# 2.996/6.971 Biomedical Devices Design Laboratory

# Lecture 2: Fundamentals and PCB Layout

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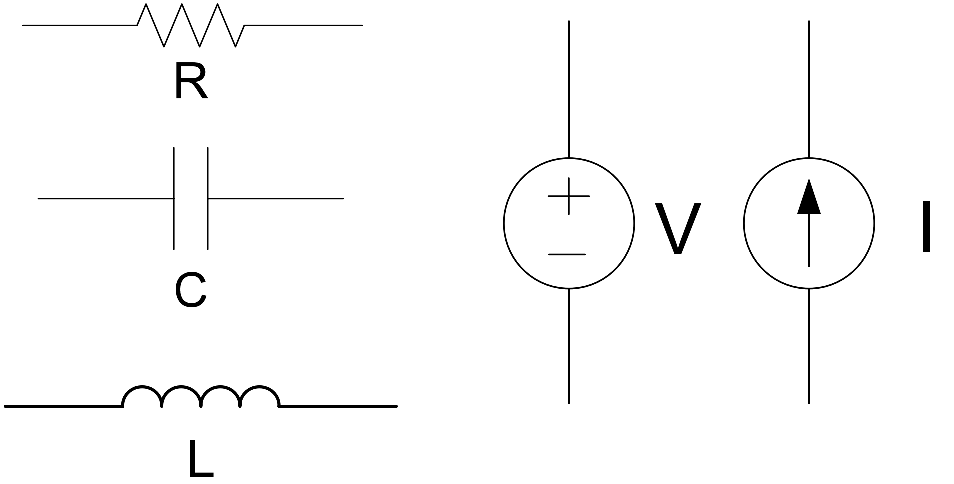
# Fundamental Elements

- Resistor (R)
- Capacitor (C)
- Inductor (L)




- Voltage Source
- Current Source

- Enough to model any physical linear circuit

# Fundamental Relationships

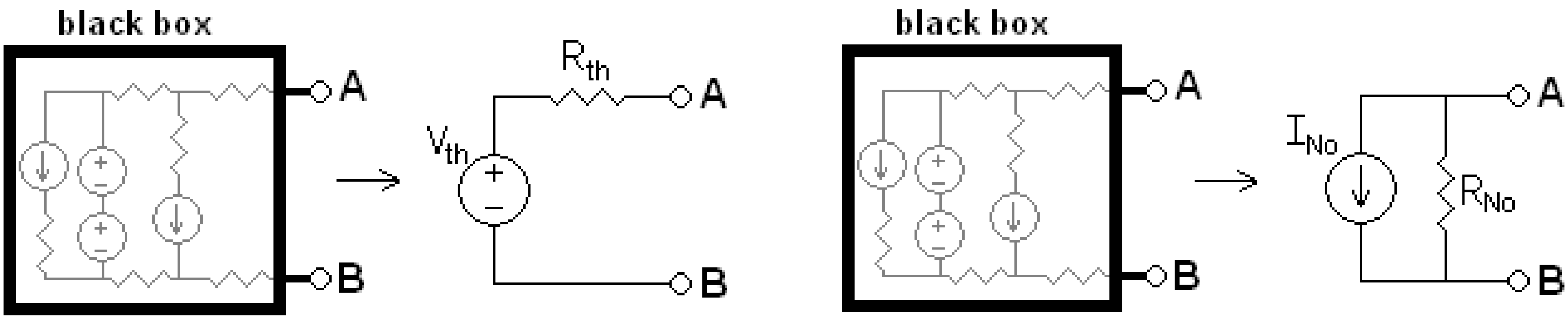
- Ohm's law: R = V / I
- KVL, KCL – Conservation laws
- Impedance:

$$Z_C = \frac{1}{j\omega C} \qquad\qquad Z_L = j\omega L$$

  – Treat capacitors and inductors as resistors

- Fundamental question:
  – Given an arbitrary circuit, what happens when you hook up another circuit up to it?

# Thevenin-Norton Equivalents




- Represent an arbitrary circuit using a source and a source impedance
- Thevenin and Norton representation is equivalent

- Result: Reduce all circuits into one fundamental circuit

# Source and Load

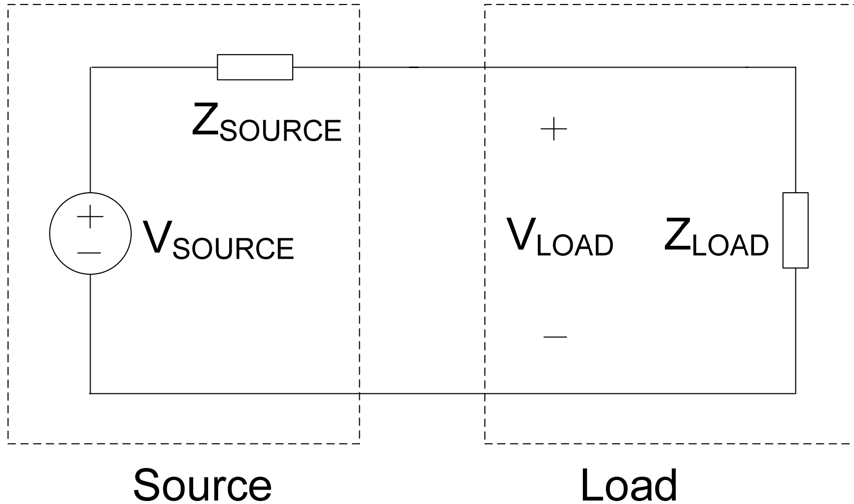
**Sources**

Power supply

Signal Generator

Sensor

Amplifier output




**Loads**

Actuator

Measurement device

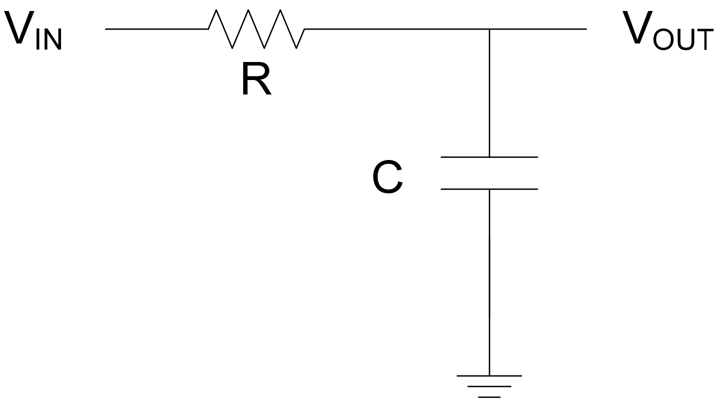
Amplifier input

- Optimize for Voltage: $Z_{LOAD} >> Z_{SOURCE}$
- Optimize for Current: $Z_{LOAD} << Z_{SOURCE}$
- Optimize for Power: $Z_{LOAD} = Z_{SOURCE}$

- Purpose of amplifier / active circuit:
  – impedance transform

# Simple Filters

- RC Low pass
- RC high pass
- Bandpass
- Bandstop (notch)



# Simple Cascaded Filters

- What if 2 stages are needed?

# Practical Introduction to Passive Components

# Resistors

- Range: 1Ω to 22MΩ
- Carbon composite (axial)
  - 5% accuracy typical
- Wirewound
  - 1% accuracy typical
- Thick film (Screen printed / electroplated)
  - Accuracies down to 1%
- Thin film (Vacuum deposited)
  - Accuracies down to 0.1%
- Temperature coefficient: 20-200 ppm / °C

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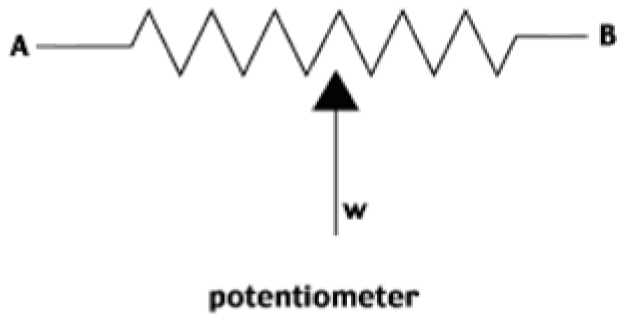
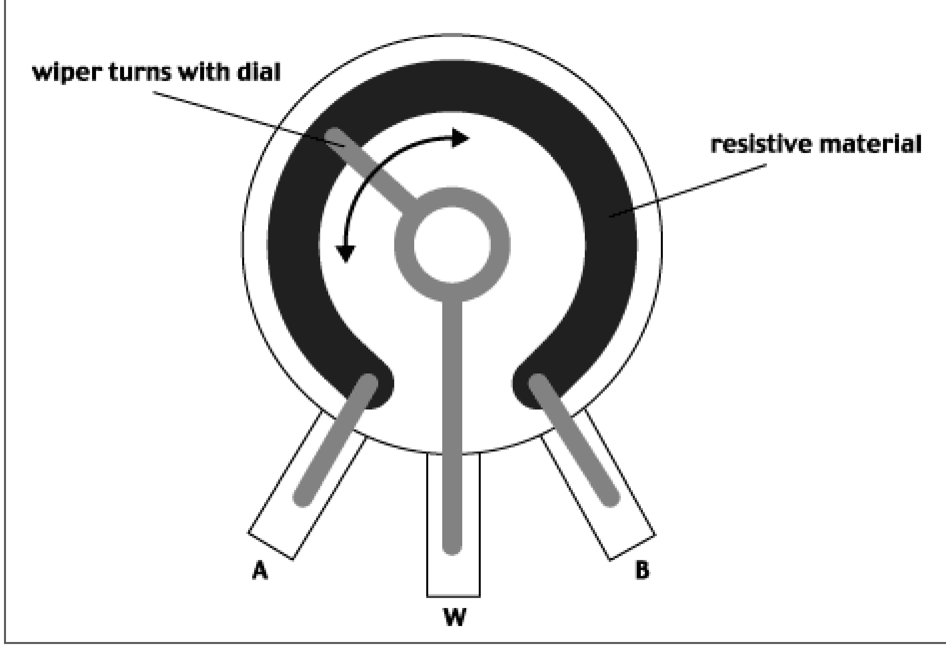
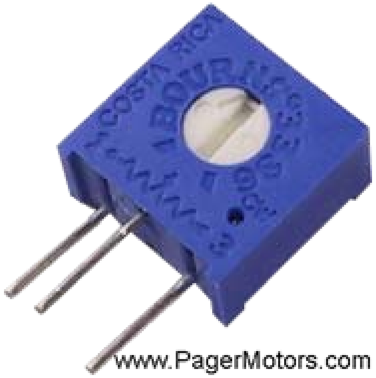
Photo examples of resistors.

# Potentiometer

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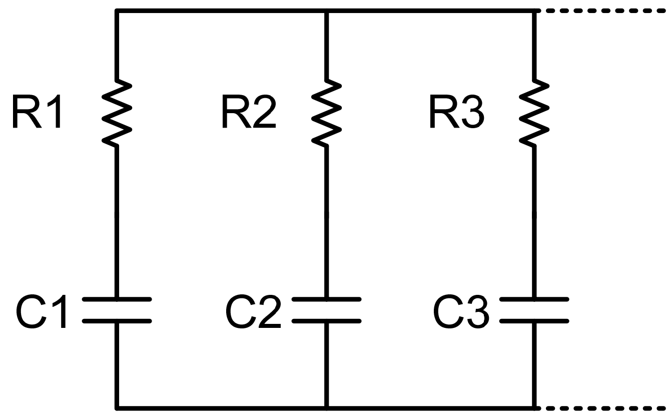
- Concerns:
  - Over-usage
  - Wiper skips – not all values are achievable
  - Mechanical stability → multi-turn not necessarily better

# Practical Capacitor Considerations

- Accuracy: ±10% typical
- Effective series capacitance
- Dielectric soakage (dielectric absorption)
- Temperature dependence


C1 >> C2 >> C3

R1 << R2 << R3

# Ceramic Capacitors

- Most common type
- 1pF to 1μF
- Accuracy
  - Through-Hole ±20%
  - SMT ±10%
- Low ESR, loss tangent ≈ 0.002
- Temperature coefficient
  - Z5U, X7R, C0G (NP0)
- Cost = ~$0.01 in quantity

Images removed due to copyright restrictions.
Photo examples of ceramic capacitors.

# Aluminum Electrolytic Capacitors

- Primary use: power supply bypassing
- Range: 1μF – 1F Typical: 100μF
- Cost: ~$0.10 depending on size

- Polar, designated by the negative terminal
- Will blow up if reverse biased
- Nonpolar versions available

Images removed due to copyright restrictions.
Photo examples of aluminum electrolytic capacitors.

- Very inaccurate
- Typical tolerance: +80%, -20%
- Limited lifetime
- High ESR, loss tangent = R/Xc ≈ 0.2

# Tantalum Electrolytics

- Similar to aluminum electrolytics, but better energy density
- More expensive than aluminum electrolytics
- Range: 0.1μF to 1000μF
- Polarity designated by the positive terminal


Photo examples of tantalum electrolytics.

# Double Layer Capacitors

- Extremely high capacitance
- Range 0.1F – 1000F
- Low voltage rating
- Used for energy storage

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Photo examples of double layer capacitors.

# Specialty Capacitors: Polypropylene

- Improved performance:
  - Accuracy
  - ESR at high frequencies
  - Low dielectric soakage
  - Temperature stability
  - Higher breakdown voltage
- Tradeoffs
  - Larger size
  - Smaller range of values
  - Higher cost: ~$0.10

Image removed due to copyright restrictions.
Photo of polypropylene capacitor.

# Power Supply Bypassing

- Ideal sources do not exist!
- Source impedance increases with frequency
- Ceramic capacitor on each IC component
- Electrolytic on both sides of the power supply

# Practical Inductors

- Inaccurate (at best ±10%)
- Expensive
- Parasitics
  - All inductors self resonate
- Avoid whenever possible

Images removed due to copyright restrictions.
Photo examples of practical inductors.

# Where to find information / parts

- Manufacturer’s website: datasheet & samples
- Distributors:
  - Digikey
  - Mouser
  - Newark
- Meta search engine: www.findchips.com

# PCB Layers

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- Substrate
  - FR-4 standard; Specialty: G-10, polyimide (Kapton), ceramic
  - Standard thicknesses: 0.062”, 0.031”
- Copper
  - 2, 4, up to 12 layers
  - Minimum trace/spacing 6 mil, smaller is possible
  - Thickness: 1 oz copper = 500 μΩ per square
  - Exposed copper tin’ed with solder
  - Interlayer connection by vias; Blind and buried vias = $$$
- Soldermask – very important → Hydrophobic to solder
- Silkscreen

# PCB Layout Error Sources

- Capacitive interference
- Inductive interference
- Electromagnetic interference

- Need a ground plane… but why?!?

# Capacitive Interference

- Cause: capacitance between nearby traces
- When to watch out for it:
  - High impedance circuit nodes
  - High-voltage excitation signals
  - High frequency signals

- How to avoid it:
  - Lower the circuit impedance
  - Use groundplanes and shielding to isolate signal lines
  - Boot-strap to reduce capacitance to ground
  - Separate analog and digital ground planes

# Inductive Interference

- Cause: mutual inductance between traces
- When to watch out for it:
  - Large AC current
  - Transient switching
  - Long traces
  - Loops

# How to Avoid Inductive Interference

- Keep traces short
- Make traces perpendicular
- Use star power / ground routing
- Reduce loop area
- Careful use of ground planes
- Watch out for return lines

# Electromagnetic Interference (EMI)

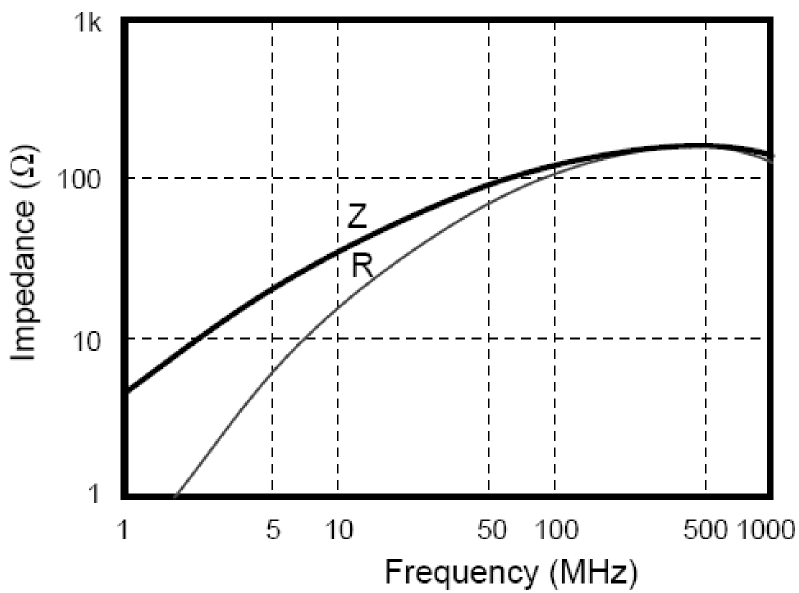
- Cause:
  - long traces/wires acting as an antenna
- When to watch out for it:
  - Length > 1/20 wavelength
- Source of interference
  - Wireless communication (900MHz, 2.4GHz, 5GHz)
  - FM radio
  - Microwave oven
  - Lightning, solar flares, cosmic rays
  - High speed processors
- Real products must pass FCC and CE testing

# Ferrite Bead

Example photos removed due to copyright restrictions.

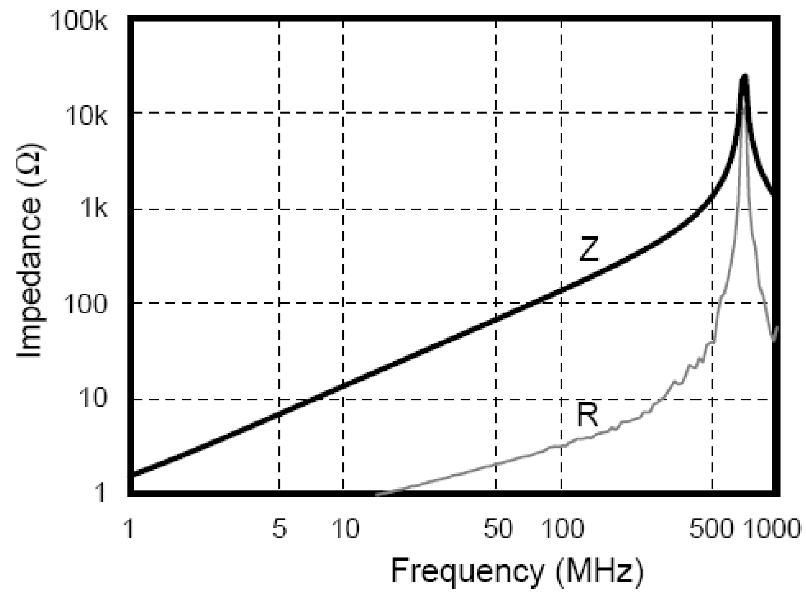
- A lossy inductor
- Resistor at high frequencies

Ferrite bead inductor




Resistance is dominant.
(The loss is high.)

Reference: Coil for high-frequency filter circuits
(Air-core coil)




Resistance is small.
(The loss is low, i.e. “Q” is high.)

# Where to put the ground planes?

- Ground planes outside, signals inside:
  - Essentially eliminate capacitive interference
- Ground planes inside, signal outside:
  - Ground plane with frewer interruptions

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# Project Teams