2.996/6.971 Biomedical Devices Design Laboratory

Lecture 2: Fundamentals and PCB Layout

Instructor: Hong Ma
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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:  \( R = \frac{V}{I} \)

• KVL, KCL – Conservation laws

• Impedance:

\[
Z_C = \frac{1}{j\omega C} \quad Z_L = j\omega L
\]

– 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
Potentiometer

• 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
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
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
- Very inaccurate
- Typical tolerance: +80%, -20%
- Limited lifetime
- High ESR, loss tangent = \( \frac{R}{X_c} \approx 0.2 \)

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

Images removed due to copyright restrictions.
Photo examples of tantalum electrolytics.
Double Layer Capacitors

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

Images removed due to copyright restrictions.
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
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

- **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

See Figure 12 here: http://www.analog.com/library/analogdialogue/archives/41-06/ground_bounce.html
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

- A lossy inductor
- Resistor at high frequencies

Resistance is dominant.
(The loss is high.)

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

Reference: Coil for high-frequency filter circuits
(Air-core coil)
Where to put the ground planes?

• Ground planes outside, signals inside:
  – Essentially eliminate capacitive interference

• Ground planes inside, signal outside:
  – Ground plane with fewer interruptions

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Project Teams