EE P 538
Analog Circuits for Sensor Systems

Spring 2020

Instructor: Jason Silver, PhD

EE P 538 Basics (1)

- Instructor
  - Jason Silver
  - Office hours Mondays @ 7pm
    - Zoom link: https://washington.zoom.us/j/780472462
- Teaching Assistant
  - Rajendra Surendra Hathwar
  - Office hours (Zoom) TBD
- Web page: https://canvas.uw.edu/courses/1372157/assignments/syllabus
  - Check regularly, especially Discussions
  - Access grades and solutions to assignments and exams
  - Participation in online discussion benefits all

EE P 538 Basics (2)

- Required text
  - P. Horowitz, *The Art of Electronics*, 3rd Ed, Cambridge, 2015.
- Course prerequisites
  - It is essential that you be familiar with:
    - Elemental circuit theory
      - KVL, KCL, Thevenin equivalent circuits, Laplace transforms
    - Semiconductor device operation and circuit analysis
      - Diodes, MOSFETs, BJTs
    - Basic linear systems
      - Frequency response, poles, zeros, Bode plots
    - Circuit simulation using some flavor of SPICE (**S**imulation **P**rogram with **I**ntegrated **C**ircuit **E**mphasis)

About Your Instructor

- PhD from UW EE in 2015
  - Wireless Sensing Lab (PI: Brian Otis)
  - Low power integrated circuit (IC) design for bioelectrical interfaces
    - EEG, EMG, neural recording
  - Focus on optimizing for power efficiency
- 12 years experience designing ICs and systems for academic and industry
  - Mixed-signal design for biomedical applications
- Current work
  - Director of Hardware Development at Nanosurface Biomedical
    - Formerly housed in UW CoMotion startup incubator (Fluke Hall)
    - Instrumentation for *in vitro* cell studies

Course Breakdown

- Weekly Assignments (40%)
  - Assigned Wednesdays, submitted online following Wednesday
  - Scores will decreased by 0.5dB per hour following deadline
- Midterm (25%)
  - “Take home”, open-book, open-notes
  - Timed, 3-4 hours
- Design project (35%)
  - Analog/mixed-signal design project with Python (MATLAB) and LTspice
  - Optimization for performance, power, cost

Software

- We will use LTspice for circuit simulation
  - [LTspice IV Getting Started]
  - You may use other tools "at your own risk"
- Design, data analysis, and results plotting using MATLAB or Python
  - Design scripts iterable and reusable
  - For plotting, more flexible than LTspice native plotting functions
  - MATLAB for UW ECE Students
  - Python for Beginners
  - Lecture examples created using Python
- Ltspice simulation basics will be presented following today's lecture

SPICE Design Methodology

- SPICE is merely a numerical simulation tool that enables you to evaluate your ideas
- Don’t simulate something you don’t already understand
  - SPICE is for verification only!
- Component models have (significant) limitations
  - Neither analytical nor simulation models provide a complete picture of reality
  - Understanding model limitations is critical to building successful circuits and systems

Announcements

- Assignment 1 is posted on Canvas
  - Due April 8 at midnight

Course Learning Goals

- Develop deeper understanding of analog circuit building blocks and how they interface with each other
- Understand factors affecting precision in circuits and systems, and how to optimize wrt to power, cost, complexity, etc.
- Develop a systematic approach to circuit/system design
  - Focus on analysis/scripting early in the design process
  - Employ SPICE to validate calculations and assumptions

Course Topics (loosely)

- Fundamental devices: resistors, capacitors, inductors, opamps, transistors
- Basic opamp gain/filter circuits
  - Sensor interfacing
  - Loading
- Precision in circuits
  - Device noise: flicker and thermal
  - Amplifier offset
  - Temperature effects
- Data converters
  - Sampling fundamentals
  - Quantization noise
- Digital communication (e.g. SPI)

AoE Chapters

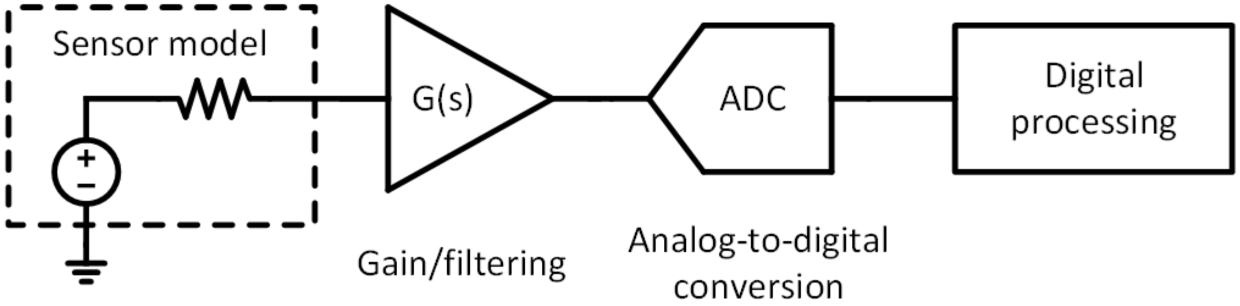
- Chapter 1 - Foundations
- Chapter 2 - Bipolar Transistors
- Chapter 3 - Field-Effect Transistors
- Chapter 4 - Operational Amplifiers
- Chapter 5 - Precision Circuits
- Chapter 6 - Filters
- Chapter 8 - Low-Noise Techniques
- Chapter 9 - Voltage Regulation and Power Conversion
- Chapter 12 - Logic Interfacing
- Chapter 13 - Digital meets Analog

Week 1

- AoE Chapter 1 - Fundamentals/review
- Getting familiar with LTspice
  - Component models
  - DC analysis
  - DC and parameter sweeps
  - AC analysis
  - Transient analysis
  - Exporting data for plotting
- Python/MATLAB
  - Modeling linear circuits/systems
  - Plotting

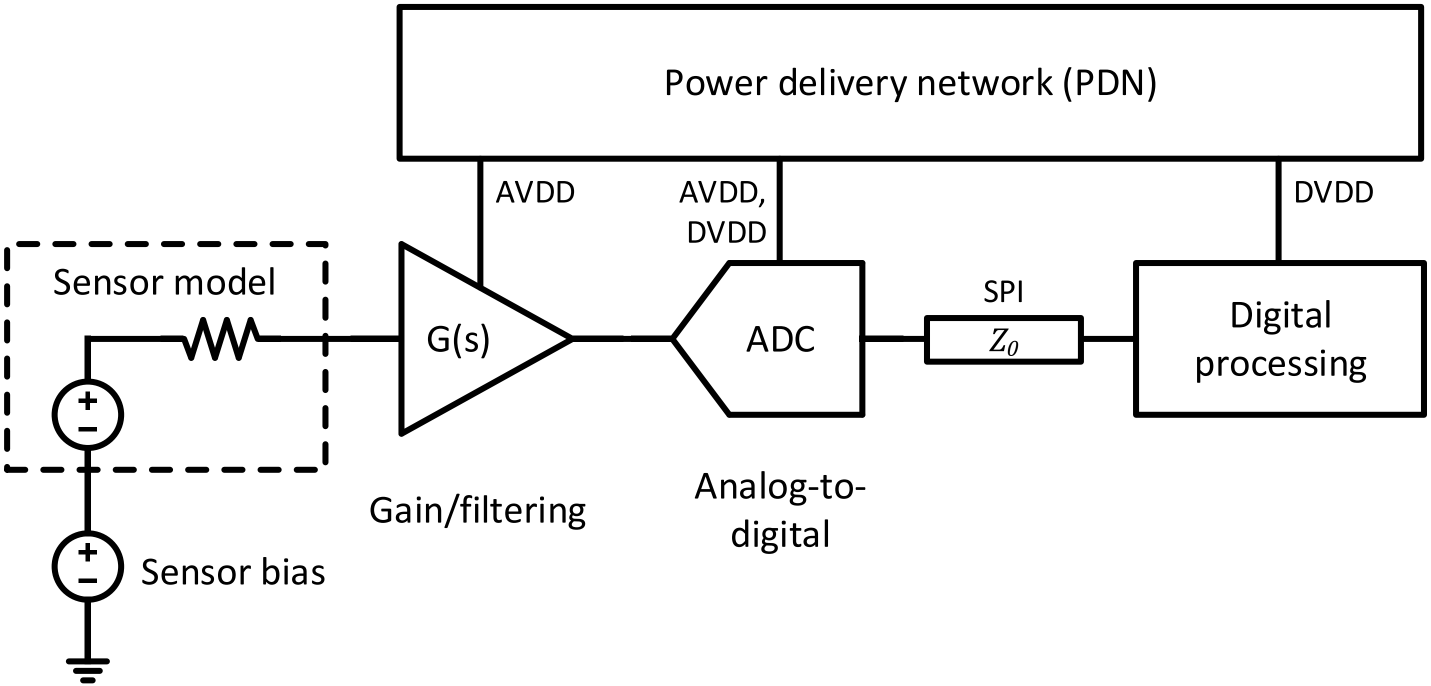
Lecture 1 – Foundations

Sensor Systems

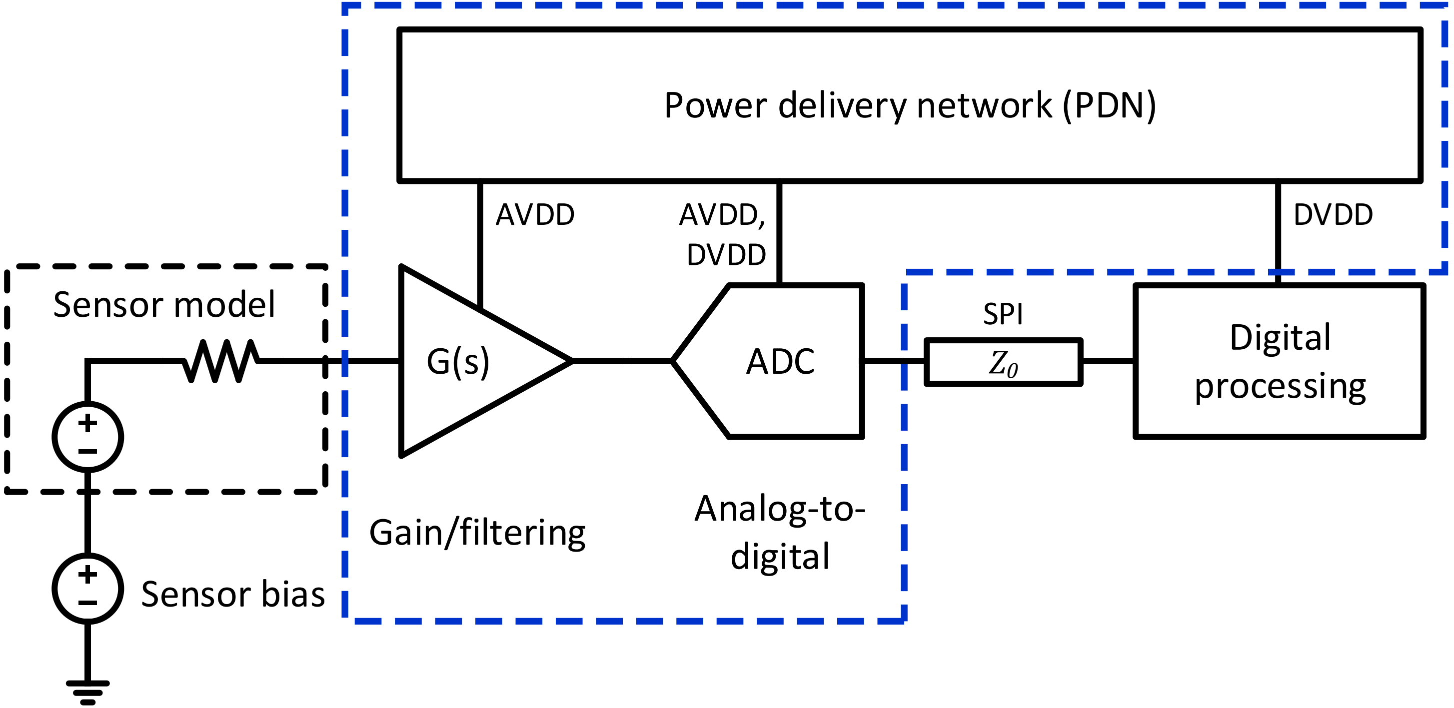


- Recent trend (past few decades) has been to move more and more processing to digital domain
- Analog circuits relegated to sensor interfacing, power delivery
- Still, analog circuits are a performance bottleneck for many systems

Sensor Systems (detailed)



EE 538 Topics



Example: Neural Signal Acquisition

	Action Potentials	**Field Potential**
Amplitude:	< 100 µV	0.5-5mV
Frequency range:	500Hz – 5kHz	< 100Hz

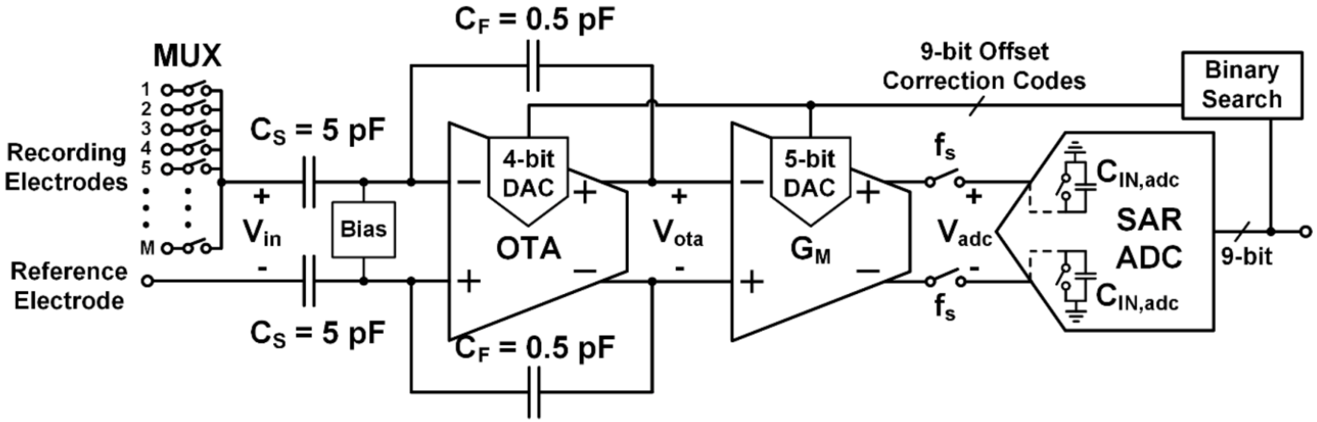
- Neural action potentials have small amplitudes (< 10’s of µV) and require relatively wide acquisition bandwidth (sub-Hz to 5 kHz)
- Local field potentials have large amplitude (mV) and occupy lower frequency range
- Large number of channels required to capture physiologically relevant data

Example: Neural Signal Acquisition

Spec	**Requirement**
HP cutoff:	300 Hz
LP cutoff:	5 kHz
Input noise:	< 2μV
Mid-band gain:	40 – 60 dB

- Wide dynamic range would require a high-performance ADC (> 16 bits), but size and power constraints prohibit this
- LFP and AP signals are separated in frequency, so filtering can help
- Difficult to implement for high channel counts (1000's of electrodes)

Example: Neural Signal Acquisition



- Time-domain multiplexing (TDM) of *M* electrodes to one analog front end (AFE)
- Offset cancelation required, due to modulation of electrode offsets
- Wide bandwidth needed to accommodate TDM increases noise equivalent bandwidth (NEB)

Figure source: Sharma, M., et. al. Acquisition of Neural Action Potentials Using Rapid Multiplexing Directly at the Electrodes. *Micromachines* **2018**, *9*, 477.

Analog Signals

- Analog signals are typically described as single sinusoids or as sums of sinusoids
- For example:

$$V(t) = \mathrm{A} \cdot \sin 2\pi f t$$

where A is the amplitude and f is the frequency in hertz

- Another common specification of sinusoidal (as well as other) signals is the root-mean-square (rms) amplitude, defined as the *square root* of the *mean square*

$$v_{rms} = \sqrt{\frac{1}{T_2 - T_1} \int_{T_1}^{T_2} [V(t)]^2 dt}$$

Decibels

- When comparing relative amplitudes of sinusoids or signals where such ratios may be large, it is often convenient to use a logarithmic measure
- Enter the decibel:

$$\mathrm{dB} = 10\log_{10}\frac{P_2}{P_1},$$

  where P_1 and P_2 represent the power in the two signals.
- For comparing amplitudes, we have

$$\mathrm{dB} = 20\log_{10}\frac{A_2}{A_1}$$

Linearity

- A linear circuit (or system) has the property that its output, when driven by the sum of two input signals, equals the sum of its individual outputs when driven by each signal independently
- When a linear circuit is “driven” by a sinewave, its output is a sinewave

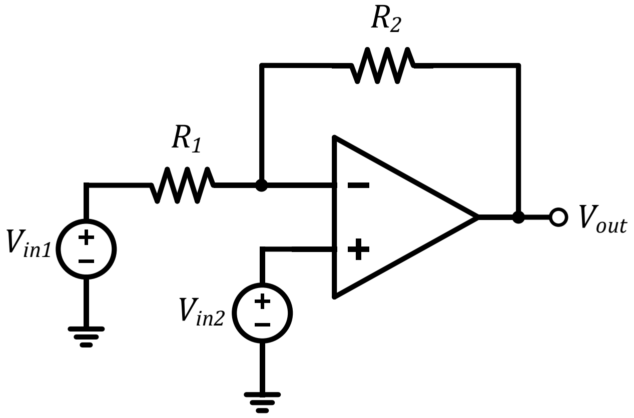
$$V_{in} = A\sin 2\pi f_0 t \rightarrow V_{out} = B\sin 2\pi f_0 t$$

- When a linear circuit is driven by a linear sum of sinewaves, its output is a linear sum of sinewaves

$$V_{in} = A_1\sin 2\pi f_1 t + A_2\sin 2\pi f_2 t$$

$$V_{out} = B_1\sin 2\pi f_1 t + B_2\sin 2\pi f_2 t$$

Superposition



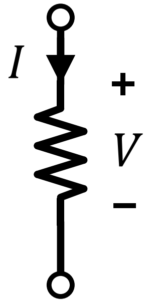
$$V_{out1} = A_1 V_{in1} \qquad V_{out2} = A_2 V_{in2}$$

$$V_{out} = V_{out1} + V_{out2} = A_1 V_{in1} + A_2 V_{in2}$$

$$V_{out} = -\frac{R_2}{R_1} V_{in1} + \left(1 + \frac{R_2}{R_1}\right) V_{in2}$$

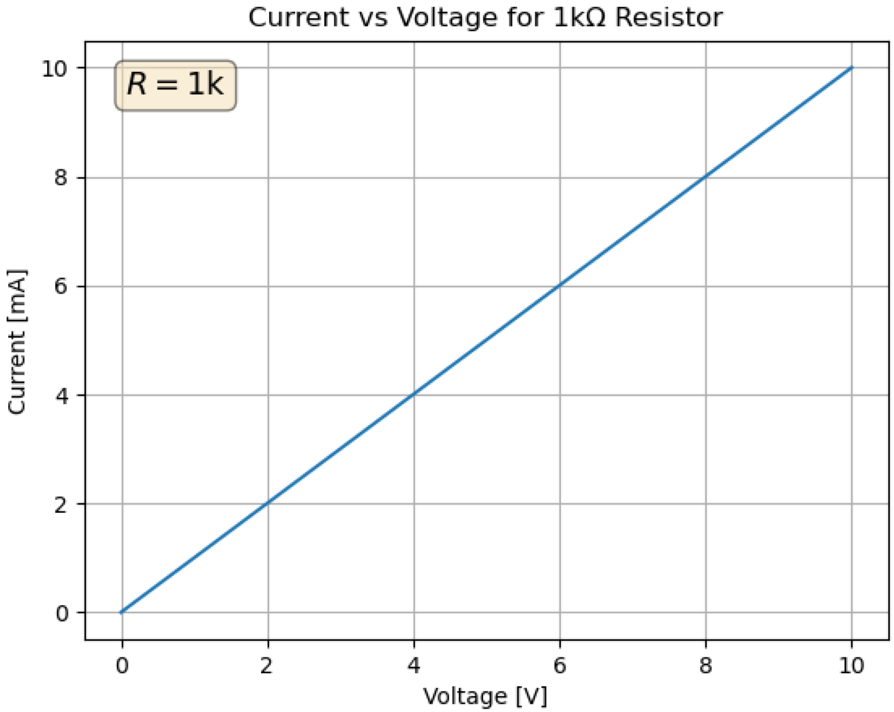
- Response of circuit (V_{out}/V_{in}) to *individual inputs* can be determined independent *all other* inputs/outputs
- Response of circuit to *all inputs* computed as the sum of individual responses

Resistance

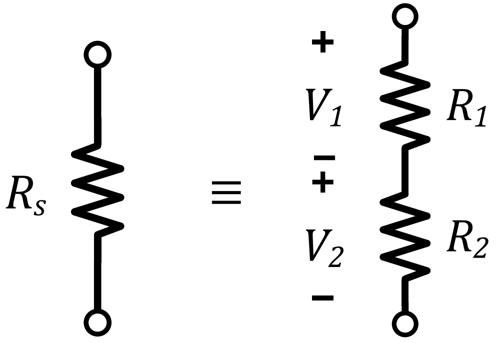


$$V = IR$$

$$R = \frac{V}{I}$$



Series/Parallel Resistances



$$V_s = V_1 + V_2$$

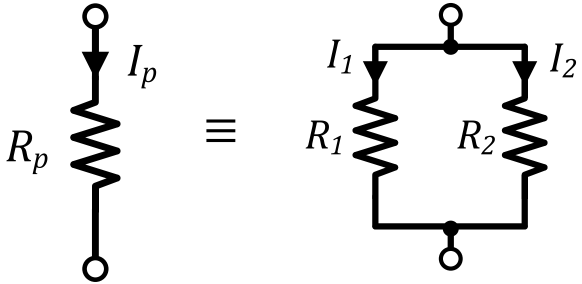
$$R_s = R_1 + R_2$$

Series Resistances

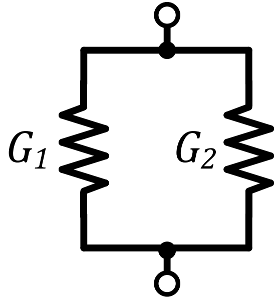
$$I_p = I_1 + I_2$$

Parallel Resistances

$$R_p = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2}} = \frac{R_1 R_2}{R_1 + R_2}$$



Conductance



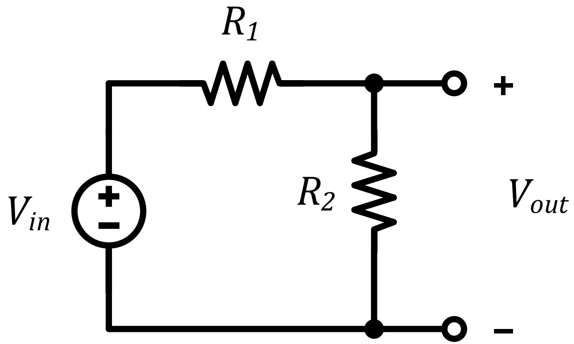
$$G = \frac{1}{R}$$

$$G_p = G_1 + G_2 = \frac{1}{R_1} + \frac{1}{R_2}$$

$$R_p = \frac{1}{G_p} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2}} = \frac{R_1 R_2}{R_1 + R_2}$$

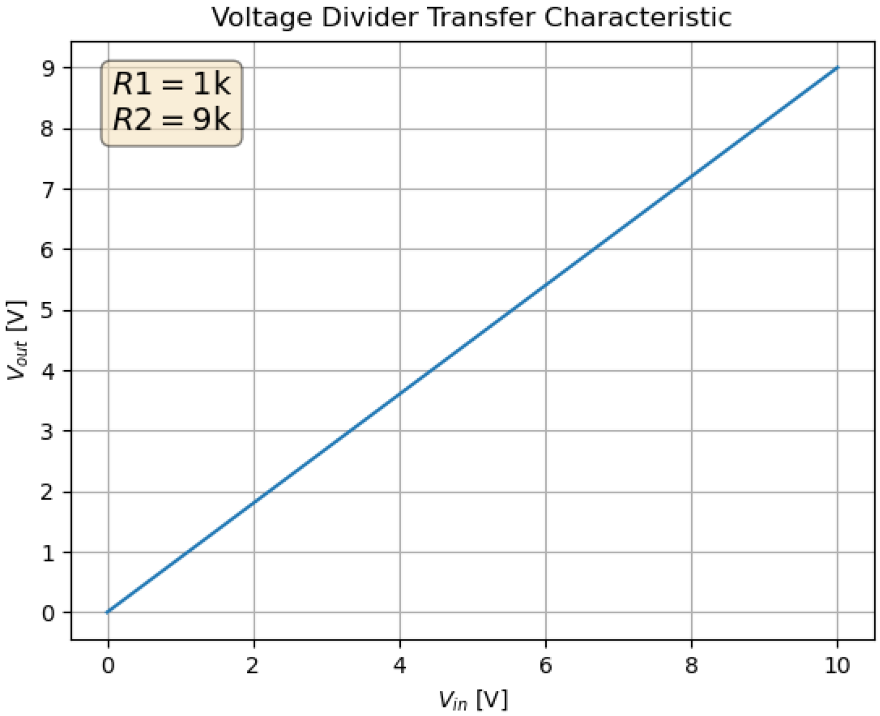
- Parallel conductances sum together
- Units of conductance are S = $1/\Omega$ (siemens) or “mhos” (ohms spelled backwards)
- Use conductance instead of resistance when it’s convenient

Voltage Divider

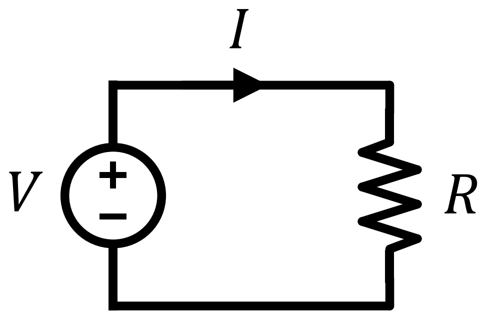


$$I_{R1} = I_{R2} = \frac{V_{in}}{R_1 + R_2}$$

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



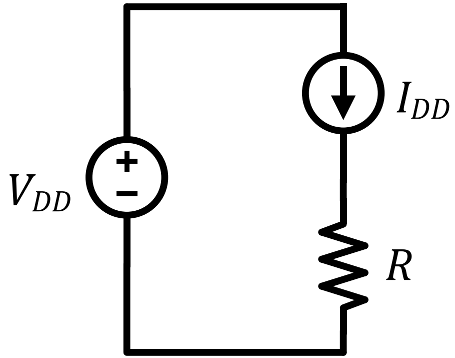
Power Dissipation (1)



$$P = V \cdot I = V\frac{V}{R} = \frac{V^2}{R} = (IR) \cdot R = I^2 R$$

- Circuits dissipate energy in the form of heat generated in resistors, diodes, and transistors
- Ideal inductors and capacitors don’t dissipate energy, they merely store it

Power Dissipation (2)



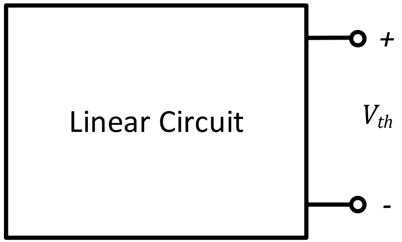
$$P = V_{DD} I_{DD}$$

$$I_{DD} R < V_{DD}$$

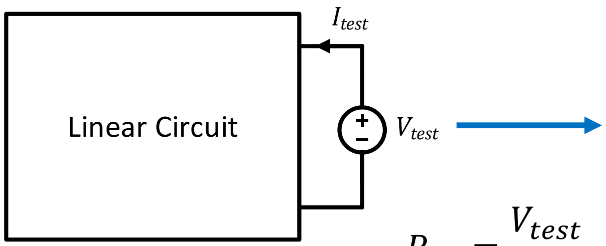
- Most linear analog circuits are current biased (more on this later)
- Many performance metrics (e.g. noise, bandwidth) depend on current
- Thus, there is a tradeoff between performance and power

Thevenin Equivalent

Thevenin voltage

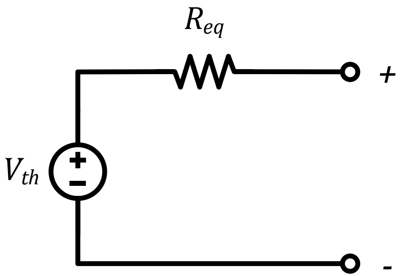


Equivalent resistance



$$R_{eq} = \frac{V_{test}}{I_{test}}$$

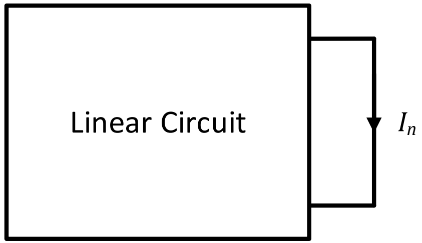
Thevenin model



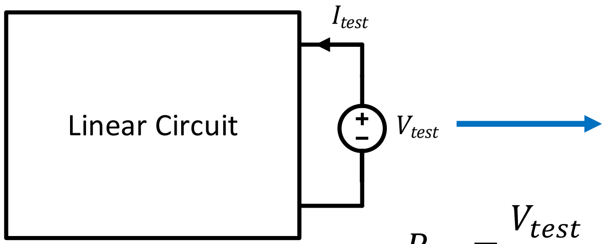
- Thevenin voltage determined by measuring the *open-circuit* (unloaded) voltage
- Equivalent resistance determined by applying a test voltage (or current) and measuring the resulting current (or voltage)

Norton Equivalent

Norton current

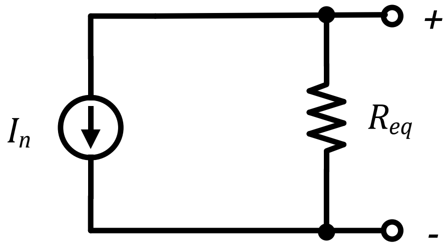


Equivalent resistance



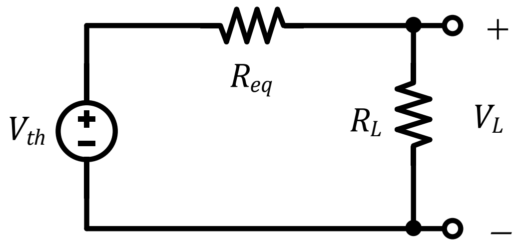
$$R_{eq} = \frac{V_{test}}{I_{test}}$$

Norton model



- Norton current determined by measuring the *short-circuit* (fully loaded) current
- Equivalent resistance same as in Thevenin model

Voltage Sources

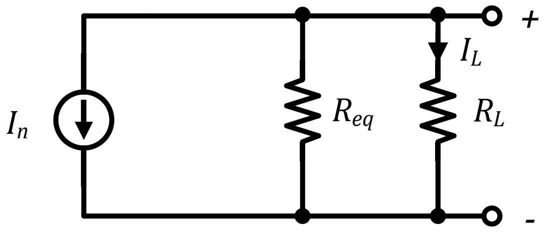


$$V_L = \frac{R_L}{R_L + R_{eq}} V_{th}$$

$$R_{eq} \to 0, V_L \to V_{th}$$

- For an ideal voltage source, $V_L = V_{th}$, regardless of the value of R_L
- This translates to *zero* source resistance ($R_{eq} \to 0$)
- For practical (real) voltage sources, R_{eq} can be made small (mΩ's) but never quite zero

Current Sources

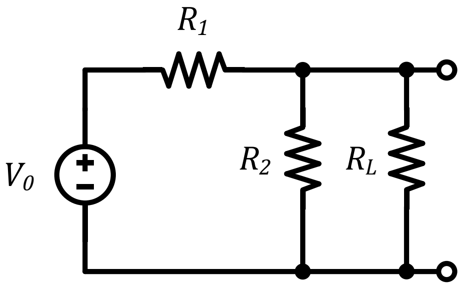


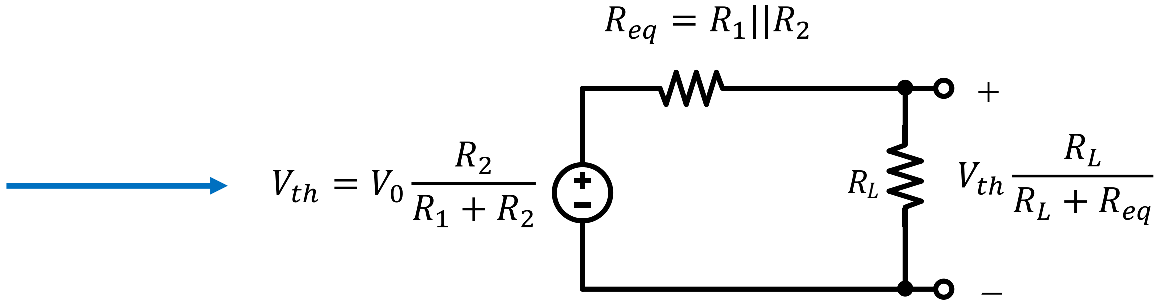
$$I_L = \frac{R_{eq}}{R_L + R_{eq}} I_n$$

$$R_{eq} \rightarrow \infty, I_L \rightarrow I_n$$

- For an ideal current source, $I_L = I_n$, regardless of the value of R_L
- This translates to *infinite* source resistance ($R_{eq} \rightarrow \infty$)
- For practical (real) current sources, R_{eq} can be made quite large ($\mathrm{M}\Omega$'s) but never inifinite

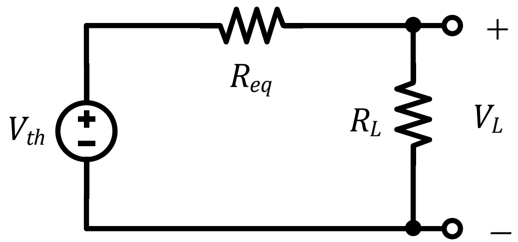
Circuit Loading





- Construct the Thévenin equivalent circuit, then determine the effect of load resistance on the output by voltage division
- Large resistances have little effect, while small resistances “load” the original voltage divider
- Ensure that R_L >> R_{eq} to minimize attenuation

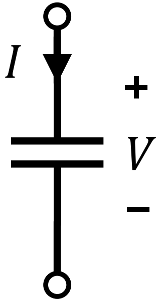
Power Transfer



$$P_L = \frac{\left(\frac{R_L}{R_{eq}+R_L} V_{th}\right)^2}{R_L} = \frac{R_L {V_{th}}^2}{\left(R_{eq}+R_L\right)^2} \le \frac{{V_{th}}^2}{4R_{eq}}$$

- In RF and power delivery systems, the goal is often to maximize power (not voltage) delivered to the load resistance
- This is done by ensuring that $R_L = R_{th}$
- For most circuits, however, minimizing voltage attenuation is key

Capacitors (1)



$$Q = CV$$

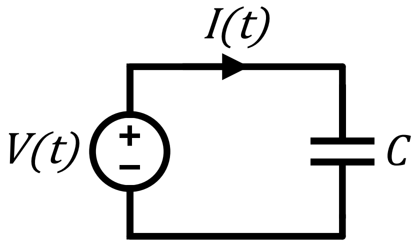
Energy: $$U_C = \frac{1}{2} C V^2$$

Time domain: $$I = C \frac{dV}{dt}$$

Frequency domain: $$Z_C = \frac{V}{C} = \frac{1}{j\omega C}$$

- Ideal (lossless) capacitors store energy in the form of electric fields
- *Phase shift*: Capacitor current "leads" voltage (voltage lags current)

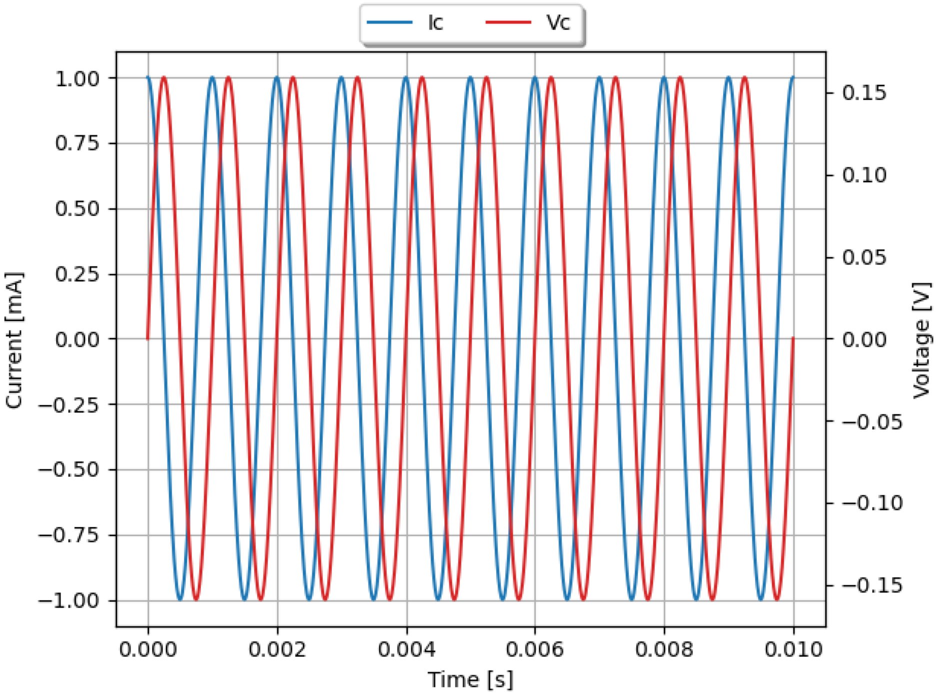
Capacitors (2)



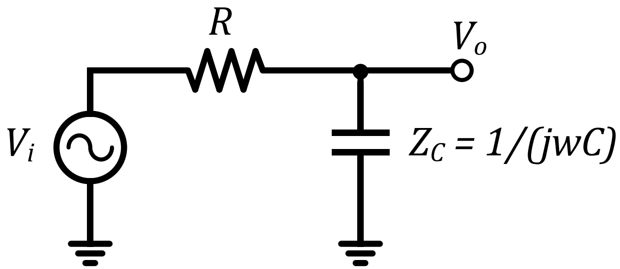
$$V(t) = V_0 \sin \omega t \qquad I(t) = C\frac{dV}{dt}$$

$$I(t) = C\frac{dV}{dt} = C\omega V_0 \cos \omega t$$

$$I = \frac{V}{1/\omega C} \qquad |Z| = \frac{V}{I} = \frac{1}{\omega C}$$



Lowpass Filter



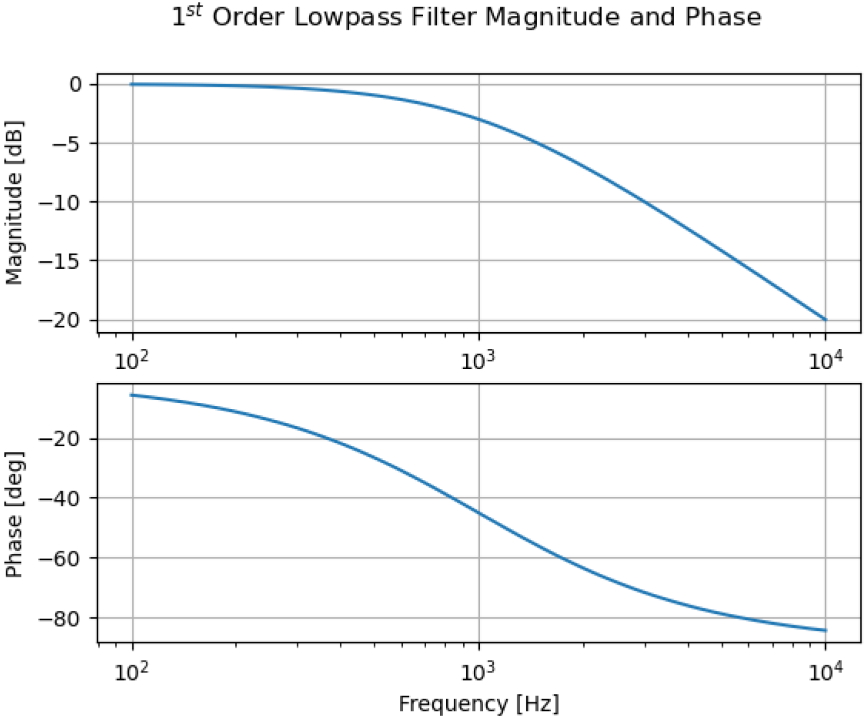
$$V_o = \frac{Z_C}{Z_C + R} V_i = \frac{1}{1 + j\omega RC} V_i = \frac{1}{1 + j\omega\tau} V_i$$

- Lowpass filter used for anti-aliasing, noise limiting
- *Frequency domain*: "Gain" is unity at DC, pole at $1/\tau$ rad/s
- *Time domain*: "Slow" signals pass directly to output, "fast" signals are attenuated

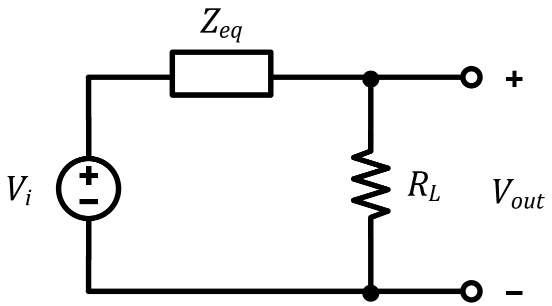
LPF Frequency Response

$$\left|\frac{V_o}{V_i}(j\omega)\right| = \frac{1}{\sqrt{1+(\omega\tau)^2}}$$

$$\angle\frac{V_o}{V_i}(j\omega) = -\tan^{-1}\omega\tau$$



LPF Loading

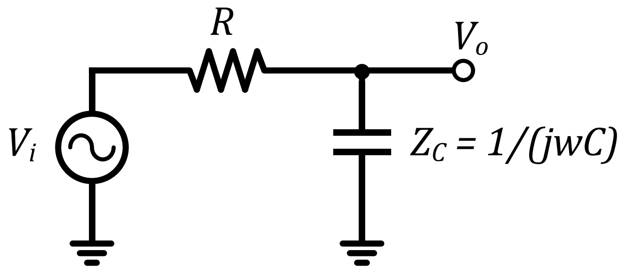


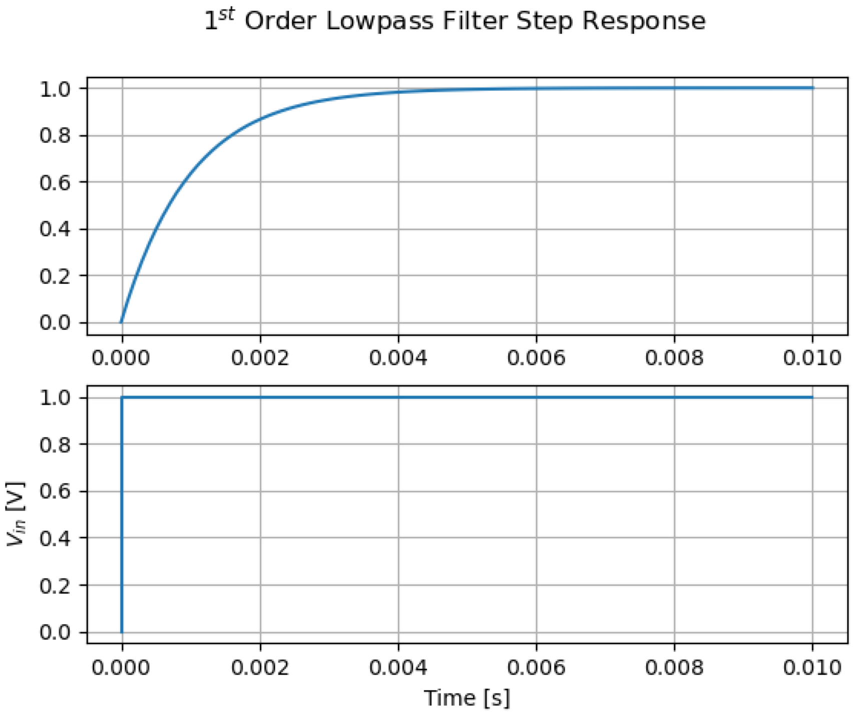
$$V_{out} = \frac{R_L}{R_L + Z_{eq}} V_i$$

$$Z_{eq} = \frac{R}{1 + j\omega RC} \leq R$$

- Equivalent impedance of the LPF consists of R and C in parallel
- As frequency increases, Z_{eq} decreases
- Worst-case loading condition determined by R

LPF Transient Response





Laplace domain: $$V_o(s) = \frac{1}{1 + sRC} U(s)$$

Time domain: $$v_o(t) = u(t)(1 - e^{\frac{-t}{\tau}})$$

Settling Time

Settling error:

$$v_{error} = 1 - e^{\frac{-t_{settle}}{\tau}}$$

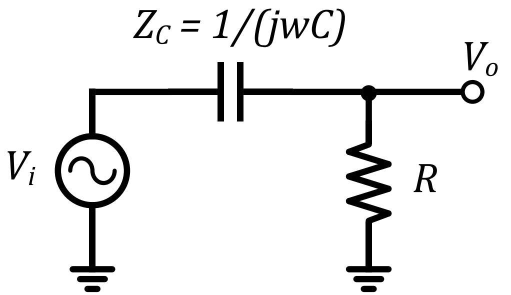
1% precision: $t_{settle} \geq -\ln 0.01 \approx 4.6\tau$

0.1% precision $t_{settle} \geq -\ln 0.001 \approx 6.9\tau$

0.01% precision: $t_{settle} \geq -\ln 0.0001 \approx 9.2\tau$

- The precision of sampled circuits (e.g. ADCs) depends on the amount of time allocated to transient settling
- Thus, there is an inherent tradeoff between speed and precision
- Higher speed translates to wider bandwidth and higher power dissipation, indicating a tradeoff between power and precision

Highpass Filter



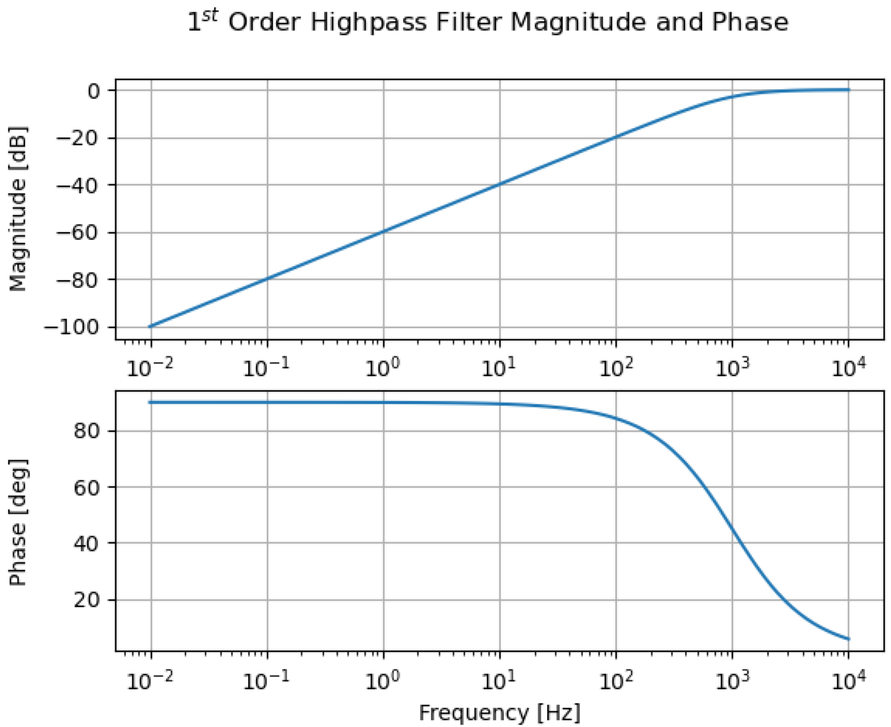
$$V_o = \frac{R}{Z_C + R} V_i = \frac{j\omega RC}{1 + j\omega RC} V_i = \frac{j\omega\tau}{1 + j\omega\tau} V_i$$

- Highpass filter (HPF) typically used for AC coupling (DC blocking)
- *Frequency domain*: Zero at DC, pole at $1/\tau$
- *Time domain*: “Fast” signals pass directly to output, “slow” signals are attenuated

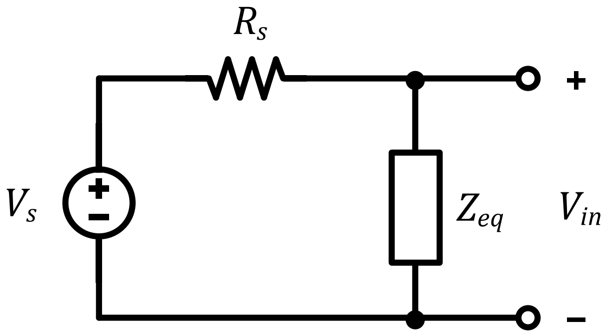
HPF Frequency Response

$$\left|\frac{V_o}{V_i}(j\omega)\right| = \frac{\omega\tau}{\sqrt{1+(\omega\tau)^2}}$$

$$\angle\frac{V_o}{V_i}(j\omega) = 90° - \tan^{-1}\omega\tau$$



HPF Loading

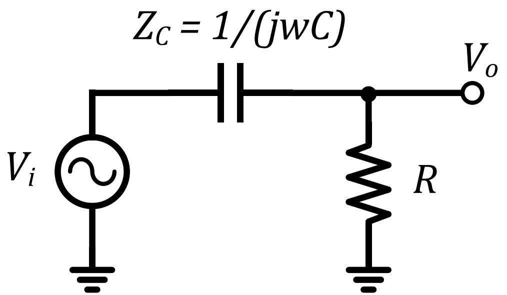


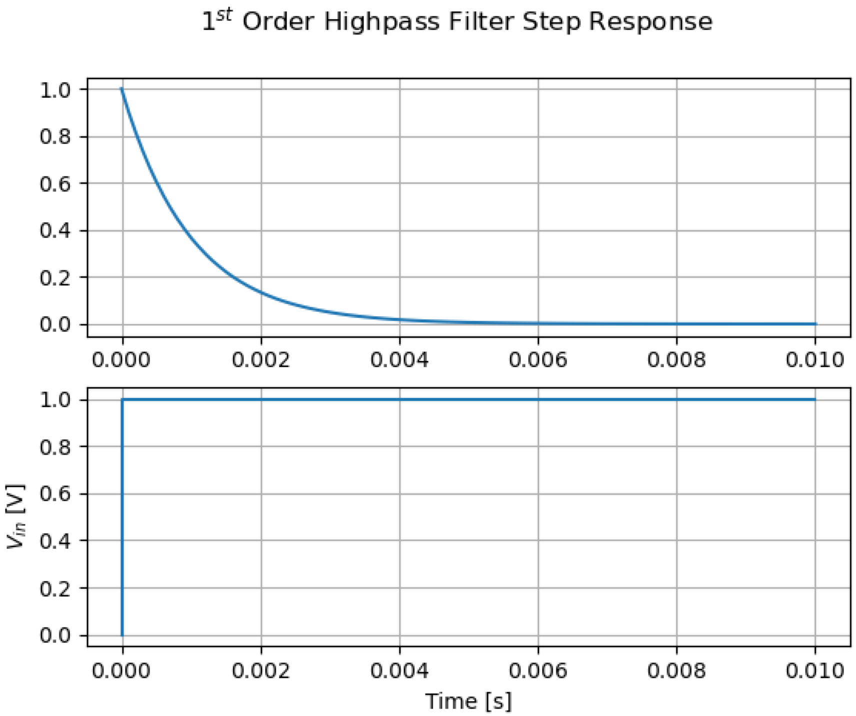
$$Z_{eq} = R + \frac{1}{j\omega C}$$

$$V_{in} = \frac{Z_{eq}}{R_s + Z_{eq}} V_i$$

- Impedance "looking into" HPF very high ($\rightarrow \infty$) at low frequencies
- As with LPF, Z_{eq} decreases with increasing frequency
- Worst case loading of driving stage (V_s, R_s) is again just equal to R

HPF Transient Response





Laplace domain: $$V_o(s) = \frac{sRC}{1 + sRC} U(s)$$

Time domain: $$v_o(t) = u(t)\, e^{\frac{-t}{\tau}}$$