Electronics

Introduction to electronics

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Outline

A Brief History of Electronics

The beginning of modern electronics

John Bardeen, William Shockley, and Walter Brattain in Brattain's laboratory in 1948.
In 1947 Brattain and Bardeen invented the bipolar transistor.

The first germanium bipolar transistor. In 2008 more than 10% of the world GDP was directly traceable to electronics.

Milestones in electronics

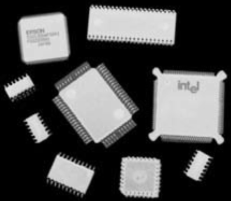
YEAR	EVENT
1874	Ferdinand Braun invents the solid-state rectifier
1906	Deforest invents triode vacuum tube (audion)
1907–27	First radio circuits developed from diodes and triodes
1925	Lilienfeld files patent application on the field-effect device
1947	Bardeen and Brattain invent the bipolar transistors
1952	Commercial production of silicon BJTs at TI
1956	Bardeen, Brattain, and Shockley receive Nobel prize
1958	Integrated circuit developed simultaneously by Kilby and Noyce-Moore
1961	First commercial digital IC available from Fairchild Sem.
1968	First commercial IC operational amplifier introduced
1970	One-transistor dynamic memory cell invented at IBM
1971	4004 microprocessor introduced by Intel
1974	First commercial 1-kilobit memory chip developed
1974	8080 microprocessor introduced
1984	Megabit memory chip introduced
1995	Experimental gigabit memory chip presented at ISSCC
2000	Alferov, Kilby, and Kromer share the Nobel prize in physics

Evolution of electronic devices

vacuum tubes

individual transistors

integrated circuits in dual-in-line packages (DIPs)



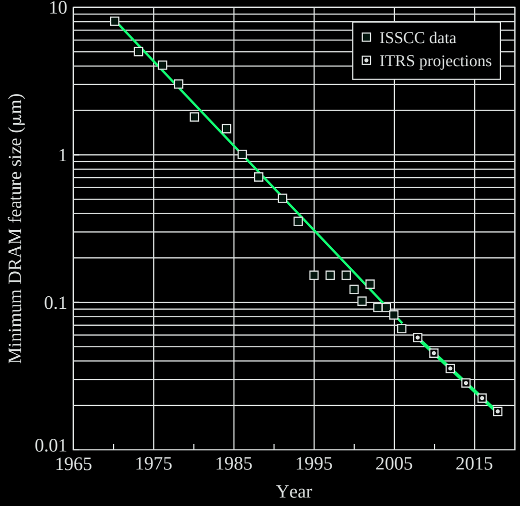
ICs in surface mount packages

Diffusion of microelectronics

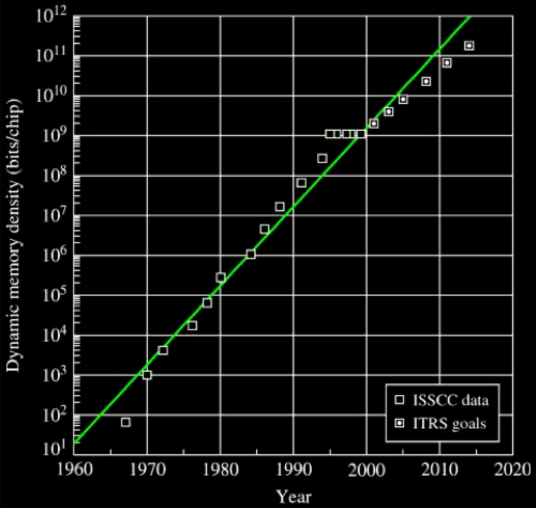
- The first integrated circuit was invented in 1958
- The complexities of memory chips and microprocessors have grown exponentially with time.
- In the four decades since 1970, the number of transistors on a microprocessor chip has increased by a factor of one million
- The increases in density have been achieved through a continued reduction of the minimum feature size
- Today discussions focus on ultra-large-scale integration (ULSI) and giga-scale integration (GSI, above 10^9 components/chip)
- Moore's law is the observation that the number of transistors in a dense integrated circuit doubles about every two years

Minimum feature size and density

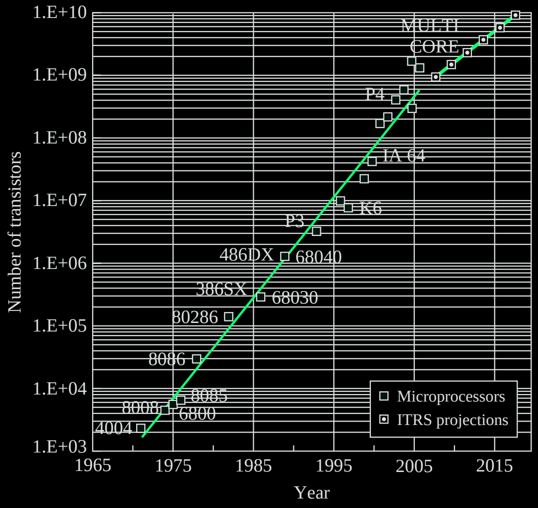
Minimum feature size



Density



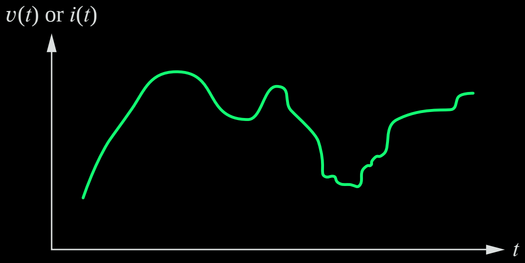
Microprocessors complexity

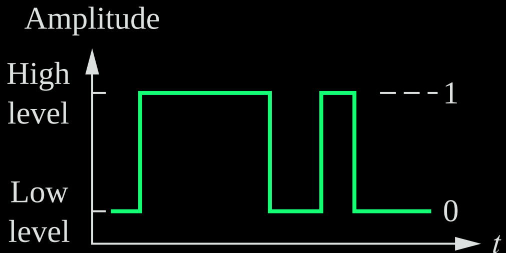


- The complexity is related to the minimum feature size
- The smaller is the minimum feature size, the larger is number of transistors per unit area

Classification of Electronic Signals

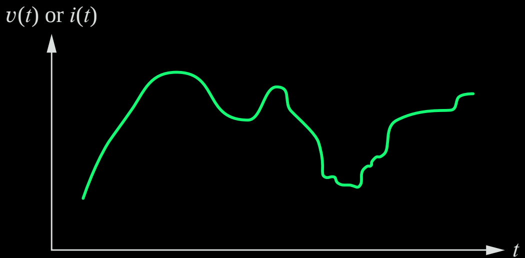
Types of signals

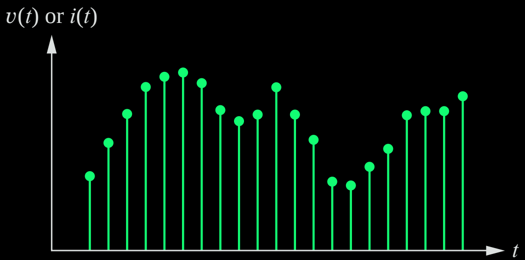




- Analog signals assume continuous values (typically, voltage or current)
- Digital signals assume discrete values
- Binary signals with two discrete levels are commonly used
- The low level is the logic-0 and the high level is the logic-1
- Modern flash memories use multilevel logic

Analog and digital signals





- Analog signals are continuous-time signals in voltage or current
- Also the charge can be used as continuous-time signal

- A digital signal is sampled and quantized
- Sampling discretizes the time intervals
- Quantization discretizes the amplitude values

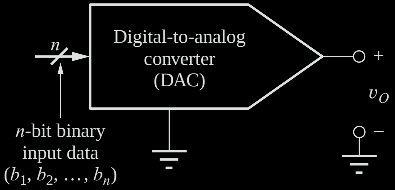
Digital-to-Analog Conversion (D/A)

- For an n-bit D/A Converter (DAC), the output voltage is

$$V_O = \left(b_1 2^{-1} + b_2 2^{-2} + \cdots + b_n 2^{-n}\right) V_{\mathrm{FS}} \quad \text{for } b_i \in \{0, 1\}$$

  being V_{FS} the full-scale voltage
- The smallest voltage change takes place when the least significant bit b_n, or LSB, changes from 0 to 1
- The minimum voltage change is the resolution of the converter

$$V_{\mathrm{LSB}} = 2^{-n} V_{\mathrm{FS}}$$

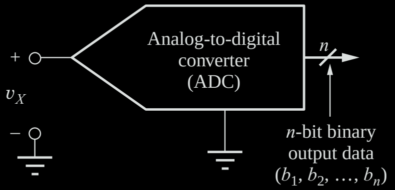


Analog-to-Digital Conversion (A/D)

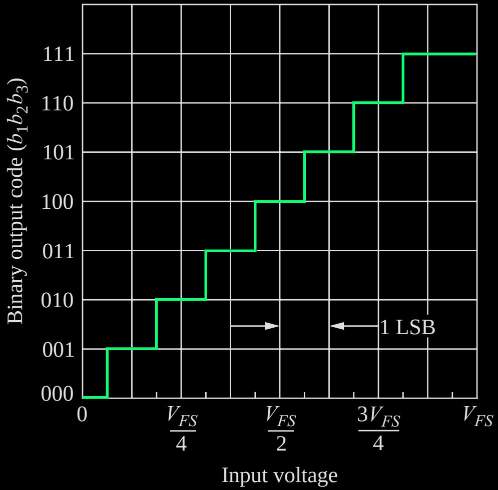
- The continuous analog input signal, v_X, is converted into an n-bit binary number that represents the ratio between the input voltage and V_{FS}
- In a 3-bit converter, the signal $0 \to V_{FS}$ leads to $000 \to 111$
- The quantization error is

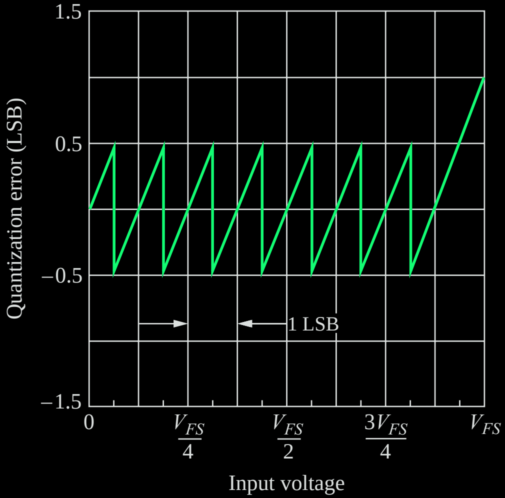
$$v_\epsilon = \left[v_X - \left(b_1 2^{-1} + b_2 2^{-2} + \cdots + b_n 2^{-n}\right) V_{FS}\right]$$

- For a given output code, the value of the input voltage lies somewhere within a 1-LSB quantization interval



ADC characteristics





$$v_\epsilon = \left[v_X - \left(b_1 2^{-1} + b_2 2^{-2} + \cdots + b_n 2^{-n}\right) V_{FS}\right]$$

Exercises

- A 10-bit D/A converter has $V_{FS} = 5.12\,\text{V}$. What is the output voltage for a binary input code of $(11\,0001\,0001)$? What is V_{LSB}? What is the size of the MSB?
  [Answers: 3.925 V; 5 mV; 2.56 V]
- An 8-bit A/D converter has $V_{FS} = 5\,\text{V}$. What is the digital output code word for an input of 1.2 V? What is the voltage range corresponding to 1 LSB of the converter?
  [Answer: 0011 1101; 19.5 mV]

Notational Conventions

Notational conventions

- In many circuits we will be dealing with both dc and time-varying values of voltages and currents
- We adopt the following conventions
    1. Total quantities will be represented by lowercase letters with capital subscripts, such as v_T and i_T
    2. The dc components are represented by capital letters with capital subscripts as, for example, V_{DC} and I_{DC}
    3. changes or variations from the dc value are represented by signal components v_{sig} and i_{sig}

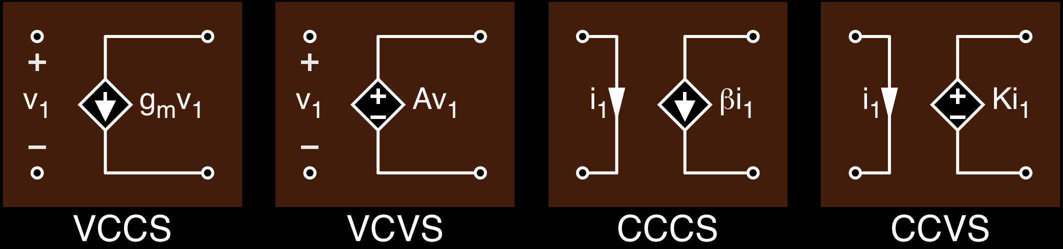
$$v_T = V_{\mathrm{DC}} + v_{\mathrm{sig}}$$
$$i_T = I_{\mathrm{DC}} + i_{\mathrm{sig}}$$

- Components, such as resistors, will be indicated as R_x or r_x
- The related conductance is

$$G_x = \frac{1}{R_x}$$

Dependent sources

- In electronics, dependent (controlled) sources are used extensively
- The voltage-controlled current source (VCCS)
- The voltage-controlled voltage source (VCVS)
- The current-controlled current source (CCCS)
- The current-controlled voltage source (CCVS)



Problem-Solving Approach

Solving problems

- State the problem as clearly as possible
- List the known information and given data
- Define the unknowns that must be found to solve the problem
- List your assumptions
- Develop an approach from a group of possible alternatives
- Perform an analysis to find a solution to the problem (be sure to draw the circuit and label the variables)
- Check the results
- Evaluate the solution
- Use computer-aided analysis (SPICE) to verify your results

Reasonable values

- Part of our results check should be to decide if the answer is “reasonable” and makes sense
- Typical power supply voltages will be in the 10- to 20-V range
- Typical resistances will range from tens of up to many GΩ
- With few exceptions, the dc voltages in our circuits cannot exceed the power supply voltages
- The peak-to-peak amplitude of an ac signal should not exceed the difference of the power supply voltages.
- The currents in our circuits will range from microamperes to no more than a hundred milliamperes

Important Concepts from Circuit Theory

Techniques of analysis

- Analysis and design of electronic circuits make continuous use of a number of important techniques from basic network theory
- Circuits are most often analyzed using a combination of
    1. Kirchhoff's voltage law (KVL) and current law (KCL)
    2. Systematic application of nodal or mesh analysis
    3. Voltage and current division
    4. Thévenin and Norton circuit transformations

Voltage division

- It can be applied when the current is shared between the two resistors

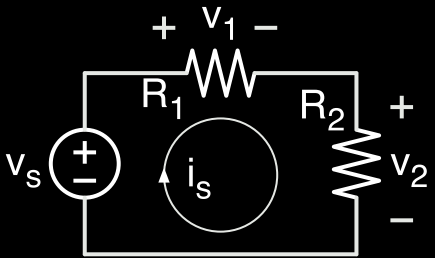
$$v_1 = i_s R_1 \qquad v_2 = i_s R_2$$

- using the KVL, we have

$$v_s = v_1 + v_2 = i_s(R_1 + R_2)$$

and

$$i_s = \frac{v_s}{R_1 + R_2}$$



- Combining the equations we have

$$v_1 = \frac{R_1}{R_1 + R_2} v_s \qquad v_2 = \frac{R_2}{R_1 + R_2} v_s$$

Current division

- It can be applied when the voltage is shared between the two resistors

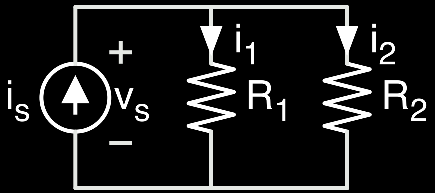
$$i_1 = \frac{v_s}{R_1} \qquad i_2 = \frac{v_s}{R_2}$$

- using the KCL, we have

$$i_s = i_1 + i_2$$

and

$$v_s = \frac{R_1 R_2}{R_1 + R_2} i_s$$

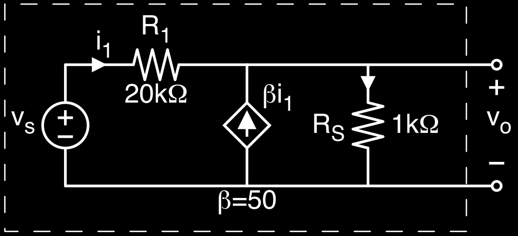


- Combining the equations we have

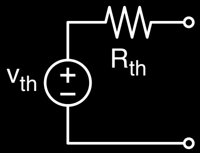
$$i_1 = \frac{R_2}{R_1 + R_2} i_s \qquad i_2 = \frac{R_1}{R_1 + R_2} i_s$$

Thévenin and Norton equivalent circuits

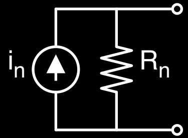
- Linear circuits can be modeled using Thévenin or Norton equivalent networks



Thévenin equivalent



Norton equivalent



Thévenin equivalent voltage evaluation

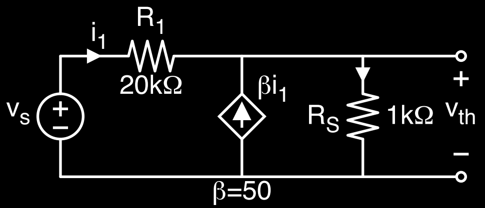
- The Thévenin voltage is the open-circuit output voltage, v_{th}
- Applying the KCL we have

$$i_1 + \beta i_1 = \frac{v_{\text{th}}}{R_S} \quad \Rightarrow \quad (\beta+1)\,\frac{v_s - v_{\text{th}}}{R_1} = \frac{v_{\text{th}}}{R_S}$$

where we considered $i_1 = (v_s - v_{\text{th}})\,/\,R_1$

- Solving for v_{th} with respect to v_s, leads to

$$\frac{\beta+1}{R_1} v_s = \left(\frac{\beta+1}{R_1} + \frac{1}{R_S}\right) v_{\text{th}} \quad \Rightarrow \quad v_{\text{th}} = \frac{(\beta+1)R_S}{(\beta+1)R_S + R_1} v_s$$



Thévenin resistance evaluation

- Applying the generator v_x at the output node and evaluating its current, i_x, the Thévenin resistance is defined by

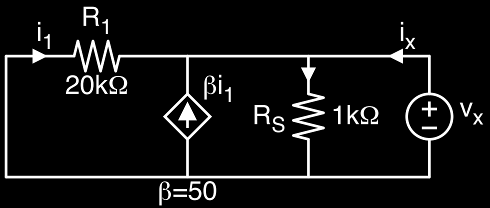
$$R_{\text{th}} = v_x / i_x$$

- Considering that $i_1 = -v_x / R_1$, current i_x is

$$i_x = \frac{v_x}{R_1} + \beta \frac{v_x}{R_1} + \frac{v_x}{R_S} \quad \Rightarrow \quad i_x = \left(\frac{\beta + 1}{R_1} + \frac{1}{R_S} \right) v_x$$

- Dividing by i_x leads to

$$R_{\text{th}} = R_S \parallel \frac{R_1}{\beta + 1}$$



Norton equivalent circuit evaluation

- The Norton current is the short-circuit output current, i_n
- Considering that the current across R_S is zero, the KCL gives

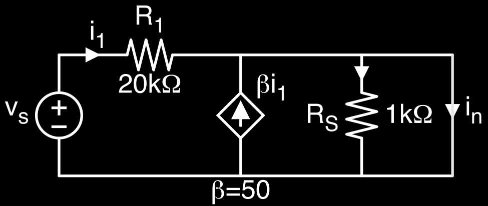
$$i_n = i_1 + \beta i_1$$

- Since $i_1 = v_s / R_1$ we obtain

$$i_n = (\beta + 1)\,\frac{v_s}{R_1}$$

- The Norton resistance is equal to the Thévenin resistance

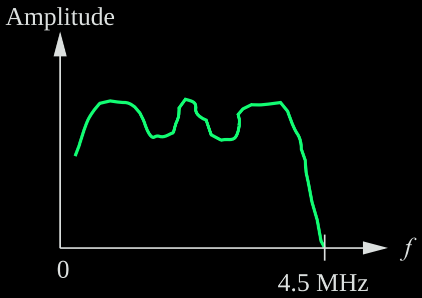
$$R_n = R_S \parallel \frac{R_1}{\beta + 1}$$



Frequency Spectrum of Electronic Signals

Frequency Spectrum of Electronic Signals

- Fourier analysis shows that complicated signals are composed of a continuum of sinusoidal components, each having a distinct amplitude, frequency, and phase
- The frequency spectrum of a signal presents the amplitude and phase of the components of the signal versus frequency
- Non-periodic signals has continuous spectrum in a wide range of frequencies
- Periodic signals contain spectral components only at discrete frequencies that are related directly to the period of the signal



Frequencies Associated with Common Signals

Audible sounds	20–20000 Hz
Baseband video (TV) signal	0–4.5 MHz
AM radio broadcasting	540–1600 kHz
HF radio communication	1.6–54 MHz
VHF television (Channels 2–6)	54–88 MHz
FM radio broadcasting	88–108 MHz
VHF radio communication	108–174 MHz
VHF television (Channels 7–13)	174–216 MHz
Maritime and government communications	216–450 MHz
Business communications	450–470 MHz
UHF television (Channels 14–69)	470–806 MHz
Analog and digital cellular	806–960 MHz
Telephones and personal communications	1710–1990 MHz
Wireless devices	1990–2690 MHz
Satellite TV	3.7–4.2 GHz
Wireless devices	5.0–5.5 GHz

The Fourier Series

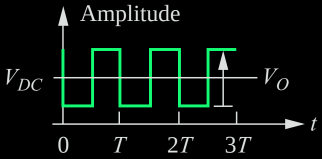
- Periodic signals contain spectral components only at discrete frequencies that are related directly to the period of the signal

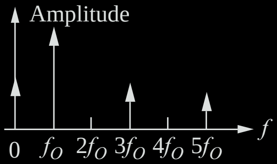
$$v(t) = c_o + \sum_{n=1}^{\infty} c_n \sin\left(n\omega_o t + \phi_n\right)$$

- A square waveform with an amplitude V_O and period $T = 1/f_o$ can be represented by the Fourier series

$$v(t) = V_{\mathrm{DC}} + \frac{2V_O}{\pi}\left(\sin\omega_o t + \frac{1}{3}\sin 3\omega_o t + \frac{1}{5}\sin 5\omega_o t + \ldots\right)$$

being $\omega_o = 2\pi f_o = 2\pi/T$ (rad/s) the fundamental frequency of the square wave





Linearity and Distortion

- The response of a linear circuit to sinusoidal input is a sinusoidal signal
- Nonlinearities can introduce undesired harmonics
- For a periodic signal

$$v(t) = c_o + \sum_{n=1}^{\infty} c_n \sin\left(n\omega_o t + \phi_n\right)$$

  we define the harmonic distortion components as

$$\mathrm{HD}_k = \frac{c_k}{c_1}$$

- The total harmonic distortion (THD) is defined as

$$\mathrm{THD} = \sqrt{\sum_{k=2}^{\infty} \mathrm{HD}_k^2}$$

Amplifiers

Amplifiers

- Analog signals are manipulated using linear amplifiers
- Linear amplifiers affect the amplitude and/or phase of the signal without changing its frequency
- Although a complex signal may have many individual components linearity permits us to use the superposition principle to treat each component individually

Linear amplifiers

- In a linear amplifier, the sinusoidal input/output signals are

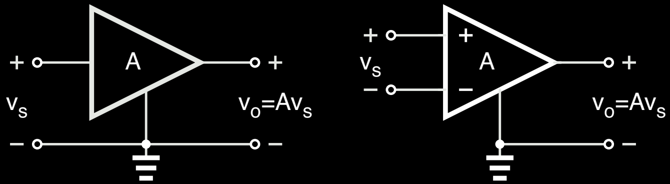
$$v_s(t) = V_S \sin(\omega_s t + \phi) \qquad \text{(input)}$$
$$v_o(t) = V_O \sin(\omega_s t + \phi + \theta) \qquad \text{(output)}$$

- Using phasor notation, we have

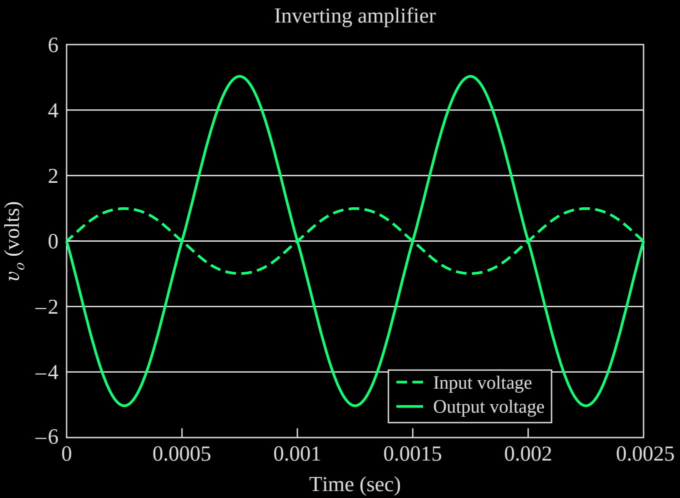
$$\mathbf{v_s} = V_S \angle \phi \quad \text{and} \quad \mathbf{v_o} = V_O \angle (\phi + \theta)$$

- The amplification, A, is a complex number defined as

$$A = \frac{\mathbf{v_o}}{\mathbf{v_s}} = \frac{V_O \angle (\phi + \theta)}{V_S \angle \phi} = \frac{V_O}{V_S} \angle \theta$$



Linear amplifiers



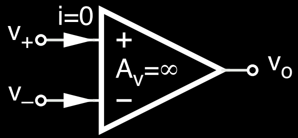
$$v_s = \sin(2000\pi t)\,\mathrm{V} \quad \text{and} \quad A = -5$$

The Operational Amplifier (OpAmp)

- The operational amplifier is a differential amplifier that responds to the signal voltage that appears between its inverting $(-)$ and non-inverting $(+)$ input terminals

$$v_o = A_v \left(v_+ - v_- \right)$$

- The ideal operational amplifier has the following properties
  1. Infinite voltage gain $(A_v = \infty)$
  2. Infinite input resistance $(R_{\text{in}} = \infty)$
  3. Zero output resistance $(R_{\text{out}} = 0)$
  4. Infinite bandwidth $(\text{BW} = \infty)$
- Although impossible to realize, the ideal OpAmp is a simple and useful model for the analysis and the design of a circuit

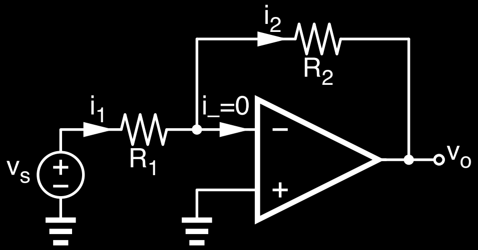


The Inverting Amplifier

- Due to the infinite gain, for the OpAmp to work properly, it must be used in a negative feedback configuration
- The negative feedback forces the output to be a finite quantity (i.e., $|v_o| < \infty$)
- Since $v_o = A_v\,(v_+ - v_-)$, for $A_v \to \infty$ the circuit imposes

$$v_- = v_+$$

which is known to as a virtual ground



The Inverting Amplifier

- Considering that $v_- = v_+ = 0$, currents across R_1 and R_2 are

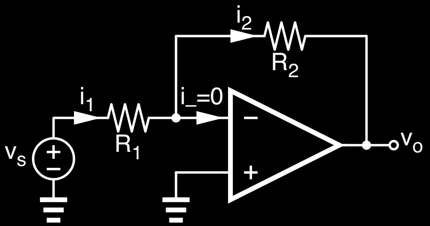
$$i_1 = \frac{v_s - v_-}{R_1} = \frac{v_s}{R_1} \quad \text{and} \quad i_2 = \frac{v_- - v_o}{R_2} = -\frac{v_o}{R_2}$$

- Considering that $i_- = 0$, the KCL imposes

$$i_1 = i_2 + i_- = i_2$$

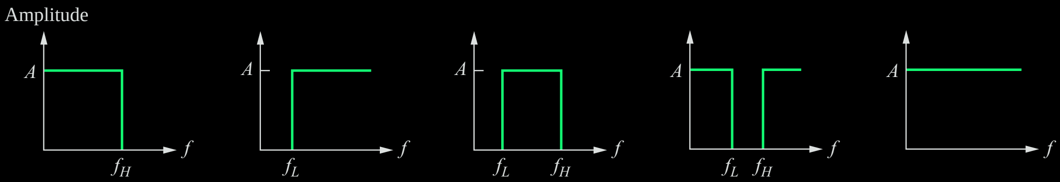
- Substituting i_1 and i_2, we obtain

$$v_o = -\frac{R_2}{R_1} v_s$$



Amplifier frequency response

- Amplifiers can also be designed to selectively process signals of different frequency ranges
- In this case, they are called Filters
- Five possible categories are shown
  1. Low-Pass Amplifier (LP)
  2. High-Pass Amplifier (HP)
  3. Band-Pass Amplifier (BP)
  4. Band-Reject Amplifier (BR)
  5. All-Pass Amplifier (AP)



Element variations in circuit design

Element variations in circuit design

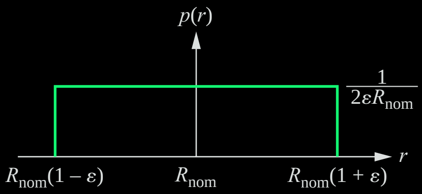
- Every passive component or semiconductor device parameter will all have tolerances associated with their nominal values
  - Discrete Resistors can be purchased with different tolerances $\pm 10\%$, $\pm 5\%$, $\pm 1\%$, or better (IC resistors can exhibit $\pm 30\%$)
  - Capacitors are asymmetric (i.e., $+20\%/-50\%$)
  - Power supply voltage tolerances are in the range of 1–10%
- The values of the circuit components and parameters will vary with temperature and circuit age
- Circuits must be designed taking into account such variations
- Two main methods are used to quantify the effects of tolerances on circuit performance
  1. Worst-case or corner analysis (PVT)
  2. Monte Carlo analysis

Mathematical modeling of tolerances

- A mathematical model for symmetrical parameter variations is

$$R_{\text{nom}}\,(1-\epsilon) \leq R \leq R_{\text{nom}}\,(1+\epsilon)$$

  being R_{nom} the nominal value for the resistor (or, in general, for a specific parameter) and ϵ its fractional tolerance
- Another modeling assumes that R is a statistical variable with a probability density function (pdf) set by $p(r)$
- The probability that R lies between r and $(r+dr)$ is equal to $p(r)\mathrm{d}r$

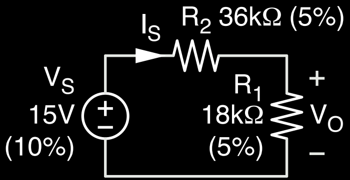


$$\int_{-\infty}^{+\infty} p(r)\,\mathrm{d}r = 1$$

Worst-case or Corner analysis

- The nominal voltage is

$$V_O^{\text{nom}} = \frac{R_1^{\text{nom}}}{R_1^{\text{nom}} + R_2^{\text{nom}}} V_S^{\text{nom}}$$
$$= \frac{18\,\text{k}}{18\,\text{k} + 36\,\text{k}} \times 15 = 5\,\text{V}$$



- Since $V_O = \frac{V_S}{1+R_2/R_1}$ the output is maximized for V_S^{max}, R_1^{max} and R_2^{min} while it is minimized for V_S^{min}, R_1^{min} and R_2^{max}

$$V_O^{\text{max}} = \frac{V_S^{\text{max}}}{1 + \frac{R_2^{\text{min}}}{R_1^{\text{max}}}} = \frac{15 \times 1.1}{1 + \frac{36\times 0.95}{18\times 1.05}} = 5.87\,\text{V}$$

$$V_O^{\text{min}} = \frac{V_S^{\text{min}}}{1 + \frac{R_2^{\text{max}}}{R_1^{\text{min}}}} = \frac{15 \times 0.9}{1 + \frac{36\times 1.05}{18\times 0.95}} = 4.20\,\text{V}$$

Temperature coefficients

- Since all circuit elements change value as the temperature changes, our circuit designs must continue to operate properly as the temperature changes
- Typical ranges are $[0^\circ\mathrm{C}, 70^\circ\mathrm{C}]$ for commercial products or $[-55^\circ\mathrm{C}, +85^\circ\mathrm{C}]$ for standard military products
- Other environments (i.e., automotive, aerospace, ...) can be even more extreme
- The typical temperature model for the behavior of a parameter P is

  $$P = P_{\text{nom}}\left(1 + \alpha_1 \Delta T + \alpha_2 \Delta T^2\right)$$

  where $\Delta T = T - T_{\text{nom}}$
- Common values for α_1 range from 0 to plus or minus several thousand of ppm/°C ($1000\,\text{ppm}/^\circ\mathrm{C} = 0.1\,\%/^\circ\mathrm{C}$)

Temperature SPICE Model

- Most SPICE programs contain models for the temperature dependencies of many circuit elements
- The temperature-dependent SPICE model for the resistor is

  ```
  R(T) = R(TNOM)*[1+TC1*(T-TNOM)+TC2*(T-TNOM)^2]
  ```

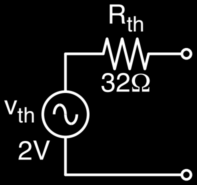
  where

  - TNOM = temperature at which the nominal resistor value is measured
  - T = temperature at which the simulation is performed
  - TC1 = first-order temperature coefficient
  - TC2 = second-order temperature coefficient

Examples

Example 1: MP3 Player Characteristics

- The MP3 player can be modeled by a Thévenin circuit with $v_{th} = 2\,\mathrm{V}$ and $R_{th} = 32\,\Omega$
- It delivers a power of about $15\,\mathrm{mW}$ with a matched impedance of $32\,\Omega$
- The output power constant over the $20\,\mathrm{Hz}$–$20\,\mathrm{kHz}$ frequency range
- The total harmonic distortion (THD) is less than 0.1%



Example 2: Amplifiers in a familiar electronic system

The FM radio receiver

- The FM radio receiver uses a number of amplifiers
- The power available from the antenna ($\sim \mu V$) may amount to only picowatts
- The audio amplifier can deliver $\sim 100\,W$ audio signal to the speaker