Electronics
019 128
Lecture Notes
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First lecture begins w/ discussion of syllabus, lab
First we review various ideas you've most likely seen already, and some terminology that might be new.

**Units**

- $Q$: charge \[\text{[Coulomb]}\]
- $V$: voltage = potential \[\text{[Volt]}\]
- $I$: current = flow of charge \[\text{[Coulomb/s]}\]
- $P$: power = energy per unit time \[\text{[Watts]}\]

**Energy**

- Electrical: $QV$ = potential energy of charge $Q$
- Mechanical: $mgH$ = mass $m$ times height $H$

Concept: zero is arbitrary for potential energy.

Mechanical, $H$ referred to sea level, floor, ...

Electrical, $V$ referred to what?
"Ground" - as a convention, zero volts = "ground potential."

- It's a large body capable of accumulating or losing lots of electrons.
- Examples:
  - Water pipe stuck into soil
  - Metal enclosure of battery-powered circuit

- Symbols:

  $\downarrow$ or $\uparrow$ or $\upharpoonright$

"Voltage Drop" = difference in potential between two points

"Bias" = a voltage, usually DC
DC vs. AC

DC
Audio freq. 5-10 Hz

RF (radio freq) 300 kHz

For RF, potl varies along length of wire, due to short λ

DC, audio: potl is nearly constant along a wire

Electrical Power

60 Hz  N. America
50 Hz  Euro, Asia

Amplitudes for AC:

\[ V_{rms} = \frac{1}{\sqrt{2}} V_{peak} \]
\[ V_{peak} = \frac{1}{2} V_{pp} \]
About schematic diagrams

An early goal of course: learn to read them.

--- wire

| node = connected |
| not connected |

\[ + \quad \frac{1}{1} \quad \text{battery} \]

\[ \frac{1}{2} \quad \text{or} \quad \frac{1}{4} \quad \text{resistor} \]
Conventions for drawing schematics:

- Positive voltage at top
- Negative voltage at bottom
- Lines representing wires are horizontal or vertical
- Sources on left, loads on right
- Signals flow from left to right
- 'nc' node: preferred style, not preferred
Statistical Treatment of Exptl. Data

here, we interrupt presentation of electronics fundamentals to review errors, so that you can do best.

Terminology

- Measurement errors are ± uncertainties
- Two kinds:
  - "Systematic" - e.g., thermometer is not calibrated
  - "Random" - unpredictable variations in exp.

- If you repeat measurement 10 times, you get 10 different results
- Examples of causes:
  - Unpredictable fluctuations in temperature, illumination
  - Observer judgment in estimating tenths of smallest division
- Small systematic errors → high "accuracy"
- Random → "precision"

Concepts for errors

- If you make only one measurement, it is sometimes hard to say whether errors are random or systematic.
- Here, "errors" does not refer to difference between theory & exp'tl measurement.
- In electronics measurement, errors typically occur in analog quantities (voltage, time, etc.) not in logic levels True & False.

How to determine error

- Usually, see mfg. specifications for instrument.
- Ex. Multimeter, Hz: mfg spec ±1.00% reading + 3.650
  (cont.) "least significant digit"
your reading: 60.12 Hz

\[ \textsuperscript{+} \]

250 \textsuperscript{\textsuperscript{+}} 0.01 Hz

your uncertainty: \[ 0.60 \pm 0.0001 \]

= 0.63

you report: \[ 60.12 \pm 0.63 \text{ Hz} \]

- Sometimes, with analog measurements, operator’s opinion of how nearly he/she can read position of needle or waveform compared to scale

- Seldom: jitter in indicated value of digital display
Propagation of Errors — use in some labs, not all

^ How you determine ± uncertainty
of a calculated quantity

\[ V_\text{out} \pm \Delta V_\text{out}, \quad V_\text{n} \pm \Delta V_\text{n} \]

you calculate \( A = \frac{V_\text{out}}{V_\text{n}} \)

you find uncertainty \( \Delta A \) using
prop of errors:

\[ (\Delta A)^2 = (\Delta V_\text{out})^2 + (\Delta V_\text{n})^2 \]

generally if \( Q \) is calculated from \( a \& b \)
then \( \Delta Q \) uncertainty is calculated:

\[ (\Delta Q)^2 = \left( \frac{\partial Q}{\partial a} \Delta a \right)^2 + \left( \frac{\partial Q}{\partial b} \Delta b \right)^2 \]

note that errors add thru their squares
back to Fundamentals

**Concepts:**

**Series / Parallel**

Series: \[ R_{\text{equivalent}} = R_1 + R_2 \]

Parallel: \[ \frac{1}{R_{\text{equivalent}}} = \frac{1}{R_1} + \frac{1}{R_2} \]

*Direction of current flow*

Positive current flows from more pos. voltage to more neg. voltage.
Ohm's Law

\[ V = I R \quad I = \frac{V}{R} \]

where:

- \( V \) = voltage "drop" across resistor
- \( I \) = current thru

Ohm's Law is empirical and good for some materials but not all.

Resistors

- Three parameters:
  - resistance \( R \)
  - tolerance typ. ±5%
  - power rating ≤ don't exceed this, or you burn it up; see this

Power dissipated

\[ P = I V \]

\[ P = I^2 R = \frac{V^2}{R} \] for a resistor
Some schematic symbols

Switches

- **SPST**
  - Single pole single throw
  - (use for on-off)

- **SPDT**
  - (use to select A or B)

- **DPST**
  - "general"

- "Open"...
- "Closed"

- "Normally open" push button
Terminology

"Open circuit"

"Closed circuit"

"Short circuit"
Kirchoff's Laws

The physics behind circuit analysis

Voltage Law

(Conservation of energy for an electron)

"Sum of Voltage Drops around a closed loop is zero"

\[
(V_2 - V_1) + (V_b - V_c) + (V_c - V_a) = 0
\]

voltage drop across \( R_1 \)
drop across \( R_c \)
drop across battery

to use law, choose either CW or CCW, then go around complete loop
Current Law

(conservation of charge)

"Sum of currents into a node is zero"

\[ I_1 + I_2 + I_3 = 0 \]

to use, first decide (arbitrarily) which direction represents positive current, arrows in example indicate choice of direction for positive current flow
Voltage Dividers

two resistors in series

\[ \frac{V_{out}}{V_{in}} \]

*Method of analysis* (you'll see this repeated for many circuits)

1st identify components, nodes, loops

2nd write their rules, in algebraic form.

3rd combine, to eliminate variables, yielding desired quantity
1st component $R_1, R_2$

nodes (B), (C)

loops none shown

2nd for $R_1$, Ohm's Law \[ \frac{V_{A} - V_{B}}{R_1} = I_1 \]

for $R_2$, \[ \frac{V_{B} - V_{C}}{R_2} = I_2 \]

note my convention:
positive current assumed
to flow from to bottom

for node (B), Kirchhoff's curr. law

= all current thru $R_1$ must go out
  either thru $R_2$, or
  toward (D)

However, (D) is an open circuit \( \Rightarrow \) no current
flows to (D)

\[ \Rightarrow I_1 = I_2 \]
we must relate $V_{out}$ & $V_{in}$ to other quantities in circuit

here, $V_{out} = V_A - V_C = V_B - V_C$

since (B) & (C) are connected

$V_{in} = V_A - V_C$

combine to eliminate variables:

$V_{out} = V_B - V_C$

$\frac{I_2 R_2}{I_2 R_2} = I_1 R_2$

$V_{in} = V_A - V_C$

$= (V_A - V_B) + (V_B - V_C)$

$\frac{I_2 R_1}{I_2 R_2}$

$\frac{I_1 R_2}{I_1 R_2}$

$= I_1 (R_1 + R_2)$

$\frac{V_{out}}{V_{in}} = \frac{I_1 R_2}{I_1 (R_1 + R_2)}$
\[ \frac{V_{out}}{V_{in}} = \frac{R_2}{R_1 + R_L} \]

Voltage Divider

\[ V_{out} = \frac{9 \text{ V}}{3 \text{ kΩ}} \cdot \frac{1 \text{ kΩ}}{3 \text{ kΩ}} \]

\[ = 3 \text{ V} \]
Terminology

"Voltage Source" provides fixed Vol regardless of current

"Current Source" I = F (V) voltag

Voltage Source:
- more common
- almost every circuit has one
- battery or power supply

"Sourcing & sinking current"

"Sourcing" if a circuit supplies positive current to a point

"Sinking" vice versa

Note: "sinking" ≠ resistive dissipation
"offset" = "bias"

- a DC voltage, which shifts an AC waveform up or down

\[
\text{AC signal} \quad \downarrow V
\]

\[
\text{AC signal with DC offset} \quad \uparrow 1 \text{DC bias}
\]

\[\text{bias}
\]

**Gain**

\[
\text{Av} = \frac{V_{\text{out}}}{V_{\text{in}}} \quad \text{voltage gain}
\]

\[
\text{Ai} = \frac{I_{\text{out}}}{I_{\text{in}}} \quad \text{current gain}
\]

"Unity Gain" \(\Rightarrow\) \(V_{\text{out}} = V_{\text{in}}\)
"Decibels"

- To compare ratio of two signals

\[
\text{dB} = 20 \log_{10} \frac{\text{amplitude}_2}{\text{amplitude}_1}
\]

- Often used for gain
- Ex. ratio is 1.4 \(\Rightarrow\sqrt{2}\)

\[
\text{dB} = 20 \log_{10} (1.4) \\
= 3 \text{dB}
\]

"Flatness"

[Graph of flatness]

\(2 \text{ dB} \text{ criterion for "flatness"}

freq
AC waveform concept

Recall \( V_{\text{rms}} = \frac{1}{\sqrt{2}} V_{\text{peak}} = \frac{1}{2 \pi} V_{\text{pp}} \)

Two components for AC circuits

Transformer

- Primary
- Secondary
- Input in \( 110 \text{Vrms} \) \( \rightarrow \) \( 156 \text{Vpeak} \)
- Output in \( 6.3 \text{Vrms} \) \( \rightarrow \) \( 8.9 \text{Vpeak} \)

Capacitor

\[ Q = CV \]

charge on plates

potential difference across plates

capacitance in Farads
\[ I = \frac{dQ}{dt} \]
\[ \rightarrow I = C \frac{dV}{dt} \]

In the laws for capacitors, analogous to \( I = \frac{V}{R} \) for resistors.

**Series**

\[ \frac{1}{C_1} = \frac{1}{C_{\text{tot}}} = \left[ \sum C_i \right]^{-1} \]

**Parallel**

\[ C_1 + C_2 = C_{\text{par}} = \sum C_i \]

**Lower case symbols**

- \( i \) = AC portion of current waveform
- \( v \) = voltage waveform

\[ V(t) = V_{dc} + v \]
Math: Complex Numbers

ref: Horowitz Hill Appendix B

\( e^j = -1 \)

\( e^j = 1 + j \)

Complex no \( z = a + bj \)

\[ z^* = a - bj \]

Magnitude or modulus

\[ |z| = \sqrt{z \cdot z^*} = \sqrt{a^2 + b^2} \]

Reel \( a = \text{Re}[z] \)

Imaginary \( b = \text{Im}[z] \)

Recall Frequencies

\[ \omega = 2\pi f \]

\( \text{units Hz} \)

\[ f = \frac{1}{\text{period}} \]

\( \text{units s}^{-1} \)
Math: Complex Exponential

\[ e^{jat} = \cos(at) + j \sin(at) \]

sinusoidal waveform:

\[ v(t) = V_0 \cos(at) \]

\[ = \Re \left[ V_0 e^{jat} \right] \]

derivatives:

\[ \frac{d}{dt} e^{jat} = jwe^{jat} \]
Impedance

- a generalized resistance
- allows rewriting law for capacitors so that it resembles Ohm's law
- symbol \( Z \)
- a ratio of voltage/current

Impedance of Capacitor

Recall law \( I = C \frac{dV}{dt} \)

AC signal with sinusoidal signal \( V(t) = V_0 e^{j\omega t} \)

\[ \frac{dV}{dt} = j\omega V(t) \]

Impedance \( Z = \frac{\text{voltage}}{\text{current}} \)

\[ = \frac{V_0 e^{j\omega t}}{j\omega C V_0 e^{j\omega t}} \]

\[ = \frac{1}{j\omega C} \]
Impedances

\[ Z_c = \frac{1}{j\omega C} \]
\[ Z_t = R \]
\[ Z_L = j\omega L \quad \text{inductor used mainly in RF circuits} \]

Ohm's Law for Impedances

\[ V(t) = I(t) Z \]
\[ I(t) = \frac{V(t)}{Z} \]

Series:

\[ Z_{total} = Z_1 + Z_2 \]
Parallel:
\[ Z_{\text{total}} = \frac{1}{Z_1} + \frac{1}{Z_2} \]

Low Pass Filter:

\[ V_{\text{in}} \]

Looks like voltage divider.
\[ V_{\text{out}} = \frac{V_{\text{in}}}{\frac{2C}{2C + R}} \]

\[ = \frac{V_{\text{in}}}{\frac{1}{j\omega C} + R} \]

\[ = \frac{1}{1 + j\omega RC} \]

↑↑
complex no.

Find amplitude, which is a real no.

\[ \text{ampl} = \left( V_{\text{out}} \times V_{\text{out}} \right)^{\frac{1}{2}} \]

↑↑
real complex

\[ V_{\text{out}} = V_{\text{in}} \cdot \frac{1}{\left( 1 + j\omega RC \right)^{\frac{1}{2}}} \]

amplitude (real nos.)

"Inverting response curve" for Low Pass Filter

\[ \frac{V_{\text{out}}}{V_{\text{in}}} \]

3 dB below unity gain

\[ (RC)^{-1} \rightarrow \omega \]
Like a voltage divider

\[ V_{\text{out}} = V_i \frac{2R}{R + 2C} \]

\[ = V_i \frac{R}{R + j\omega C} \]

\[ V_{\text{out}} = V_i \frac{j\omega RC}{j\omega RC + 1} \]

Complex nos.

Find amplitude
\[ V_{\text{out}} = V_i \frac{\omega RC}{1 + \omega^2 RC^2} \]

applications

Low pass filter: eliminate high freq. noise in a transmission of human voice or signal e.g. kHz

High pass filter: eliminate dc bias in ac waveform
Capacitor terminology:

"Roll-off frequency" of a filter \( = (RC)^{-1} \)

"Time constant" \( = RC \)

"DC blocking capacitor"

- Insert a capacitor to remove DC bias
- Ex. "AC coupling" of scope

\[ \begin{align*}
\text{Vin} & \xrightarrow{\text{rest of scope}} \text{Out} \\
& \Downarrow \\
& \text{Ima}
\end{align*} \]

- Also called "capacitive coupling" of a signal

Audio amps are often capacitively coupled
- Use capacitor coupling to eliminate dc bias

- Add a voltage divider to apply a desired dc bias

blocks any unwanted dc bias, adds desired dc bias
**Terminology**

- **Time domain**: waveform \( V(t) \)
- **Frequency domain**: dependence of amplitude on frequency

In lecture, we have considered filters in the "freq. domain".

In lab, you will also measure filter performance in "time domain".

Ex. time domain, applying a pulse input to a low pass filter.

```
\[ \text{Input} \quad \text{Output} \]
```

```
\[ t \quad V(t) \]
```
Diodes

Anode Cathode

Recall: positive current flows from a more pos. voltage toward a more neg. voltage.

Diode conduction

"Forward biased" diode conducts

"Reverse biased" diode doesn't conduct
Current-voltage characteristics of diode

Ideal: $I$ vs $V$

Actual: $I$ vs $V$

- $0.6$ volt "diode drop"
- Reverse biased
- Forward biased
Diode Applications

- Rectifier (convert AC to DC)

  **Example:** "Half-Wave Rectifier"

![Half-Wave Rectifier Diagram]

- Circuit diagram showing a diode followed by a load resistor.
- "Clamp" - prevent output from exceeding a certain positive voltage

\[ V_n \]

+5V

\[ R_1 \]

\[ V_\text{out} \]

\[ R_{\text{load}} \]

"Clamp"

- Output voltage cannot exceed \(+5V + 0.6V = +5.6V\) because at higher voltages the diode would conduct and act like a zero resistance in parallel with load.

- \( R_1 \) is a "current limiting resistor" to avoid burning up diode. When diode conducts, typically \( R_1 \) is
- *Diode Limiter* - prevent output from exceeding pos or neg voltage

```
\[ \text{in} \rightarrow R \rightarrow \text{out} \]
```

prevents output from exceeding ±0.6 volt

- *How to burn up a diode*

```
\[ \text{no limiting resistor} \]
```

in forward conduction, diode resistance \( \rightarrow 0 \)

Power dissipated in diode \( \frac{V^2}{0} \rightarrow \infty \)
Types of diodes:

- Signal e.g. 1N914 - for low power use
- Power - for high power supplies

Zener diode

\[ V_{Z} \]

Like an avalanche diode, but with a zener effect:

- Reverse biased
- Forward biased

A zener diode conducts when reverse-biased by more than the "zener voltage."
Zener application: voltage regulator

It produces a steady output voltage when you apply a larger (unsteady) input.

Zener is reverse biased.

Zeners available for various small zener voltages, e.g., 5V.