Outline

- Input/output impedance
- RC circuits
  - Solving honestly!
  - Differentiation/integration
  - Response to sine waves
  - High/low pass filters – probably next week.

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Input/output impedance

- “Impedance” is a fancy word for resistance for now.
  - When capacitors and inductors are introduced, “impedance” will have an expanded meaning.
- $R_{\text{mic}}$ is output impedance of the mic.
- $R_{\text{amp}}$ is input impedance of the amp.

![Input/output impedance diagram]

Volume control

- What is the input impedance of the amp, as seen by the mic?

![Volume control diagram 1]

- What is the output impedance of the mic + volume control, as seen by the internal amp? Assume that “real amp” has no influence on it.

![Volume control diagram 2]

Can you calc $Z_{\text{in}}/Z_{\text{out}}$ for simple circuits?

- To get $Z_{\text{in}}$ one leaves the output open (as is) – in this class!
- What is the resistance between input terminals?
- $Z_{\text{in}} = 10 \, k\Omega$

![Can you calc Z in/Z out diagram]

Another way

- To get $Z_{\text{in}}$ one leaves the output open (as is)
- Imagine connecting a battery of voltage $V$. How much current, $I$, will go into the circuit?
- Then $Z_{\text{in}} = V/I = 10 \, k\Omega$

![Another way diagram]
How about $Z_{\text{out}}$?

- To get $Z_{\text{out}}$ one shorts the input – in this class!
- What is the resistance between output terminals?
- $Z_{\text{in}} = 0 \ \Omega$

Another way to find $Z_{\text{out}}$?

- Connect a battery on the input (instead of shorting – turns out the same)
- When the output is open, output voltage is $V$.
- When $R$ is connected, output is still $V$ and $I = \frac{V}{R}$
  - $R_{\text{TH}} = R * 0 = 0$
  - $Z_{\text{in}} = 0 \ \Omega$

RC circuits

- How do we analyze R circuits?
  - Ohm’s law
  - Kirchhoff’s laws (currents and voltage loops)
- Alternatively,
  - One can use method based on “superposition principle,” and “turn on” one battery at a time.

Realization of Kirchhoff

- Nodal method
  - Voltage of each node (relative to a reference points) is the unknown.
  - This method guarantees that loop voltage don’t need to be concerned.
  - There will be $n$ unknown voltages to be found.
  - There will be $n$ equations arising from $\Sigma I = 0$ at all nodes.

Realization of Kirchhoff II

- Mesh-Loop method
  - Current assigned to each loop guarantees that currents are conserved at each node – current coming into a node always leaves
  - There will be $n$ unknown currents to be found.
  - There will be $n$ equations arising from $\Sigma V = 0$.
- Either method usually involves horrendous algebra to be solved.

What’s Ohm’s Law for “C”?

- What “formula” do you know about capacitors?
  - $Q = C V$.
- Where is the current?
  - $I = dQ/dt$. So if you differentiate the above Eq., we can relate $I$ and $V$.
  - $I = C \frac{dV}{dt}$. 
Once “Ohm’s Law” is known,

- Kirchhoff’s Laws still apply to circuits, and everything is the same.
- Now everything is a function of time, and \( \frac{dV}{dt} \) or \( \int I \, dt \) is involved, so equations will be differential equations, rather than algebra equations.

**Simple RC circuit(s)**

- How many nodes?

![Simple RC circuit](image)

**Call the voltage at the node \( V_i \)**

- \( i_1 = i_2 \), where (main equation for a node)
- \( i_1 = (V_{\text{in}} - V_i)/R \), and
- \( i_2 = C \frac{dV_i}{dt} \).

\* \( i_1 \) and \( i_2 \) are not independent unknowns, but derived from \( V \)'s

![RC circuit diagram](image)

**We end up with this equation:**

- \( (V_{\text{in}} - V_i)/R = C \frac{dV_i}{dt} \)
- \( V_i \) is the only unknown, but
- We need to solve differential equation.
- \( \frac{dV_i}{dt} = (V_{\text{in}} - V_i)/RC \), where \( V_{\text{in}} \) is typically a function of time, \( t \), i.e. \( V_{\text{in}}(t) \).
- General solution is \( V_i = A \, e^{-t/RC} \), and
- Specific solution is \( V_i = \frac{\exp(-t/RC) \int_0^t d\tau \exp(t'/RC) V_{\text{in}}(t')} {RC} \).

**Specific case I**

- \( V_i(t) = 0 \) for \( t < 0 \) and \( = V_0 \) for \( t > 0 \), i.e. step function input.

- Then
  - \( V_i(0) = V_i - A = V_0 \).
  - Assuming that \( V_i(0) = 0 \), \( A = V_0 \).
  - \( V_i(t) = V_0(1 - e^{-t/RC}) \).
- One may not intentionally soften the wedge of a square pulse
- Unwanted capacitance in a circuit may do this to distort pulses.