y-axis: Drain current  $I_D$
- X-axis: Drain-source voltage  $V_{DS}$
- Multiple curves for different gate voltages  $V_{GS}$
- Initial portion of each curve (low  $V_{DS}$ ) shows linear relationship
- Slope of linear portion = channel conductance  $g_d = 1/R_{DS(on)}$
- Higher  $V_{GS}$  produces steeper slope (lower resistance)

#### Region Nomenclature:

The ohmic region has multiple names:

- **Ohmic region:** Emphasizes Ohm's Law-like linear voltage-current relationship
- **Linear region:** Highlights linear response of current to voltage changes
- **Triode region:** Historical term from vacuum tube electronics (three-element device)

Note: "Linear region" is inconsistently used in MOSFET literature and can cause confusion. Some contexts use "linear" to refer to linear amplification (which actually occurs in saturation region for MOSFETs). To avoid ambiguity, prefer "ohmic region" when referring to the voltage-controlled resistor behavior.

#### Voltage-Controlled Resistor Behavior:

The MOSFET in ohmic region acts as a resistor with resistance controlled by  $V_{GS}$ :

$$R_{DS(on)} = f(V_{GS}) \quad (\text{decreases as } V_{GS} \text{ increases})$$

Drain current follows Ohm's Law approximately:

$$I_D \approx \frac{V_{DS}}{R_{DS(on)}}$$

The on-resistance  $R_{DS(on)}$  is specified in datasheets at a particular gate voltage (typically when MOSFET is fully enhanced).

#### Transition to Saturation Region:

As drain voltage increases:

- Initially in ohmic region:  $I_D$  increases linearly with  $V_{DS}$
- At boundary:  $V_{DS} = V_{GS} - V_{TH}$  (critical voltage)
- Beyond boundary: MOSFET enters saturation region,  $I_D$  becomes independent of  $V_{DS}$

The transition occurs because the channel begins to pinch off at the drain end when  $V_{DS}$  becomes large enough. The pinch-off point moves the MOSFET from ohmic (uniform channel) to saturation (pinched channel) operation.

#### Applications of Ohmic Region:

- **Analog switches:** Low on-resistance for minimal voltage drop and power loss
- **Variable resistors:** Gate voltage controls resistance for gain control, impedance matching
- **Multiplexers:** Switching between signal paths
- **Sample-and-hold circuits:** Low-resistance connection during sampling phase
- **Active loads:** Voltage-controlled resistance in amplifier circuits

#### Design Considerations:

To ensure operation in ohmic region:

- Keep  $V_{DS}$  well below  $V_{GS} - V_{TH}$
- Use sufficiently high gate voltage to minimize  $R_{DS(on)}$
- Consider temperature effects on threshold voltage and on-resistance
- Account for voltage drop across MOSFET when calculating circuit voltages

### Practical Example & Numerical

#### Ohmic Region Operation Example:

Consider an N-channel MOSFET with  $V_{TH} = 1.5\text{ V}$ :

#### Operating Point Analysis:

- Gate-source voltage:  $V_{GS} = 3.5\text{ V}$
- First condition:  $V_{GS} = 3.5\text{ V} > V_{TH} = 1.5\text{ V} \checkmark$  (MOSFET ON)
- Critical drain voltage:  $V_{DS,crit} = V_{GS} - V_{TH} = 3.5 - 1.5 = 2.0\text{ V}$
- Second condition for ohmic region:  $V_{DS} < 2.0\text{ V}$

#### Drain Voltage Sweep in Ohmic Region:

Starting from  $V_{DS} = 0\text{ V}$  and increasing:

- $V_{DS} = 0.2\text{ V}$ :  $0.2 < 2.0 \rightarrow$  Ohmic region, assume  $I_D = 50\text{ mA}$  (linear behavior)
- $V_{DS} = 0.5\text{ V}$ :  $0.5 < 2.0 \rightarrow$  Ohmic region,  $I_D \approx 125\text{ mA}$  (proportional increase)
- $V_{DS} = 1.0\text{ V}$ :  $1.0 < 2.0 \rightarrow$  Ohmic region,  $I_D \approx 250\text{ mA}$  (continues linear)
- $V_{DS} = 1.8\text{ V}$ :  $1.8 < 2.0 \rightarrow$  Still ohmic,  $I_D \approx 450\text{ mA}$
- $V_{DS} = 2.0\text{ V}$ : Boundary condition, transition to saturation
- $V_{DS} = 3.0\text{ V}$ :  $3.0 > 2.0 \rightarrow$  Saturation region,  $I_D$  no longer increases with  $V_{DS}$

#### Voltage-Controlled Resistor Calculation:

If at  $V_{GS} = 3.5\text{ V}$  and  $V_{DS} = 1.0\text{ V}$  we measure  $I_D = 250\text{ mA}$ :

$$R_{DS(on)} = \frac{V_{DS}}{I_D} = \frac{1.0\text{ V}}{250\text{ mA}} = 4\ \Omega$$

This low resistance allows the MOSFET to pass current efficiently with minimal voltage drop.

#### Effect of Gate Voltage:

Increasing gate voltage reduces on-resistance:

- $V_{GS} = 3.0\text{ V}$ :  $R_{DS(on)} \approx 8\ \Omega$  (higher resistance)
- $V_{GS} = 3.5\text{ V}$ :  $R_{DS(on)} \approx 4\ \Omega$  (medium resistance)
- $V_{GS} = 5.0\text{ V}$ :  $R_{DS(on)} \approx 2\ \Omega$  (lower resistance, fully enhanced)

Higher gate voltage attracts more charge carriers to channel, increasing conductivity and reducing resistance.

#### Analog Switch Application:

Using MOSFET as analog switch:

- OFF state:  $V_{GS} = 0\text{ V} < V_{TH} \rightarrow$  Cutoff, open circuit
- ON state:  $V_{GS} = 5\text{ V} > V_{TH} \rightarrow$  Ohmic region (if  $V_{DS}$  kept low)
- With signal voltage swing  $\pm 1\text{ V}$  and  $R_{DS(on)} = 2\ \Omega$
- Voltage drop across switch:  $V_{drop} = I_{signal} \times 2\ \Omega$  (minimal)
- Low on-resistance ensures signal integrity and minimal power dissipation

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

- **Ohmic region conditions:**  $V_{GS} > V_{TH}$  and  $V_{DS} < (V_{GS} - V_{TH})$
- MOSFET acts as voltage-controlled resistor with linear voltage-current relationship
- Drain current approximately proportional to drain-source voltage:  $I_D \propto V_{DS}$
- Channel resistance  $R_{DS(on)}$  controlled by gate voltage: higher  $V_{GS} \rightarrow$  lower  $R_{DS(on)} \rightarrow$  higher conductivity

- Also called linear region or triode region (nomenclature inconsistent; prefer "ohmic")
- Mimics Ohm's Law behavior in initial portion of characteristic curve
- Critical voltage separating ohmic and saturation:  $V_{DS,crit} = V_{GS} - V_{TH}$
- Below critical voltage: linear behavior; above critical voltage: saturation (constant current)
- Applications: analog switches, variable resistors, multiplexers, sample-and-hold circuits
- Low  $R_{DS(on)}$  in ohmic region minimizes voltage drop and power dissipation in switching applications
- Avoid confusion: "linear region" for MOSFETs  $\neq$  linear amplification (amplification uses saturation region)

# Saturation Region and Breakdown Region

## TL;DR (The Gist)

The saturation region is where MOSFET amplification occurs. Drain current is maximum for a given gate voltage and remains nearly constant regardless of drain voltage changes. Conditions:  $V_{GS} > V_{TH}$  and  $V_{DS} \geq (V_{GS} - V_{TH})$ . The breakdown region occurs when excessive drain voltage causes channel breakdown and uncontrolled current flow, potentially damaging the device. These regions define the operating limits and applications of MOSFETs in amplifiers and switching circuits.

## Detailed Explanation

### 2. Detailed Explanation

#### Saturation Region Characteristics:

The saturation region (also called active region) is where:

$$V_{GS} > V_{TH} \quad \text{and} \quad V_{DS} \geq (V_{GS} - V_{TH})$$

#### Key Behavior:

- Drain current reaches maximum value for given gate voltage
- $I_D$  is strongly influenced by  $V_{GS}$  but hardly affected by  $V_{DS}$
- Increasing drain voltage (within saturation region) does not significantly change drain current
- To increase drain current, must increase gate voltage
- MOSFET acts as voltage-controlled current source

#### Physical Mechanism:

As drain voltage increases beyond  $V_{GS} - V_{TH}$ :

- Channel begins to pinch off near drain terminal
- Voltage drop along channel creates non-uniform channel depth
- At drain end, channel narrows (depletion region forms)
- Pinch-off point creates current saturation effect
- Increasing  $V_{DS}$  further widens depletion region slightly but doesn't significantly change current
- Current limited by channel conductance near source (controlled by  $V_{GS}$ )

#### Saturation Region Drain Current:

Drain current in saturation follows square-law relationship (simplified):

$$I_{D,\text{sat}} = k \cdot (V_{GS} - V_{TH})^2$$

where  $k$  is a device constant depending on MOSFET geometry and material properties. This shows drain current is primarily determined by gate voltage, not drain voltage.

#### MOSFET vs BJT Terminology - Important Distinction:

**CRITICAL: MOSFET "Saturation"  $\neq$  BJT "Saturation"**

#### BJT Regions:

- **Cutoff:**  $V_{BE} < 0.7\text{ V}$ , transistor OFF,  $I_C = 0$
- **Active (linear amplification):**  $V_{BE} > 0.7\text{ V}$ ,  $V_{CE}$  sufficient,  $I_C = \beta I_B$
- **Saturation (fully ON switch):**  $V_{BE}$  and  $V_{BC}$  both forward-biased,  $V_{CE,\text{sat}} \approx 0.2\text{ V}$ , used for switching

#### MOSFET Regions:

- **Cutoff:**  $V_{GS} < V_{TH}$ , transistor OFF,  $I_D = 0$
- **Ohmic (fully ON switch):**  $V_{DS}$  low, low  $R_{DS(\text{on})}$ , used for switching
- **Saturation (linear amplification):**  $V_{DS}$  sufficient,  $I_D$  controlled by  $V_{GS}$ , used for amplification

#### Correspondence:

- BJT Active Region  $\leftrightarrow$  MOSFET Saturation Region (both for amplification)
- BJT Saturation Region  $\leftrightarrow$  MOSFET Ohmic Region (both for switching ON state)

This terminology difference is a common source of confusion. Remember:

- For **BJT**: Saturation = fully ON switch (low  $V_{CE}$ )
- For **MOSFET**: Saturation = amplification region (constant current source)

#### Amplification in Saturation Region:

MOSFETs provide linear amplification when operated in saturation region because:

- Drain current changes proportionally with gate voltage changes
- High input impedance (no gate current) prevents signal source loading
- Output current relatively independent of load (voltage-controlled current source)

- Transconductance  $g_m = \partial I_D / \partial V_{GS}$  defines voltage-to-current conversion

For small-signal amplification, MOSFET must operate in saturation region, NOT ohmic region (despite "linear region" name potentially suggesting otherwise).

#### Breakdown Region:

The breakdown region occurs when:

$$V_{DS} > V_{DS, \text{breakdown}}$$

#### Breakdown Characteristics:

- Drain voltage exceeds maximum safe operating limit
- Drain-source channel breaks down
- Drain current increases drastically and uncontrollably
- MOSFET loses ability to regulate current
- Can cause permanent damage (irreversible)

#### Breakdown Voltage Variation:

On characteristic curves, breakdown voltage varies with gate voltage:

- Lower  $V_{GS} \rightarrow$  Higher breakdown voltage
- Higher  $V_{GS} \rightarrow$  Lower breakdown voltage (more conductive channel, easier breakdown)

#### Breakdown Testing Conditions:

Datasheet breakdown voltage typically specified with:

- Gate tied to source ( $V_{GS} = 0 \text{ V}$ )
- This represents worst-case or most conservative specification
- Ensures MOSFET won't break down even when completely OFF

#### Preventing Breakdown:

- Always keep  $V_{DS}$  below rated breakdown voltage from datasheet
- Include safety margin (e.g., operate at 80% of maximum rating)
- Use snubber circuits or voltage clamps for inductive loads (voltage spikes)
- Consider transient overvoltage events in circuit design
- Heat dissipation: excessive voltage + current = high power dissipation, thermal damage

#### Consequences of Breakdown:

- Uncontrolled high current flow
- Excessive power dissipation:  $P = V_{DS} \times I_D$
- Thermal runaway (device heats up, breakdown worsens)
- Permanent damage to MOSFET structure
- Device failure (short circuit or open circuit)

### Practical Example & Numerical

#### Saturation Region Operation:

Consider N-channel MOSFET with  $V_{TH} = 1.5 \text{ V}$ :

##### Case 1: Saturation Region Confirmation

- Gate-source voltage:  $V_{GS} = 4.0 \text{ V}$
- Drain-source voltage:  $V_{DS} = 5.0 \text{ V}$
- Check condition 1:  $V_{GS} = 4.0 \text{ V} > V_{TH} = 1.5 \text{ V} \checkmark$
- Check condition 2:  $V_{DS} = 5.0 \text{ V} \geq (V_{GS} - V_{TH}) = 4.0 - 1.5 = 2.5 \text{ V} \checkmark$
- Result: MOSFET in saturation region
- Behavior: Drain current determined by  $V_{GS}$ , independent of  $V_{DS}$

##### Case 2: Drain Voltage Independence

- Fixed gate voltage:  $V_{GS} = 4.0 \text{ V}$
- $V_{DS} = 3.0 \text{ V} \rightarrow I_D = 500 \text{ mA}$  (saturation)
- $V_{DS} = 5.0 \text{ V} \rightarrow I_D \approx 500 \text{ mA}$  (minimal change)
- $V_{DS} = 8.0 \text{ V} \rightarrow I_D \approx 500 \text{ mA}$  (still approximately constant)
- Observation: Changing  $V_{DS}$  from 3 V to 8 V barely affects drain current

##### Case 3: Gate Voltage Control

- To increase drain current in saturation, increase gate voltage:
- $V_{GS} = 3.0 \text{ V} \rightarrow I_D \approx 225 \text{ mA}$  (using square law:  $(3 - 1.5)^2 = 2.25$ )
- $V_{GS} = 4.0 \text{ V} \rightarrow I_D \approx 500 \text{ mA}$  ( $(4 - 1.5)^2 = 6.25$ , ratio  $6.25/2.25 \approx 2.78$ )
- $V_{GS} = 5.0 \text{ V} \rightarrow I_D \approx 980 \text{ mA}$  ( $(5 - 1.5)^2 = 12.25$ )

- Drain current increases with gate voltage (square-law relationship in saturation)

#### Breakdown Region Example:

MOSFET with  $V_{DS, \text{breakdown}} = 60 \text{ V}$  (from datasheet):

#### Safe Operation:

- $V_{DS} = 40 \text{ V}$ : Safe, well below breakdown voltage
- Operating in saturation with controlled current
- Normal MOSFET behavior

#### Breakdown Condition:

- $V_{DS} = 65 \text{ V}$ : Exceeds 60 V breakdown rating
- Channel breaks down, drain current spikes uncontrollably
- Power dissipation:  $P = 65 \text{ V} \times I_D$  (potentially hundreds of watts)
- Result: Thermal damage, device failure (permanent)

#### BJT vs MOSFET Region Comparison:

Designing a switching application (LED driver):

#### Using BJT:

- OFF state: Cutoff ( $V_{BE} < 0.7 \text{ V}$ )
- ON state: Saturation ( $V_{CE, \text{sat}} \approx 0.2 \text{ V}$ , low voltage drop)
- Use saturation region for efficient switching

#### Using MOSFET:

- OFF state: Cutoff ( $V_{GS} < V_{TH}$ )
- ON state: Ohmic region ( $V_{DS}$  low, minimal  $R_{DS(on)}$ )
- Use ohmic region for efficient switching (NOT saturation)

Designing an amplifier application:

#### Using BJT:

- Bias in active region for linear amplification
- $I_C = \beta I_B$ , output current proportional to input current

#### Using MOSFET:

- Bias in saturation region for linear amplification
- $I_D \propto (V_{GS} - V_{TH})^2$ , output current controlled by input voltage

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

- **Saturation region conditions:**  $V_{GS} > V_{TH}$  and  $V_{DS} \geq (V_{GS} - V_{TH})$
- Drain current maximum for given gate voltage, nearly independent of drain voltage
- To increase  $I_D$  in saturation, increase  $V_{GS}$  (not  $V_{DS}$ )
- MOSFET acts as voltage-controlled current source in saturation region
- Drain current follows square-law:  $I_D \propto (V_{GS} - V_{TH})^2$
- **CRITICAL: MOSFET saturation  $\neq$  BJT saturation**
- BJT active region  $\leftrightarrow$  MOSFET saturation region (both for amplification)
- BJT saturation region  $\leftrightarrow$  MOSFET ohmic region (both for switching ON state)
- Linear amplification uses MOSFET saturation region (high input impedance, voltage-controlled)
- **Breakdown region:**  $V_{DS} > V_{DS, \text{breakdown}}$ , uncontrolled current increase, device damage
- Lower  $V_{GS}$  increases breakdown voltage; datasheet specifies breakdown at  $V_{GS} = 0 \text{ V}$
- Always operate below rated breakdown voltage with safety margin
- Breakdown causes permanent damage through thermal runaway and excessive current
- Prevent breakdown with proper circuit design, voltage clamps, and transient protection

# MOSFET Datasheet Analysis

## TL;DR (The Gist)

MOSFET datasheets provide critical parameters for device selection and circuit design. Key specifications include absolute maximum ratings (drain-source voltage, gate-source voltage, drain current limits), threshold voltage range, on-resistance, and characteristic curves (transfer characteristics, output characteristics). Understanding datasheet parameters prevents device damage and ensures proper circuit operation within safe operating limits.

## Detailed Explanation

### 2. Detailed Explanation

#### Absolute Maximum Ratings:

Datasheets begin with absolute maximum ratings—stresses exceeding these values may damage the device.

##### 1. Maximum Drain-Source Voltage ( $V_{DS,max}$ ):

- Typical specification:  $V_{DS,max} = 60\text{ V}$  (example value)
- Measured with gate-source shorted ( $V_{GS} = 0\text{ V}$ )
- Exceeding this voltage causes breakdown region entry
- At  $V_{GS} = 0\text{ V}$ , N-channel enhancement MOSFET is OFF (no channel conduction)
- Even with MOSFET OFF, excessive  $V_{DS}$  can break down drain-source structure
- Different  $V_{GS}$  values may have slightly different breakdown voltages (lower  $V_{GS} \rightarrow$  higher breakdown)
- Datasheet specifies most conservative case (gate grounded)

##### 2. Maximum Gate-Source Voltage ( $V_{GS,max}$ ):

- Typical specification:  $\pm 20\text{ V}$  continuous,  $\pm 40\text{ V}$  transient ( $< 50\text{ }\mu\text{s}$  pulse)
- Gate oxide extremely thin (nanometers), vulnerable to voltage stress
- Excessive voltage can puncture oxide insulation (permanent damage)
- Continuous rating: Maximum sustained gate voltage
- Transient rating: Brief overvoltage tolerance (e.g., switching transients, gate drive spikes)
- Negative limit important for N-channel (gate can be driven negative in some circuits)
- Always include gate protection (resistors, zener diodes) in sensitive applications

##### 3. Maximum Drain Current ( $I_{D,max}$ ):

- Continuous drain current:  $I_{D,DC} = 280\text{ mA}$  (example)
- Pulsed drain current:  $I_{D,pulse} = 1.5\text{ A}$  (example, with rapid on/off switching)
- Continuous rating limited by thermal dissipation (steady-state heating)
- Pulsed rating higher because device doesn't reach thermal equilibrium during brief pulses
- Exceeding continuous rating causes overheating and potential failure
- Requires heatsinking if operating near maximum continuous current
- Pulsed current depends on pulse width, duty cycle, and thermal mass

##### 4. Drain-Source Breakdown Voltage ( $V_{(BR)DSS}$ ):

- Example:  $V_{(BR)DSS} \geq 60\text{ V}$
- Same as maximum drain-source voltage specification
- Breakdown voltage when gate shorted to source
- Ensures MOSFET won't break down even when completely OFF
- Design circuits to keep  $V_{DS}$  well below this limit (80% rule common)

#### Threshold Voltage ( $V_{GS(th)}$ or $V_{TH}$ ):

Critical parameter defining turn-on voltage:

- Example specification:  $V_{TH} = 0.8\text{ V}$  to  $3.0\text{ V}$
- **Range, not single value:** Manufacturing variations cause threshold spread
- Typical value: Middle of range ( $\sim 1.9\text{ V}$  for  $0.8\text{--}3.0\text{ V}$  range)
- Test conditions specified (e.g., measured at  $I_D = 250\text{ }\mu\text{A}$ )
- Temperature coefficient: Threshold decreases with increasing temperature (typically  $-2$  to  $-5\text{ mV}/^\circ\text{C}$ )
- Circuit design must account for threshold variation (worst-case analysis)
- For reliable turn-on, use gate voltage well above maximum threshold ( $V_{GS} \geq V_{TH,max} + \text{margin}$ )
- For reliable turn-off, use gate voltage well below minimum threshold ( $V_{GS} \leq V_{TH,min} - \text{margin}$ )

#### Transfer Characteristics Graph:

Plot of drain current vs gate-source voltage (at constant  $V_{DS}$ ):

- X-axis: Gate-source voltage  $V_{GS}$
- Y-axis: Drain current  $I_D$
- Shows turn-on behavior and transconductance
- Example: At  $V_{GS} < 2\text{ V}$ ,  $I_D \approx 0\text{ A}$  (below threshold)
- Example: At  $V_{GS} = 6\text{ V}$ ,  $I_D \approx 1\text{ A}$  (at room temperature)
- Slope = transconductance  $g_m$  (steeper slope = higher gain)
- Temperature curves show threshold shift and current change with temperature
- Useful for determining operating point and small-signal gain

#### Output Characteristics Graph (I-V Curves):

Plot of drain current vs drain-source voltage for various gate voltages:

- X-axis: Drain-source voltage  $V_{DS}$
- Y-axis: Drain current  $I_D$
- Multiple curves, each for different  $V_{GS}$
- Shows ohmic, saturation, and breakdown regions clearly
- Example curve at  $V_{GS} = 4\text{ V}$ :
  - $V_{DS} < 1\text{ V}$ : Ohmic region (linear slope,  $I_D$  proportional to  $V_{DS}$ )
  - $V_{DS} \geq 1\text{ V}$ : Saturation region (flat curve,  $I_D \approx 400\text{ mA}$  constant)
- Boundary between ohmic and saturation visible as curve knee
- Higher  $V_{GS}$  curves show higher saturation current
- Useful for load line analysis and operating point selection

#### On-Resistance ( $R_{DS(on)}$ ):

Resistance in ohmic region (specified at particular  $V_{GS}$ ):

- Example:  $R_{DS(on)} = 0.5\ \Omega$  at  $V_{GS} = 10\text{ V}$
- Lower  $R_{DS(on)}$   $\rightarrow$  better switching efficiency (less voltage drop, less power loss)
- Increases with temperature (positive temperature coefficient)
- Critical for switching applications (determines conduction losses)
- Power dissipation in ON state:  $P = I_D^2 \times R_{DS(on)}$

#### Practical Datasheet Usage:

When selecting a MOSFET:

1. Identify circuit requirements:  $V_{DS,max}$ ,  $I_{D,max}$ ,  $V_{GS,available}$
2. Check absolute maximum ratings: Ensure circuit voltages/currents within limits (with margin)
3. Verify threshold voltage: Confirm gate drive voltage adequately above/below threshold for ON/OFF states
4. Check on-resistance: Calculate conduction losses for switching applications
5. Review characteristic curves: Confirm operating region (ohmic for switches, saturation for amplifiers)
6. Consider thermal: Calculate power dissipation, ensure adequate cooling

### Practical Example & Numerical

#### Datasheet Parameter Application:

N-channel enhancement MOSFET datasheet excerpt:

- $V_{DS,max} = 60\text{ V}$
- $V_{GS,max} = \pm 20\text{ V}$  continuous
- $I_{D,continuous} = 280\text{ mA}$
- $I_{D,pulse} = 1.5\text{ A}$
- $V_{TH} = 0.8\text{ to }3.0\text{ V}$
- $R_{DS(on)} = 0.8\ \Omega$  at  $V_{GS} = 10\text{ V}$

#### Application 1: LED Driver Switch

Requirements: Drive 200 mA LED from 12 V supply with logic-level control (5 V gate drive).

##### Voltage Check:

- Maximum drain voltage:  $12\text{ V} < 60\text{ V}$  ✓ (large safety margin)
- Gate drive voltage:  $5\text{ V} < 20\text{ V}$  ✓ (safe)

##### Current Check:

- Required drain current:  $200\text{ mA} < 280\text{ mA}$  ✓ (within continuous rating)

##### Threshold Voltage Analysis:

- Gate voltage available: 5 V
- Maximum threshold: 3.0 V

- Margin:  $5 - 3 = 2 \text{ V}$  ✓ (adequate for reliable turn-on)

#### Power Dissipation:

- On-resistance at  $V_{GS} = 5 \text{ V}$ : Assume  $\sim 1.5 \Omega$  (higher than at  $10 \text{ V}$  spec)
- Voltage drop:  $V_{drop} = I_D \times R_{DS(on)} = 0.2 \text{ A} \times 1.5 \Omega = 0.3 \text{ V}$
- Power dissipation:  $P = I_D^2 \times R_{DS(on)} = (0.2)^2 \times 1.5 = 0.06 \text{ W} = 60 \text{ mW}$
- Result: Low power dissipation, no heatsink required

#### Application 2: Using Transfer Characteristics

From transfer characteristics graph at  $T = 25^\circ\text{C}$ :

- $V_{GS} = 2 \text{ V} \rightarrow I_D \approx 0 \text{ A}$  (below/near threshold)
- $V_{GS} = 3 \text{ V} \rightarrow I_D \approx 150 \text{ mA}$
- $V_{GS} = 4 \text{ V} \rightarrow I_D \approx 450 \text{ mA}$
- $V_{GS} = 6 \text{ V} \rightarrow I_D \approx 1 \text{ A}$

To achieve  $I_D = 200 \text{ mA}$ , interpolate:  $V_{GS} \approx 3.2 \text{ V}$  required.

#### Application 3: Using Output Characteristics

From output characteristics at  $V_{GS} = 4 \text{ V}$ :

- $V_{DS} = 0.5 \text{ V} \rightarrow I_D \approx 200 \text{ mA}$  (ohmic region, linear slope)
- $V_{DS} = 1.0 \text{ V} \rightarrow I_D \approx 400 \text{ mA}$  (transition to saturation)
- $V_{DS} = 2.0 \text{ V} \rightarrow I_D \approx 400 \text{ mA}$  (saturation, constant current)
- $V_{DS} = 5.0 \text{ V} \rightarrow I_D \approx 400 \text{ mA}$  (saturation continues)

Boundary between ohmic and saturation:  $V_{DS} \approx V_{GS} - V_{TH} = 4 - 1.9 \approx 2.1 \text{ V}$  (matches graph).

#### Application 4: Exceeding Ratings (Failure Scenario)

Mistake: Apply  $V_{DS} = 70 \text{ V}$  (exceeds  $60 \text{ V}$  rating):

- MOSFET enters breakdown region
- Drain current spikes uncontrollably (e.g.,  $> 5 \text{ A}$ )
- Power dissipation:  $P = 70 \text{ V} \times 5 \text{ A} = 350 \text{ W}$
- Result: Immediate thermal damage, device destroyed
- Prevention: Always include safety margin, never exceed absolute maximum ratings

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

- Absolute maximum ratings define safe operating limits; exceeding causes damage
- $V_{DS,max}$ : Maximum drain-source voltage (specified at  $V_{GS} = 0 \text{ V}$ ), typically  $20\text{-}1000 \text{ V}$  depending on device
- $V_{GS,max}$ : Maximum gate-source voltage (continuous and transient ratings), typically  $\pm 10$  to  $\pm 20 \text{ V}$
- $I_{D,max}$ : Maximum drain current (continuous and pulsed), limited by thermal dissipation
- Threshold voltage  $V_{TH}$  specified as range (e.g.,  $0.8\text{-}3.0 \text{ V}$ ) due to manufacturing variations
- Design must account for threshold extremes: gate voltage high enough above max  $V_{TH}$  for ON, low enough below min  $V_{TH}$  for OFF
- Transfer characteristics show  $I_D$  vs  $V_{GS}$  (turn-on behavior, transconductance)
- Output characteristics show  $I_D$  vs  $V_{DS}$  for various  $V_{GS}$  (ohmic/saturation/breakdown regions visible)
- On-resistance  $R_{DS(on)}$  determines conduction losses in switching:  $P = I_D^2 \times R_{DS(on)}$
- Lower  $R_{DS(on)}$  better for switching efficiency (check specification at intended  $V_{GS}$ )
- Temperature affects threshold voltage (decreases), on-resistance (increases), and drain current
- Always include safety margins when operating near maximum ratings (80% rule common)
- Datasheet graphs essential for operating point selection and performance prediction

# Section 31 – DC-to-DC Switching Converters

## Switching Regulator Types and Overview

### TL;DR (The Gist)

DC-to-DC converters translate voltage from one level to another, essential for powering multiple components requiring different voltages from a single power source. Switching regulators use high-frequency on/off switching with inductors and capacitors to achieve voltage conversion with high efficiency (up to 90%). Three main types: Buck (step-down), Boost (step-up), and Buck-Boost (step-up or step-down). Switching regulators offer superior efficiency compared to linear regulators but require more complex circuitry.

### Detailed Explanation

## 2. Detailed Explanation

### Need for DC-to-DC Conversion:

Modern electronic systems (mobile devices, embedded systems) typically have:

- Single power source with fixed voltage (e.g., battery at 3.7 V or 12 V supply)
- Multiple components requiring different voltage levels
- Some parts need voltage lower than source voltage
- Some parts need voltage higher than source voltage

DC-to-DC converters enable voltage translation from one level to another to supply all components from a single source.

### Two Main Categories:

#### 1. Linear Regulators:

- Always step down voltage (output < input)
- Example: LM317 adjustable regulator (up to 1.5 A output)
- Output voltage controlled by resistor divider ratio:  $V_{out} = 1.25(1 + R_2/R_1)$
- Cannot increase input voltage, only lower it
- Simple circuit configuration, few external parts
- Low noise generation
- **Disadvantages:** Poor efficiency, heat generation, step-down only

#### 2. Switching Regulators:

Use switching devices (MOSFETs) turned on/off at high frequency with specific patterns. Average voltage over time produces desired output. Transform incoming power into pulsed voltage, then filtered using capacitors and inductors.

### Advantages:

- High efficiency (up to 90%, significantly better than linear regulators)
- Less heat generation
- Can step down OR step up voltage
- Better for battery-powered applications where energy conservation crucial

### Disadvantages:

- More external parts required
- Much more complicated design
- Generate electrical noise (high-frequency switching creates electromagnetic interference)

### Noise Generation Mechanism:

Switching circuit (control circuit) rapidly turns transistor on/off at very high speeds (tens to hundreds of kHz or MHz). General rule: faster circuits switch, more noise generated. High-frequency switching creates:

- Conducted emissions (noise on power lines)
- Radiated emissions (electromagnetic interference)
- Voltage/current spikes during transitions

Mitigation requires careful PCB layout, filtering, shielding.

### Three Main Switching Converter Types:

#### 1. Buck Converter (Step-Down):

- Produces output voltage lower than input voltage ( $V_{out} < V_{in}$ )
- Used to power lower-voltage devices from higher-voltage source

- Example: Power 3.3 V microcontroller from 12 V battery
- Most common switching regulator topology

## 2. Boost Converter (Step-Up):

- Produces output voltage higher than input voltage ( $V_{out} > V_{in}$ )
- Steps voltage up as name suggests
- Used in LED drivers (extract extra power from lithium cell)
- Battery life extension (boost low battery voltage back to useful level)
- Many other applications requiring voltage increase

## 3. Buck-Boost Converter (Dual Purpose):

- Can step up OR step down voltage
- Output may be higher or lower than input
- Can produce positive or negative voltages
- Used in variety of applications requiring flexible voltage conversion
- Inverting topology produces negative output from positive input

## Power Relationship:

Critical principle: Power in = Power out (in ideal case)

$$P_{in} = P_{out} \Rightarrow V_{in} \times I_{in} = V_{out} \times I_{out}$$

If boost converter increases voltage, current must decrease proportionally:

$$\text{If } V_{out} > V_{in}, \text{ then } I_{out} < I_{in}$$

Example: Boost converter at 100% efficiency converts 5 V, 2 A input to 10 V output:

$$I_{out} = \frac{V_{in} \times I_{in}}{V_{out}} = \frac{5 \times 2}{10} = 1 \text{ A}$$

Voltage doubled, current halved, power conserved (10 W in both cases).

## Application Selection Criteria:

### Use Linear Regulator when:

- Low noise critical (audio circuits, precision analog)
- Simple design preferred
- Input-output voltage difference small
- Load current low (minimal heat dissipation)
- Cost-sensitive application (fewer components)

### Use Switching Regulator when:

- Efficiency critical (battery-powered devices)
- Large input-output voltage difference
- High load currents
- Voltage step-up required
- Thermal management challenging (limited cooling)

## Practical Example & Numerical

### Voltage Conversion Requirements Example:

Mobile device powered by 3.7 V lithium-ion battery contains:

- Microcontroller: requires 1.8 V at 100 mA
- Display backlight LEDs: requires 12 V at 50 mA
- Radio transceiver: requires 3.3 V at 200 mA
- Memory: requires 2.5 V at 80 mA

### Converter Selection:

#### Microcontroller (3.7 V $\rightarrow$ 1.8 V):

- Buck converter (step-down from 3.7 V to 1.8 V)
- Efficiency  $\approx 85\%$
- Power out:  $P_{out} = 1.8 \times 0.1 = 0.18 \text{ W}$
- Power in:  $P_{in} = 0.18/0.85 = 0.212 \text{ W}$

#### Display Backlight (3.7 V $\rightarrow$ 12 V):

- Boost converter (step-up from 3.7 V to 12 V)

- Efficiency  $\approx 88\%$
- Power out:  $P_{out} = 12 \times 0.05 = 0.6 \text{ W}$
- Power in:  $P_{in} = 0.6/0.88 = 0.682 \text{ W}$
- Input current:  $I_{in} = 0.682/3.7 = 184 \text{ mA}$

**Radio Transceiver (3.7 V  $\rightarrow$  3.3 V):**

- Could use buck converter OR linear regulator (small voltage drop)
- Linear regulator acceptable if noise more critical than efficiency
- Buck converter if efficiency paramount

**Memory (3.7 V  $\rightarrow$  2.5 V):**

- Buck converter (step-down from 3.7 V to 2.5 V)
- Efficiency  $\approx 85\%$

**Total Battery Current:**

Sum of all input currents from converters determines battery drain and runtime.

**Linear vs Switching Comparison for Microcontroller:**

**Using Linear Regulator:**

- Efficiency:  $\eta = V_{out}/V_{in} = 1.8/3.7 = 48.6\%$
- Input current = output current = 100 mA
- Power dissipated:  $P_{diss} = (3.7 - 1.8) \times 0.1 = 0.19 \text{ W}$

**Using Buck Converter:**

- Efficiency:  $\eta = 85\%$
- Input current:  $I_{in} = 0.18/(3.7 \times 0.85) = 57.3 \text{ mA}$
- Power dissipated:  $P_{diss} = 0.212 - 0.18 = 0.032 \text{ W}$

Buck converter saves  $(100 - 57.3) = 42.7 \text{ mA}$  battery current and dissipates 6 times less heat.

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- DC-to-DC converters translate voltage levels to power multiple components from single source
- Two categories: Linear regulators (step-down only, simple, low noise) and Switching regulators (step-up/down, efficient, complex)
- Linear regulators: simple, low noise, poor efficiency, heat generation, step-down only
- Switching regulators: high efficiency (up to 90%), less heat, can step-up or step-down, more complex, generate noise
- Three main switching types: Buck (step-down), Boost (step-up), Buck-Boost (both directions)
- Power conservation principle:  $V_{in} \times I_{in} = V_{out} \times I_{out}$  (ideal case)
- Boost converter: if voltage increases, current decreases proportionally
- Faster switching  $\rightarrow$  more electromagnetic noise (trade-off with efficiency)
- Use linear for low noise, simple design, small voltage drops; use switching for efficiency, battery power, large voltage changes
- Switching regulators essential for battery-powered devices where energy conservation critical

# Buck Converter (Step-Down) Working Principle

## TL;DR (The Gist)

The buck converter efficiently steps down DC voltage using high-frequency switching with an inductor, diode, capacitor, and MOSFET switch. Operation alternates between two phases: ON state (MOSFET conducts, energy stored in inductor) and OFF state (inductor releases energy through freewheeling diode to maintain output current). Output voltage controlled by duty cycle:  $V_{out} = D \times V_{in}$  where  $D$  is the duty ratio ( $0 < D < 1$ ). Efficiency reaches 85-95%, vastly superior to linear regulators.

## Detailed Explanation

### 2. Detailed Explanation

#### Motivation for Buck Converter:

Linear regulators waste power when voltage drop is large. Example:

- Power 3.3 V microcontroller from 12 V supply using LM1117 linear regulator
- LED strip consumes 20 mA
- Power dissipated:  $P_{diss} = (V_{in} - V_{out}) \times I_{out} = (12 - 3.3) \times 0.02 = 0.174 \text{ W}$
- For higher current (500 mA):  $P_{diss} = 8.7 \times 0.5 = 4.35 \text{ W}$  (excessive heat)
- Efficiency:  $\eta = V_{out}/V_{in} = 3.3/12 = 27.5\%$  (pathetic)

Linear regulators inefficient for large voltage drops. Buck converters provide efficient alternative, stepping down voltage cleverly without resistive voltage drop.

#### Buck Converter Fundamental Circuit:

Core components:

- **Switch (MOSFET):** Rapidly turned on/off by PWM signal
- **Inductor (L):** Stores energy in magnetic field, limits current change rate
- **Diode (D):** Freewheeling diode provides current path when switch OFF
- **Capacitor (C):** Output filter, smooths voltage ripple
- **Load (R):** Component being powered

#### Operating Principle - Two-Phase Operation:

##### Phase 1: Switch ON (MOSFET Conducts):

1. MOSFET turns ON, connecting input voltage to inductor
2. Current flows:  $V_{in} \rightarrow \text{MOSFET} \rightarrow \text{Inductor (L)} \rightarrow \text{Load} \rightarrow \text{Ground}$
3. Inductor limits charging current, voltage across capacitor cannot rise instantly
4. Energy stored in inductor's magnetic field (building phase)
5. Capacitor charges gradually during switching cycle
6. Diode reverse-biased (large positive voltage on cathode), plays no role
7. Voltage across capacitor during ON phase not full input voltage (inductor limits)

##### Phase 2: Switch OFF (MOSFET Not Conducting):

1. MOSFET turns OFF, breaks direct connection to input
2. Inductor current cannot change suddenly (fundamental inductor property:  $V_L = L \, dI/dt$ )
3. Inductor generates back-EMF (voltage reverses polarity)
4. Back-EMF keeps current flowing through: Inductor  $\rightarrow$  Load  $\rightarrow$  Diode (now forward-biased)  $\rightarrow$  Inductor
5. Energy stored in magnetic field released back into circuit
6. Diode provides freewheeling path, maintaining output current throughout cycle
7. Capacitor supplies additional current to load as inductor voltage falls

These two phases repeat thousands of times per second (typical switching frequency: 50 kHz to 2 MHz), resulting in continuous regulated output.

#### PWM Control and Duty Cycle:

Turning MOSFET on/off requires PWM (Pulse Width Modulation) signal:

- Square wave with adjustable duty cycle
- Duty cycle  $D$  = ratio of ON time to total period
- Switching frequency  $f$  determines period:  $T = 1/f$
- ON time:  $t_{on}$
- OFF time:  $t_{off}$
- Total period:  $T = t_{on} + t_{off}$
- Duty ratio:  $D = t_{on}/T$

### Output Voltage Equation:

The theoretical DC output voltage:

$$V_{out} = D \times V_{in} = \frac{t_{on}}{T} \times V_{in}$$

Since frequency is fixed, period  $T$  is constant. Output voltage controlled solely by duty cycle  $D$ .

Example calculations:

- $D = 50\%$ :  $V_{out} = 0.5 \times V_{in}$  (half input voltage)
- $D = 25\%$ :  $V_{out} = 0.25 \times V_{in}$  (quarter input voltage)
- $D = 75\%$ :  $V_{out} = 0.75 \times V_{in}$  (three-quarters input voltage)

Since  $0 < D < 1$ , buck converter always steps down:  $V_{out} < V_{in}$ .

### Why Use MOSFET Instead of BJT:

#### Advantages of MOSFET:

1. **Lower power consumption:** Much lower on-resistance  $R_{DS(on)}$  compared to BJT  $V_{CE,sat}$
2. Typical MOSFET:  $R_{DS(on)} = 15 \text{ m}\Omega \rightarrow$  voltage drop  $= I \times 0.015$  (minimal)
3. Typical BJT:  $V_{CE,sat} = 0.2\text{-}0.5 \text{ V}$  (much higher voltage drop and power loss)
4. Lower on-resistance = less power dissipation = higher efficiency
5. **Simpler biasing:** Voltage-controlled (not current-controlled like BJT)
6. Gate requires virtually zero current, easy to drive with logic-level signals
7. BJT requires continuous base current, more complex drive circuitry
8. **Faster switching:** No minority carrier storage delay
9. Can switch at higher frequencies for smaller components

### MOSFET Operating Regions in Buck Converter:

For efficient switching operation:

- **ON state:** MOSFET in ohmic (linear) region, fully enhanced
- Maximum gate voltage applied  $\rightarrow$  minimum  $R_{DS(on)} \rightarrow$  maximum current capability
- Acts as low-resistance switch (nearly short circuit)
- **OFF state:** MOSFET in cutoff region
- $V_{GS} < V_{TH} \rightarrow$  no channel  $\rightarrow$  open circuit
- No current flows through MOSFET

Avoid operating in saturation region (for BJT: active region) during switching—this causes high power dissipation.

### Energy Flow Analysis:

#### During ON Period:

- Current flows from DC supply to load
- Energy stored in inductor magnetic field:  $E_L = \frac{1}{2}LI^2$
- Capacitor gradually charges
- Diode reverse-biased, no participation

#### During OFF Period:

- Inductor voltage reverses polarity (back-EMF)
- Stored magnetic energy released back to circuit
- Current continues flowing via freewheeling diode
- Capacitor discharges, maintaining load current
- Diode forward-biased, completes current loop

### Why High Efficiency:

- No resistive voltage drop (unlike linear regulator series pass transistor)
- MOSFET on-resistance very low (minimal  $I^2R$  losses)
- Inductor and capacitor ideally lossless (store and release energy)
- Main losses: MOSFET switching losses, diode forward voltage drop, inductor DC resistance
- Typical efficiency: 85%-95% (compared to linear regulator 27%-50% for same application)

## Practical Example & Numerical

### Buck Converter Design Example:

Convert 12 V input to 5 V output at 1 A load current.

#### Required Duty Cycle:

$$D = \frac{V_{out}}{V_{in}} = \frac{5}{12} = 0.417 = 41.7\%$$

#### Switching Frequency and Timing:

Choose switching frequency  $f = 100 \text{ kHz}$ :

- Period:  $T = 1/f = 10 \mu\text{s}$
- ON time:  $t_{on} = D \times T = 0.417 \times 10 = 4.17 \mu\text{s}$
- OFF time:  $t_{off} = T - t_{on} = 10 - 4.17 = 5.83 \mu\text{s}$

#### Power and Efficiency:

Assume buck converter efficiency  $\eta = 90\%$ :

- Output power:  $P_{out} = V_{out} \times I_{out} = 5 \times 1 = 5 \text{ W}$
- Input power:  $P_{in} = P_{out}/\eta = 5/0.9 = 5.56 \text{ W}$
- Input current:  $I_{in} = P_{in}/V_{in} = 5.56/12 = 0.463 \text{ A}$
- Power dissipated in converter:  $P_{diss} = P_{in} - P_{out} = 0.56 \text{ W}$

#### Comparison with Linear Regulator:

Same  $12 \text{ V} \rightarrow 5 \text{ V}$  at  $1 \text{ A}$  using linear regulator:

- Efficiency:  $\eta = 5/12 = 41.7\%$
- Input current:  $I_{in} = I_{out} = 1 \text{ A}$
- Input power:  $P_{in} = 12 \times 1 = 12 \text{ W}$
- Output power:  $P_{out} = 5 \times 1 = 5 \text{ W}$
- Power dissipated:  $P_{diss} = 12 - 5 = 7 \text{ W}$  (requires large heatsink!)

#### Buck Converter Advantages:

- Input current:  $0.463 \text{ A}$  vs  $1 \text{ A}$  (saves 53.7% input current)
- Power dissipation:  $0.56 \text{ W}$  vs  $7 \text{ W}$  (dissipates 92% less heat!)
- Efficiency:  $90\%$  vs  $41.7\%$  (more than double)
- Thermal management: minimal vs requires large heatsink/forced air

#### MOSFET Voltage Drop:

With  $R_{DS(on)} = 15 \text{ m}\Omega$  and  $I_{out} = 1 \text{ A}$ :

$$V_{drop} = I \times R_{DS(on)} = 1 \times 0.015 = 0.015 \text{ V} = 15 \text{ mV}$$

Compare to BJT  $V_{CE,sat} \approx 0.3 \text{ V}$ : MOSFET drops 20 times less voltage, resulting in 20 times less conduction loss.

### Key Points (Interview Focus)

#### 4. Key Points (Interview Focus)

- Buck converter efficiently steps down DC voltage using switching technique
- Core components: MOSFET switch, inductor, freewheeling diode, output capacitor
- Two-phase operation: ON (MOSFET conducts, energy stored in inductor) and OFF (inductor releases energy via diode)
- Output voltage controlled by duty cycle:  $V_{out} = D \times V_{in}$  where  $D = t_{on}/T$
- Duty cycle range  $0 < D < 1$  ensures  $V_{out} < V_{in}$  (step-down only)
- MOSFET preferred over BJT: lower on-resistance ( $R_{DS(on)} \ll V_{CE,sat}$ ), simpler biasing, faster switching
- MOSFET operates in ohmic region (ON) and cutoff region (OFF) for efficient switching
- Inductor stores energy during ON phase (magnetic field builds), releases during OFF phase (back-EMF)
- Freewheeling diode provides current path during OFF phase, maintaining continuous output current
- High efficiency (85%-95%) due to minimal resistive losses (no voltage drop like linear regulator)
- Typical switching frequency:  $50 \text{ kHz}$  to  $2 \text{ MHz}$  (higher frequency  $\rightarrow$  smaller components)
- Main losses: MOSFET switching/conduction, diode forward drop, inductor resistance
- Vastly superior to linear regulator for large voltage drops and high currents

# Buck Converter IC Implementation and Design

## TL;DR (The Gist)

Practical buck converters use integrated circuit controllers containing built-in oscillator, feedback control, and PWM comparator, eliminating need for external PWM generation. Popular ICs like LM2596 include 150 kHz internal oscillator, supply up to 3 A, and feature automatic duty cycle adjustment via feedback loop. External components (inductor, capacitor, diode) values specified in datasheet. Feedback maintains constant regulated output despite input voltage or load current changes. Schottky diodes preferred for low forward voltage drop and fast recovery time.

## Detailed Explanation

### 2. Detailed Explanation

#### Practical Implementation Challenges:

Building discrete buck converter from scratch requires:

- External PWM signal generator circuit
- Feedback mechanism to maintain constant output (adjust duty cycle automatically)
- Component value calculations (inductor, capacitor sizing)
- Output voltage sensing and comparison
- Complex design, difficult calculations

Solution: Use buck converter IC with integrated control circuitry.

#### Buck Converter IC Example: LM2596

##### Key Specifications:

- Built-in oscillator: 150 kHz fixed frequency
- Output current: up to 3 A continuous
- Input voltage range: 4.5 V to 40 V
- Available versions: Fixed output (3.3 V, 5 V, 12 V) and adjustable output
- Integrated frequency compensation (stable without external components)
- Internal thermal shutdown and current limiting protection

##### Pin Configuration:

- **VIN:** Input voltage pin
- **OUTPUT:** Regulated output voltage
- **FEEDBACK:** Voltage feedback input for regulation
- **ON/OFF:** Enable pin (active low—pull low to turn OFF)
- **GND:** Ground reference

##### Typical Application Circuit:

External components required (minimal):

- $L_1$ : Inductor (energy storage element)
- $D_1$ : Freewheeling diode (Schottky recommended)
- $C_{in}$ : Input filter capacitor (decoupling, reduces input voltage ripple)
- $C_{out}$ : Output filter capacitor (smooths output voltage)
- $R_1, R_2$ : Feedback voltage divider (for adjustable version)

No external PWM generator needed—oscillator built into IC!

##### Feedback Control Mechanism:

##### Feedback Pin Function:

The feedback pin takes output voltage (stepped down via voltage divider  $R_1, R_2$ ) and compares to internal reference voltage (typically 1.23 V or 1.33 V depending on IC).

##### How Feedback Maintains Regulation:

1. Output voltage divided by  $R_1, R_2$  to produce feedback voltage
2. Error amplifier compares feedback voltage to internal reference
3. Error signal controls PWM comparator
4. PWM comparator adjusts duty cycle of switching signal
5. Duty cycle increases/decreases to maintain output at set point

##### Regulation Process:

##### Case 1: Output voltage too high

- Feedback voltage  $>$  reference voltage
- Error amplifier drives PWM comparator

- Duty cycle decreases
- Less energy delivered to output
- Output voltage drops back to set point

#### Case 2: Output voltage too low

- Feedback voltage < reference voltage
- Error amplifier compensates
- Duty cycle increases
- More energy delivered to output
- Output voltage rises back to set point

#### Beauty of Feedback:

Single feedback loop corrects for:

- Input voltage variations (line regulation)
- Output current changes due to load variations (load regulation)
- Component tolerance variations
- Temperature effects

Output remains constant despite disturbances.

#### Adjustable Output Voltage Configuration:

For adjustable version, output voltage set by resistor divider:

$$V_{out} = V_{ref} \times \left(1 + \frac{R_1}{R_2}\right)$$

where  $V_{ref}$  is internal reference voltage (e.g., 1.23 V for LM2596).

Example: For  $V_{out} = 5$  V with  $V_{ref} = 1.23$  V:

$$\frac{R_1}{R_2} = \frac{V_{out}}{V_{ref}} - 1 = \frac{5}{1.23} - 1 = 3.07$$

Choose  $R_2 = 1$  k $\Omega$ , then  $R_1 = 3.07$  k $\Omega$  (use standard 3 k $\Omega$  or 3.3 k $\Omega$ ).

#### Schottky Diode Selection:

##### Why Schottky Diode:

1. **Low forward voltage drop:**  $V_f \approx 0.2$ - $0.3$  V (vs  $0.6$ - $0.7$  V for standard silicon diode)
2. Lower voltage drop  $\rightarrow$  less power dissipation  $\rightarrow$  higher efficiency
3. **Fast recovery time:** Critical for high-frequency switching
4. Recovery time: time required to turn OFF after conducting forward current
5. Low recovery charge prevents reverse current spike during switching
6. **Improved efficiency:** Both lower  $V_f$  and fast recovery contribute

##### Diode Selection Criteria:

- **Voltage rating:**  $V_R \geq V_{in,max}$  (with safety margin)
- **Current rating:**  $I_F \geq I_{out,max}$  (continuous forward current)
- **Recovery time:**  $< 50$  ns for frequencies  $> 100$  kHz
- Schottky diodes meet all requirements for buck converter applications

#### Functional Block Diagram:

Inside buck converter IC:

- **Oscillator:** Generates fixed-frequency clock (150 kHz for LM2596)
- **Sawtooth generator:** Creates ramp waveform from oscillator
- **Error amplifier:** Compares feedback voltage to reference, amplifies difference
- **PWM comparator:** Compares error signal to sawtooth, outputs PWM
- **Driver stage:** Buffers PWM signal to drive power MOSFET(s)
- **Power switch:** Internal MOSFET (Darlington configuration for high current)
- **Protection circuits:** Thermal shutdown, current limiting, undervoltage lockout

#### PWM Generation Technique:

- Sawtooth waveform compared to DC error voltage
- When sawtooth < error voltage: PWM output HIGH
- When sawtooth > error voltage: PWM output LOW
- Higher error voltage  $\rightarrow$  wider pulse (higher duty cycle)
- Lower error voltage  $\rightarrow$  narrower pulse (lower duty cycle)
- Automatic duty cycle adjustment based on output feedback

#### Component Value Selection from Datasheet:

Datasheets typically provide:

- Component value tables for common input/output combinations
- Calculation equations for custom designs
- Recommended inductor range: e.g.,  $4.7\ \mu\text{H}$  to  $22\ \mu\text{H}$
- Recommended capacitor values:  $C_{in} = 100\ \mu\text{F}$ ,  $C_{out} = 1000\ \mu\text{F}$  (electrolytic)
- May include ceramic bypass capacitors for high-frequency noise

If values not shown in table, equations provided for calculation based on:

- Input/output voltage ratio
- Maximum output current
- Desired output ripple voltage
- Switching frequency

#### Advantages of Using Buck Converter IC:

- Built-in oscillator eliminates external PWM generation
- Automatic feedback control maintains regulation
- Reduced component count (cost, size, complexity)
- Proven designs with application circuits in datasheet
- Integrated protection features (thermal, overcurrent)
- Small footprint (TO-220 or surface-mount packages)
- Reliable, cheap, easy to use
- Design time reduced significantly

### Practical Example & Numerical

#### LM2596 Buck Converter Design: $12\ \text{V} \rightarrow 5\ \text{V}$ at $2\ \text{A}$

##### Given Specifications:

- Input voltage:  $V_{in} = 12\ \text{V}$  (e.g., car battery)
- Output voltage:  $V_{out} = 5\ \text{V}$
- Output current:  $I_{out} = 2\ \text{A}$  (maximum)
- LM2596 version: Fixed  $5\ \text{V}$  output or adjustable

##### Option 1: Fixed 5V Version

Simplest implementation:

- Use LM2596-5.0 (fixed  $5\ \text{V}$  output version)
- External components from datasheet:
  - $C_{in} = 100\ \mu\text{F}$  /  $25\ \text{V}$  electrolytic (input decoupling)
  - $L_1 = 47\ \mu\text{H}$  /  $3\ \text{A}$  inductor
  - $D_1 = \text{Schottky diode } 3\ \text{A} / 20\ \text{V}$  (e.g., 1N5822)
  - $C_{out} = 1000\ \mu\text{F}$  /  $10\ \text{V}$  electrolytic (output filtering)
- ON/OFF pin: Tie to VIN or ground via switch for enable control
- Total external components: 4 (minimal design)

##### Option 2: Adjustable Version

Using LM2596-ADJ for  $5\ \text{V}$  output:

- Same external LC components as fixed version
- Add feedback resistor divider:
- Reference voltage:  $V_{ref} = 1.23\ \text{V}$
- Choose  $R_2 = 1\ \text{k}\Omega$  (standard value)
- Calculate  $R_1$ :  $R_1 = R_2 \times (V_{out}/V_{ref} - 1) = 1000 \times (5/1.23 - 1) = 3065\ \Omega$
- Use  $R_1 = 3\ \text{k}\Omega$  (standard value, slight output adjustment)
- Actual output:  $V_{out} = 1.23 \times (1 + 3000/1000) = 1.23 \times 4 = 4.92\ \text{V}$  (within tolerance)
- For precise  $5.0\ \text{V}$ : Use potentiometer or precision resistors

##### Power and Efficiency Calculations:

- Output power:  $P_{out} = 5 \times 2 = 10\ \text{W}$
- Assuming efficiency  $\eta = 85\%$ :
- Input power:  $P_{in} = 10/0.85 = 11.76\ \text{W}$
- Input current:  $I_{in} = 11.76/12 = 0.98\ \text{A}$  (average)
- Power dissipated:  $P_{diss} = 11.76 - 10 = 1.76\ \text{W}$
- TO-220 package with heatsink manages  $1.76\ \text{W}$  easily

### Comparison: Linear Regulator for Same Specs

Using 7805 linear regulator:

- Input current:  $I_{in} = I_{out} = 2\text{ A}$
- Input power:  $P_{in} = 12 \times 2 = 24\text{ W}$
- Output power:  $P_{out} = 5 \times 2 = 10\text{ W}$
- Power dissipated:  $P_{diss} = 24 - 10 = 14\text{ W}$  (huge!)
- Efficiency:  $\eta = 10/24 = 41.7\%$
- Thermal management: Requires large heatsink + forced air cooling

### Buck Converter Advantages for This Application:

- Power dissipation: 1.76 W vs 14 W (reduces heat by 87.4%)
- Efficiency: 85% vs 41.7% (doubles efficiency)
- Input current: 0.98 A vs 2 A (halves battery drain)
- Thermal: Small heatsink vs large heatsink + fan
- Battery runtime: Approximately doubled for same capacity

### Output Ripple Voltage:

With  $C_{out} = 1000\text{ }\mu\text{F}$  and  $f = 150\text{ kHz}$ :

Ripple voltage typically  $< 50\text{ mV}$  peak-to-peak ( $\approx 1\%$  of output).

Can be further reduced with larger capacitor or additional ceramic capacitor in parallel.

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- Practical buck converters use integrated ICs (e.g., LM2596) with built-in oscillator, feedback, PWM control
- IC eliminates need for external PWM generator—only passive components (L, C, D) required externally
- Typical IC features: fixed-frequency oscillator (50-500 kHz), internal error amplifier, automatic duty cycle adjustment
- Feedback loop compares output to reference voltage, adjusts duty cycle to maintain constant regulated output
- Single feedback corrects for input voltage changes (line regulation) AND load current changes (load regulation)
- Adjustable output set by resistor divider:  $V_{out} = V_{ref}(1 + R_1/R_2)$
- Schottky diodes preferred: low forward voltage (0.2-0.3 V vs 0.6-0.7 V), fast recovery time
- Lower diode forward drop improves efficiency (less power dissipated in freewheeling path)
- Datasheet provides component values (tables or equations) for inductor, capacitors based on operating conditions
- PWM generated by comparing sawtooth to error voltage: higher error  $\rightarrow$  wider pulse  $\rightarrow$  higher duty cycle
- Integrated protection: thermal shutdown, current limiting, undervoltage lockout
- Buck converter IC advantages: simple design, small footprint, reliable, cost-effective, proven application circuits
- Typical efficiency 85%-90% vastly superior to linear regulator 25%-50% for large voltage drops

# Boost Converter (Step-Up) Working Principle

## TL;DR (The Gist)

The boost converter steps up DC voltage using switched inductor energy storage. During ON phase, inductor stores energy from input. During OFF phase, inductor's collapsing magnetic field produces back-EMF that adds to input voltage, creating higher output. Output voltage determined by duty cycle:  $V_{out} = V_{in}/(1 - D)$ . Critical: as voltage increases, current decreases proportionally (power conservation). Essential for applications requiring higher voltage than available source (LED drivers, battery life extension, electric vehicle power systems).

## Detailed Explanation

### 2. Detailed Explanation

#### Applications Requiring Voltage Boost:

##### 1. Electric Vehicle Motor Drives:

- Motors require  $\sim 500$  V for efficient operation
- Battery packs alone insufficient (weight/space constraints)
- Boost converter steps battery voltage up to motor requirements
- Fewer batteries + voltage boosting = practical solution

##### 2. Battery Life Extension:

- Battery voltage decreases as charge depletes
- At some point, voltage too low to power circuit directly
- Boost converter boosts low battery voltage back to useful level
- Extends battery life significantly
- Example: 2.5 V depleted battery boosted to 3.3 V for microcontroller

##### 3. LED Drivers:

- LEDs require specific forward voltage (often  $>$  battery voltage)
- Boost converter extracts maximum power from lithium cell
- Steps up 3.7 V battery to 12 V for LED strings

##### 4. DC Input Sources:

- Rectified AC mains
- Solar panels (varying output voltage)
- Fuel cells
- Dynamos and DC generators
- All benefit from voltage boost capability

#### Boost Converter vs Buck Converter:

##### Similarity:

- Same core components: inductor, diode, capacitor, switching transistor (MOSFET)
- Positions rearranged for opposite function

##### Difference:

- Buck: Output voltage  $\leq$  input voltage (step-down)
- Boost: Output voltage  $\geq$  input voltage (step-up)

#### Power Conservation Principle:

Critical concept: Power in = Power out (ideal case)

$$P_{in} = P_{out} \Rightarrow V_{in} \times I_{in} = V_{out} \times I_{out}$$

If boost converter increases voltage, current MUST decrease:

$$I_{out} = \frac{V_{in}}{V_{out}} \times I_{in}$$

Example: 100% efficient boost converter

- Input:  $V_{in} = 5$  V,  $I_{in} = 2$  A  $\rightarrow P_{in} = 10$  W
- Output:  $V_{out} = 10$  V
- Output current:  $I_{out} = P_{in}/V_{out} = 10/10 = 1$  A
- Voltage doubled, current halved, power conserved

Cannot get something for nothing—higher voltage means lower current capability.

#### Boost Converter Operating Principle:

##### Component Arrangement:

- Inductor between input and switch node
- MOSFET switch from switch node to ground
- Diode from switch node to output
- Capacitor across output (filter)
- Load across capacitor

**Phase 1: MOSFET ON (Inductor Charging):**

1. MOSFET conducts, connecting right side of inductor to ground
2. Short circuit path: Input positive  $\rightarrow$  Inductor  $\rightarrow$  MOSFET  $\rightarrow$  Ground  $\rightarrow$  Input negative
3. Current flows through inductor, storing energy in magnetic field
4. Energy storage:  $E_L = \frac{1}{2}LI^2$  increases as current ramps up
5. Inductor voltage:  $V_L = V_{in}$  (positive terminal at input side)
6. Virtually no current flows to output (rest of circuit has much higher impedance than MOSFET path)
7. Diode reverse-biased (capacitor voltage higher than switch node voltage)
8. Load powered by output capacitor discharging

**Phase 2: MOSFET OFF (Energy Release):**

1. MOSFET rapidly turns OFF, breaking ground connection
2. Inductor current cannot change suddenly ( $V_L = L dI/dt$ )
3. Inductor generates back-EMF to maintain current flow
4. Back-EMF polarity reverses: now positive on right side, negative on left side
5. Voltages add in series:  $V_{total} = V_{in} + V_{back-EMF}$
6. This higher voltage forward-biases diode (now switch node voltage  $>$  capacitor voltage)
7. Current path: Input  $\rightarrow$  Inductor  $\rightarrow$  Diode  $\rightarrow$  Capacitor/Load  $\rightarrow$  Ground  $\rightarrow$  Input
8. Capacitor charges to  $V_{in} + V_{back-EMF}$  (minus diode drop)
9. Stored inductor energy transfers to output

**Phase 3: MOSFET ON Again (Cycle Repeats):**

1. MOSFET conducts again, output isolated from input
2. Diode turns OFF (reverse-biased)
3. Load continues drawing current from charged capacitor
4. Capacitor discharges slightly during this period
5. Inductor recharges for next cycle
6. Capacitor recharged each time MOSFET turns OFF
7. Almost steady output voltage maintained across load

Continuous switching (thousands of times per second) maintains steady boosted output voltage.

**Output Voltage Equation:**

Theoretical output voltage:

$$V_{out} = \frac{V_{in}}{1 - D}$$

where  $D$  is duty cycle ( $0 < D < 1$ ).

**Example Calculations:**

Input voltage  $V_{in} = 9\text{ V}$ , switching period  $T = 10\text{ }\mu\text{s}$ :

**Case 1:**  $D = 0.5$  (ON time =  $5\text{ }\mu\text{s}$ )

$$V_{out} = \frac{9}{1 - 0.5} = \frac{9}{0.5} = 18\text{ V}$$

**Case 2:**  $D = 0.75$  (ON time =  $7.5\text{ }\mu\text{s}$ )

$$V_{out} = \frac{9}{1 - 0.75} = \frac{9}{0.25} = 36\text{ V}$$

**Case 3:**  $D = 0.99$  (ON time =  $9.9\text{ }\mu\text{s}$ )

$$V_{out} = \frac{9}{1 - 0.99} = \frac{9}{0.01} = 900\text{ V}$$

**Critical Observation:**

As duty cycle approaches 1 (100%), output voltage approaches infinity! In practice:

- Component ratings limit maximum voltage
- Circuit would fail before reaching theoretical voltage
- Serious damage, smoke, component destruction
- Duty cycle kept well below dangerous levels
- Typically  $D < 0.8$  for safety and stability

### Duty Cycle Control Critical:

Boost converter output voltage highly sensitive to duty cycle changes near high values. Small duty cycle error can cause huge voltage overshoot. Precise control essential for:

- Safety (prevent component damage)
- Regulation (maintain stable output)
- Efficiency (optimize operating point)

Unless specifically designed for very high voltages, duty cycle changes kept moderate.

### Energy Transfer Mechanism:

#### ON period:

- Input supplies energy
- Energy stored in inductor magnetic field
- No energy delivered to output (diode blocks)
- Capacitor sustains load

#### OFF period:

- Inductor releases stored energy
- Back-EMF adds to input voltage
- Combined voltage charges output capacitor
- Energy transferred to load

Net effect: Input energy stored then released at higher voltage, achieving voltage boost.

## Practical Example & Numerical

### Boost Converter Design Example:

Design boost converter to power 12 V LED strip from 5 V USB power source. LED strip draws 200 mA at 12 V.

#### Required Duty Cycle:

From output voltage equation:

$$V_{out} = \frac{V_{in}}{1-D} \Rightarrow D = 1 - \frac{V_{in}}{V_{out}}$$

$$D = 1 - \frac{5}{12} = 1 - 0.417 = 0.583 = 58.3\%$$

#### Switching Timing:

Choose switching frequency  $f = 200 \text{ kHz}$ :

- Period:  $T = 1/f = 5 \mu\text{s}$
- ON time:  $t_{on} = D \times T = 0.583 \times 5 = 2.915 \mu\text{s}$
- OFF time:  $t_{off} = T - t_{on} = 5 - 2.915 = 2.085 \mu\text{s}$

#### Power and Current Calculations:

- Output power:  $P_{out} = V_{out} \times I_{out} = 12 \times 0.2 = 2.4 \text{ W}$
- Assuming efficiency  $\eta = 88\%$ :
- Input power:  $P_{in} = P_{out}/\eta = 2.4/0.88 = 2.727 \text{ W}$
- Input current:  $I_{in} = P_{in}/V_{in} = 2.727/5 = 0.545 \text{ A}$

#### Verification of Power Conservation:

Ideal case (100% efficiency):

$$I_{in,ideal} = \frac{V_{out} \times I_{out}}{V_{in}} = \frac{12 \times 0.2}{5} = 0.48 \text{ A}$$

Actual input current higher due to losses: 0.545 A vs 0.48 A.

#### USB Power Limitation:

- USB 2.0 provides max 500 mA at 5 V
- Required input current: 545 mA (exceeds USB 2.0 limit)
- Solutions:
  - Use USB 3.0 (900 mA capability)
  - Use dedicated USB charger (1-2 A capability)
  - Reduce LED strip current
  - Use higher input voltage source

#### Duty Cycle Sensitivity Example:

What happens if duty cycle has 5% error?

**Correct:**  $D = 0.583$

$$V_{out} = \frac{5}{1 - 0.583} = \frac{5}{0.417} = 12.0 \text{ V} \quad \checkmark$$

**Error:**  $D = 0.633$  (increased by 0.05)

$$V_{out} = \frac{5}{1 - 0.633} = \frac{5}{0.367} = 13.6 \text{ V} \quad (13\% \text{ overvoltage!})$$

**Error:**  $D = 0.683$  (increased by 0.1)

$$V_{out} = \frac{5}{1 - 0.683} = \frac{5}{0.317} = 15.8 \text{ V} \quad (32\% \text{ overvoltage!})$$

Small duty cycle errors cause large output voltage errors, especially at higher duty cycles. Precise feedback control essential.

**Component Stress:**

- MOSFET voltage stress: Must withstand  $V_{out} = 12 \text{ V}$  (choose  $\geq 20 \text{ V}$  rating)
- Diode voltage stress: Must block  $V_{out} = 12 \text{ V}$  reverse voltage
- Inductor current: Peak current higher than input average (current ripple)
- Capacitor voltage: Must be rated  $\geq V_{out}$  with margin

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- Boost converter steps UP voltage:  $V_{out} > V_{in}$  (opposite of buck converter)
- Applications: LED drivers, battery life extension, electric vehicle motors, low-voltage source boosting
- Same components as buck (L, D, C, MOSFET) but rearranged positions
- Power conservation:  $V_{in} \times I_{in} = V_{out} \times I_{out} \rightarrow$  if voltage increases, current decreases
- Two-phase operation: ON (inductor stores energy from input), OFF (inductor releases energy via back-EMF adding to input)
- Output voltage equation:  $V_{out} = V_{in}/(1 - D)$  where  $D$  is duty cycle
- As  $D \rightarrow 1$ ,  $V_{out} \rightarrow \infty$  (theoretical)—practical circuits limit duty cycle for safety/stability
- During ON: inductor charges, diode blocks, output isolated, capacitor powers load
- During OFF: inductor back-EMF adds to input voltage, diode conducts, capacitor charges to boosted voltage
- Output voltage highly sensitive to duty cycle at high  $D$  values—precise control critical
- Typical maximum duty cycle:  $D < 0.8$  to prevent instability and excessive voltage
- Duty cycle small error causes large output voltage error (especially near  $D = 1$ )
- Efficiency typically 85%-92% depending on components and operating conditions

# Boost Converter IC Implementation and Linear vs Switching Efficiency

## TL;DR (The Gist)

Boost converter ICs (e.g., MT3608) integrate oscillator, error amplifier, PWM comparator, and feedback control, simplifying design to external L, C, D components. Internal reference voltage (0.6 V typical) compared to divided output voltage controls duty cycle automatically. Schottky diodes essential for efficiency (low forward drop 0.2 V, fast recovery). Switching regulators achieve 85-95% efficiency vs linear regulators 25-50% because transistor operates fully ON (low loss) or fully OFF (zero current), not in linear region dissipating power continuously.

## Detailed Explanation

### 2. Detailed Explanation

#### Boost Converter IC Example: MT3608

##### Key Specifications:

- Built-in oscillator: 1.2 MHz switching frequency
- Output current: up to 2 A continuous
- Input voltage range: 2 V to 24 V
- Output voltage: up to 28 V (adjustable)
- Integrated compensation and protection
- Small package (SOT-23 or similar)

##### Pin Configuration:

- **SW:** Switch pin (internal MOSFET drain connection)
- **GND:** Ground reference
- **FB:** Feedback pin (voltage sensing for regulation)
- **EN:** Enable pin (turn IC on/off)
- **VIN:** Input voltage pin

##### Typical Application Circuit:

Minimal external components:

- $L_1$ : Inductor (4.7 to 22  $\mu$ H recommended, higher current rating than output)
- $D_1$ : Schottky diode (fast recovery, low  $V_f$ )
- $C_{in}$ : Input capacitor (22  $\mu$ F ceramic recommended)
- $C_{out}$ : Output capacitor (22  $\mu$ F ceramic)
- $R_1, R_2$ : Feedback voltage divider (sets output voltage)

No external oscillator—built into IC!

##### Output Voltage Adjustment:

Internal reference voltage  $V_{ref} = 0.6$  V. Output voltage determined by resistor divider:

$$V_{out} = V_{ref} \times \left(1 + \frac{R_1}{R_2}\right) = 0.6 \times \left(1 + \frac{R_1}{R_2}\right)$$

Example: For  $V_{out} = 12$  V:

$$\frac{R_1}{R_2} = \frac{V_{out}}{V_{ref}} - 1 = \frac{12}{0.6} - 1 = 20 - 1 = 19$$

Choose  $R_2 = 10$  k $\Omega$ , then  $R_1 = 190$  k $\Omega$ .

##### Feedback Control Operation:

##### Internal Block Diagram:

- **Oscillator:** Generates 1.2 MHz clock
- **Sawtooth generator:** Creates ramp waveform
- **Error amplifier:** Compares FB voltage to 0.6 V reference
- **PWM comparator:** Compares error output to sawtooth, generates PWM
- **Driver:** Buffers PWM to drive internal MOSFET switch

##### Regulation Process:

1. Output voltage divided by  $R_1, R_2$  produces FB voltage
2. Error amplifier compares FB voltage to 0.6 V reference
3. If  $V_{FB} > 0.6$  V: Output too high  $\rightarrow$  Error amplifier decreases PWM duty cycle
4. If  $V_{FB} < 0.6$  V: Output too low  $\rightarrow$  Error amplifier increases PWM duty cycle
5. PWM duty cycle automatically adjusted to maintain  $V_{FB} = 0.6$  V

6. When  $V_{FB} = 0.6\text{ V}$ , output voltage equals desired set point

### Schottky Diode Selection:

#### Recommended Values for MT3608:

- Inductor:  $4.7$  to  $22\text{ }\mu\text{H}$  (higher inductance  $\rightarrow$  lower ripple current)
- Input capacitor:  $22\text{ }\mu\text{F}$  ceramic (X5R or X7R dielectric)
- Output capacitor:  $22\text{ }\mu\text{F}$  ceramic (low ESR for ripple reduction)

#### Schottky Diode Critical:

- Forward voltage:  $V_f = 0.2\text{ V}$  typical (vs  $0.6\text{--}0.7\text{ V}$  standard diode)
- Lower forward drop = less power loss during OFF phase
- Fast recovery time ( $< 10\text{ ns}$ ) essential for  $1.2\text{ MHz}$  switching
- Slow recovery causes reverse current spike, efficiency loss
- Voltage rating: Must exceed  $V_{out}$
- Current rating: Must exceed peak inductor current

### Linear vs Switching Regulator Efficiency Analysis:

Example:  $24\text{ V} \rightarrow 6\text{ V}$  at  $1\text{ A}$  Load

#### Linear Regulator Operation:

##### Circuit Components:

- Pass transistor (Q1) in series between input and output
- Op-amp with negative feedback controls Q1
- Zener diode provides reference voltage
- Voltage divider senses output

##### Voltage Control Mechanism:

Transistor voltage drop:  $V_{Q1} = V_{in} - V_{out} = 24 - 6 = 18\text{ V}$

Op-amp adjusts Q1 base drive to regulate output:

- If  $V_{out} > V_{ref}$ : Drive Q1 less  $\rightarrow V_{Q1}$  increases  $\rightarrow V_{out}$  decreases
- If  $V_{out} < V_{ref}$ : Drive Q1 more  $\rightarrow V_{Q1}$  decreases  $\rightarrow V_{out}$  increases

##### Current Path:

Input current = Output current (op-amp draws negligible current):

$$I_{in} = I_{out} = 1\text{ A}$$

##### Power Calculations:

- Input power:  $P_{in} = V_{in} \times I_{in} = 24 \times 1 = 24\text{ W}$
- Output power:  $P_{out} = V_{out} \times I_{out} = 6 \times 1 = 6\text{ W}$
- Power dissipated:  $P_{diss} = P_{in} - P_{out} = 24 - 6 = 18\text{ W}$
- Efficiency:  $\eta = P_{out}/P_{in} = 6/24 = 25\%$  (pathetic!)

##### Simplified Efficiency Formula:

For linear regulator:

$$\eta_{linear} = \frac{V_{out}}{V_{in}}$$

Greater input-output voltage difference  $\rightarrow$  lower efficiency  $\rightarrow$  more power dissipated.

##### Thermal Issues:

Transistor dissipates  $18\text{ W}$  with typical thermal resistance  $\theta_{JA} = 20^\circ\text{C/W}$  (TO-220 no heatsink):

Temperature rise:  $\Delta T = P_{diss} \times \theta_{JA} = 18 \times 20 = 360^\circ\text{C}$  above ambient!

This would destroy transistor immediately. Requires:

- Large heatsink (reduces  $\theta_{JA}$  to  $\sim 5^\circ\text{C/W}$ )
- Forced air cooling (fan)
- Adds size, cost, complexity
- Negates linear regulator benefits (simplicity, low cost)

### Buck Regulator (Switching) Operation:

##### Circuit Differences:

- Diode and LC filter on output
- Transistor switches fully ON or fully OFF (not linear region)
- High-frequency switching creates square wave at switch node
- LC filter extracts DC average value

##### Transistor Control:

Transistor driven to two extreme states:

1. **Fully ON:** Short circuit (ideally  $V_{CE} = 0\text{ V}$  or  $R_{DS(on)}$  very low)
2. **Fully OFF:** Open circuit (ideally  $I_C = 0\text{ A}$ )

Never operates in linear region between ON and OFF.

##### PWM Voltage Control:

Square wave at switch node, amplitude =  $V_{in}$ .  
Average voltage controlled by duty ratio  $D$ :

$$V_{avg} = D \times V_{in}$$

For  $V_{out} = 6\text{ V}$  from  $V_{in} = 24\text{ V}$ :

$$D = \frac{V_{out}}{V_{in}} = \frac{6}{24} = 0.25 = 25\%$$

LC low-pass filter allows only DC average through to output.

#### Power Loss Analysis:

##### ON State (Transistor Conducting):

- Transistor voltage drop:  $V_{CE} \approx 0\text{ V}$  (or  $V = I \times R_{DS(on)}$  for MOSFET)
- Current flows from input to output through transistor
- Power dissipated in transistor:  $P_{on} = V_{CE} \times I \approx 0\text{ W}$  (ideal)
- Other components (L, C, D) ideally lossless

##### OFF State (Transistor Open):

- Transistor voltage:  $V_{CE} = V_{in} = 24\text{ V}$
- Transistor current:  $I_C = 0\text{ A}$  (open circuit)
- Power dissipated in transistor:  $P_{off} = V \times 0 = 0\text{ W}$

In both states, ideally zero power dissipated in transistor!

#### Switching Regulator Efficiency:

##### Average Input Power:

During ON time, input power =  $V_{in} \times I_{out}$ .

During OFF time, no current from input, input power =  $0\text{ W}$ .

Average input power over switching cycle:

$$P_{in,avg} = (V_{in} \times I_{out}) \times D$$

For buck converter,  $D = V_{out}/V_{in}$ :

$$P_{in,avg} = (V_{in} \times I_{out}) \times \frac{V_{out}}{V_{in}} = V_{out} \times I_{out} = P_{out}$$

Theoretical efficiency = 100%!

#### Real-World Losses:

- MOSFET  $R_{DS(on)}$  causes  $I^2R$  losses during conduction
- MOSFET switching transitions (ON $\leftrightarrow$ OFF) dissipate energy
- Diode forward voltage drop ( $V_f$ ) during conduction
- Inductor DC resistance (DCR) causes  $I^2R$  losses
- Capacitor ESR (Equivalent Series Resistance)
- Core losses in inductor (hysteresis, eddy currents)

Despite real losses, typical switching regulator efficiency: 85%-95% (vastly better than linear).

#### Efficiency Comparison Summary:

- **Linear regulator:** Efficiency =  $V_{out}/V_{in}$  (component-independent)
- Maximum efficiency when  $V_{out} \approx V_{in}$  (small dropout)
- Large voltage drop  $\rightarrow$  poor efficiency
- **Switching regulator:** Efficiency depends on components and operating conditions
- Theoretical maximum = 100% (practical 85%-95%)
- Efficiency relatively independent of input-output voltage ratio

#### Practical Implications:

For example application ( $24\text{ V} \rightarrow 6\text{ V}$  at  $1\text{ A}$ ):

##### Linear Regulator:

- Requires large heatsink + forced air cooling
- Heatsink bulky, expensive
- Fan adds noise, power consumption, failure point
- System size/cost/complexity increase
- Negates linear regulator advantages

##### Switching Regulator:

- Dissipates  $< 1\text{ W}$  (assuming 90% efficiency)
- Small heatsink or no heatsink required
- No forced air needed
- Compact, efficient, cost-effective solution

- Upfront complexity offset by system benefits

Side-by-side thermal comparison shows switching regulator allows same operating temperature range as linear regulator (with massive heatsink) using off-the-shelf components without special cooling.

## Practical Example & Numerical

### Boost Converter IC Design: 5 V → 14 V

Using MT3608 to boost 5 V input to 14 V output.

#### Feedback Resistor Calculation:

Reference voltage:  $V_{ref} = 0.6 \text{ V}$

$$\frac{R_1}{R_2} = \frac{V_{out}}{V_{ref}} - 1 = \frac{14}{0.6} - 1 = 23.33 - 1 = 22.33$$

Choose  $R_2 = 10 \text{ k}\Omega$ :

$$R_1 = 22.33 \times 10 \text{ k} = 223.3 \text{ k}\Omega$$

Use standard value  $R_1 = 220 \text{ k}\Omega$ :

$$V_{out} = 0.6 \times \left(1 + \frac{220}{10}\right) = 0.6 \times 23 = 13.8 \text{ V}$$

Close enough (within 1.4%). For precise 14 V, use trimmer or precision resistors.

#### Component Selection:

- Inductor:  $L_1 = 22 \mu\text{H}$ , current rating  $> 2 \text{ A}$
- Diode: Schottky,  $V_R > 14 \text{ V}$ ,  $I_F > 2 \text{ A}$  (e.g., SS24 or equivalent)
- Input cap:  $C_{in} = 22 \mu\text{F}$  ceramic /10 V
- Output cap:  $C_{out} = 22 \mu\text{F}$  ceramic /25 V

#### Efficiency Comparison: Linear vs Switching for 12 V → 5 V, 2 A

##### Linear Regulator (7805 at 2 A):

- $P_{in} = 12 \times 2 = 24 \text{ W}$
- $P_{out} = 5 \times 2 = 10 \text{ W}$
- $P_{diss} = 24 - 10 = 14 \text{ W}$
- $\eta = 10/24 = 41.7\%$
- Temperature rise (TO-220,  $\theta_{JA} = 20^\circ\text{C/W}$ ):  $\Delta T = 14 \times 20 = 280^\circ\text{C}$
- Requires large heatsink reducing  $\theta_{JA}$  to  $\sim 3^\circ\text{C/W}$ :  $\Delta T = 14 \times 3 = 42^\circ\text{C}$  (acceptable with fan)

##### Buck Switching Regulator (e.g., LM2596 at 2 A):

- $P_{out} = 10 \text{ W}$
- Efficiency  $\eta = 90\%$
- $P_{in} = 10/0.9 = 11.11 \text{ W}$
- $P_{diss} = 11.11 - 10 = 1.11 \text{ W}$
- Temperature rise (TO-220,  $\theta_{JA} = 50^\circ\text{C/W}$  with small heatsink):  $\Delta T = 1.11 \times 50 = 55.5^\circ\text{C}$
- Acceptable without forced air!

#### Comparison Summary:

- Power dissipation: 14 W vs 1.11 W (buck dissipates 92% less!)
- Efficiency: 41.7% vs 90% (buck 2.16× more efficient)
- Input current: 2 A vs 0.926 A (buck saves 53.7% input current)
- Thermal management: Large heatsink + fan vs small heatsink, no fan
- Cost: Higher (cooling) vs lower (fewer thermal components)
- Size: Bulky (heatsink) vs compact
- Reliability: Fan is failure point vs solid-state only

For battery-powered applications, buck regulator approximately doubles battery runtime compared to linear regulator!

## Key Points (Interview Focus)

### 4. Key Points (Interview Focus)

- Boost converter ICs (e.g., MT3608) integrate oscillator, error amplifier, PWM control—only external L, C, D required

- Output voltage set by resistor divider:  $V_{out} = V_{ref}(1 + R_1/R_2)$  where  $V_{ref} \approx 0.6\text{ V}$  typical
- Feedback loop compares divided output to reference, automatically adjusts duty cycle for regulation
- Schottky diodes essential: low  $V_f$  (0.2 V vs 0.6 V), fast recovery ( $< 10\text{ ns}$ ), improve efficiency
- Component values (L, C) specified in datasheet based on operating conditions
- **Linear regulator efficiency:**  $\eta = V_{out}/V_{in}$  (independent of components), poor for large voltage drops
- **Switching regulator efficiency:** Theoretical 100%, practical 85-95% (depends on components)
- Linear regulator: transistor operates in linear region, dissipates  $(V_{in} - V_{out}) \times I_{out}$  continuously
- Switching regulator: transistor fully ON ( $P \approx 0$ ) or fully OFF ( $P = 0$ ), minimal dissipation
- Linear:  $I_{in} = I_{out}$  always; Switching:  $I_{in} < I_{out}$  (buck) or  $I_{in} > I_{out}$  (boost) on average
- Large voltage drop applications: linear requires massive heatsink + cooling, switching needs minimal/no heatsink
- Switching regulator upfront complexity (more components, design) offset by system benefits (efficiency, size, thermal)
- Battery applications: switching regulator can double runtime compared to linear for same load

