Laboratory Training Manual for IYPT

Electronics Fundamentals, Circuits, and Practical Skills

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Contents

1 Introduction to Laboratory Safety

1.1 General Safety Rules

Laboratory work requires strict adherence to safety protocols:

Critical Safety Rules

- Always wear safety glasses when soldering
- Ensure proper ventilation when soldering (solder fumes are hazardous)
- Keep your work area clean and organized
- Never touch live circuits with bare hands
- Double-check power supply settings before connecting to circuits
- Use ESD (Electrostatic Discharge) protection when handling sensitive components
- Keep food and drinks away from the work area
- Know the location of fire extinguishers and first aid kits

1.2 Electrical Hazards

- **Voltage levels**: While IYPT experiments typically use low voltages (5-24V), treat all circuits with respect
- **Current**: Even low voltages can be dangerous if high currents are involved
- **Capacitors**: Large capacitors can store charge; always discharge them before handling
- **Heat**: Soldering irons reach 300-400°C; never leave them unattended when powered

2 Basic Electronic Components

2.1 Resistors

Resistors limit current flow and divide voltages. They follow Ohm's Law:

$$V = IR \tag{1}$$

where V is voltage (Volts), I is current (Amperes), and R is resistance (Ohms, Ω).

2.1.1 Color Code

Resistors use color bands to indicate their value:

Example: Yellow-Violet-Red-Gold = 47×10^2 Ω $\pm 5\%$ = 4.7 kΩ $\pm 5\%$

Color	Digit	Multiplier	Tolerance
Black	0	10^0	-
Brown	1	10^1	$\pm1\%$
Red	2	10^2	$\pm2\%$
Orange	3	10^3	-
Yellow	4	10^4	-
Green	5	10^5	$\pm0.5\%$
Blue	6	10^6	$\pm0.25\%$
Violet	7	10^7	$\pm0.1\%$
Gray	8	10^8	-
White	9	10^9	-
Gold	-	10^{-1}	$\pm5\%$
Silver	-	10^{-2}	$\pm10\%$

Table 1: Resistor Color Code

2.1.2 Power Rating

Resistors dissipate power as heat:

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

Common power ratings: 1/8W, 1/4W, 1/2W, 1W, 2W

2.2 Capacitors

Capacitors store electrical charge. Capacitance is measured in Farads (F):

$$Q = CV \tag{3}$$

where Q is charge (Coulombs), C is capacitance, and V is voltage.

2.2.1 Types of Capacitors

- **Ceramic**: Small, non-polarized, values from pF to μF
- **Electrolytic**: Polarized, large values (μF to mF), must observe polarity
- **Tantalum**: Polarized, compact, stable
- **Film**: Non-polarized, stable, good for precision applications

Warning: Electrolytic capacitors will explode if connected with reversed polarity!

2.3 Inductors

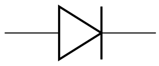
Inductors store energy in magnetic fields. Inductance is measured in Henries (H).

$$V = L\frac{dI}{dt} \tag{4}$$

Common in filters and power supplies. Less common in IYPT experiments but important to recognize.

2.4 Diodes

Diodes allow current flow in one direction only.



⟶ Current flows this way

Key parameters:

- Forward voltage drop: ∼0.7V for silicon, ∼0.3V for Schottky
- Reverse breakdown voltage
- Maximum forward current

Types:

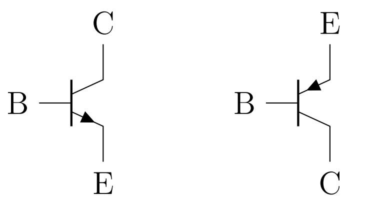
- **Rectifier diodes**: Convert AC to DC
- **Zener diodes**: Voltage regulation
- **LEDs**: Light emission (forward voltage 1.8-3.3V depending on color)
- **Photodiodes**: Light detection (used in photometry!)

2.5 Transistors

Transistors act as switches or amplifiers.

2.5.1 Bipolar Junction Transistors (BJT)

Two types: NPN and PNP



NPN PNP

Basic operation: Small base current controls large collector current

$$I_C = \beta I_B \tag{5}$$

where β (current gain) is typically 50-300.

2.5.2 MOSFETs

Voltage-controlled devices: gate voltage controls drain-source current. Advantages: high input impedance, low power consumption, fast switching.

2.6 Integrated Circuits (ICs)

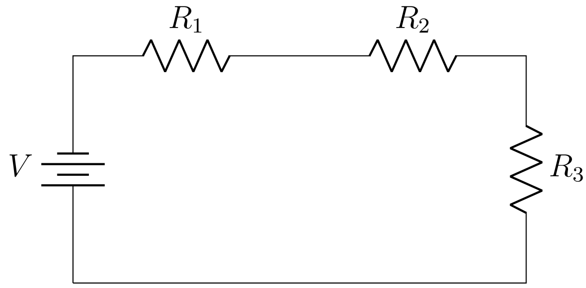
- **Operational Amplifiers (Op-Amps)**: Versatile analog building blocks (e.g., LM358, TL072)
- **Voltage Regulators**: Provide stable voltage (e.g., 7805 for 5V, LM317 adjustable)
- **Timers**: 555 timer for oscillators and timing circuits
- **Logic Gates**: Digital circuits (74xx series)
- **Microcontrollers**: Arduino, STM32, etc.

3 Circuit Fundamentals

3.1 Series and Parallel Circuits

3.1.1 Series Resistors

$$R_{total} = R_1 + R_2 + R_3 + \dots \tag{6}$$



Same current flows through all components: $I = I_1 = I_2 = I_3$

3.1.2 Parallel Resistors

$$\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \dots \tag{7}$$

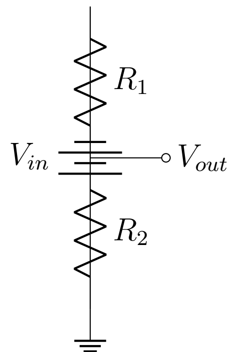
For two resistors:

$$R_{total} = \frac{R_1 R_2}{R_1 + R_2} \tag{8}$$

Same voltage across all components: $V = V_1 = V_2 = V_3$

3.2 Voltage Divider

Essential circuit for sensor interfaces:



$$V_{out} = V_{in} \frac{R_2}{R_1 + R_2} \tag{9}$$

3.3 Kirchhoff's Laws

3.3.1 Kirchhoff's Current Law (KCL)

Sum of currents entering a node equals sum of currents leaving:

$$\sum I_{in} = \sum I_{out} \tag{10}$$

3.3.2 Kirchhoff's Voltage Law (KVL)

Sum of voltages around any closed loop equals zero:

$$\sum V = 0 \tag{11}$$

3.4 Thévenin and Norton Equivalents

Any linear circuit can be represented as:

- **Thévenin**: Voltage source V_{th} in series with resistance R_{th}
- **Norton**: Current source I_N in parallel with resistance R_N

Relationship: $V_{th} = I_N R_N$ and $R_{th} = R_N$

4 DC Power Supplies

4.1 Types of Power Supplies

4.1.1 Linear Power Supplies

- Transform AC mains to lower AC voltage
- Rectify to DC
- Filter with capacitors
- Regulate with linear regulator
- **Pros**: Clean output, low noise
- **Cons**: Inefficient, heavy, generate heat

4.1.2 Switching Power Supplies

- High-frequency switching for voltage conversion
- **Pros**: Efficient (80-95%), lightweight, compact
- **Cons**: Switching noise, more complex

4.2 Using a Bench Power Supply

4.2.1 Front Panel Controls

Typical bench power supply features:

1. **Voltage adjust**: Sets output voltage
2. **Current limit**: Sets maximum current (overcurrent protection)
3. **Display**: Shows voltage and current
4. **Output enable**: Turns output on/off
5. **Terminals**: Positive (red), Negative (black), Ground (green)

4.2.2 Operating Modes

Constant Voltage (CV) Mode:

- Power supply maintains set voltage
- Current varies based on load
- LED indicator typically shows "CV"
- Used for most circuit testing

Constant Current (CC) Mode:

- Power supply maintains set current
- Voltage varies based on load
- LED indicator shows "CC"
- Activates when current limit is reached
- Useful for LED testing, battery charging

4.2.3 Setup Procedure

Power Supply Setup Checklist

1. Ensure output is OFF
2. Set voltage to desired level
3. Set current limit (typically 0.1-1A for testing)
4. Double-check polarity of connections
5. Connect circuit with output OFF
6. Verify connections
7. Turn output ON
8. Monitor voltage and current readings
9. If CC mode activates unexpectedly, TURN OFF immediately (likely short circuit)

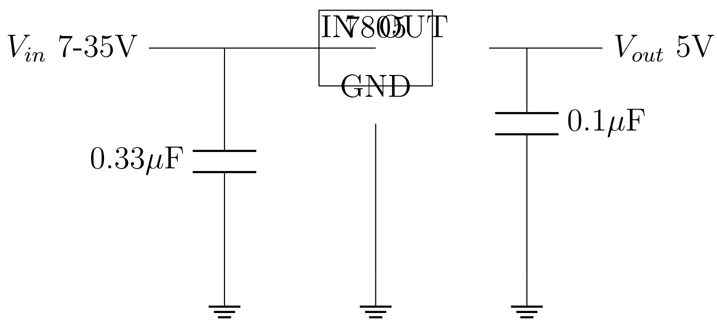
4.3 Common Voltage Levels

- **3.3V**: Modern microcontrollers, sensors
- **5V**: Arduino, USB, TTL logic, many sensors
- **9V**: Op-amp circuits, analog circuits
- **12V**: Motors, automotive applications
- **±15V**: Bipolar op-amp circuits

4.4 Voltage Regulation

4.4.1 Linear Regulators

Example: 7805 (5V output)



Requirements:

- Input voltage must be at least 2V higher than output (dropout voltage)

- Input capacitor for stability
- Output capacitor for filtering
- Heat sink if current > 500mA

4.4.2 Low Dropout (LDO) Regulators

Examples: LM1117, AMS1117

- Dropout voltage < 1V
- Better for battery applications
- More efficient than standard linear regulators

5 Multimeter Usage

5.1 Multimeter Functions

5.1.1 Voltage Measurement (V)

DC Voltage (DCV):

- Select DC voltage range (auto-ranging recommended)
- Connect probes in parallel with component
- Red probe to higher potential, black to lower
- Read display

AC Voltage (ACV):

- Select AC voltage mode
- Measures RMS (root mean square) value
- Used for mains voltage (CAUTION!)

5.1.2 Current Measurement (A)

Warning

Current measurement requires breaking the circuit. Never measure current in parallel!

Procedure:

1. Turn off power
2. Move red probe to current input (mA or 10A depending on expected current)
3. Select current range

4. Break circuit and insert meter in series
5. Turn on power and read current
6. For high currents (> 200mA), use 10A input (usually unfused!)

5.1.3 Resistance Measurement (Ω)

- Turn off power to circuit
- Select resistance range
- Touch probes to resistor leads
- For in-circuit measurements, other components may affect reading
- For best accuracy, remove component from circuit

5.1.4 Continuity Test

- Selects continuity mode (beeper symbol)
- Beeps if resistance $< \sim 50\Omega$
- Essential for checking:
  - Wire connections
  - PCB traces
  - Solder joints
  - Fuses
  - Switch contacts

5.1.5 Diode Test

- Diode symbol mode
- Measures forward voltage drop
- Good silicon diode: 0.5-0.8V one direction, OL (open) reverse
- LED: 1.8-3.3V forward, OL reverse
- Short circuit: $\sim$0V both directions
- Open circuit: OL both directions

5.2 Measurement Best Practices

- Always start with highest range if unsure
- Check probe connections before measuring
- Never exceed voltage/current ratings
- For very high resistance, use a digital meter (not analog)
- Zero ohmmeter before critical measurements
- Keep probes clean
- Check battery regularly

6 Oscilloscope Basics

6.1 Introduction

An oscilloscope displays voltage as a function of time - essential for observing signal waveforms, timing, and dynamic behavior.

6.2 Key Concepts

6.2.1 Vertical System

- **Volts/Division (V/div)**: Vertical scale
- **Position**: Shifts trace up/down
- **Coupling**: AC (blocks DC), DC (shows DC + AC), Ground (0V reference)
- **Bandwidth**: Maximum frequency that can be accurately displayed

6.2.2 Horizontal System

- **Time/Division (s/div)**: Horizontal scale
- **Position**: Shifts trace left/right

6.2.3 Trigger System

Stabilizes repeating waveforms:

- **Edge trigger**: Triggers on rising or falling edge
- **Level**: Voltage level where trigger occurs
- **Source**: Which channel provides trigger signal
- **Mode**: Auto (free-runs if no trigger), Normal (waits for trigger), Single (one shot)

6.3 Making Measurements

6.3.1 Setup

1. Connect probe to CH1 (or CH2)
2. Ensure probe attenuation matches scope setting (usually 10X)
3. Perform probe compensation (adjust trimmer for square wave)
4. Connect ground clip to circuit ground
5. Set appropriate V/div and s/div
6. Adjust trigger level

6.3.2 Common Measurements

- **Amplitude**: Peak-to-peak voltage (V_{pp})

$$V_{pp} = V_{max} - V_{min} \tag{12}$$

- **Period (T)**: Time for one complete cycle
- **Frequency**: $f = 1/T$
- **Duty cycle**: For square waves

$$D = \frac{t_{high}}{T} \times 100\% \tag{13}$$

- **Rise time**: Time from 10% to 90% of amplitude
- **Fall time**: Time from 90% to 10% of amplitude

6.4 Probe Types

- **1X probe**: Direct connection, low impedance, loads circuit
- **10X probe**: 10:1 attenuation, high impedance, preferred for most measurements
- **Current probe**: Measures current via magnetic field
- **Differential probe**: Measures voltage difference without ground reference

7 Breadboard Prototyping

7.1 Breadboard Structure

A breadboard (solderless breadboard) allows temporary circuit assembly:

- **Power rails**: Vertical columns on sides, marked with + and - (red and blue lines)
- **Terminal strips**: Horizontal rows, 5 holes connected internally
- **Center gap**: Separates two sides, designed for IC placement

7.2 Best Practices

1. Use red wire for positive, black for ground, other colors for signals
2. Keep wires short and neat
3. Route power and ground first
4. Place ICs across center gap
5. Use jumper wires, not component leads
6. Draw schematic before building
7. Test power connections before adding components
8. Build in stages, test each stage
9. Avoid crossing wires over ICs
10. Leave space between components for modifications

7.3 Common Breadboard Problems

- **Loose connections**: Press components firmly
- **Wrong holes**: Count carefully, check continuity
- **Bent IC pins**: Straighten before insertion
- **Power rail gaps**: Some breadboards have breaks in power rails
- **Worn contacts**: Replace old breadboards

8 Printed Circuit Boards (PCBs)

8.1 PCB Basics

8.1.1 PCB Structure

- **Substrate**: Insulating material (usually FR-4 fiberglass)
- **Copper layers**: Conductive traces (typically 35μm thick)
- **Soldermask**: Protective coating (usually green)
- **Silkscreen**: Component labels and markings
- **Pads**: Copper areas for component attachment
- **Vias**: Plated holes connecting layers

8.1.2 PCB Types

- **Single-sided**: One copper layer
- **Double-sided**: Copper on both sides
- **Multi-layer**: 4, 6, 8+ layers (internal layers for power/ground planes)

8.2 Through-Hole vs Surface Mount

8.2.1 Through-Hole (THT)

- Component leads go through holes
- Easier to solder by hand
- More mechanically robust
- Larger footprint
- Common for connectors, power components

8.2.2 Surface Mount (SMT)

- Components mount on surface pads
- Smaller size, higher density
- Requires more skill to hand-solder
- Better high-frequency performance
- Standard in modern electronics

8.3 Reading PCB Markings

8.3.1 Reference Designators

- **R**: Resistor (R1, R2, ...)
- **C**: Capacitor (C1, C2, ...)
- **L**: Inductor (L1, L2, ...)
- **D**: Diode (D1, D2, ...)
- **LED**: Light-emitting diode
- **Q**: Transistor (Q1, Q2, ...)
- **U** or **IC**: Integrated circuit (U1, U2, ...)
- **J** or **P**: Connector/Jack (J1, P1, ...)
- **SW**: Switch
- **TP**: Test point

8.3.2 Polarity Markings

- **Diodes/LEDs**: Cathode marked with line or flat edge
- **Electrolytic capacitors**: Negative side marked with stripe or minus signs
- **ICs**: Pin 1 marked with dot, notch, or chamfer

8.4 PCB Assembly

8.4.1 Component Placement Order

1. Inspect PCB for defects
2. Sort components
3. Solder in this order:
   (a) Smallest/flattest first: resistors, diodes, small capacitors
   (b) ICs and sockets
   (c) Larger components: electrolytic capacitors
   (d) Connectors and mechanical parts last
4. Clean flux residue if required
5. Inspect all joints
6. Test continuity of critical connections

8.4.2 Component Orientation

- **Resistors**: No polarity (can be either way)
- **Ceramic capacitors**: No polarity
- **Electrolytic capacitors**: MUST observe polarity
- **Diodes**: Cathode band aligns with PCB marking
- **LEDs**: Long lead = anode (+), short = cathode (-)
- **ICs**: Pin 1 indicator must match PCB marking

9 Soldering Techniques

9.1 Soldering Equipment

9.1.1 Soldering Iron

- **Temperature**: 300-350°C for electronics (too hot damages components!)
- **Tip types**:

  - Conical: General purpose
  - Chisel: Best for through-hole, good heat transfer
  - Bevel: SMD components

- **Features to look for**: Temperature control, grounded tip (ESD protection), comfortable grip

9.1.2 Solder

- **Composition**:
  - Lead-based: 60/40 or 63/37 tin/lead (easier to work with, melts at 183°C)
  - Lead-free: Various alloys (e.g., SAC305: tin/silver/copper), melts at 217°C
- **Core**: Rosin flux core cleans oxidation during soldering
- **Diameter**: 0.5-1.0mm for electronics work

9.1.3 Accessories

- **Soldering stand**: Holds hot iron safely
- **Sponge/brass wool**: Cleans tip
- **Tip tinner**: Maintains tip condition
- **Flux pen**: Additional flux for difficult joints
- **Solder wick**: Desoldering braid
- **Desoldering pump**: Removes solder
- **Helping hands**: Holds work
- **Wire cutters**: Flush cutters for trimming leads
- **Tweezers**: Holding small components
- **Magnifying glass**: Inspecting joints
- **Fume extractor**: Removes harmful fumes

9.2 Soldering Procedure

9.2.1 Through-Hole Soldering

Perfect Through-Hole Joint - Step by Step

1. **Preparation**
   - Heat iron to 350°C
   - Clean tip on sponge/brass wool
   - Tin the tip (coat with fresh solder)
2. **Component insertion**
   - Insert component through holes
   - Bend leads slightly to hold in place
   - Component should sit flush against board
3. **Soldering**
   - Touch iron tip to BOTH pad and lead simultaneously
   - Heat for 1-2 seconds
   - Feed solder to the joint (NOT to the iron tip)
   - Solder should flow and form a cone shape
   - Remove solder, then remove iron (in that order!)
   - Total time: 2-3 seconds
   - Do not move component while cooling (2-3 seconds)
4. **Finishing**
   - Trim excess lead with flush cutters
   - Leave 1-2mm above joint
   - Cut away from face

9.2.2 Good vs Bad Solder Joints

Good joint characteristics:

- Shiny, smooth surface (not dull or grainy)
- Concave fillet shape (volcano or cone)
- Solder wets both pad and lead
- Pad outline visible through solder
- No excess solder (not a ball)

Bad joint types:

- **Cold joint**: Dull, grainy appearance - reheat properly
- **Insufficient solder**: Pad not fully covered - add more solder
- **Excess solder**: Large ball, may bridge to adjacent pads - remove with wick
- **Solder bridge**: Connects adjacent pads - remove with wick
- **Lifted pad**: Pad separated from board - caused by overheating
- **Disturbed joint**: Component moved during cooling - reheat

9.3 Surface Mount Soldering

9.3.1 SMD Component Sizes

Common sizes (imperial code):

- **1206**: 3.2mm × 1.6mm (easiest to hand-solder)
- **0805**: 2.0mm × 1.25mm (moderate difficulty)
- **0603**: 1.6mm × 0.8mm (difficult, requires magnification)
- **0402**: 1.0mm × 0.5mm (very difficult, microscope recommended)

9.3.2 SMD Soldering Techniques

Two-pad components (resistors, capacitors, diodes):

1. Apply flux to pads
2. Tin one pad with small amount of solder
3. Pick up component with tweezers
4. Reheat tinned pad, slide component into position
5. Remove iron, component is tacked in place
6. Solder the other pad normally
7. Reheat first pad, add solder if needed
8. Clean flux residue

Multi-pin ICs (SOIC, TSSOP, QFP):

1. Apply flux to all pads
2. Align IC carefully on pads
3. Tack opposite corner pins to hold in place
4. Check alignment, adjust if needed by reheating
5. Solder all pins (drag soldering technique):

- Add flux liberally
- Touch solder to iron tip
- Drag iron across pins
- Flux prevents bridges

6. Inspect under magnification
7. Fix bridges with solder wick
8. Clean flux

9.4 Desoldering Techniques

9.4.1 Using Solder Wick (Desoldering Braid)

1. Place wick over joint
2. Press hot iron on top of wick
3. Solder wicks into braid by capillary action
4. Move to fresh section of wick
5. Remove wick and iron together
6. Cut off used section

Tips:

- Add flux to wick for better wicking
- Use chisel tip for better contact
- Don't leave iron too long (will damage wick and pad)

9.4.2 Using Desoldering Pump (Solder Sucker)

1. Cock pump spring
2. Heat joint until solder melts
3. Quickly place pump nozzle over joint
4. Press release button
5. Vacuum sucks up molten solder
6. May need multiple attempts
7. Clean pump after use

9.4.3 Removing Through-Hole Components

- **Single lead**: Heat and pull gently with tweezers
- **Multi-lead components**:
  - Heat all joints alternately, rock component gently
  - Or remove solder from all holes first
  - Or cut leads, remove component, then remove leads individually
- **ICs**: Use IC extraction tool, or cut pins and remove individually

9.5 Common Soldering Problems

Problem	**Cause**	**Solution**
Cold joints	Insufficient heat, moved during cooling	Reheat properly, hold still
Solder won't stick	Dirty/oxidized surfaces, wrong temp	Clean surfaces, add flux, check temperature
Solder bridges	Too much solder, moved iron sideways	Remove with wick, use less solder
Lifted pads	Overheating, excessive force	Use lower temp, gentler technique; repair difficult
Component overheating	Too long contact time	Work faster, heat sink on leads
Tip won't tin	Oxidized tip	Clean, apply tip tinner/activator, replace if needed
Flux spattering	Too hot, contaminated	Reduce temperature, clean tip

Table 2: Soldering Troubleshooting

9.6 Tip Maintenance

- Clean tip regularly on damp sponge or brass wool
- Keep tip tinned when not in use (coat with solder)
- Never file or sand tip (removes protective plating)
- Use tip tinner/cleaner for stubborn oxidation
- Store with tinned tip
- Replace tip when pitted or not taking solder

10 PCB Wiring and Connections

10.1 Wire Types and Selection

10.1.1 Solid vs Stranded Wire

- **Solid core**:
  - Single conductor
  - Better for breadboards (fits holes well)
  - Holds shape
  - Breaks with repeated bending
  - Typically 22-24 AWG for breadboards
- **Stranded core**:
  - Multiple thin conductors
  - Flexible, resists fatigue
  - Better for moving connections
  - Needs tinning or ferrules for secure connections
  - Various strand counts (7/30, 19/32, etc.)

10.1.2 Wire Gauge (AWG)

American Wire Gauge - smaller number = thicker wire

AWG	Diameter (mm)	Max Current
18	1.02	16 A
20	0.81	11 A
22	0.64	7 A
24	0.51	3.5 A
26	0.40	2.2 A
28	0.32	1.4 A
30	0.25	0.86 A

Table 3: Wire Gauge Reference (for chassis wiring at 60°C)

For IYPT applications:

- **22 AWG**: Power connections up to 5A, breadboard jumpers
- **24 AWG**: Signal wires, low-power connections
- **26-28 AWG**: Sensor connections, data lines
- **30 AWG**: Wire-wrapping (specialized technique)

10.1.3 Insulation Types

- **PVC**: Common, inexpensive, rated to 80°C
- **PTFE (Teflon)**: High temperature (200°C+), chemical resistant
- **Silicone**: Very flexible, high temperature (180°C)
- **Kynar**: Wire-wrap wire, tough, soldering rated

10.2 Wire Stripping

10.2.1 Using Wire Strippers

1. Select correct gauge notch
2. Insert wire into stripper
3. Close handles gently
4. Pull stripper toward end of wire
5. Insulation slides off

Tips:

- Strip 5-7mm for through-hole soldering
- Strip 2-3mm for connectors
- Don't nick conductor (weakens wire)
- Stranded wire may need trimming of stray strands

10.3 Wire Termination Techniques

10.3.1 Tinning Stranded Wire

1. Strip wire to appropriate length
2. Twist strands together
3. Apply flux
4. Touch iron to wire
5. Apply solder - it will wick into strands
6. Remove excess solder if needed
7. Result: solid, easy-to-solder end

10.3.2 Crimping

For connectors (Dupont, JST, etc.):

1. Strip wire (typically 2-3mm)
2. Insert into crimp pin/socket
3. Conductor should be in crimp barrel
4. Insulation should be in strain relief crimp
5. Use crimp tool at correct position
6. Squeeze firmly in one motion
7. Tug test - should not pull out
8. Insert contact into connector housing

Good crimp characteristics:

- Conductor barrel crimped in center
- No conductor strands visible outside crimp
- Insulation held by strain relief
- Contact insertion wings not damaged

10.4 Making Reliable Connections

10.4.1 Screw Terminals

1. Strip wire appropriate length (terminal depth)
2. For stranded: tin wire end or use ferrule
3. Form clockwise hook for screw terminals
4. Insert wire under terminal
5. Tighten screw firmly (not over-tight)
6. Tug to verify

10.4.2 Headers and Connectors

Common types for IYPT:

- **Dupont/jumper wires**: Breadboard connections
- **JST**: Small, polarized, various sizes (PH, XH, etc.)
- **Molex**: Larger power connections
- **Pin headers**: 2.54mm pitch, soldered to PCBs
- **Screw terminals**: Secure, field-serviceable
- **Banana plugs**: Power supplies, test equipment

10.5 Cable Management

10.5.1 Best Practices

- Use appropriate length (not too long, not too short)
- Bundle related wires together
- Separate power and signal wires
- Use cable ties (zip ties) sparingly - don't over-tighten
- Label wires at both ends
- Provide strain relief at connection points
- Keep wires away from heat sources
- Use different colors: red (+), black (ground), others for signals

10.5.2 Strain Relief

Critical for reliability:

- Never rely on solder joint for mechanical strength
- Use cable ties or clamps near connections
- Provide service loops (slight slack)
- Hot glue can be used for light strain relief
- Use cable glands for enclosures

11 Circuit Assembly Workflow

11.1 From Schematic to Working Circuit

Complete Assembly Process

1. **Planning Phase**
   - Study schematic thoroughly
   - Identify all components
   - Understand circuit function
   - Check component availability
2. **Component Preparation**
   - Sort components by type
   - Check values (resistor colors, capacitor markings)
   - Test suspicious components
   - Organize in labeled containers
3. **Breadboard Prototype**
   - Build circuit on breadboard first
   - Test functionality before committing to PCB
   - Make modifications easily
   - Document any changes
4. **PCB Assembly** (if applicable)
   - Inspect PCB
   - Solder smallest components first
   - Progress to larger components
   - Polarized components last (can verify orientation)
   - Connectors and mechanical parts last
5. **Visual Inspection**
   - Check all solder joints
   - Verify component values and orientations
   - Look for solder bridges
   - Ensure no components touching where they shouldn't
6. **Continuity Testing**
   - Power OFF
   - Test power rails for shorts

11.2 Troubleshooting Techniques

11.2.1 Systematic Approach

1. **Define the problem**: What doesn't work? What should it do?
2. **Visual inspection**: Obvious issues? Burnt components? Bridges?
3. **Power supply**: Correct voltages everywhere?
4. **Signal tracing**: Follow signal from input to output
5. **Component substitution**: Replace suspected faulty parts
6. **Divide and conquer**: Isolate circuit sections

11.2.2 Common Problems and Solutions

Circuit doesn't power on:

- Check power supply voltage and current
- Verify power switch (if present)
- Test fuses
- Check power connections
- Measure voltage at various points
- Look for short circuits (measure resistance with power OFF)

Incorrect voltages:

- Verify regulator functionality
- Check voltage dividers
- Test for loading effects
- Verify reference voltages

Intermittent operation:

- Check all solder joints (reflow suspicious ones)
- Test connections (wiggle wires)
- Look for cold solder joints
- Check for loose components
- Verify breadboard contacts

Wrong signal levels:

- Check component values (resistors, capacitors)

- Verify op-amp gains
- Test voltage dividers
- Check for loading effects

Oscillation/instability:

- Add decoupling capacitors near ICs
- Check for ground loops
- Shorten wire lengths
- Verify feedback networks
- Check for positive feedback

11.2.3 Measurement Techniques

DC measurements:

- Measure with respect to ground
- Check supply voltages first
- Verify voltage drops across components
- Look for unexpected voltages

AC measurements:

- Use oscilloscope for waveforms
- Check frequency and amplitude
- Look for distortion
- Verify timing relationships

Current measurements:

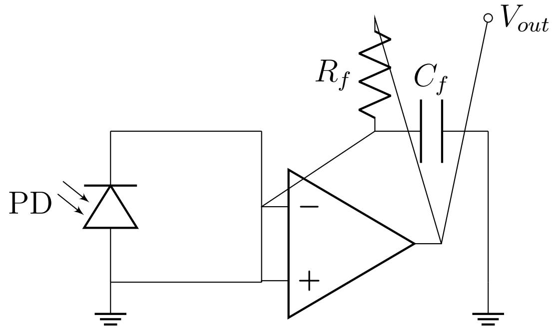
- Measure supply current first
- Compare to expected values
- High current indicates short or overload
- No current may indicate open circuit

12 Practical IYPT Applications

12.1 Photodetector Circuits

12.1.1 Photodiode Amplifier

Essential for photometry in CCDs:



Transimpedance amplifier:

$$V_{out} = -I_{PD} \cdot R_f \tag{14}$$

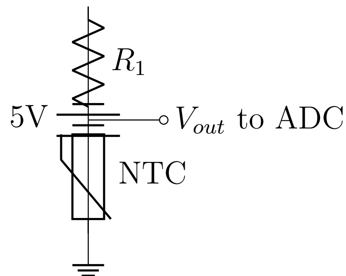
Design considerations:

- R_f: Sets gain (1 MΩ - 100 MΩ typical)
- C_f: Limits bandwidth, reduces noise (1-10 pF)
- Op-amp: Low input bias current (FET input like TL072)
- Shield from electromagnetic interference
- Keep photodiode wiring short

12.2 Temperature Measurement

12.2.1 Thermistor Circuit

NTC (Negative Temperature Coefficient) thermistors:



Steinhart-Hart equation:

$$\frac{1}{T} = A + B\ln(R) + C(\ln(R))^3 \tag{15}$$

where T is temperature in Kelvin, R is resistance, and A, B, C are calibration constants.

12.2.2 Thermocouple Amplifier

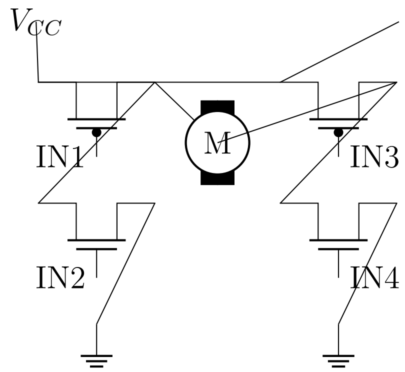
For wider temperature ranges:

- Thermocouples generate microvolts per degree
- Require high-gain, low-noise amplification
- Need cold junction compensation
- Specialized ICs available (e.g., MAX31855)

12.3 Motor Control

12.3.1 H-Bridge for DC Motors

For telescope mount control:



Control logic:

- Forward: Q1, Q4 ON; Q2, Q3 OFF
- Reverse: Q2, Q3 ON; Q1, Q4 OFF
- Brake: Q2, Q4 ON; Q1, Q3 OFF (or Q1, Q3 ON)
- Coast: All OFF
- **NEVER**: Q1 & Q2 ON or Q3 & Q4 ON (shoot-through!)

Use dedicated H-bridge ICs (L293D, L298N, DRV8833) for reliability.

12.4 Sensor Interface Circuits

12.4.1 Analog-to-Digital Conversion

Most microcontrollers have built-in ADCs:

- Typical resolution: 10-12 bits
- Reference voltage: Internal or external
- Input range: 0 to V_{ref}

- For bipolar signals: Add offset and scale

ADC calculation:

$$\text{Digital Value} = \frac{V_{in}}{V_{ref}} \times (2^n - 1) \tag{16}$$

where n is number of bits.

12.4.2 Signal Conditioning

Often needed between sensor and ADC:

- **Amplification**: Increase signal to fill ADC range
- **Filtering**: Remove noise (RC low-pass filter)
- **Level shifting**: Center signal in ADC range
- **Impedance matching**: Buffer high-impedance sensors

Simple RC low-pass filter:

$$f_c = \frac{1}{2\pi RC} \tag{17}$$

Choose f_c above signal frequency but below noise frequency.

13 Advanced Topics

13.1 Grounding and Noise Reduction

13.1.1 Ground Loops

Occur when multiple ground paths exist:

- Causes: Different ground potentials, current flow through ground
- Symptoms: 50/60 Hz hum, noise in measurements
- Solutions: Single-point grounding, star ground topology

13.1.2 Power Supply Decoupling

Critical for stable operation:

- Place 0.1 μF ceramic capacitor near each IC power pin
- Add 10-100 μF electrolytic at power entry
- Keeps supply voltage stable during current transients
- Prevents one IC from affecting another

Placement:

- As close as possible to IC power pins
- Short traces to ground plane
- Both V_{CC} and GND

13.1.3 Shielding

For sensitive measurements:

- Use shielded cable for low-level signals
- Ground shield at one end only (prevent ground loops)
- Metal enclosures reduce EMI
- Keep signal wires away from power wires

13.2 Electromagnetic Compatibility (EMC)

13.2.1 Emission Reduction

- Use slower edge rates where possible
- Filter outputs
- Use ground planes in PCBs
- Keep high-frequency traces short
- Use differential signaling for long runs

13.2.2 Immunity Improvement

- Input filtering
- Transient voltage suppressors (TVS diodes)
- Optoisolation for noisy environments
- Twisted pair wiring for signals

13.3 ESD Protection

13.3.1 Electrostatic Discharge Sensitivity

Many components are ESD-sensitive:

- MOSFETs: Very sensitive (100V can damage)
- CMOS ICs: Sensitive (100-1000V)
- Microcontrollers: Moderately sensitive
- Human body can generate 10,000+ volts

13.3.2 ESD Protection Measures

- Use ESD wrist strap (grounded through 1 MΩ resistor)
- Work on ESD mat
- Store sensitive components in ESD bags
- Handle ICs by the body, not pins
- Leave components in packaging until needed
- Avoid synthetic clothing in dry environments

14 Documentation and Lab Practices

14.1 Lab Notebook

14.1.1 What to Record

- Date and time
- Objective of experiment
- Circuit schematic
- Component values used
- Procedures followed
- Measurements taken (with units!)
- Observations (including unexpected behavior)
- Conclusions
- Problems encountered and solutions

14.1.2 Best Practices

- Write legibly in pen
- Number pages
- Draw clear diagrams
- Include photos when helpful
- Record failures as well as successes
- Date all entries
- Never tear out pages

14.2 Circuit Documentation

14.2.1 Schematic Drawing

- Use standard symbols
- Show all connections
- Label all components with values
- Indicate power supply voltages
- Add notes for critical points
- Include title, date, revision

14.2.2 Tools

- **KiCad**: Free, full-featured (schematic and PCB)
- **Eagle**: Popular, free version available
- **LTspice**: Free, excellent for simulation
- **Fritzing**: Good for beginners, breadboard view
- **CircuitLab**: Online tool

15 Common IYPT Laboratory Experiments

15.1 Experiment 1: Voltage Divider and Ohm's Law

Objective: Verify Ohm's law and voltage divider behavior.

Components:

- Resistors: 1kΩ, 2.2kΩ, 4.7kΩ
- DC power supply
- Multimeter
- Breadboard
- Jumper wires

Procedure:

1. Build voltage divider with 1kΩ and 2.2kΩ in series
2. Apply 5V across the series combination
3. Measure current through circuit
4. Calculate expected current: $I = V/R_{total} = 5/(1000 + 2200) = 1.56$ mA
5. Measure voltage across each resistor

6. Calculate expected voltages using voltage divider
7. Compare measured vs. calculated values
8. Repeat with different resistor combinations
9. Calculate measurement uncertainty

Analysis:

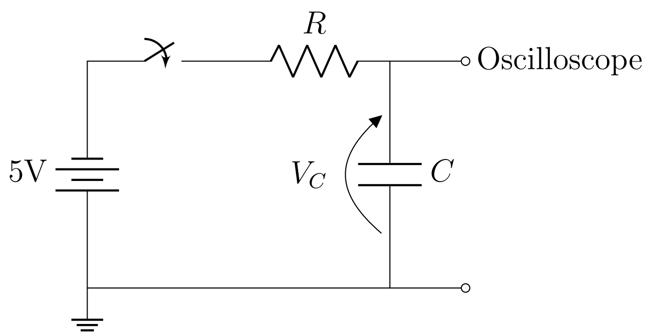
- Calculate percentage error
- Account for resistor tolerance
- Consider multimeter accuracy
- Verify Kirchhoff's voltage law: $V_{supply} = V_{R1} + V_{R2}$

15.2 Experiment 2: RC Circuit Time Constant

Objective: Measure RC time constant and observe exponential decay.
Components:

- Resistors: 10kΩ, 100kΩ
- Capacitors: 10μF, 100μF electrolytic
- DC power supply
- Oscilloscope
- Switch or pushbutton
- Multimeter

Circuit:



Theory: Charging equation:

$$V_C(t) = V_{supply}(1 - e^{-t/RC}) \tag{18}$$

Time constant: $\tau = RC$
At $t = \tau$: $V_C = 0.632 \cdot V_{supply}$
Procedure:

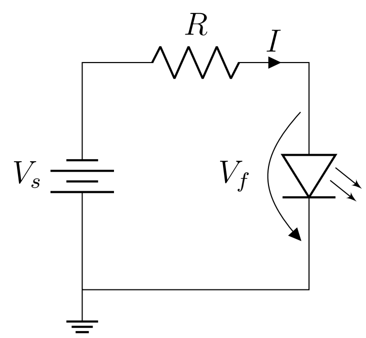
1. Calculate expected time constant
2. Set oscilloscope to appropriate time base
3. Connect oscilloscope to monitor capacitor voltage
4. Close switch and observe charging curve
5. Measure time to reach 63.2% of final voltage
6. Open switch and observe discharging curve
7. Capture oscilloscope traces
8. Repeat with different RC combinations

15.3 Experiment 3: LED Characteristics

Objective: Determine LED forward voltage and current requirements.
Components:

- LEDs: Red, green, blue, white
- Resistors: 220Ω, 470Ω, 1kΩ
- DC power supply
- Multimeters (2)
- Breadboard

Circuit:



Current-limiting resistor calculation:

$$R = \frac{V_s - V_f}{I_{LED}} \tag{19}$$

Procedure:

1. Start with 1kΩ resistor for safety
2. Connect LED (observe polarity!)
3. Apply 5V

4. Measure LED forward voltage V_f
5. Measure LED current
6. Calculate resistance: $R = (V_s - V_f)/I$
7. Try different supply voltages
8. Plot I-V characteristic curve
9. Repeat for different color LEDs
10. Observe brightness vs. current

Typical values:

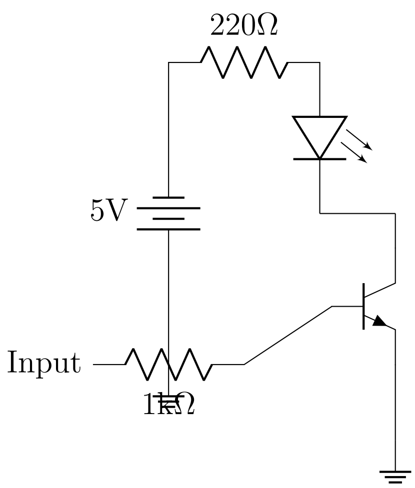
- Red LED: $V_f \approx 1.8 - 2.2V$
- Green LED: $V_f \approx 2.0 - 2.4V$
- Blue/White LED: $V_f \approx 3.0 - 3.6V$
- Typical $I_{LED} = 10 - 20$ mA

15.4 Experiment 4: Transistor Switching

Objective: Use transistor as a switch to control high-current load.
Components:

- NPN transistor: 2N2222 or BC547
- Resistors: 1kΩ (base), 220Ω (LED)
- LED
- Diode: 1N4148 (flyback protection if using relay/motor)
- DC power supply
- Signal generator or microcontroller

Circuit:



Design calculations:

- Load current: $I_C = (5V - 2V)/220\Omega \approx 13.6$ mA
- Required base current: $I_B = I_C/\beta$
- Assume $\beta = 100$: $I_B = 136$ μA minimum
- Use 10× safety factor: $I_B = 1.36$ mA
- Base resistor: $R_B = (V_{in} - 0.7V)/I_B$
- For 5V input: $R_B = 4.3V/1.36mA \approx 3.2k\Omega$
- Use 1kΩ for good saturation

Procedure:

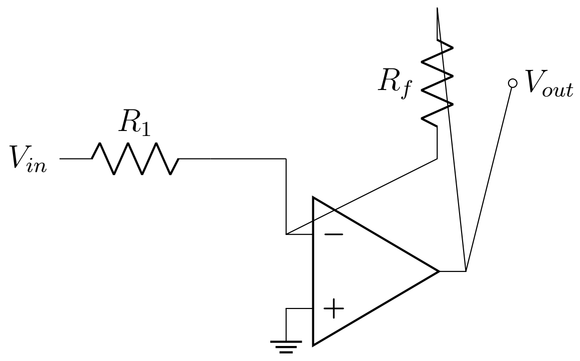
1. Build circuit
2. Apply 0V to input - LED should be OFF
3. Apply 5V to input - LED should be ON
4. Measure $V_{CE(sat)}$ (collector-emitter voltage when saturated)
5. Should be $< 0.3V$ for good saturation
6. Measure base current
7. Calculate actual β
8. Try different base resistor values
9. Observe switching speed with oscilloscope

15.5 Experiment 5: Operational Amplifier - Inverting Amplifier

Objective: Build and test op-amp amplifier circuit.
Components:

- Op-amp: LM358 or TL072
- Resistors: 10kΩ, 100kΩ
- Capacitors: 0.1μF (decoupling)
- DC power supply (±9V or ±15V)
- Function generator
- Oscilloscope
- Breadboard

Circuit:



Gain calculation:

$$A_v = -\frac{R_f}{R_1} \tag{20}$$

For $R_1 = 10k\Omega$, $R_f = 100k\Omega$:

$$A_v = -\frac{100k}{10k} = -10 \tag{21}$$

Procedure:

1. Wire circuit carefully
2. Connect decoupling capacitors near power pins
3. Apply power (±9V or ±15V)
4. Check output with no input - should be near 0V
5. Apply 100mV DC input
6. Measure output - should be $-1V$ (10× gain, inverted)
7. Apply sine wave input (1kHz, 100mV)
8. Observe input and output on oscilloscope
9. Verify 180° phase shift
10. Measure actual gain
11. Determine bandwidth (frequency where gain drops to 0.707×)
12. Observe distortion at high amplitudes

Analysis:

- Compare measured gain to calculated
- Account for resistor tolerances
- Observe gain-bandwidth product
- Note output voltage limitations (rail limitations)

15.6 Experiment 6: Photodiode Light Sensor

Objective: Build light detector circuit for photometry.

Components:

- Photodiode (e.g., BPW34)
- Op-amp: TL072 (FET input, low bias current)
- Resistors: 1MΩ, 10MΩ
- Capacitor: 10pF (for stability)
- DC power supply
- Multimeter or ADC
- Light source with variable intensity

Procedure:

1. Build transimpedance amplifier
2. Start with 1MΩ feedback resistor
3. Power the circuit
4. Shield photodiode from light - output should be near 0V
5. Expose to light source
6. Measure output voltage
7. Vary light intensity, record output
8. Calculate responsivity: $R = V_{out}/(I_{PD} \cdot R_f)$
9. Try different feedback resistors for different gain
10. Test frequency response with modulated light
11. Calibrate against known light source

Applications:

- Star photometry
- Light curve measurements
- Variable star observations
- Exoplanet transit detection

16 Safety and Ethics

16.1 Electrical Safety

Critical Safety Reminders

- Never work on live high-voltage circuits
- Use isolation transformer for AC mains work
- One hand rule: Keep one hand in pocket when probing live circuits
- Discharge capacitors before handling
- Respect current ratings - high current can cause fires
- Never bypass safety features
- Know the location of emergency shutoff
- Work with a buddy when possible

16.2 Chemical Safety

Solder and flux:

- Lead solder: Wash hands after use, never eat while soldering
- Flux fumes: Use fume extractor, ensure ventilation
- Flux residue: Use appropriate cleaner (isopropyl alcohol)

Cleaning agents:

- Isopropyl alcohol: Flammable, use in ventilated area
- Flux remover: Follow manufacturer's safety instructions
- Conformal coating: Use in well-ventilated area

16.3 Environmental Responsibility

Waste disposal:

- Electronic components: E-waste recycling
- Lead solder: Hazardous waste
- Batteries: Special recycling programs
- Chemicals: Follow local regulations
- PCBs: E-waste recycling

Sustainable practices:

- Reuse components when possible
- Proper storage extends component life
- Design for repairability
- Use lead-free solder when appropriate
- Minimize waste through careful planning

16.4 Academic Integrity

- Document all sources and references
- Acknowledge assistance from others
- Report your own data honestly
- Don't fabricate or falsify results
- Respect intellectual property
- Follow competition rules strictly
- Collaborate ethically

17 Appendices

17.1 Appendix A: Standard Resistor Values (E12 Series)

Base	**×10**	**×100**	**×1k**
1.0	10 Ω	100 Ω	1.0 kΩ
1.2	12 Ω	120 Ω	1.2 kΩ
1.5	15 Ω	150 Ω	1.5 kΩ
1.8	18 Ω	180 Ω	1.8 kΩ
2.2	22 Ω	220 Ω	2.2 kΩ
2.7	27 Ω	270 Ω	2.7 kΩ
3.3	33 Ω	330 Ω	3.3 kΩ
3.9	39 Ω	390 Ω	3.9 kΩ
4.7	47 Ω	470 Ω	4.7 kΩ
5.6	56 Ω	560 Ω	5.6 kΩ
6.8	68 Ω	680 Ω	6.8 kΩ
8.2	82 Ω	820 Ω	8.2 kΩ

Table 4: E12 series resistor values (continues for ×10k, ×100k, ×1M)

17.2 Appendix B: Standard Capacitor Values

Common ceramic capacitor values (pF to nF):

- pF range: 10, 22, 47, 100, 220, 470
- nF range: 1, 2.2, 4.7, 10, 22, 47, 100

Common electrolytic values (μF to mF):

- μF range: 0.1, 0.22, 0.47, 1, 2.2, 4.7, 10, 22, 47, 100, 220, 470, 1000
- mF range: 2200, 4700

17.3 Appendix C: IC Pinouts

17.3.1 7805 Voltage Regulator

TO-220 package (facing front):

- Pin 1: INPUT (7-35V)
- Pin 2: GROUND
- Pin 3: OUTPUT (5V)

17.3.2 LM358 Dual Op-Amp

DIP-8 package:

- Pin 1: OUT A
- Pin 2: IN- A
- Pin 3: IN+ A
- Pin 4: GND
- Pin 5: IN+ B
- Pin 6: IN- B
- Pin 7: OUT B
- Pin 8: VCC

17.3.3 2N2222 NPN Transistor

TO-92 package (flat side facing you):

- Pin 1 (left): EMITTER
- Pin 2 (middle): BASE
- Pin 3 (right): COLLECTOR

Prefix	Symbol	Multiplier	Example
tera	T	10^{12}	1 TΩ
giga	G	10^{9}	1 GHz
mega	M	10^{6}	1 MΩ
kilo	k	10^{3}	1 kΩ
-	-	10^{0}	1 Ω
milli	m	10^{-3}	1 mA
micro	μ	10^{-6}	1 μF
nano	n	10^{-9}	1 nF
pico	p	10^{-12}	1 pF
femto	f	10^{-15}	1 fF

Table 5: Metric prefixes used in electronics

17.4 Appendix D: Unit Prefixes

17.5 Appendix E: Common Formulas Reference

17.5.1 Basic Laws

$$V = IR \quad \text{(Ohm's Law)} \tag{22}$$

$$P = VI = I^2R = \frac{V^2}{R} \quad \text{(Power)} \tag{23}$$

$$\sum I_{in} = \sum I_{out} \quad \text{(KCL)} \tag{24}$$

$$\sum V = 0 \quad \text{(KVL around loop)} \tag{25}$$

17.5.2 Series and Parallel

$$R_{series} = R_1 + R_2 + R_3 + \dots \tag{26}$$

$$\frac{1}{R_{parallel}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \dots \tag{27}$$

$$C_{series} : \frac{1}{C_{total}} = \frac{1}{C_1} + \frac{1}{C_2} + \dots \tag{28}$$

$$C_{parallel} = C_1 + C_2 + C_3 + \dots \tag{29}$$

17.5.3 Time Constants

$$\tau_{RC} = RC \tag{30}$$

$$\tau_{RL} = \frac{L}{R} \tag{31}$$

$$V_C(t) = V_0 e^{-t/RC} \quad \text{(discharge)} \tag{32}$$

$$V_C(t) = V_{final}(1 - e^{-t/RC}) \quad \text{(charge)} \tag{33}$$

17.5.4 Filters

$$f_c = \frac{1}{2\pi RC} \quad \text{(RC low-pass)} \tag{34}$$

$$f_c = \frac{R}{2\pi L} \quad \text{(RL low-pass)} \tag{35}$$

$$Q = \frac{f_0}{\Delta f} \quad \text{(Quality factor)} \tag{36}$$

17.6 Appendix F: Troubleshooting Checklist

Quick Diagnostic Checklist

Before applying power:

- ☐ Visual inspection for obvious errors
- ☐ All ICs oriented correctly
- ☐ Polarized components correct direction
- ☐ No solder bridges
- ☐ All connections made
- ☐ Power supply set to correct voltage
- ☐ Current limit set appropriately

Initial power-up:

- ☐ Monitor current draw
- ☐ Check for hot components
- ☐ Verify supply voltages at all points
- ☐ Check ground connections

If circuit doesn't work:

- ☐ Recheck schematic vs. actual circuit
- ☐ Verify all component values
- ☐ Test continuity of critical paths
- ☐ Check for cold solder joints
- ☐ Verify IC functionality (swap if available)
- ☐ Isolate problem to specific section

17.7 Appendix G: Recommended Tools and Equipment

17.7.1 Essential Tools

- Temperature-controlled soldering station (40-60W)
- Digital multimeter with diode/continuity test
- Wire strippers (22-30 AWG)
- Flush cutters
- Needle-nose pliers
- Tweezers (straight and bent)
- ESD wrist strap
- Helping hands/PCB holder
- Magnifying glass or loupe

17.7.2 Consumables

- Solder (0.5-1.0mm diameter)
- Solder wick
- Flux pen
- Isopropyl alcohol (for cleaning)
- Jumper wire kit
- Assorted resistors, capacitors
- LEDs
- Common ICs (op-amps, regulators)

17.7.3 Test Equipment

- Bench power supply (0-30V, 0-3A minimum)
- Digital oscilloscope (50-100 MHz minimum)
- Function generator
- Breadboards (various sizes)
- Logic analyzer (for digital work)

17.8 Appendix H: Online Resources

17.8.1 Datasheets and Reference

- **AllDataSheet.com**: Component datasheets
- **Octopart.com**: Component search and comparison
- **TI.com, Analog.com**: Application notes and design tools
- **Falstad.com/circuit**: Online circuit simulator

17.8.2 Learning Resources

- **Electronics Tutorials**: electronicstutorials.ws
- **All About Circuits**: allaboutcircuits.com
- **SparkFun Learn**: learn.sparkfun.com
- **Adafruit Learn**: learn.adafruit.com

17.8.3 Design Tools

- **KiCad**: kicad.org - Free PCB design software
- **LTspice**: analog.com - Free circuit simulation
- **EasyEDA**: easyeda.com - Online PCB design
- **CircuitJS**: falstad.com - Interactive simulator

18 Conclusion

This manual has covered the essential laboratory skills needed for IYPT preparation.

- **Safety**: Always prioritize safety in the laboratory
- **Components**: Understanding basic electronic components and their properties
- **Circuits**: Fundamental circuit analysis and design principles
- **Measurement**: Proper use of multimeters, oscilloscopes, and other instruments
- **Construction**: Breadboarding, PCB assembly, and soldering techniques
- **Troubleshooting**: Systematic approaches to finding and fixing problems

Key takeaways for IYPT success:

1. Practice regularly - skills improve with repetition
2. Work methodically - don't rush

3. Document everything - keep good lab notebooks
4. Learn from mistakes - failures are learning opportunities
5. Ask questions - seek help when stuck
6. Stay curious - explore beyond the basics

Good luck with your IYPT preparation!