Signal and Amplifier Basics

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* Most figures and examples are from the course textbook "Microelectronic Circuits" by Adel S. Sedra and Kenneth C. Smith, 6th Edition, © 2010 by Oxford University Press, Inc.

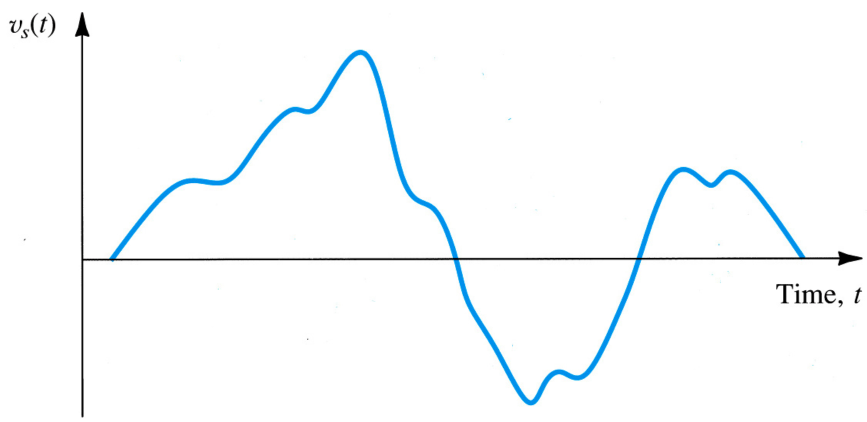
Outline

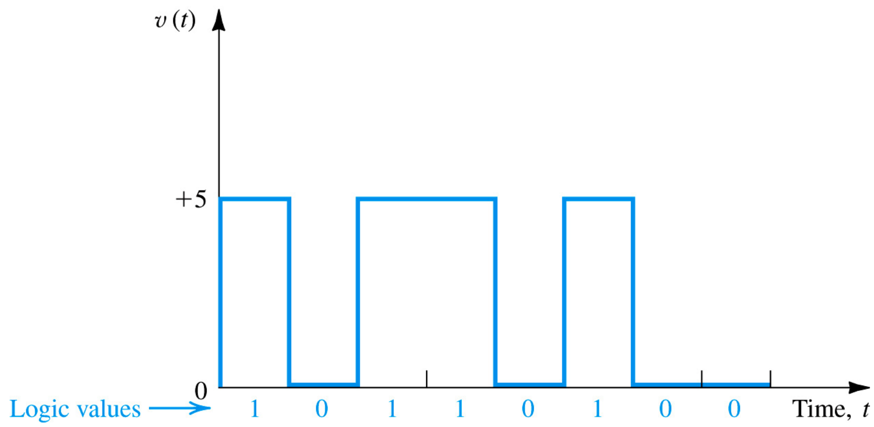
- Signal basics
  - What is a signal?
  - Different types of signals
    - Voltage and current, sound, light, etc.
    - Analog vs Digital representations
  - Thevenin and Norton signal models
  - Frequency spectrum of signals
  - Signal processing
- Amplifier basics
  - Voltage amplifiers
  - The 4 different types of amplifiers
  - Thevenin and Norton amplifier models
  - Frequency response
- Summary of key concepts

What is a signal?

- In its most basic form, a signal is something (anything!) that carries information. Examples include :
  - Sound: doorbells, car horns, telephones, etc.
  - Light: elevator indicators, traffic lights, videos, etc.
- Electrical systems typically use voltages and currents to carry information (but not always!)
  - e.g., fiber optic networks use light to transfer information
- Sensors and transducers change the form of a signal
  - Sensors change temperature, air pressure, etc., into voltages
  - Microphones change sounds into voltages
  - Speakers change voltages into sounds
- But, not everything is a signal!
  - e.g., traffic noise, DC supply voltages are not signals

Analog vs Digital signals

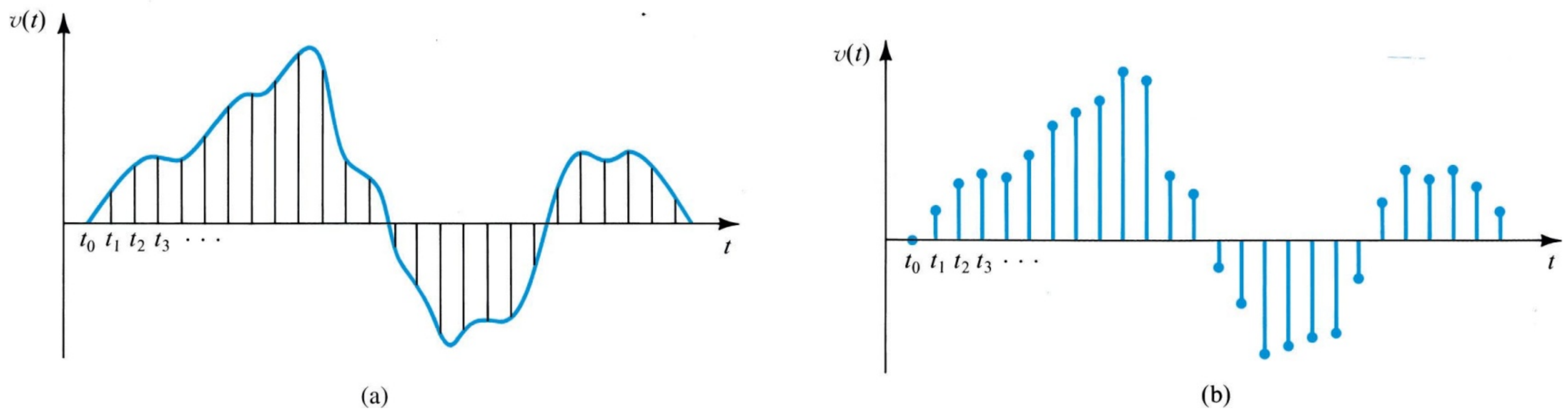




- Analog signals are continuous in both value and time. They can be any value, at any time. (e.g., an analog clock)

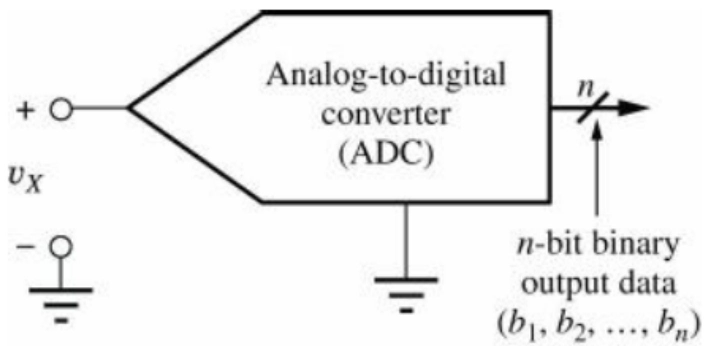
- Digital signals are discrete in both value and time. They can only be certain fixed values, and can only change at fixed times.

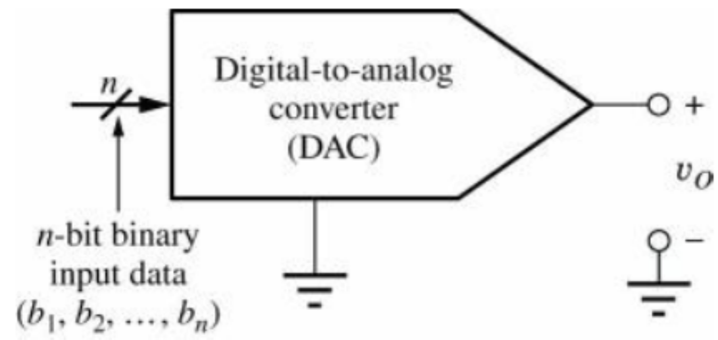
Analog vs Digital signals



- Analog signals like the voltage above can be sampled at regular times and converted to digital representations.
- Digital signals used to represent analog signals can be discrete in time, value, or both. (So information is lost!)

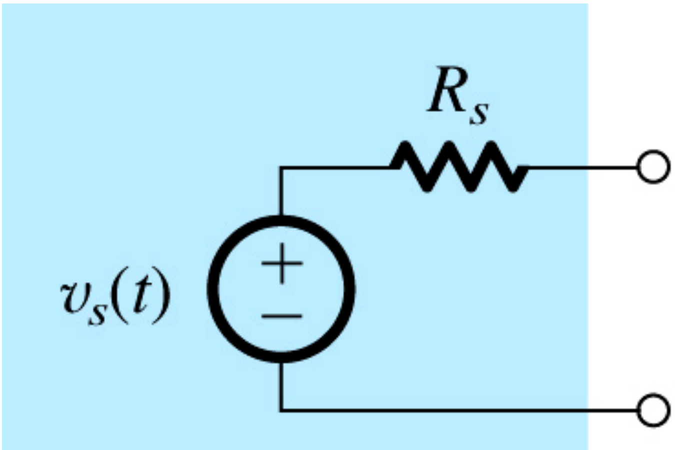
Analog vs Digital signals





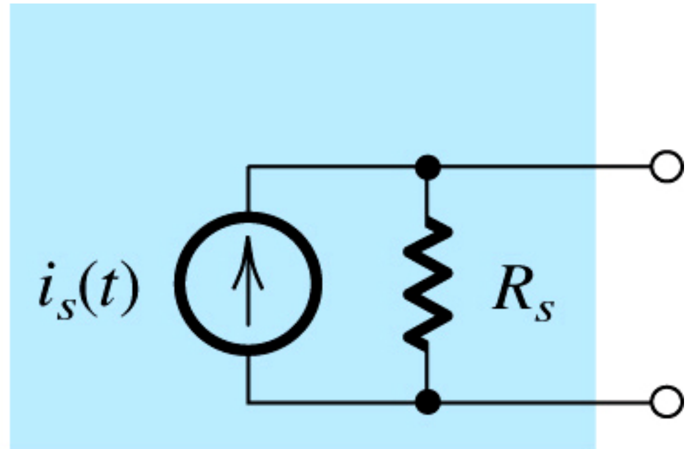
- Analog-to-digital converters (ADCs) are used to convert analog signals into digital signals. (Some information is lost!)
- Digital-to-analog converters (DACs) are used to convert digital signals into analog signals. (No information is lost)

Analog Voltage, Current Signal Models



(a)

$$v_s(t) = R_s\, i_s(t)$$

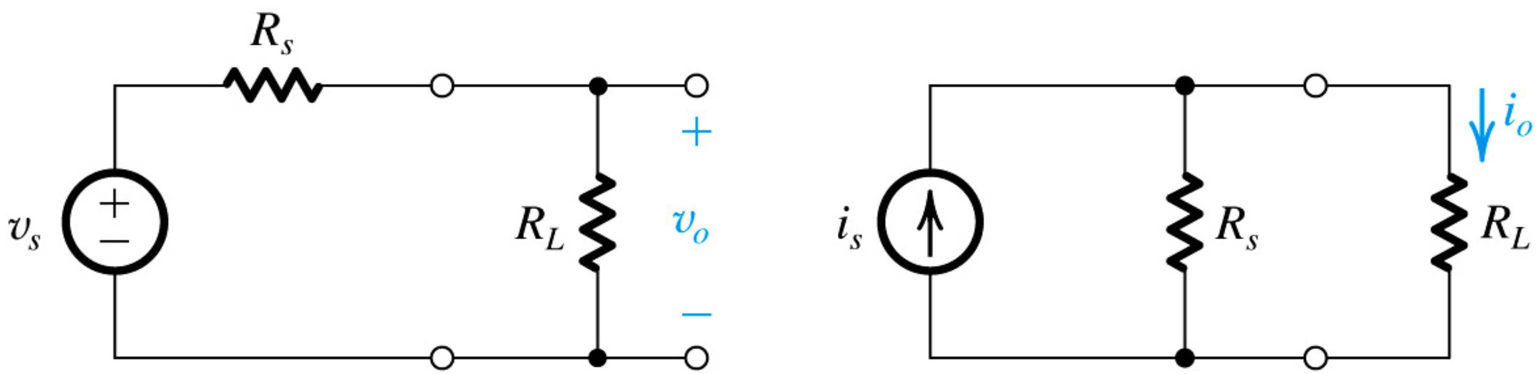


(b)

- Voltages signals are usually modeled with a Thevenin's equivalent
  - R_s is used to model the source resistance
- Current signals are usually modeled with a Norton's equivalent
  - R_s is used to model the source resistance

Analog Voltage, Current Signal Models

Some signal is lost when a load is connected !



(a) (b)

$$v_o = v_s \frac{R_L}{R_L + R_S}$$

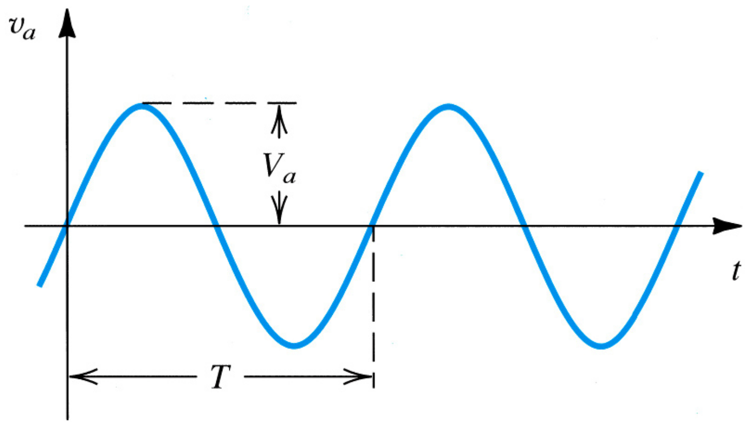
$$\Rightarrow v_o \approx v_s \quad If \; R_S << R_L$$

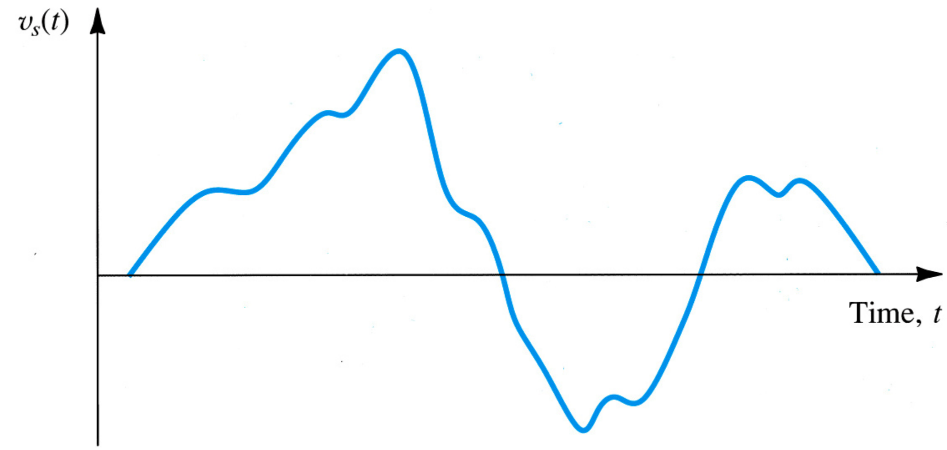
$$i_o = i_s \frac{R_S}{R_L + R_S}$$

$$\Rightarrow i_o \approx i_s \quad If \; R_S >> R_L$$

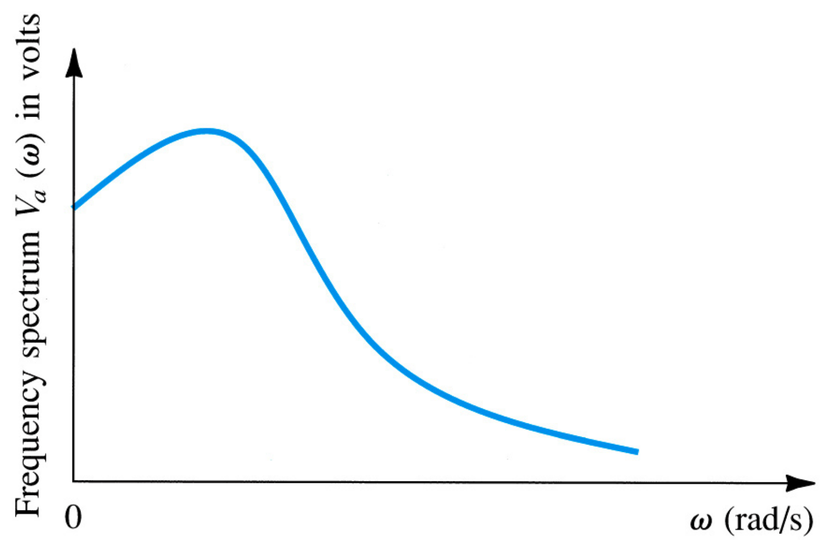
Need small *R*$_S$ for voltages! **Need large *R*$_S$ for currents!**

Frequency Spectrum of Signals





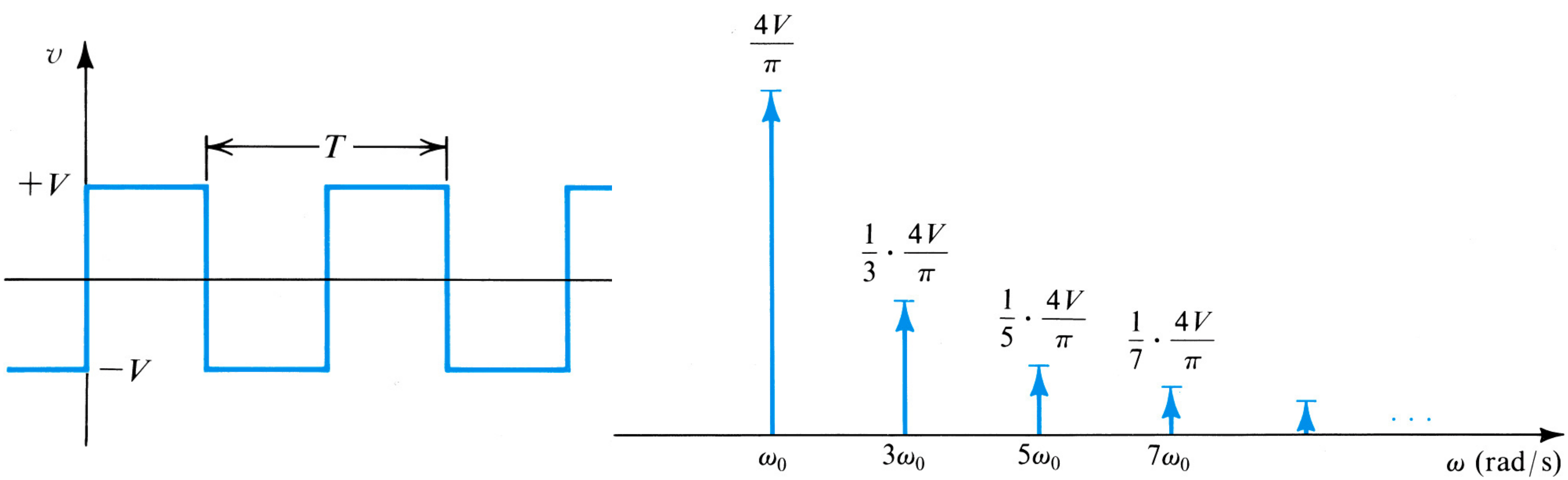
- Sine waves only have a single frequency, $f = 1/T$ (or, $\omega = 2\pi f = 2\pi/T$)
- Arbitrary signals consist of many frequencies!
- Any signal can be written as a series of sine waves using Fourier analysis!



Frequency Spectrum of Signals

- For example, a symmetric square wave with period = T and amplitude = V can be written as a Fourier series :

$$v(t) = \frac{4V}{\pi}(\sin \omega_0 t + \tfrac{1}{3}\sin 3\omega_0 t + \tfrac{1}{5}\sin 5\omega_0 t + \cdots)$$

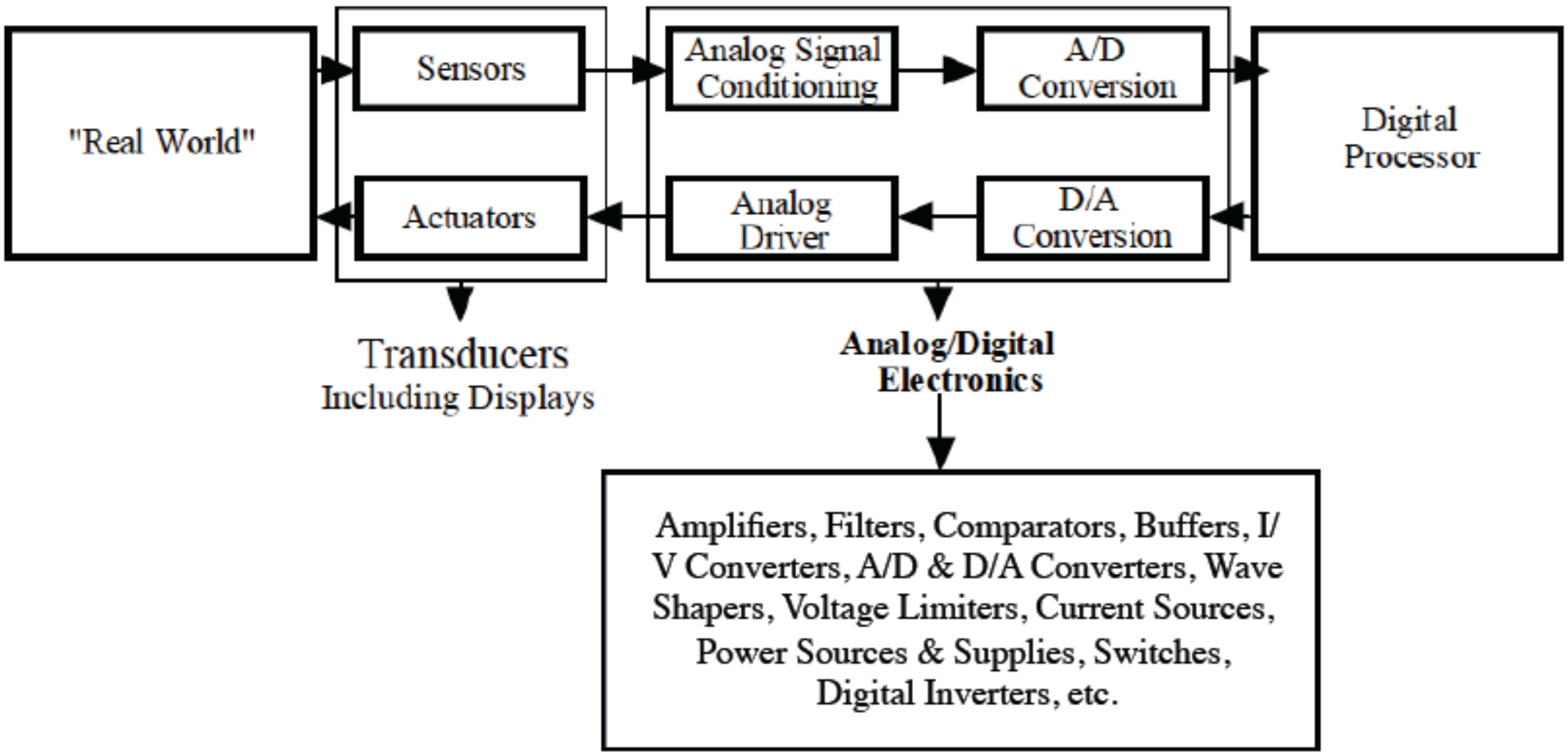


- Signals exist in both the **time and frequency domains**!
- The higher frequency **harmonics** are at frequencies which are integer multiples of the **fundamental frequency**

Signal Processing

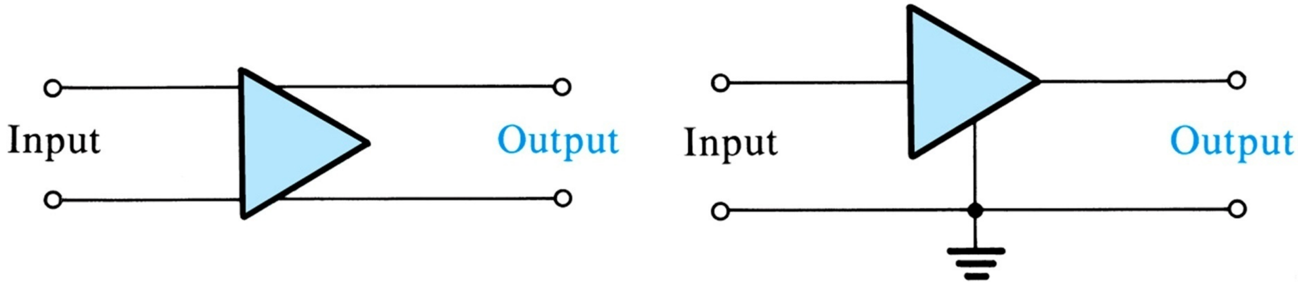
- Much of electronics focuses on the use of transistors (diodes, BJTs and MOSFETs) to create circuits which process either analog or digital signals, in either the time domain or frequency domain
- Common signal processing functions include :
  - **Amplifiers** make the signal larger (in voltage, current, or power)
  - **Filters** select some signals and reject others, often based on frequency content (low pass, high pass, bandpass, notch filters)
  - **Data converters** (ADCs and DACs) convert signals from analog to digital representations, or from digital to analog
- Other common functions performed by electronic circuits are converting voltages from AC to DC (Power supplies), creating clocks for digital circuits (Phase-Locked Loops), and comparing analog signals (Comparators)

Example of an Electronic System*



* Courtesy of Professor John Oldenburg (CSUS EEE, retired)

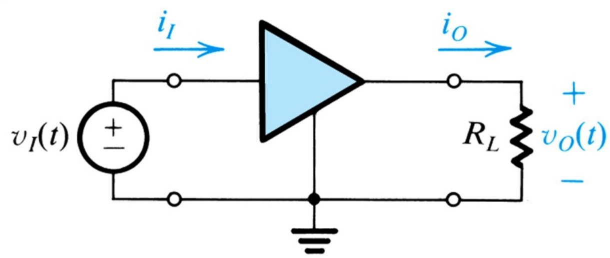
Amplifier Basics



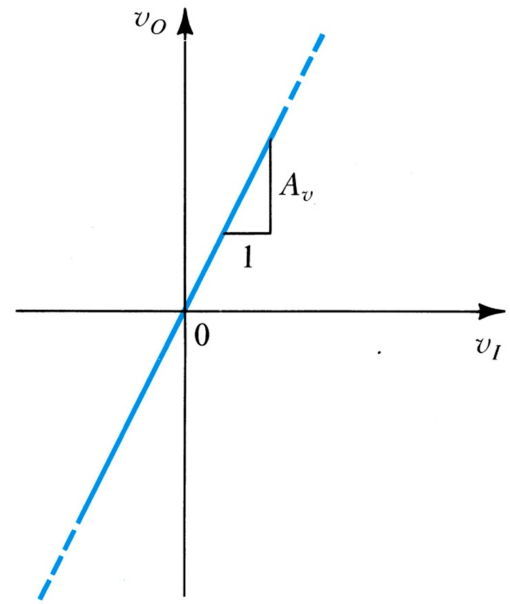
(a) (b)

- Amplifiers provide **gain** to make signals bigger!
  - Signals are usually voltage, current, or power
- Signals are typically measured between 2 terminals
  - **Single-ended amplifiers** measure signals between a single terminal and a power supply (usually ground)
  - **Differential amplifiers** measure signals as the difference between 2 single-ended signals
  - Amplifiers can also use a mix of these techniques (e.g., differential inputs, single-ended outputs)

Different types of amplifier gain



(a)



(b)

<u>Amplifiers can provide different types of gain :</u>

- **Voltage gain** : $A_v = v_o/v_i$ = the slope of a plot of v_o vs v_i
- **Current gain** : $A_i = i_o/i_i$ = the slope of a plot of i_o vs i_i
- **Power gain** : $A_P = P_L/P_i = (v_o \cdot i_o)/(v_i \cdot i_i)$

Expressing Gain in Decibels

Gain is also often expressed in Decibels, or "dB" :

- Voltage gain in decibels = 20 $\log_{10}(|A_V|)$ dB (units = dB)
- Current gain in decibels = 20 $\log_{10}(|A_i|)$ dB (units = dB)

and since power is related to voltage or current squared :
Power = V^2/R or Power = I^2R →

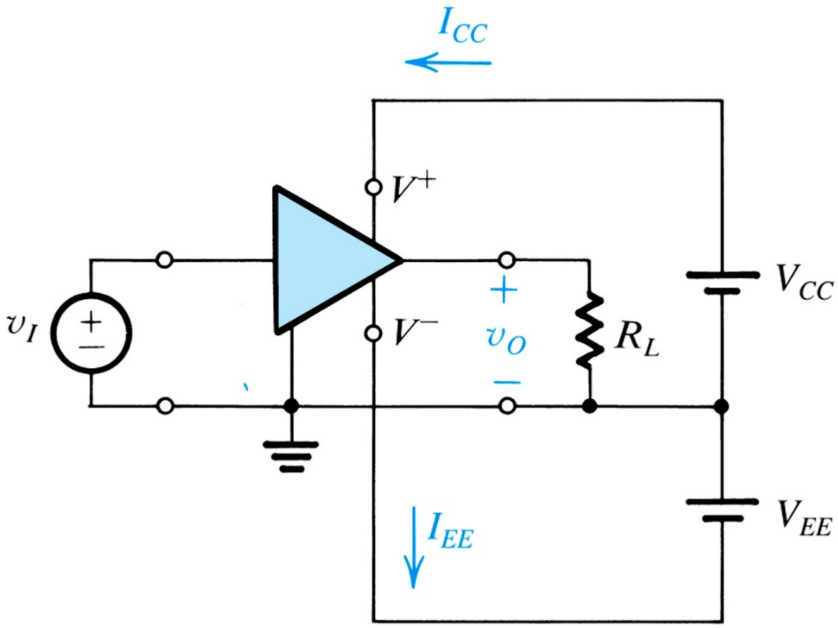
- Power gain in decibels = **10** $\log_{10}(|A_P|)$ dB (units = dB)

(Recall trig identity : $\log(A^x) = x \log(A)$)

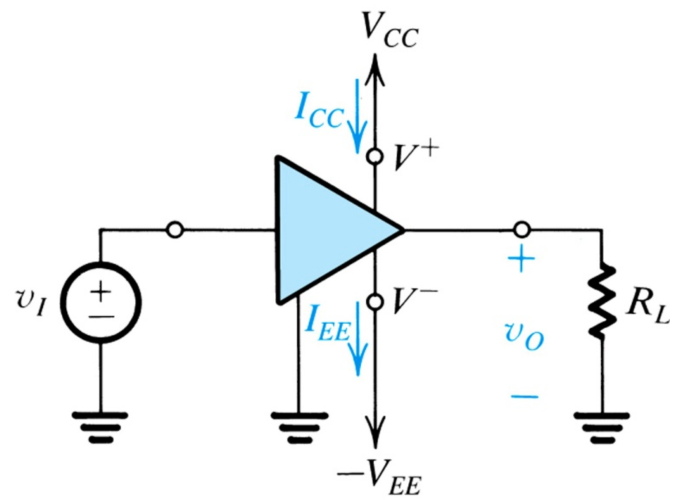
Note the use of the absolute value here, since a negative gain implies a phase shift of 180°, not that the magnitude of the gain is < 1 !

(Useful Tip: +20dB → 10x increase in V or I, -20dB → 10x decrease)
+6dB → 2x increase in V or I, -6dB → 2x decrease

Amplifier Power Supplies



(a)



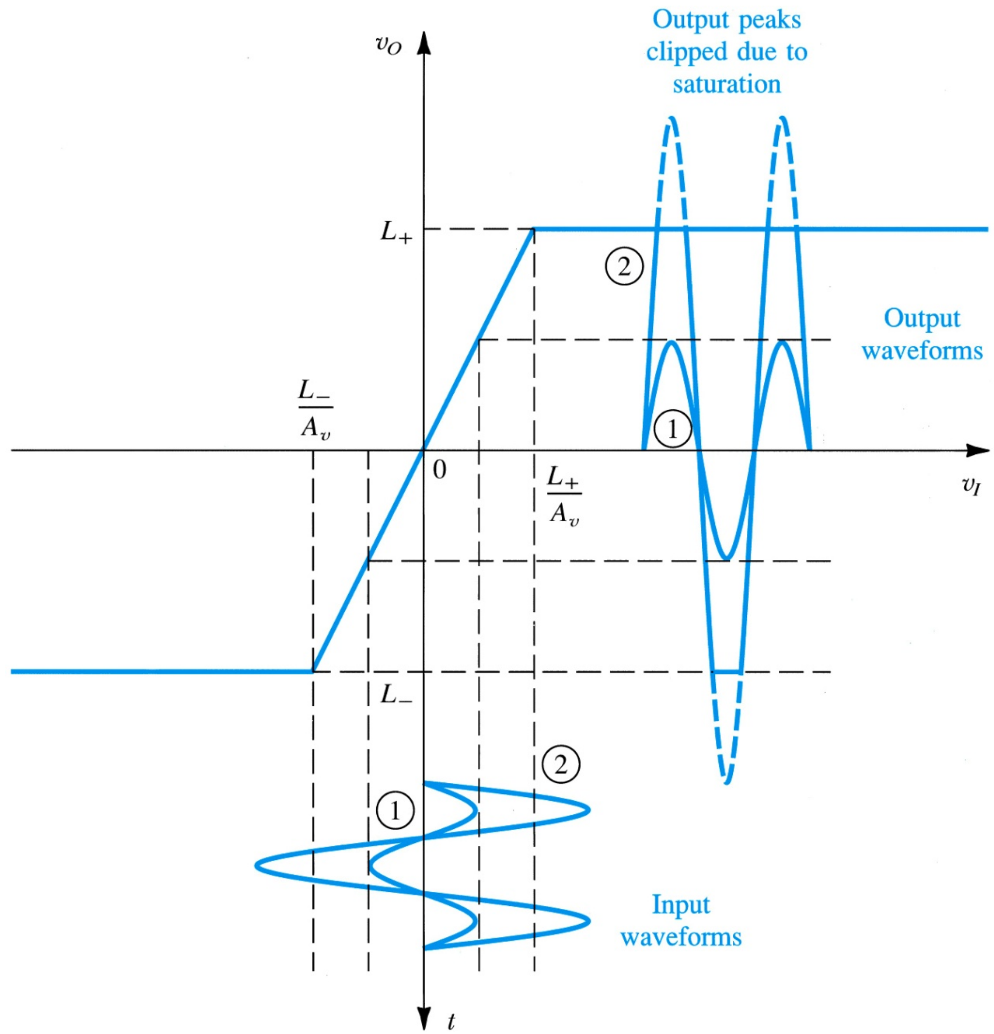
(b)

- Amplifiers do need power supplies to operate!
  - Some amplifiers use + and – power supplies (e.g., +5V and -5V)
  - Some amplifiers use ground for the – supply (e.g., +10V and 0V)
- All signals must stay between the + and – supplies

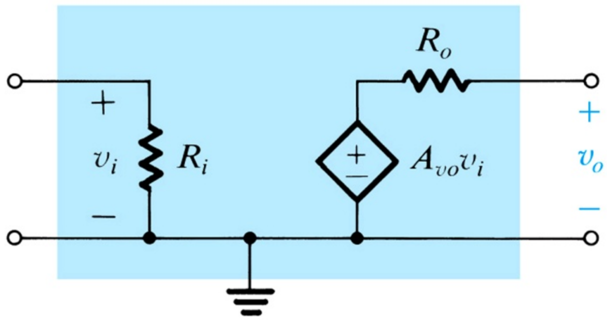
Clipping due to Power Supply limits

- An amplifier v_o vs v_i DC transfer curve can be used like a mirror to “reflect” the input to the output
- The slope of the v_o vs v_i curve is the gain of the amplifier
- **But all signals are limited by the DC power supplies**

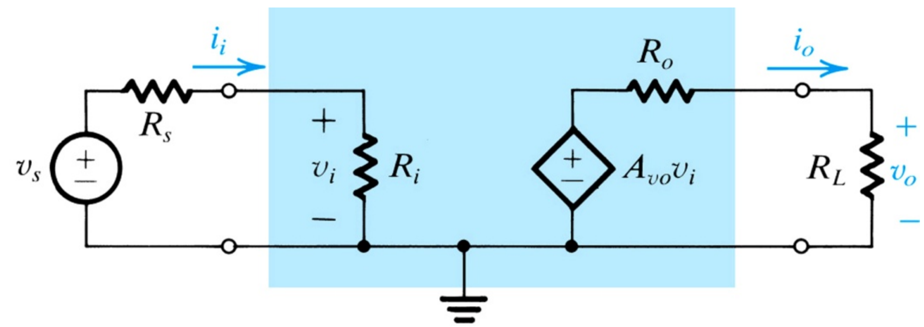
→ If the output signal gets too large, it will be “**clipped**”!



Signal losses due to Ri and Ro



(a)



(b)

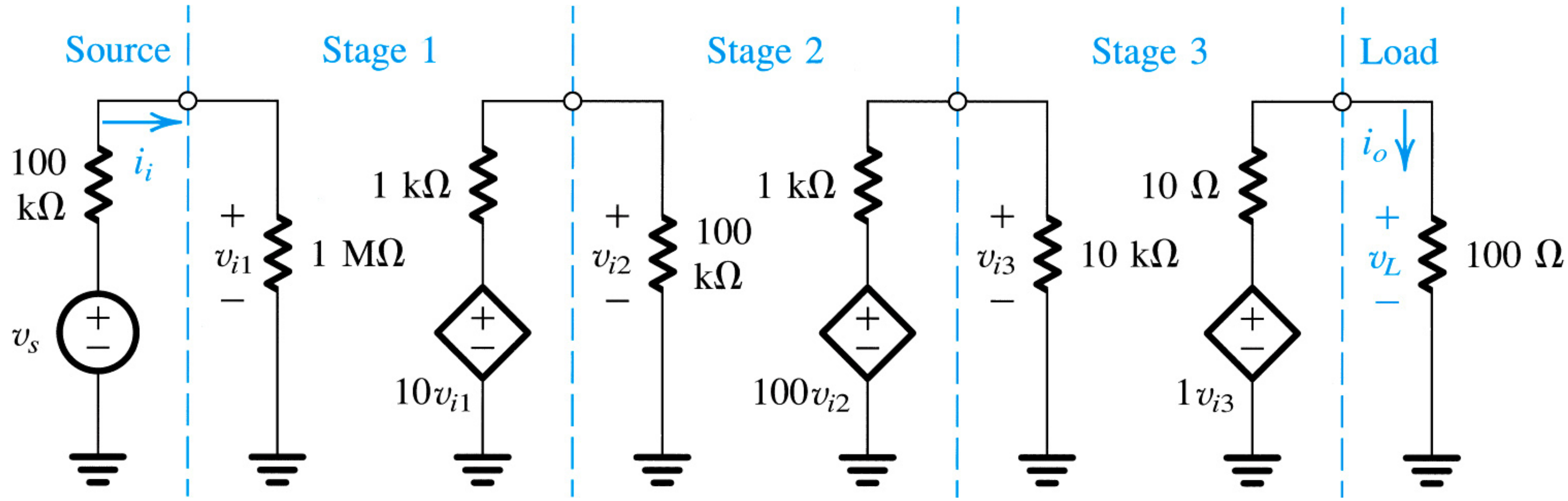
- Amps have input resistance, R_i, and output resistance, R_o, which cause signal to be lost at both input & output

$$v_i = v_s \frac{R_i}{R_i + R_S} \qquad v_o = A_{vo} v_i \frac{R_L}{R_L + R_o}$$

$$\Rightarrow v_i \approx v_s \;\; If \;\; R_i >> R_S \qquad \Rightarrow v_o \approx A_{vo} v_i \;\; If \;\; R_o << R_L$$

- To reduce signal loss, need $R_i >> R_S$ and $R_o << R_L$
  (true for voltage amplifiers, different for other types of amplifiers)

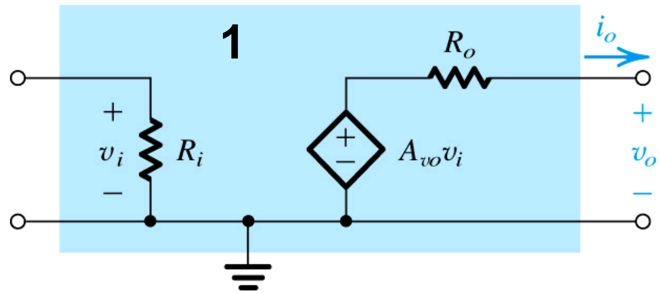
Example of signal loss between Ri, Ro

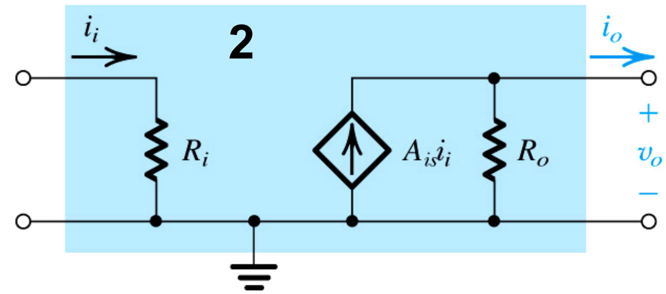


- In an amplifier with multiple stages, signal loss must be considered at the interface between each stage!
  - Large source resistance → R_i for 1st stage must be kept high
  - Small load resistance → R_o for last (3rd) stage must be kept low
  - Approx 1% of the signal is lost between Stage 1 and Stage 2
  - Approx 10% of the signal is lost between Stage 1 and Stage 2

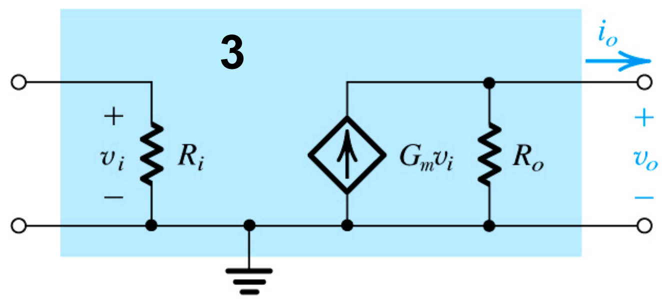
Question: How much would A_v go down if we swapped Stages 1 and 3?

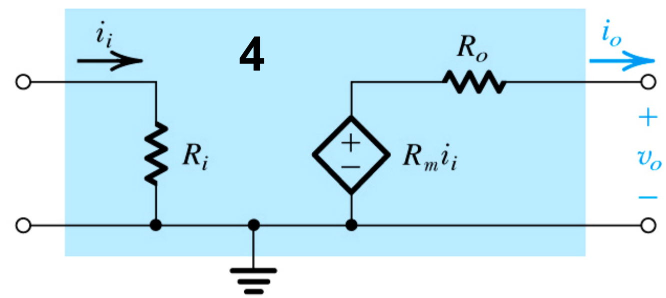
Four Types of Amplifiers





Note the use of Thevenin model for V output, Norton model for I output

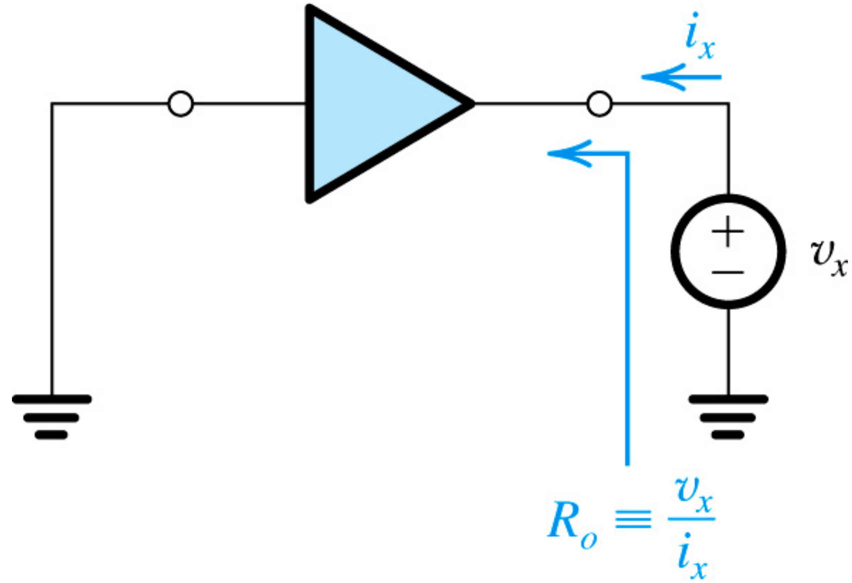




<u>Signal can be V or I at input and output → 4 types of amps:</u>

1. Voltage amp : $A_v = v_o/v_i$ → need high R_i , low R_o
2. Current amp : $A_i = i_o/i_i$ → need low R_i , high R_o
3. Transconductance amp : $G_m = i_o/v_i$ → need high R_i , high R_o
4. Transresistance amp : $R_m = v_o/i_i$ → need low R_i , low R_o

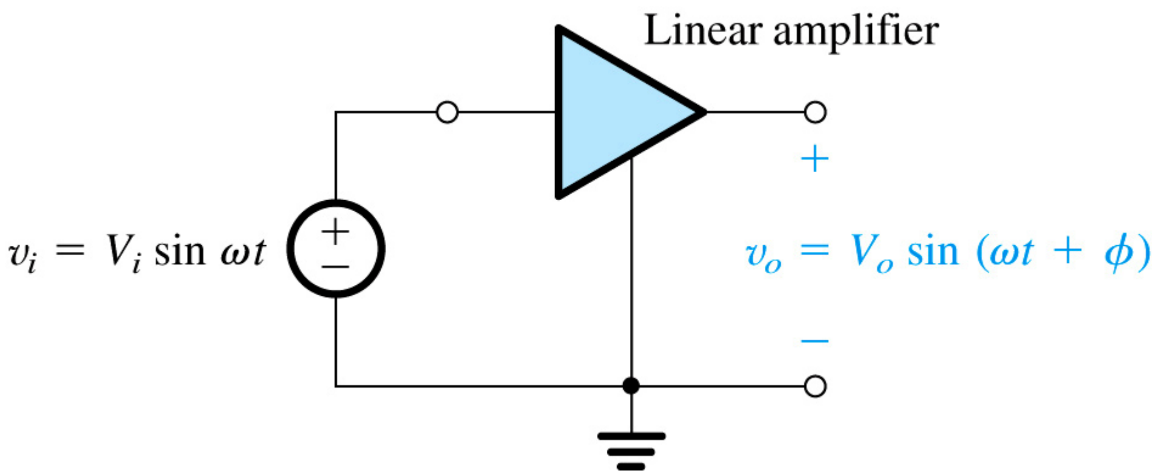
How to find the resistance at a node



<u>To determine the resistance at a node :</u>

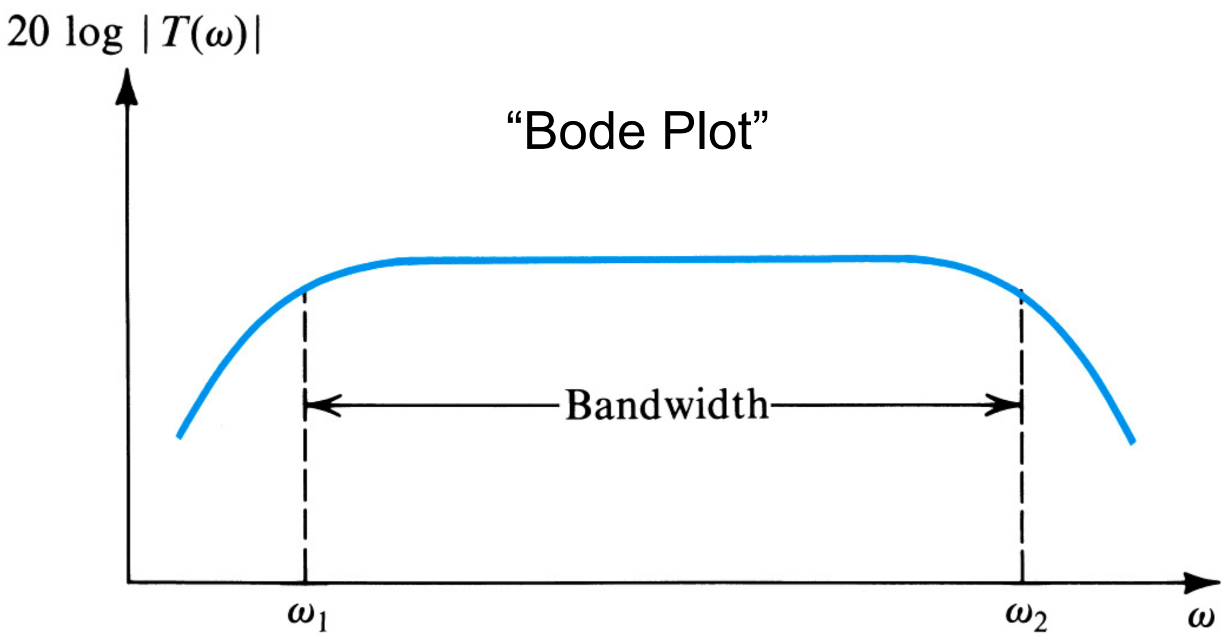
1. Kill all independent sources (V → short ckt, I → open ckt)
2. Apply a test source (either v_x or i_x) at the node
3. Find i_x if v_x source is applied, or find v_x if i_x is applied
4. Solve for $R = v_x/i_x$

Amplifier Frequency Response



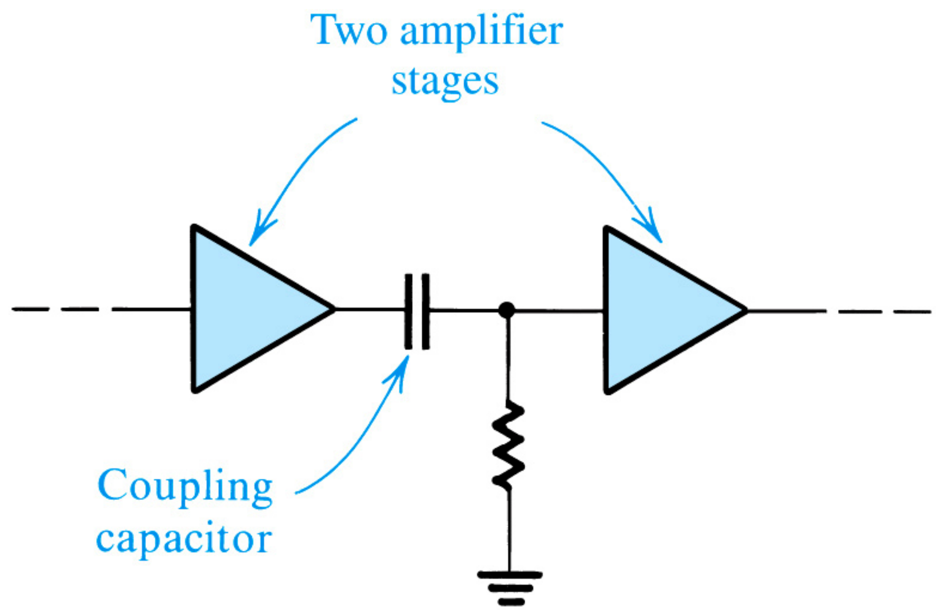
- Since most signals contain many different frequencies (e.g., music, speech) we need to measure the gain of amplifiers over a range of frequencies. This is called the **amplifier frequency response**
- This can be thought of as measuring the gain of the amplifier (both magnitude and phase) at several different frequencies one at a time and then plotting the results

Amplifier Frequency Response



- The gain of most amplifiers is constant over a wide range of frequencies, often called the **mid-band** frequencies
  – The gain of all amplifiers rolls off at high frequencies, due to parasitic capacitances in the transistors and circuit
  – The gain of amplifiers which use coupling and bypass capacitors also rolls off at low frequencies as these caps look like open ckts

Example of a capacitively coupled amp



- Amplifiers built on printed circuit boards (PCBs) using discrete components often use large coupling capacitors between stages to keep the DC bias separate for each
  - Caps look like open circuits at low freq, so no signal gets through
- Integrated Circuit (IC) amps seldom use these big caps since they use a lot of area and therefore the cost is high

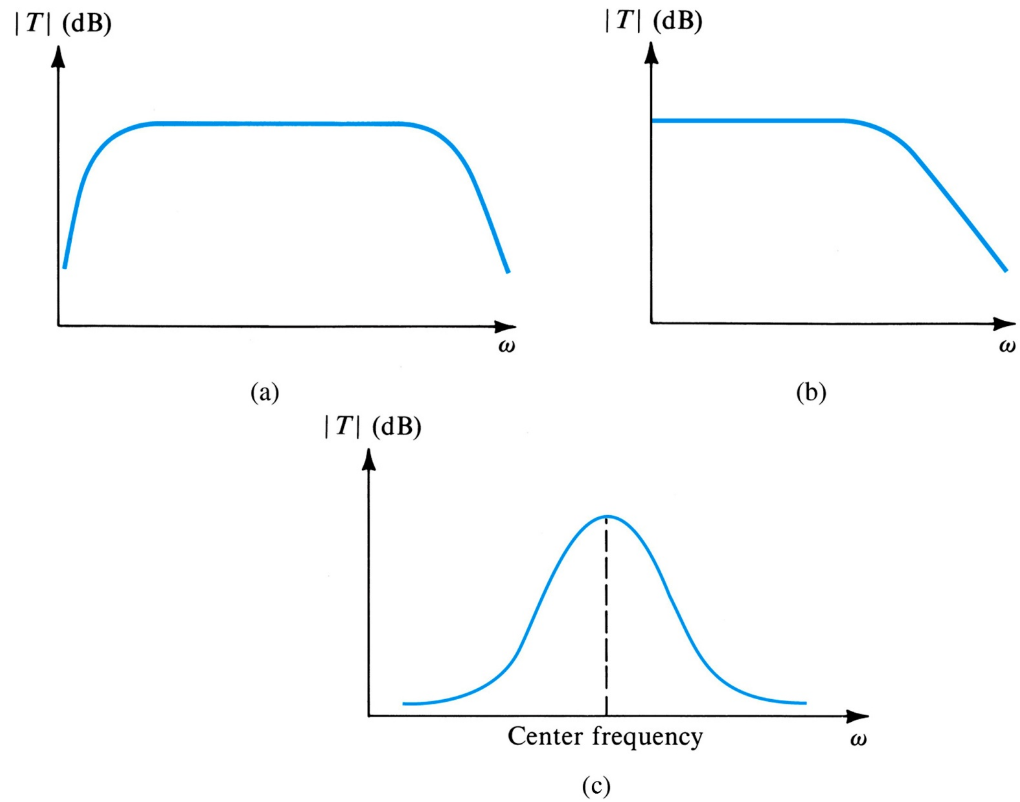
Amplifier Frequency Response

Frequency response for :

a) A capacitively coupled amplifier ("AC coupled")

b) A direct coupled amplifier (without coupling caps) ("DC coupled")

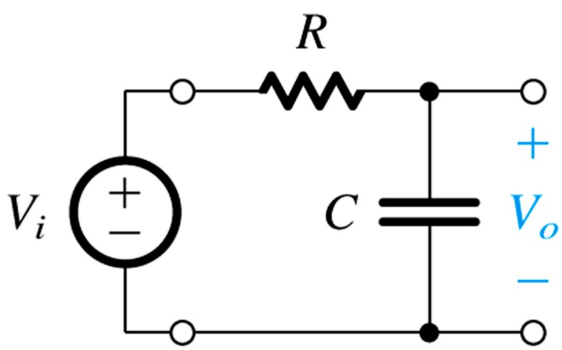
c) A "tuned" amplifier ("bandpass filter")



Most PCB amps look like (a), most IC amps like (b)

Single Time Constant (STC) Response

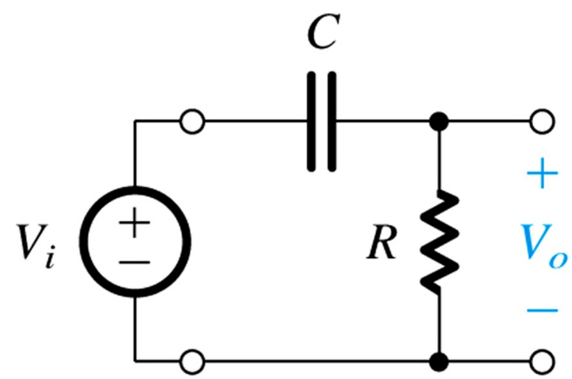
Recall that the impedance of a capacitor, Z_c = 1/sC = 1/jwC so capacitors look like open circuits at low frequencies, and look like short circuits at high frequencies



"Low pass"

$$v_o = v_i \frac{Z_C}{Z_C + R}$$

$$\Rightarrow v_o \approx v_i \ \text{for low } \omega$$

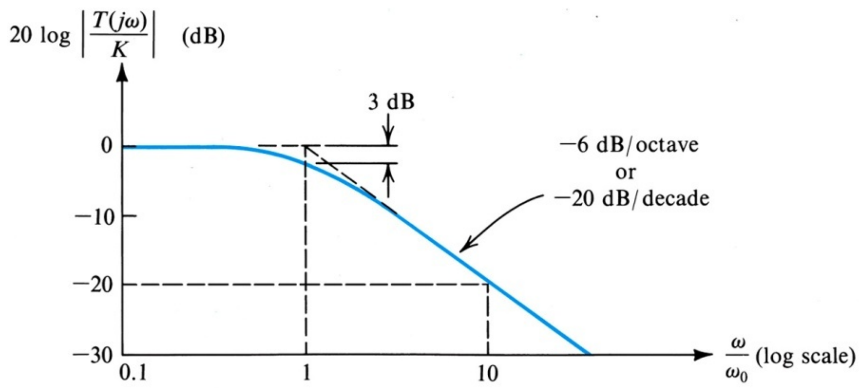


"High pass"

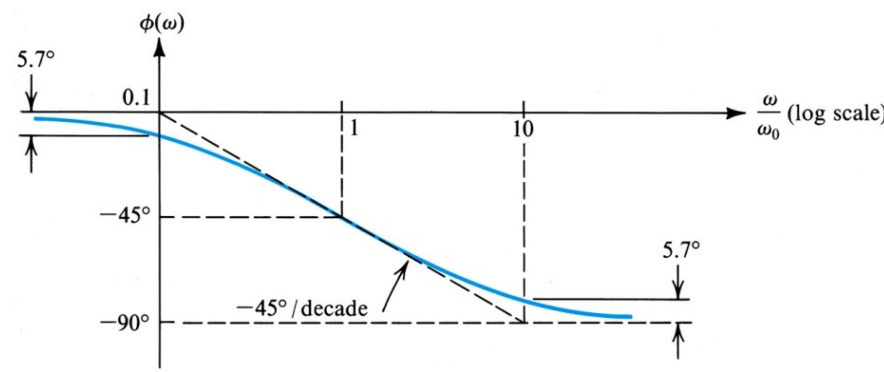
$$v_o = v_i \frac{R}{Z_C + R}$$

$$\Rightarrow v_o \approx v_i \ \text{for high } \omega$$

Low Pass STC Response



(a)



(b)

- The magnitude response for a Single Time Constant (STC) lowpass rolls off as frequency increases at :

  -20dB/decade (10x in freq)
  -6dB/octave (2x in freq)

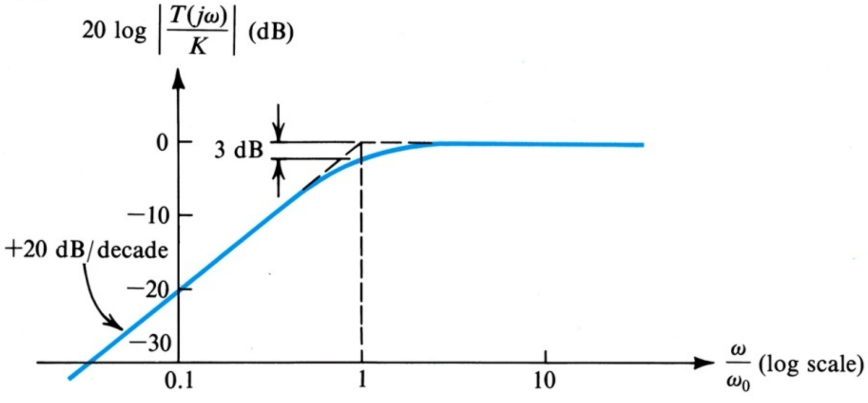
- Also referred to as a "**single pole rolloff**"

- The phase response for a Single Time Constant (STC) lowpass rolls off as frequency increases at :

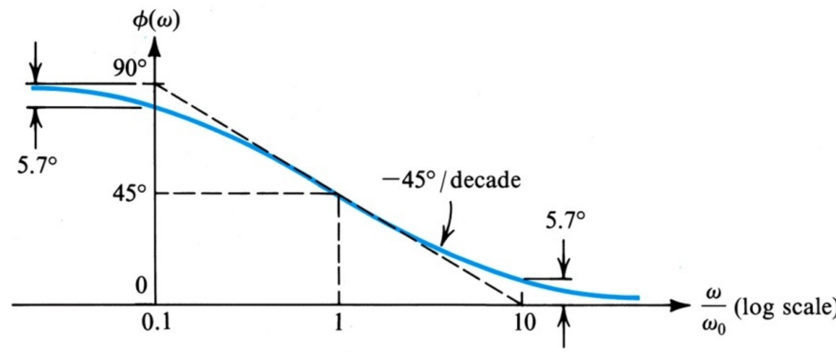
  -45°/decade (10x in freq)

- Phase is -45° at ω_{-3dB} = 1/time constant = 1/RC **"the pole frequency"**

High Pass STC Response



(a)



(b)

- The magnitude response for a Single Time Constant (STC) highpass increases as frequency increases at:

  +20dB/decade (10x in freq)
  +6dB/octave (2x in freq

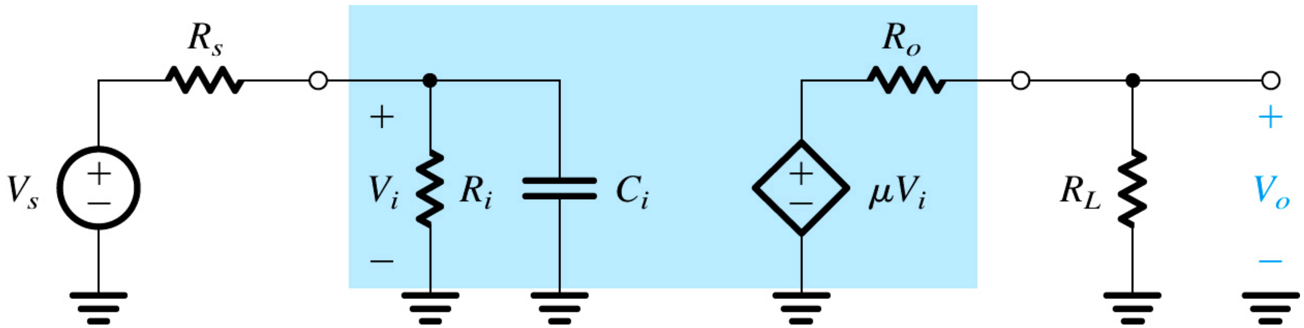
  and flattens out at ω_{-3dB} = 1/time constant = 1/RC

- The phase response for a Single Time Constant (STC) highpass rolls off as frequency increases at :

  -45°/decade (10x in freq)

- Phase starts at +90° at low frequencies and then decreases to ~ 0° at ω_{-3dB}

Example of Amp Frequency Response



- Amplifiers typically have parasitic capacitances at both the input and output which short out the signal and thus reduce the gain as frequency increases
- Using the values given in the textbook Example 1.5 of :
  R_S = 20kΩ, R_i = 100kΩ, C_i = 60pF, R_o = 200Ω, R_L = 1kΩ, μ = 144V/V

$$\Rightarrow A_v \; at\; DC = \mu\left(\frac{R_i}{R_i + R_S}\right)\left(\frac{R_L}{R_L + R_o}\right) = 144\left(\frac{100}{100+20}\right)\left(\frac{1}{1+0.2}\right) = 100\frac{V}{V} = 40dB$$

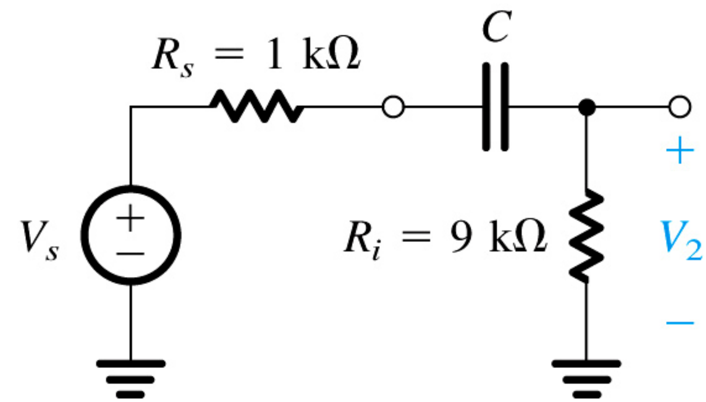
$$f_{-3db} = \left(\frac{1}{2\pi}\right)\left(\frac{1}{C_i\,(R_S \parallel R_i)}\right) = \left(\frac{1}{2\pi}\right)\left(\frac{1}{(60\,pF)(20k\Omega \parallel 100k\Omega)}\right) = \left(\frac{10^6}{2\pi}\right) = 159.2\,kHz$$

so A_v = 1 at f_T = 15.92 MHz "unity gain frequency"

Example of Amp Frequency Response

From textbook Exercise 1.24:

If a source with R_S = 1kΩ is AC coupled to an amp with R_i = 9kΩ, how big must C be to set the low -3dB frequency to no larger than 100Hz?



$$f_{-3db} = \left(\frac{1}{2\pi}\right)\left(\frac{1}{C\,(R_S + R_i)}\right) = \left(\frac{1}{2\pi}\right)\left(\frac{1}{C\,(1k\Omega + 9k\Omega)}\right) = 100\,Hz$$

$$Solving\ \ for\ C \Rightarrow C = 0.16\mu F$$

- Note that in the last example C_i “saw” a resistance equal to R_s || R_i , but in this example C “sees” a resistance of R_s + R_i (Why?)

Summary of Key Concepts

- There are many different types of signals!
  - Signals can be anything that carries information! (e.g., light)
  - Analog signals are continuous in both value and time
  - Digital signals are discrete in value, time, or both
- Data Converters can be used to convert between forms
  - Analog-to-Digital Converters (ADCs) are used to covert signals from analog format to digital representations (information is lost!)
  - Digital-to-Analog Converters (DACs) are used to covert signals from digital representations to analog form (no information lost)
- Voltage and Current signals use different models
  - Voltage signals are modeled using Thevenin equivalents
  - Current signals are modeled using Norton equivalents
  - Signal is lost between the source resistance, Rs, and the input resistance driven by the source, Ri, by voltage or current division

Summary of Key Concepts

- Signals can contain many different frequencies!
- There are 4 different types of electrical amplifiers
  - Voltage, Current, Transresistance, Transconductance amplifiers
- Different amplifier types require different models
  - Thevenin models are used for amplifiers with voltage outputs
  - Norton models are used for amplifiers with current outputs
  - Signal is lost between an amplifier's output resistance, Ro, and the load resistance driven by the amplifier, RL, through either voltage or current division
- All amplifiers have limited frequency response
  - The gain of DC-coupled amplifiers roll off at high frequencies due to unwanted parasitic capacitors (on every circuit node!)
  - The gain of AC-coupled amplifiers roll off at high frequencies, but also at low frequencies due to coupling & bypass capacitors