EDIT 2011
Basic Electronics

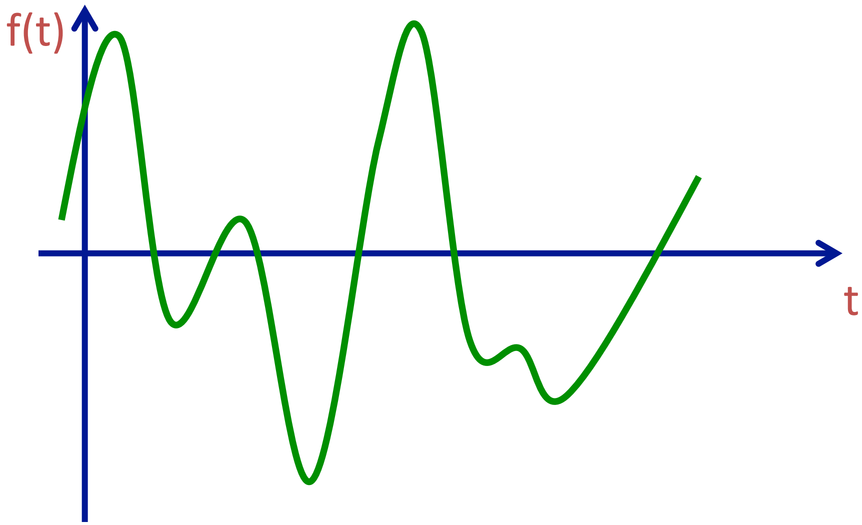
X.Llopart

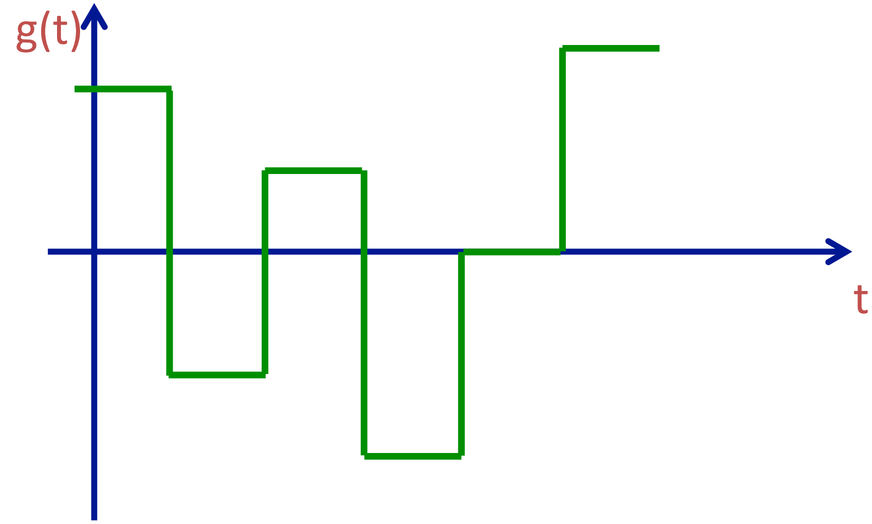
R.Ballabriga

Outline

- Digital and Analog Domains
- Analog Circuits
  - Analog electronics design tools
  - Circuits with passive components
  - Circuits using active components
    - Differential amplifier
- Digital Circuits

Signals: Analog vs Digital



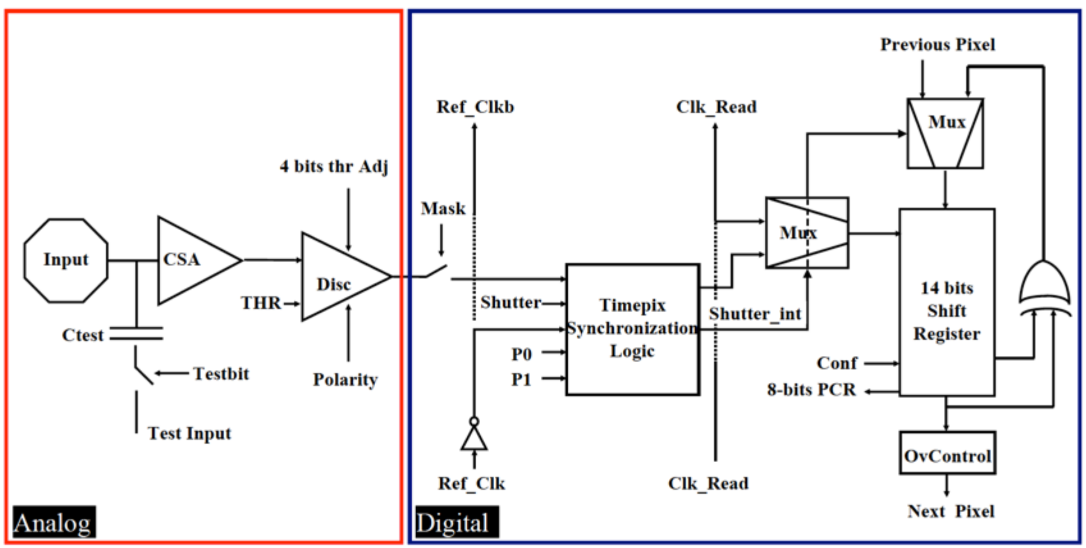


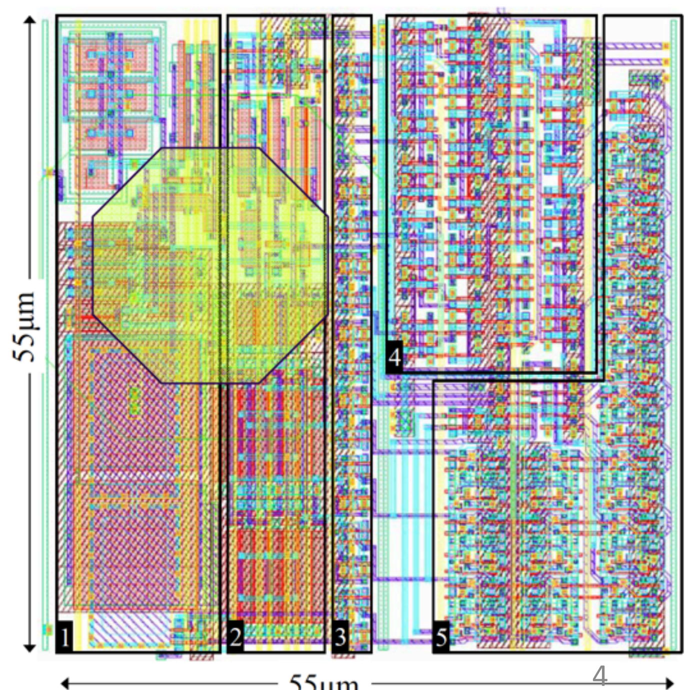
- The magnitude of an **analog signal** can take on any value
- The amplitude of an analog signal exhibits a continuous variation over its range of activity

- An alternative form of representation is that of a sequence of numbers, each number representing the signal magnitude at an instant of time
- The resulting signal is called **digital signal**

Mixed-mode circuits: Analog and digital

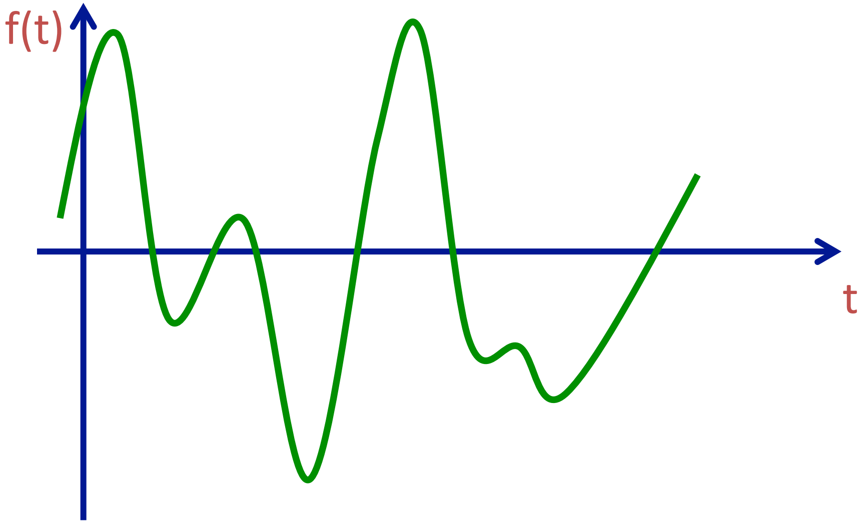
- Although the digital processing of signals is present everywhere there are many signal -processing functions that are best performed by analog circuits
- Many electronic systems include both analog and digital parts: **Mixed-Signal** or **mixed-mode** design





Timepix pixel schematic and layout (2006)

Analog Circuits

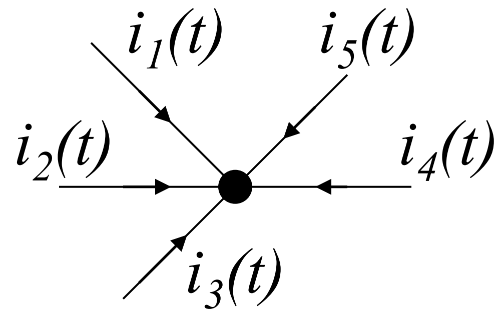


Introduction to analog electronics

- Analog electronics design tools:
  - Kirchoff's current and voltage Law (KCL and KVL)
  - Superposition Theorem
  - Thevenin and Norton Theorem
  - The Decibels
  - Frequency domain (Fourier theorem (jw) ➔ Laplace(π))

- Electronics analog circuits building components:
  - Passives components:
    - Resistors
    - Capacitors
    - Inductors
  - Active components:
    - Diodes
    - Transistors
    - Operational Amplifier

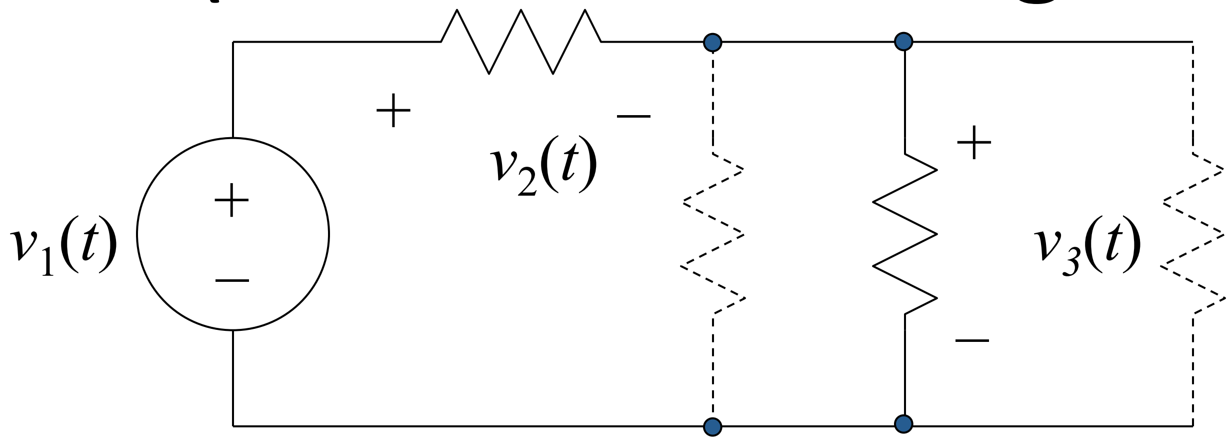
KCL (Kirchhoff's Current Law)



At any node (junction) in an electrical circuit, the sum of currents flowing into that node is equal to the sum of currents flowing out of that node.

$$\sum_{j=1}^{n} i_j(t) = 0$$

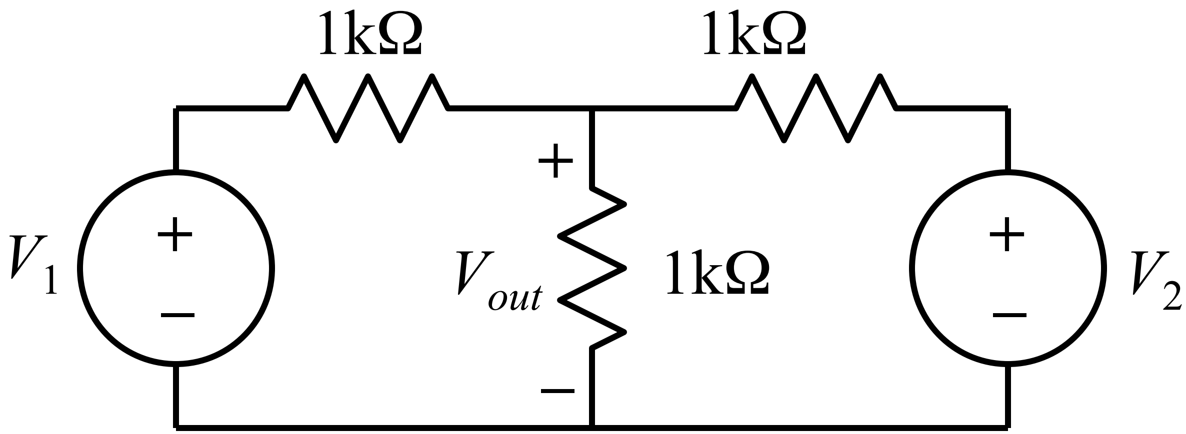
KVL (Kirchhoff's Voltage Law)

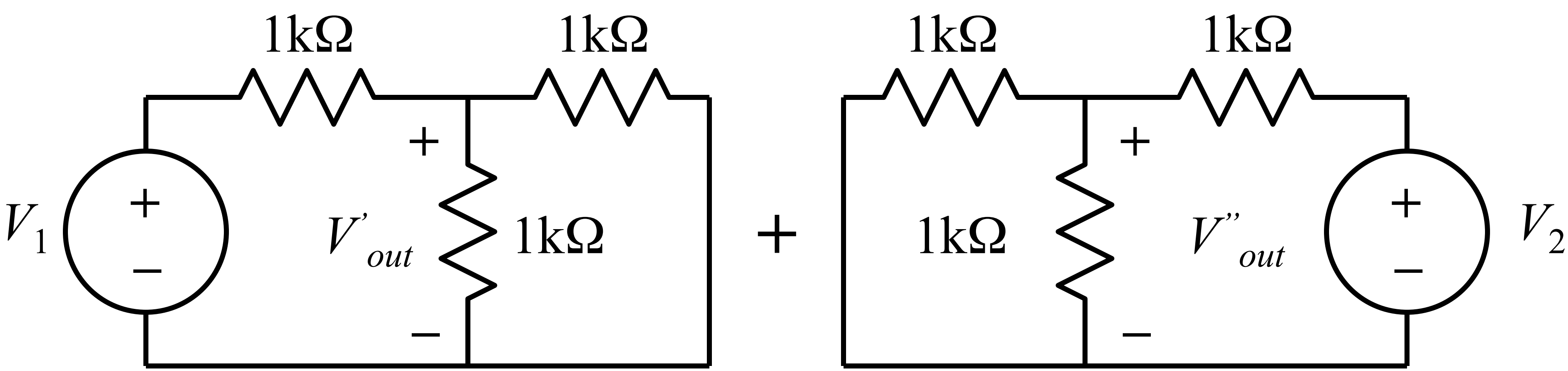


The directed sum of the electrical potential differences (voltage) around any closed circuit is zero.

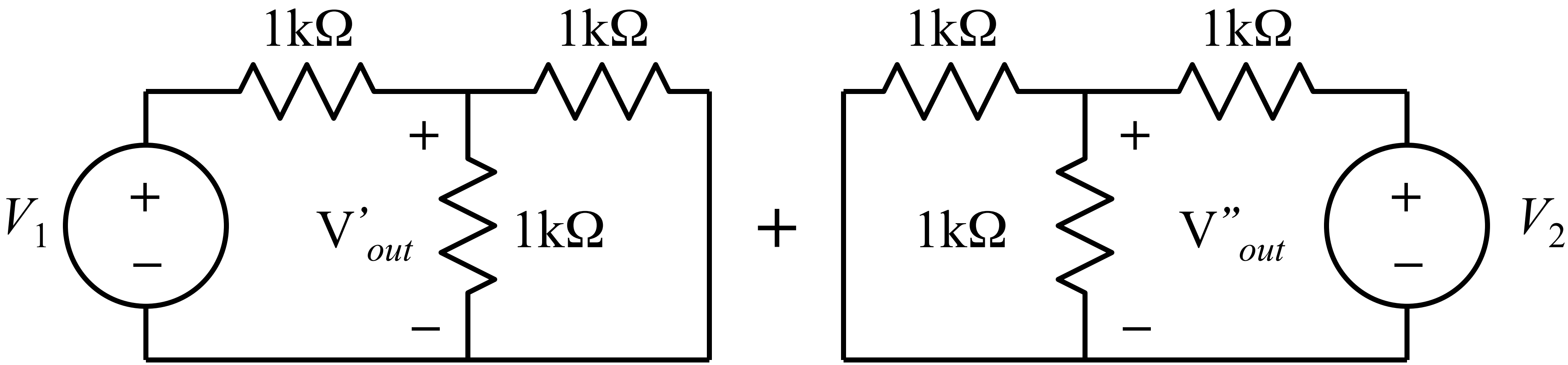
$$\sum_{j=1}^{n} v_j(t) = 0$$

Superposition Theorem





How to use the superposition theorem?

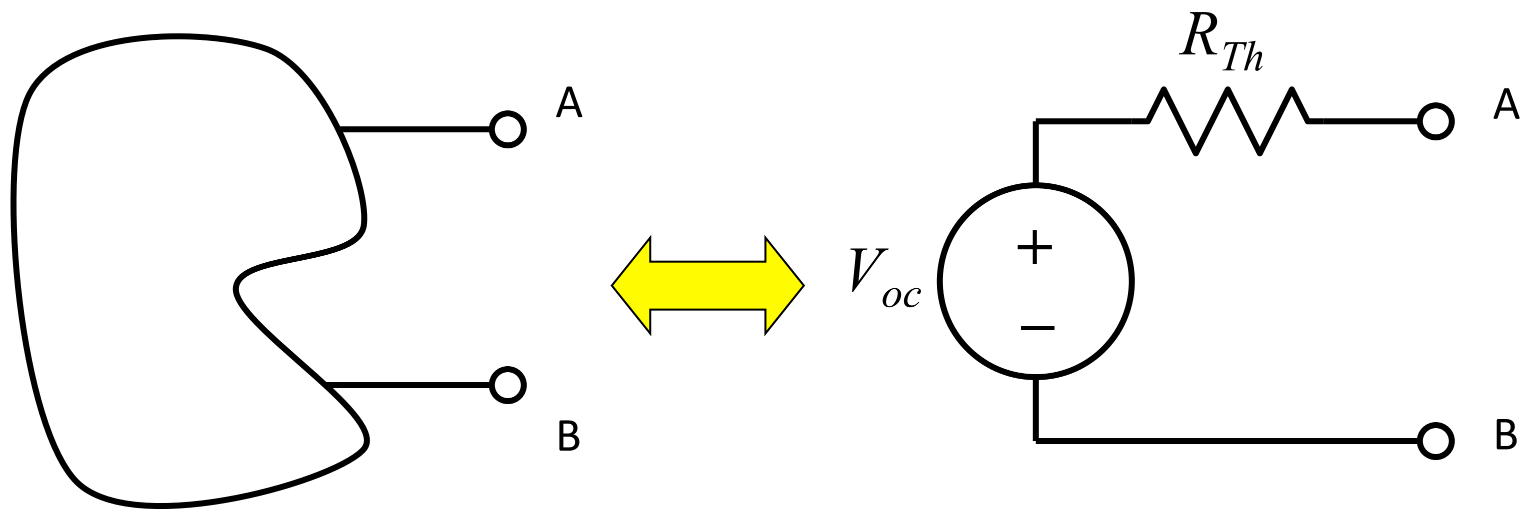


$$V'_{out} = V_1/3$$

$$V''_{out} = V_2/3$$

$$V_{out} = V'_{out} + V''_{out} = V_1/3 + V_2/3$$

Thevenin's theorem

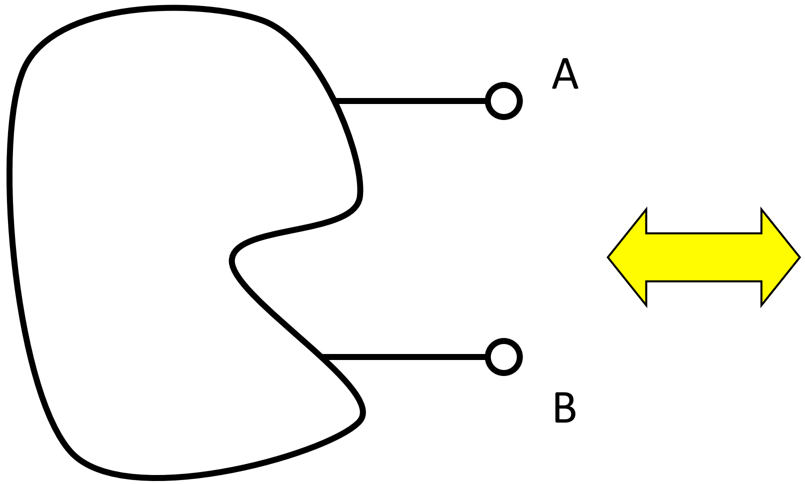


Circuit with independent sources

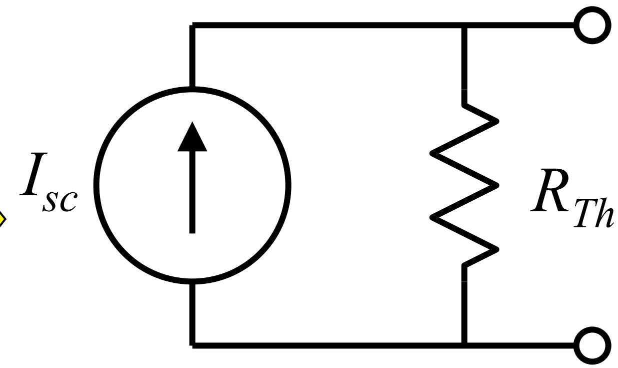
Thevenin equivalent circuit

- **Thevenin's theorem** states that any two-terminal, resistive circuit can be replaced with an equivalent circuit formed by an ideal voltage (Voc) source an a serial resistor (Rth)

Norton's theorem



Circuit with independent sources



Norton equivalent circuit

- **Norton's theorem** states that any two-terminal, resistive circuit can be replaced with an equivalent circuit formed by an ideal current source (Isc) and a parallel resistor (Rth)

The Decibels (dB)

- The decibels (dB) is a power (or voltage) logarithmic relationship
- Very useful when we work with signals of with different order of magnitude

$$\left.\frac{P_1}{P_2}\right|_{dB} = 10\log\left(\left.\frac{P_1}{P_2}\right|_{lin}\right)$$

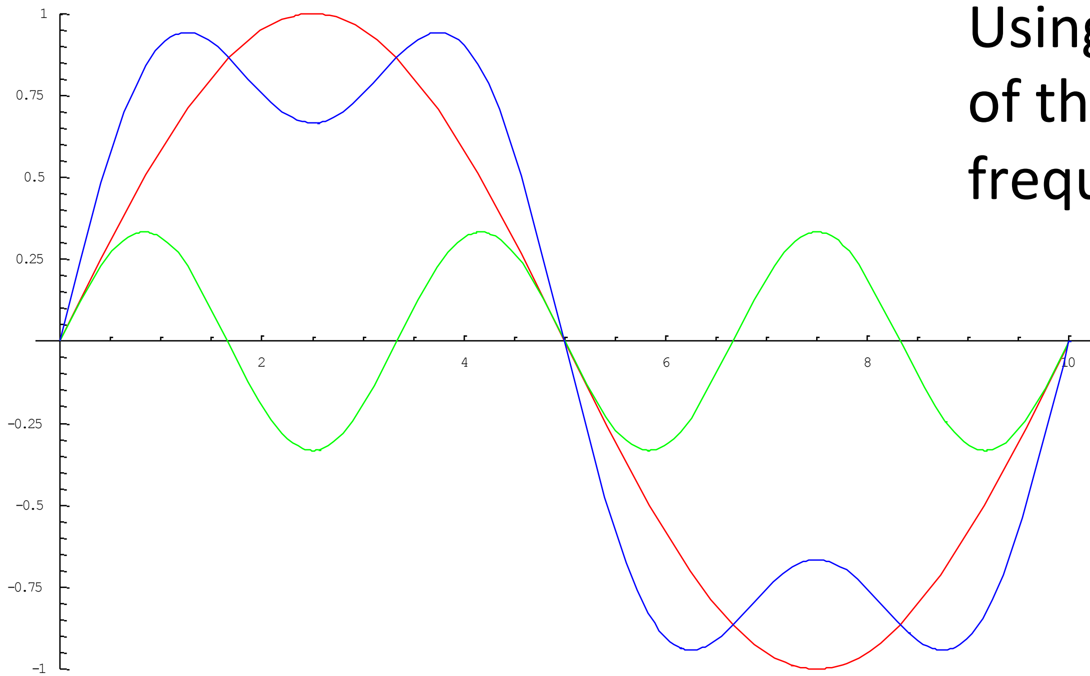
$$\left.\frac{V_1}{V_2}\right|_{dB} = 10\log\left(\left.\frac{V_1^2 \cdot R_{LOAD}}{V_2^2 \cdot R_{LOAD}}\right|_{lin}\right) = 20\log\left(\left.\frac{V_1}{V_2}\right|_{lin}\right)$$

- Example: If the transmitting power of a mobile phone station is 80W. If a mobile phone receives 0.000 000 002W, the power relationship is of 106dB

Frequency spectrum of signals Fourier's Theorme

- An extremely useful characterization of a Signal, and for that matter of any arbitrary function of time, is in terms of its **frequency spectrum**
- The Fourier series allows us to express a given periodic function of time as the sum of an infinite number of sinusoids whose frequencies are harmonically related
- For example, a periodic square wave in time. Can we represent it as a sum of sinus and cosinus?

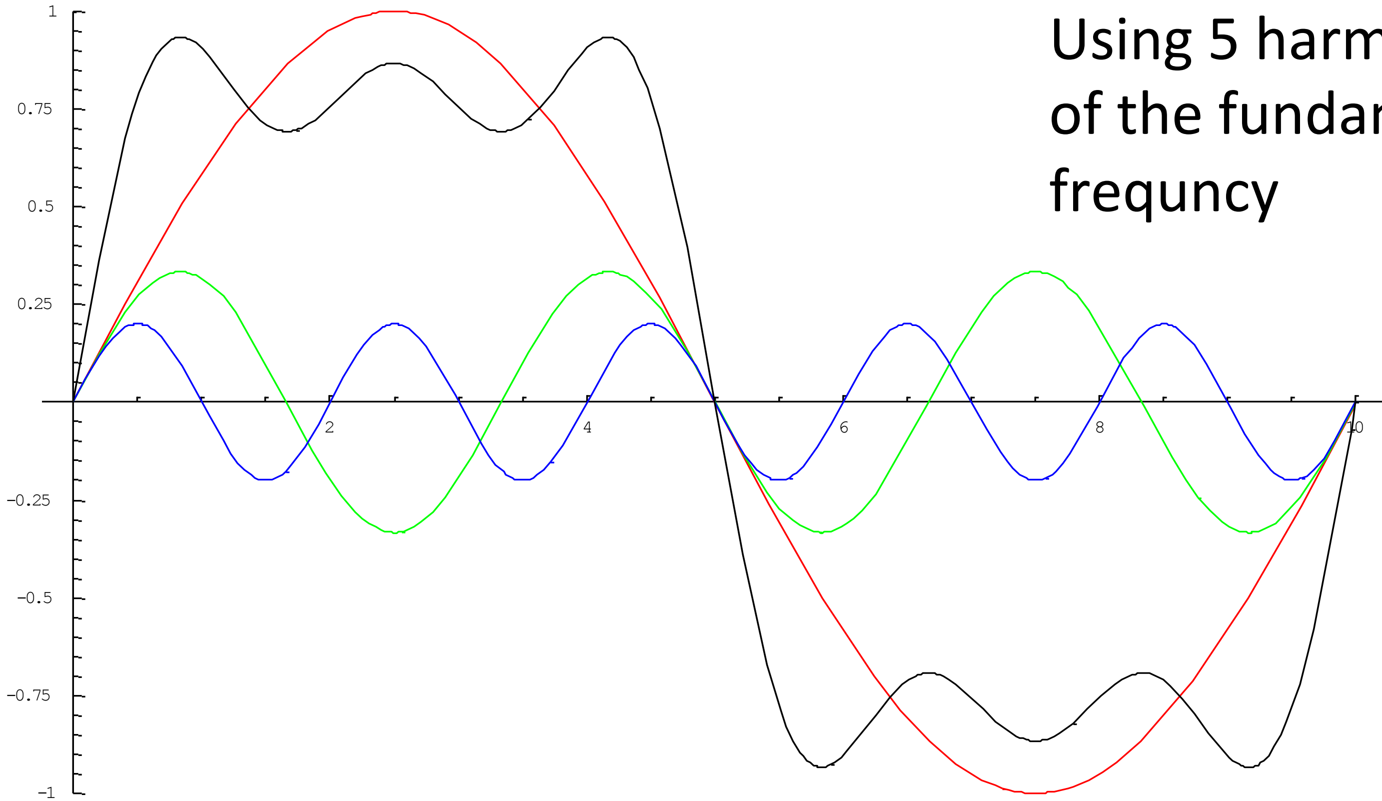
Fourier's Theorem: Representation of an square signal (1)



Using 3 harmonics of the fundamental frequncy

$$v(t) = \frac{4V}{\pi}(\sin \varpi_o t + \frac{1}{3}\sin 3\varpi_o t + \frac{1}{5}\sin 5\varpi_o t + ...)$$

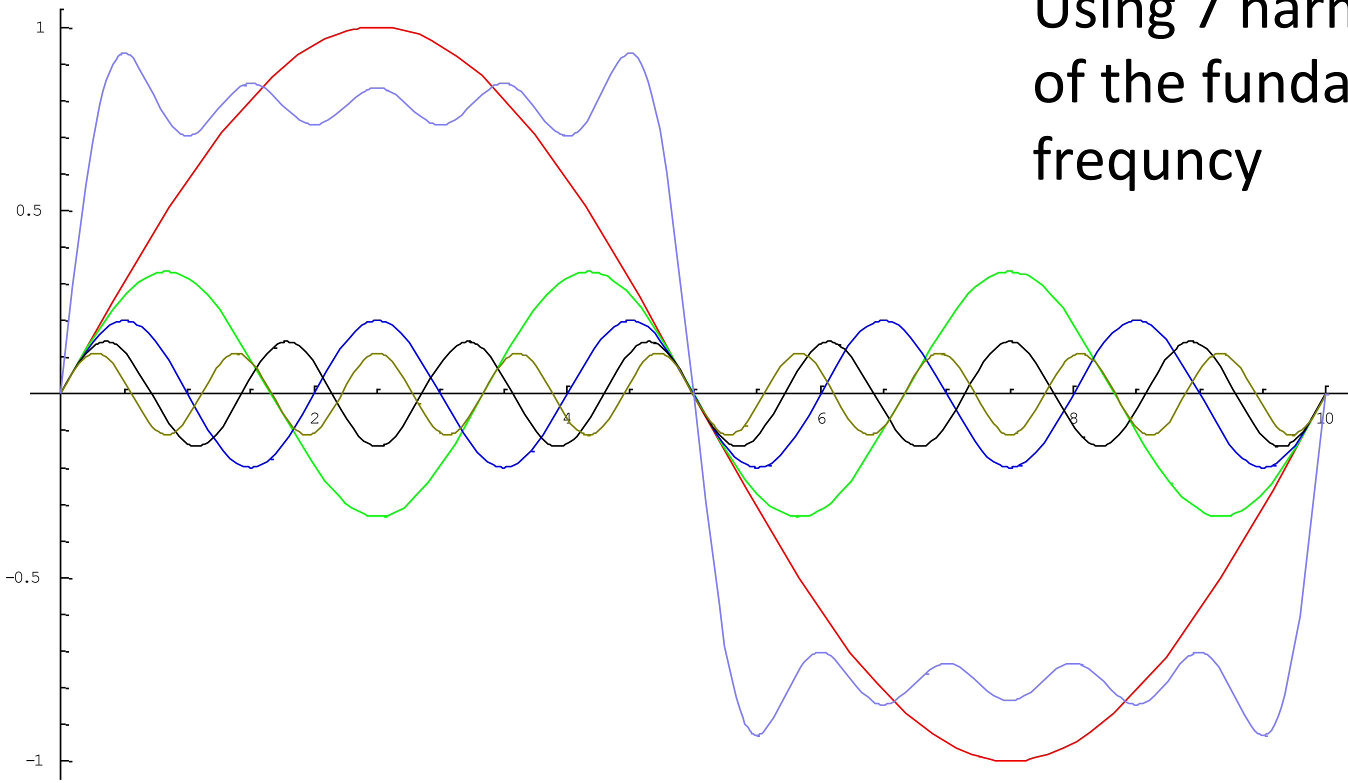
Fourier's Theorem: Representation of an square signal (2)



Using 5 harmonics of the fundamental frequncy

$$v(t) = \frac{4V}{\pi}\left(\sin \varpi_o t + \frac{1}{3}\sin 3\varpi_o t + \frac{1}{5}\sin 5\varpi_o t + \ldots\right)$$

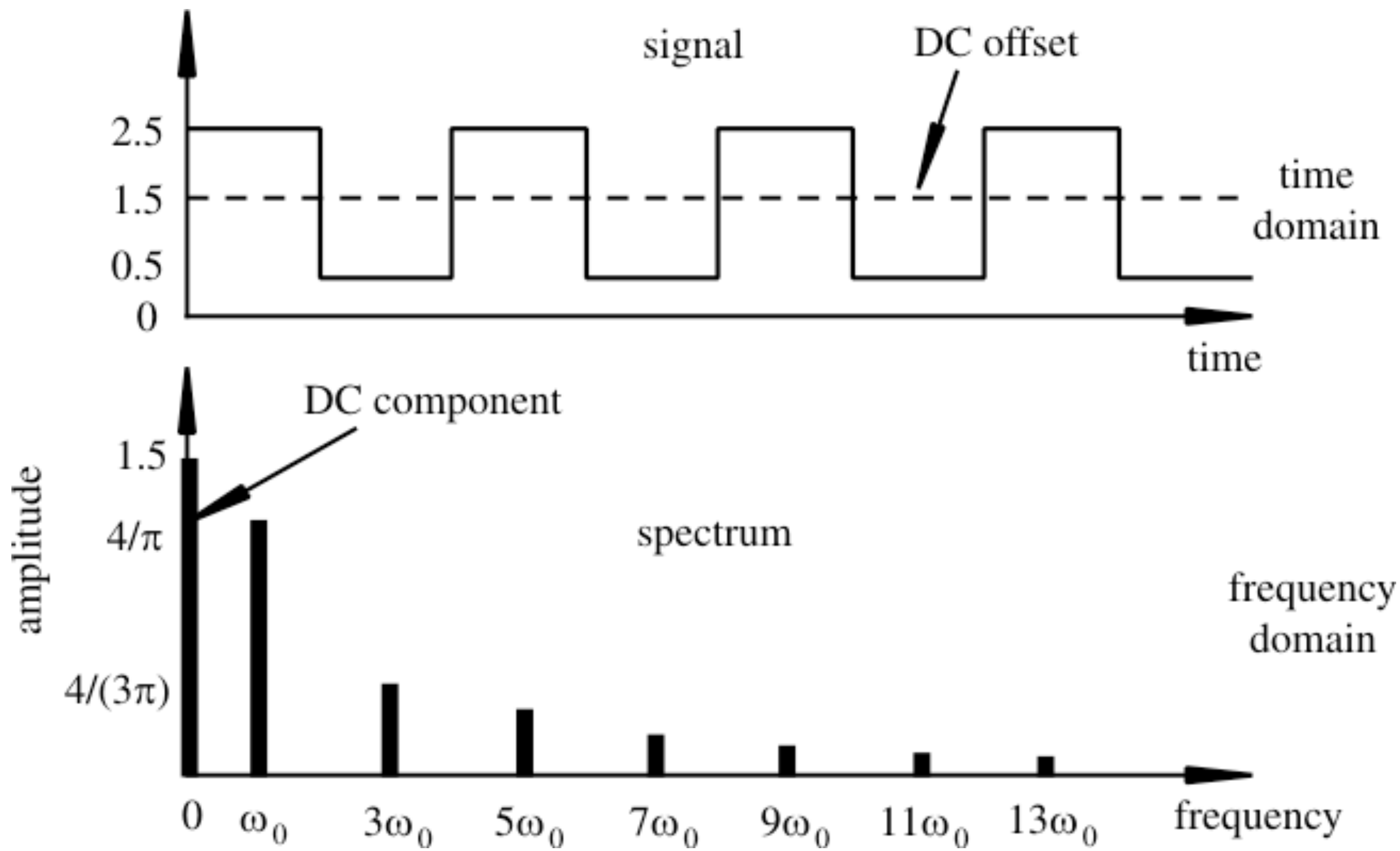
Fourier's Theorem: Representation of an square signal (3)



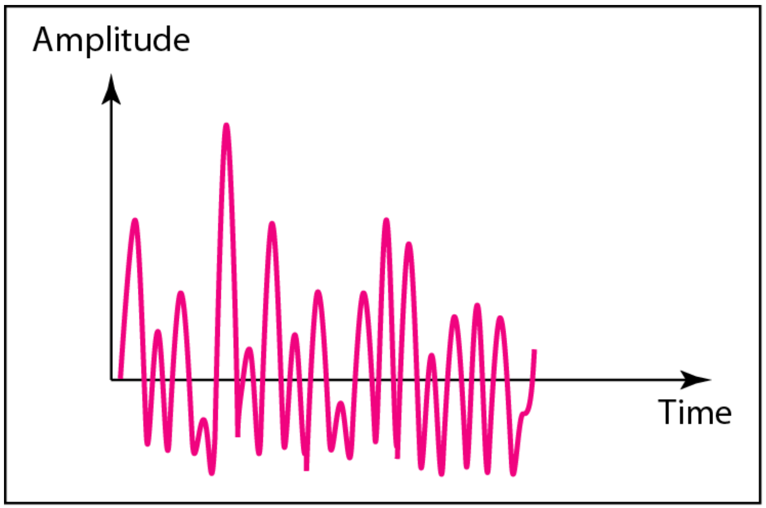
Using 7 harmonics of the fundamental frequncy

$$v(t) = \frac{4V}{\pi}(\sin \varpi_o t + \frac{1}{3}\sin 3\varpi_o t + \frac{1}{5}\sin 5\varpi_o t + \ldots)$$

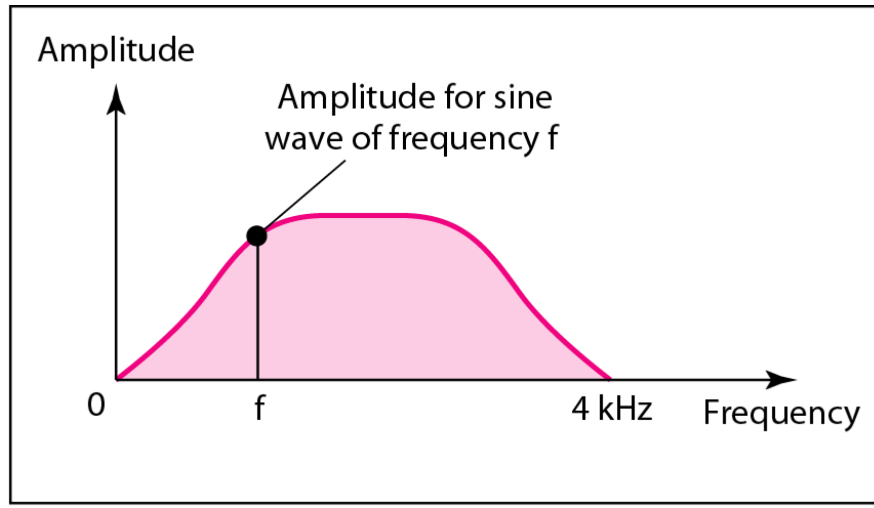
Frequency spectrum of a periodic square wave



The time and frequency domains of a non-periodic signal



a. Time domain



b. Frequency domain

Difference Fourier vs Laplace

- Fourier is a subset of Laplace. Laplace is a more generalized transform
- Fourier is used primarily for steady state signal analysis
- Laplace is used for transient signal analysis
- Laplace is good at looking for the response to pulses, step functions, delta functions, while Fourier is good for continuous signals.

$$F(s) = L\{f(t)\} = \int_0^\infty e^{-s \cdot t} f(t)\, dt$$

$$s = \sigma + jw$$

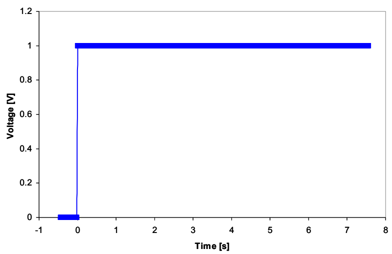
Why the analysis in frequency?

INPUT

SYSTEM

OUTPUT

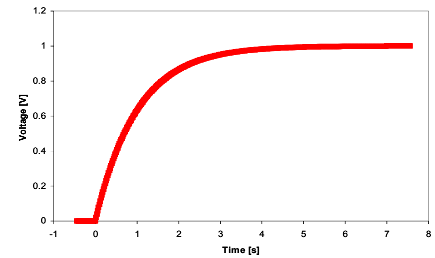
TIME DOMAIN



$$v_{in}(t) = 1(t)$$

$$v_{out}(t) = H(t) * v_{in}(t)$$

$$v_{out}(t) = \int_{-\infty}^{\infty} H(\tau) v_{in}(t-\tau) d\tau$$



$$v_{out}(t) = 1(t)\left(1 - e^{-\frac{1}{RC}}\right)$$

Much easier calculation !!!

L

L^{-1}

LAPLACE DOMAIN

$$V_{in}(s) = \frac{1}{s}$$

$$V_{out}(s) = H(s) \cdot V_{in}(s)$$

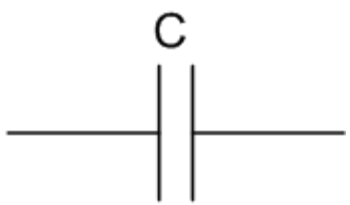
$$H(s) = \frac{1}{1 + sRC}$$

$$V_{out}(s) = \frac{1}{s} \cdot \frac{1}{1 + sRC}$$

Electronic Passive Components

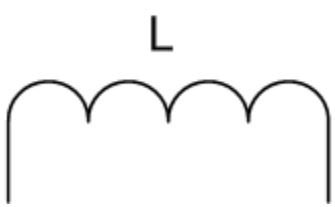
$$v(t) = i(t) \cdot R$$

$$\text{Impedance: } Z = \frac{V}{I} = R \ [\Omega]$$



$$v(t) = \frac{1}{C}\int i(t)dt$$

$$\text{Impedance: } Z = \frac{V}{I} = \frac{1}{j\omega C} = \frac{1}{sC} \ [\mathrm{F}]$$

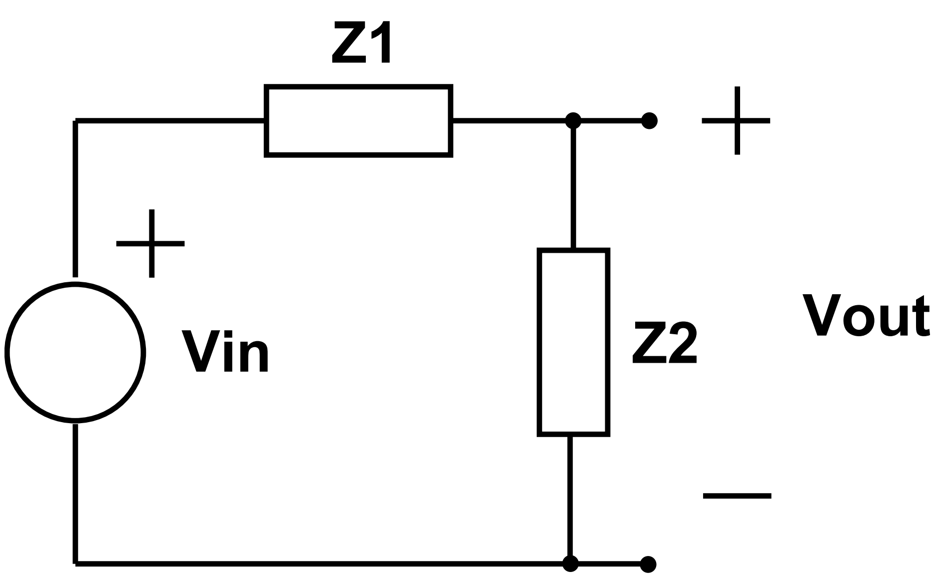


$$v(t) = L\frac{di(t)}{dt}$$

$$\text{Impedance: } Z = \frac{V}{I} = j\omega L = sL \ [\mathrm{H}]$$

Why we work using impedances

- The impedance depends on frequency (w=2πf)
- The impedance is often a complex number
- Working using impedances helps us to work using tools to solve DC circuits

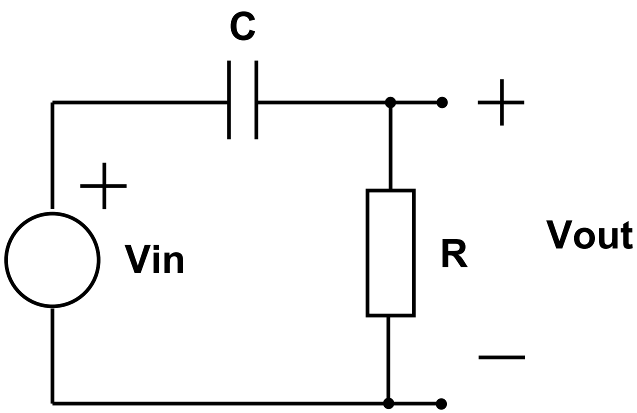


$$\frac{V_{out}}{V_{in}} = \frac{Z_2}{Z_1 + Z_2}$$

High-pass type Filter

- The transfer function

$$\frac{V_{out}}{V_{in}} = \frac{Z_R}{Z_R + Z_C} = \frac{R}{R + \frac{1}{j\omega C}} = \frac{1}{1 - \frac{1}{\omega RC} j}$$



- At high frequencies
  - Vout/Vin ≈1

$$\frac{V_{out}}{V_{in}} = \frac{Z_R}{Z_R + Z_C} = \frac{R}{R + \frac{1}{j\omega C}} = \frac{1}{1 - \frac{1}{\omega RC} j}$$

- At low frequences
  - Vout/Vin ≈0

$$\frac{V_{out}}{V_{in}} = \frac{Z_R}{Z_R + Z_C} = \frac{R}{R + \frac{1}{j\omega C}} = \frac{1}{1 - \frac{1}{\omega RC} j}$$

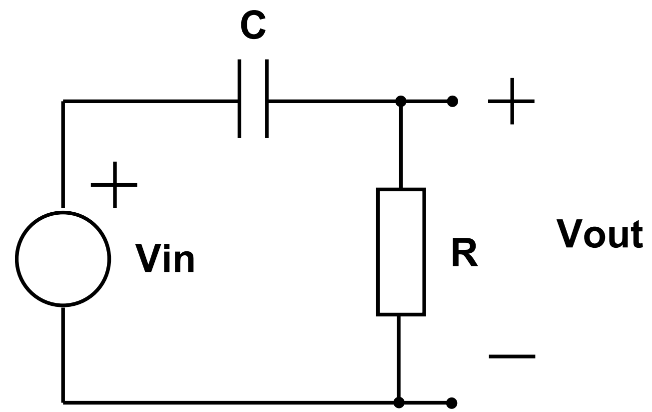
High-pass type Filter

- Gain

$$\left|\frac{Vout}{Vin}\right|(\omega) = \frac{1}{\sqrt{1+\left(\frac{1}{\omega CR}\right)^2}}$$

$$\left|\frac{Vout}{Vin}\right|_{\omega=\frac{1}{RC}} = \frac{1}{\sqrt{1+1}} = \frac{1}{\sqrt{2}}$$

Gain @ -3dB



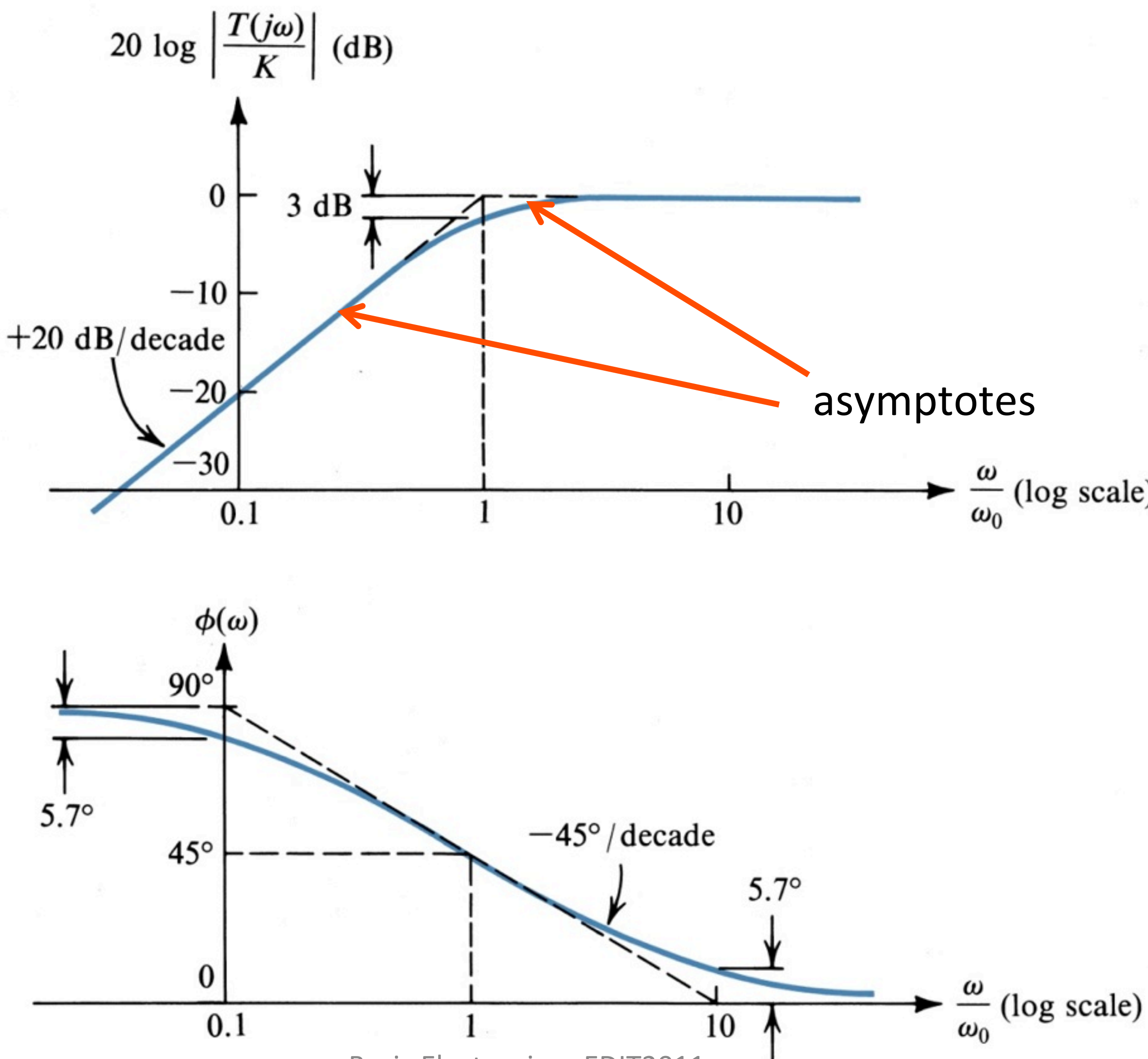
$$Gain_{dB} = 20\log\left(Gain_{lin}\right)$$

$$f_c = \frac{1}{2\pi RC}$$

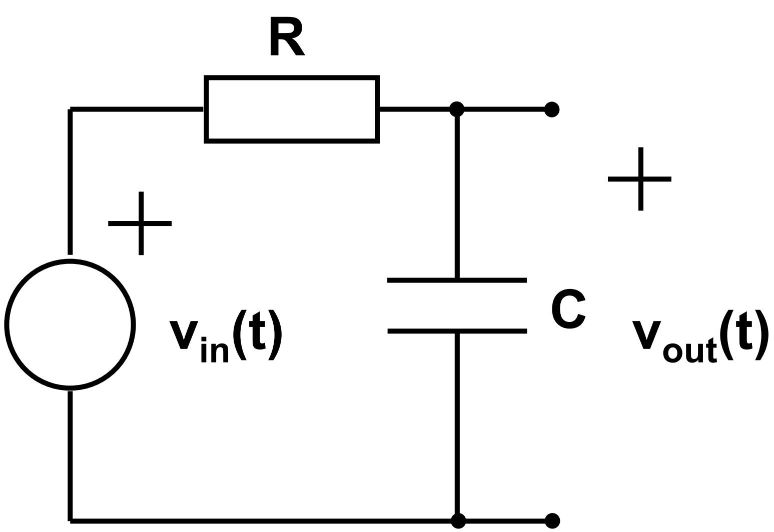
Corner frequency or break frequency (fc):

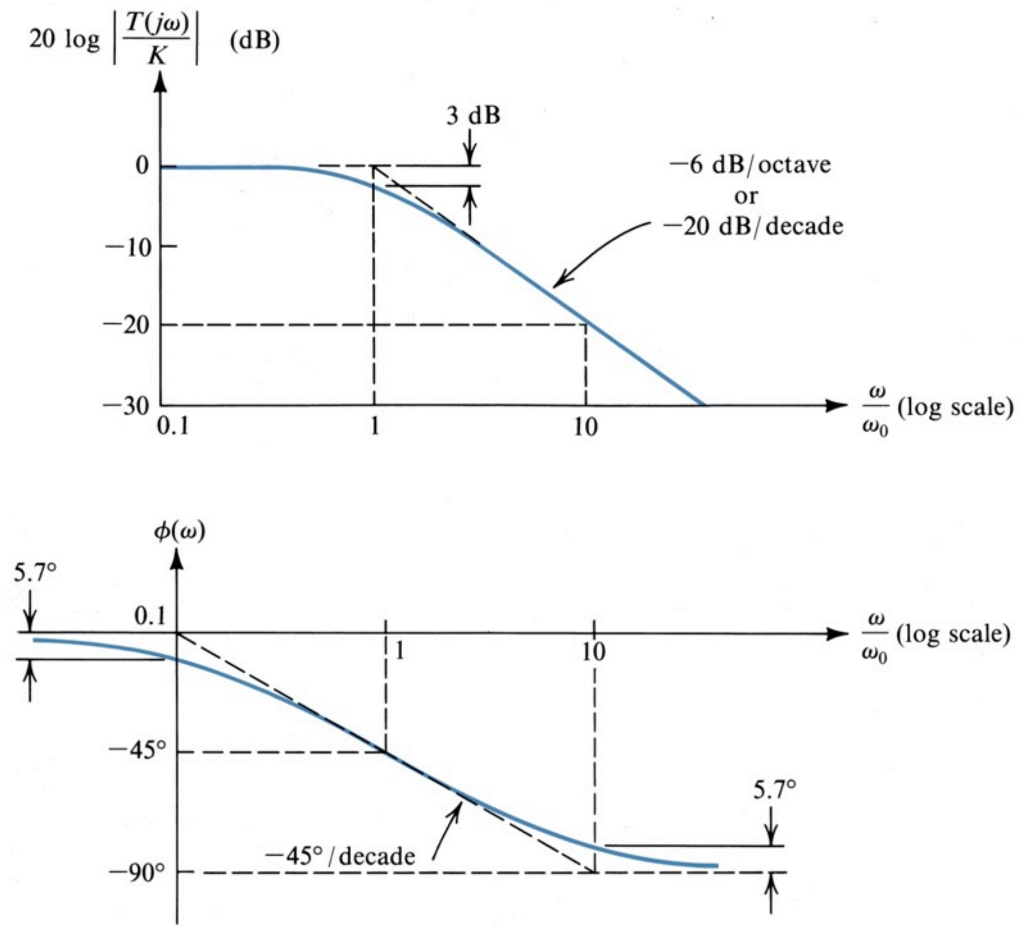
Frequency at which the impedance of the Resistor equals the impedance of the Capacitor (@-3dB)

High pass filter Bode plot

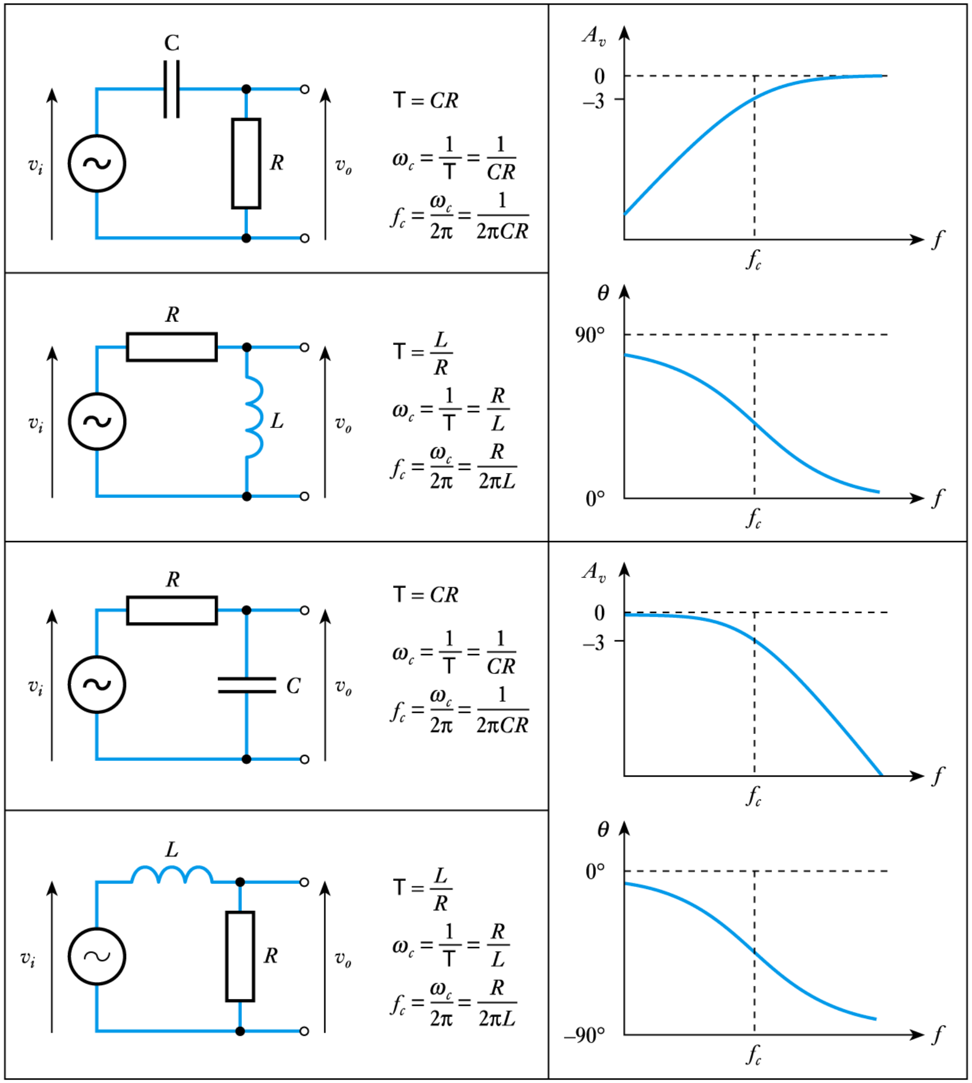


A low pass-filter



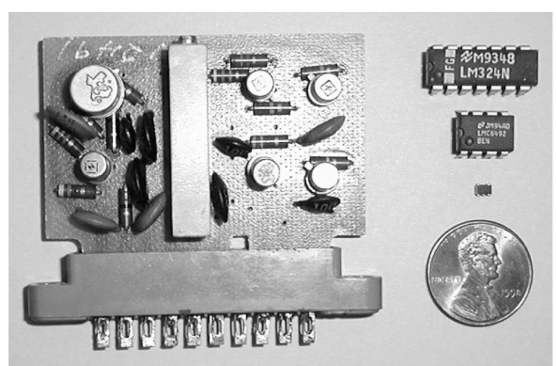


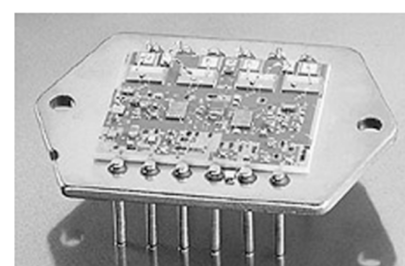
Singe-Time-constant networks



Active components → Op-Amp

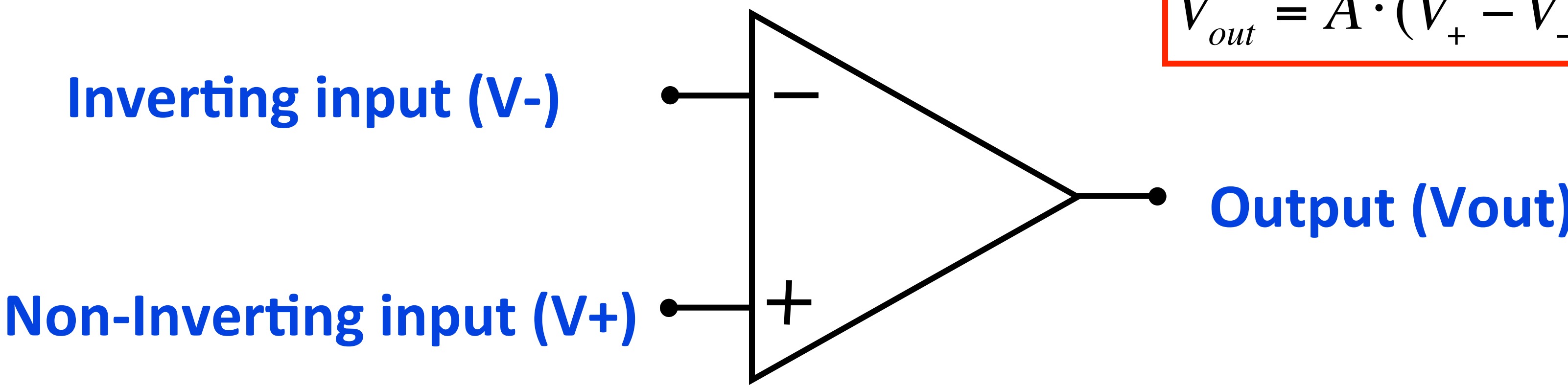
- Diodes and transistors are the discrete building active components in all modern (>1960) electronic circuits
- Operational Amplifier (Op Amps) are the basic components used to build analog circuits
- The name “operational amplifier” comes from the fact that they were originally used to perform mathematical operations such as integration and differentiation.
- Integrated circuit fabrication techniques have made high-performance operational amplifiers very inexpensive in comparison to older discrete devices.





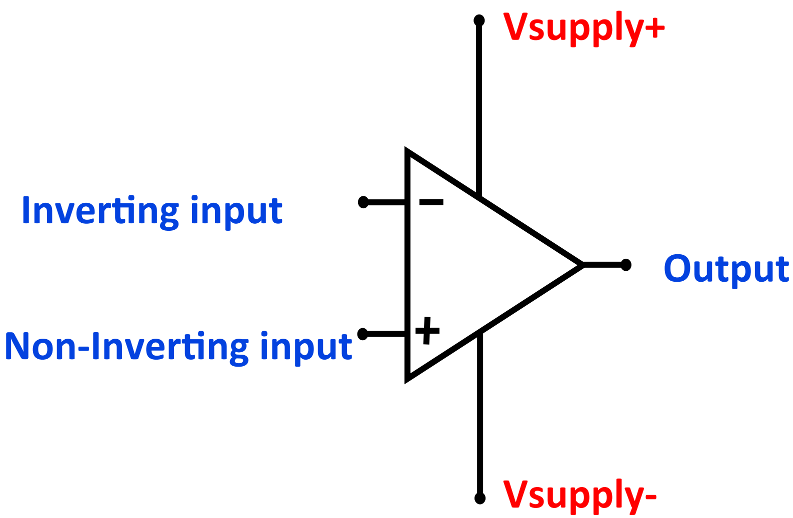
Ideal Operational Amplifiers

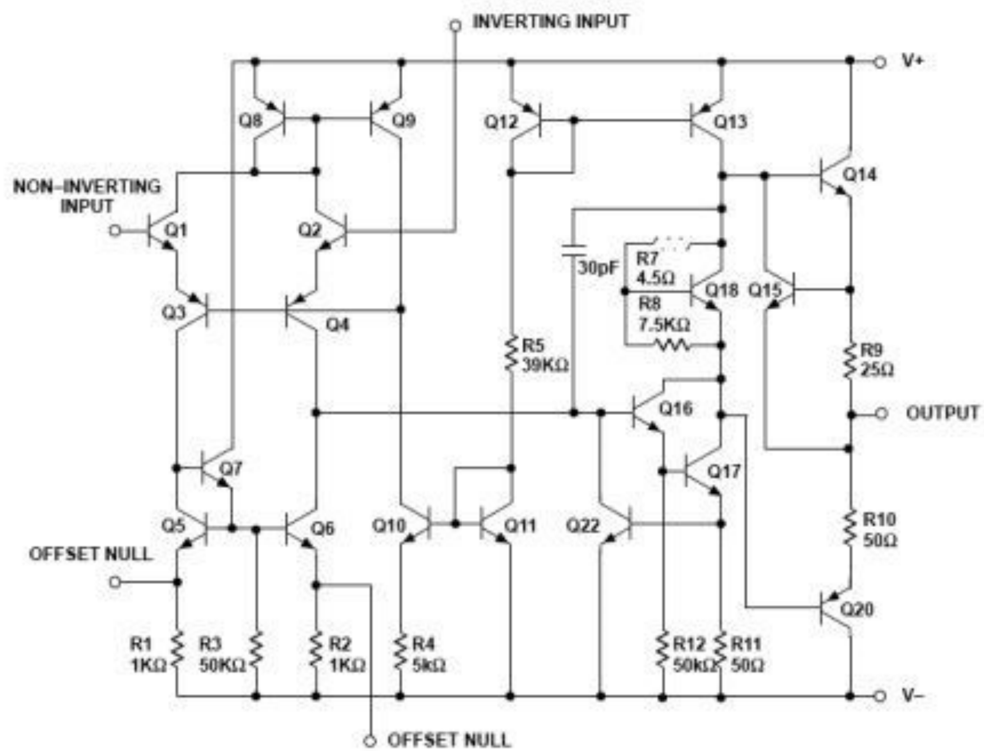
$$V_{out} = A \cdot (V_+ - V_-)$$



- Output is proportional to the difference between the non-inverting and inverting inputs
- Active device! requires power to work, even though power connections often not shown

Op-Amp with power connections



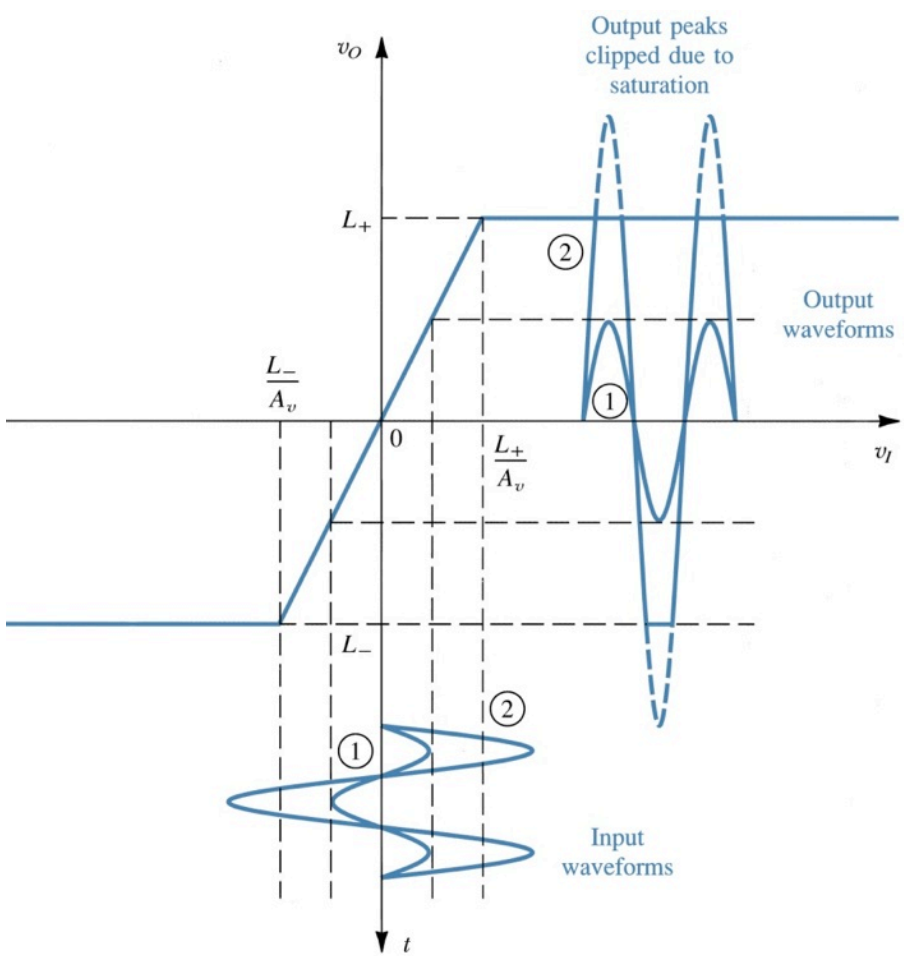


UA741 (General purpose Op-Amp)

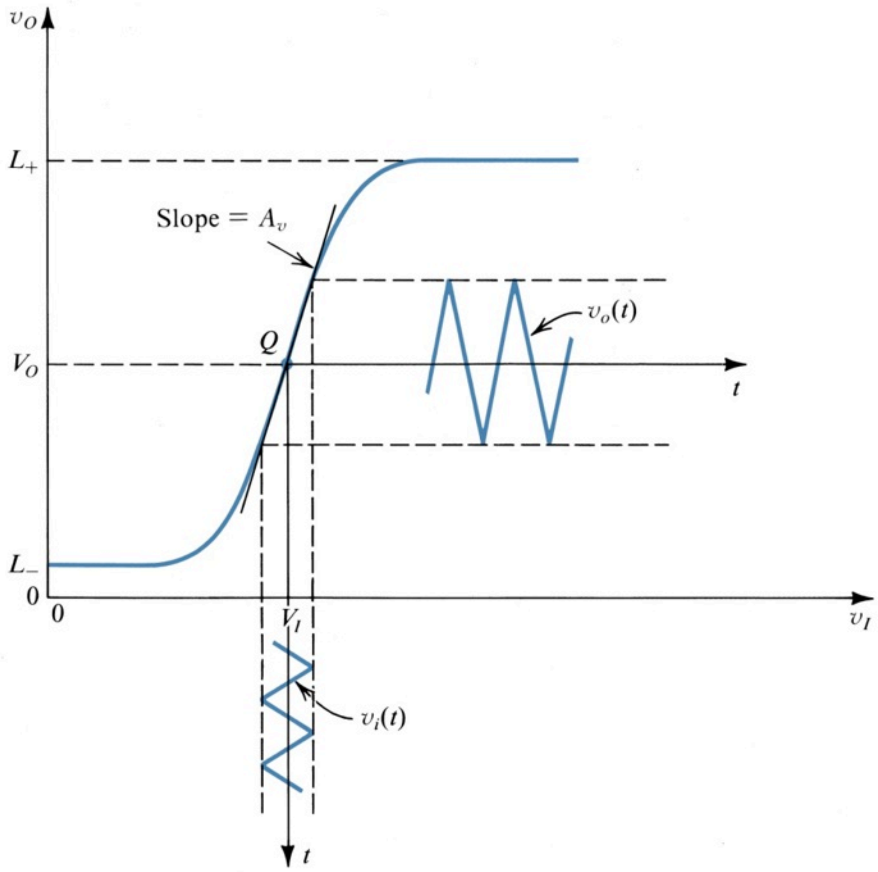
Operational amplifier supply voltage rules

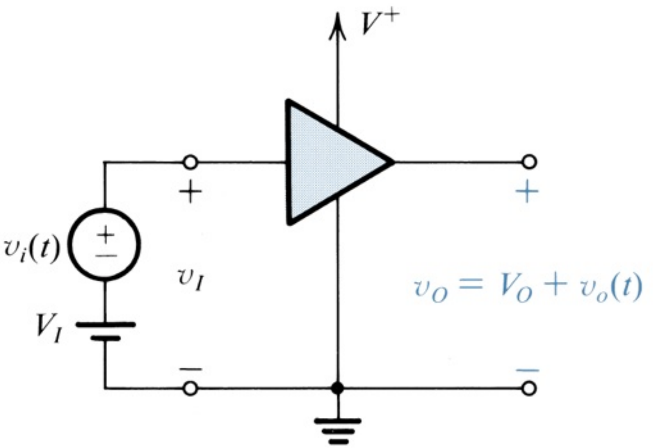
- **Vsupply+** is the positive supply.
- **Vsupply-** is the negative supply.
- In a single supply op amp, the negative supply can be ground.
- These voltage limits are also called rails.
- **The output of an op amp can't go outside the supply voltages** → Rail-to-rail Op-Amp
- Single supply Op-Amp are an exception; you usually can usually get within a few mV of the negative supply
- When an op amp hits one of the rails, its output can be called saturated, or we can say the op amp is in saturation.

Amplifier Saturation



Non-Linear Transfer Characteristics and Biasing





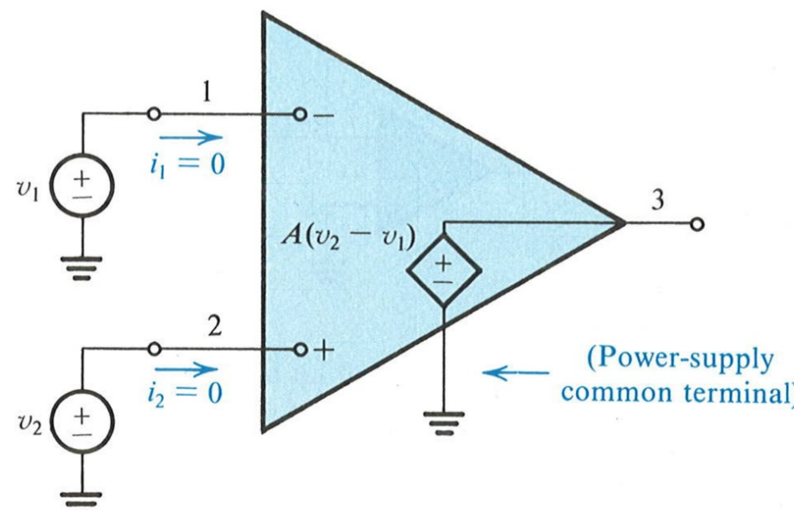
(left) An amplifier transfer characteristic that shows considerable nonlinearity

(right) To obtain linear operation the amplifier is biased as shown, and the signal amplitude is kept small.

Equivalent circuit of Ideal Op-Amp

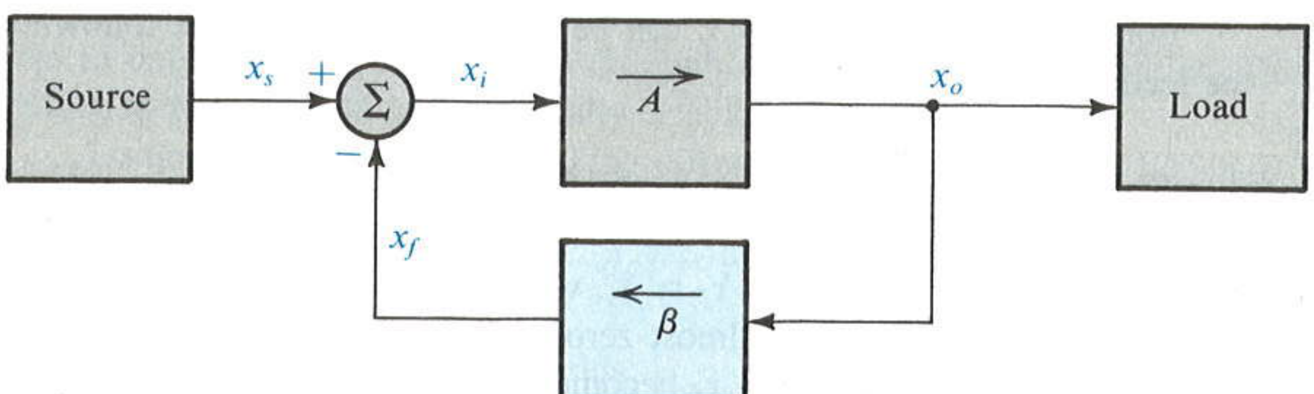
- Sense the difference between the voltages signals applied at its two input terminals and multiplies this by A (open loop gain)

- Ideally such an amplifier has:
  - Infinite input impedance (Zin)
  - 0 output impedance (Zout)
  - Infinite bandwidth
  - Infinite open loop gain

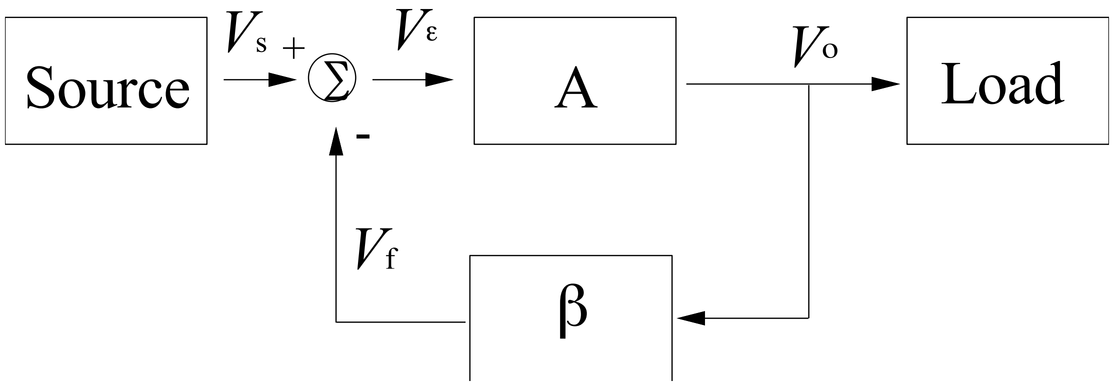


Feedback in amplifiers

- Op amps are rarely used in the open-loop configuration → They usually use negative feedback
- β is called the feedback factor and β (0,1)
- It is the proportion of the output fed back into the input
- If it goes into the inverting input, it is negative feedback
- If it goes into the non-inverting input, it is positive feedback



General feedback structure



A : Open Loop Gain
$A = V_o / V_\varepsilon$

β : feedback factor
$\beta = V_f / V_o$

$$V_\varepsilon = V_s - V_f$$
$$V_f = \beta \cdot V_o$$
$$V_\varepsilon = V_S - \beta \cdot V_o$$
$$V_o = A \cdot V_\varepsilon$$

Close loop gain : $A_{CL} = \frac{V_o}{V_s} = \frac{A}{1 + A\beta} = \frac{1}{\beta}\left(\frac{T}{1+T}\right)$

Loop Gain : $T = A \cdot \beta$

Amount of feedback : $1 + A \cdot \beta$

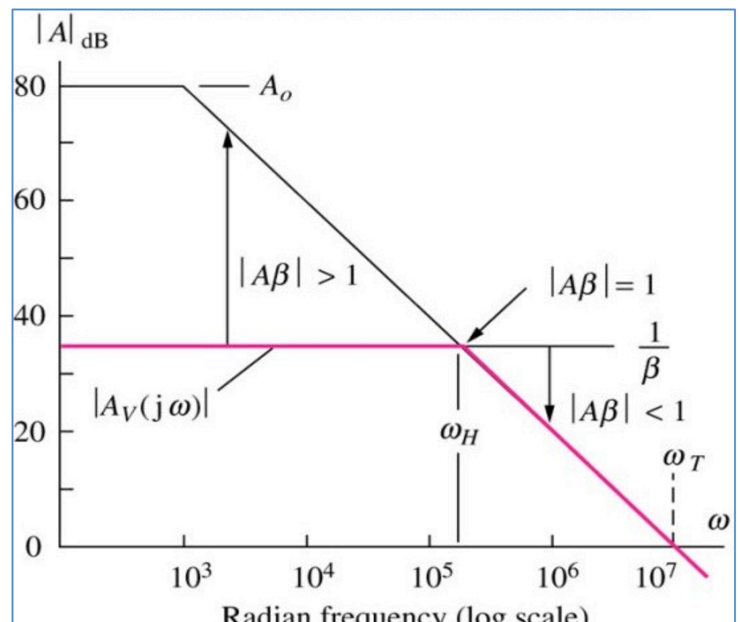
Note : $A_{CL}\big|_{A \to \infty} = \frac{1}{\beta}$

But why negative feedback is important?

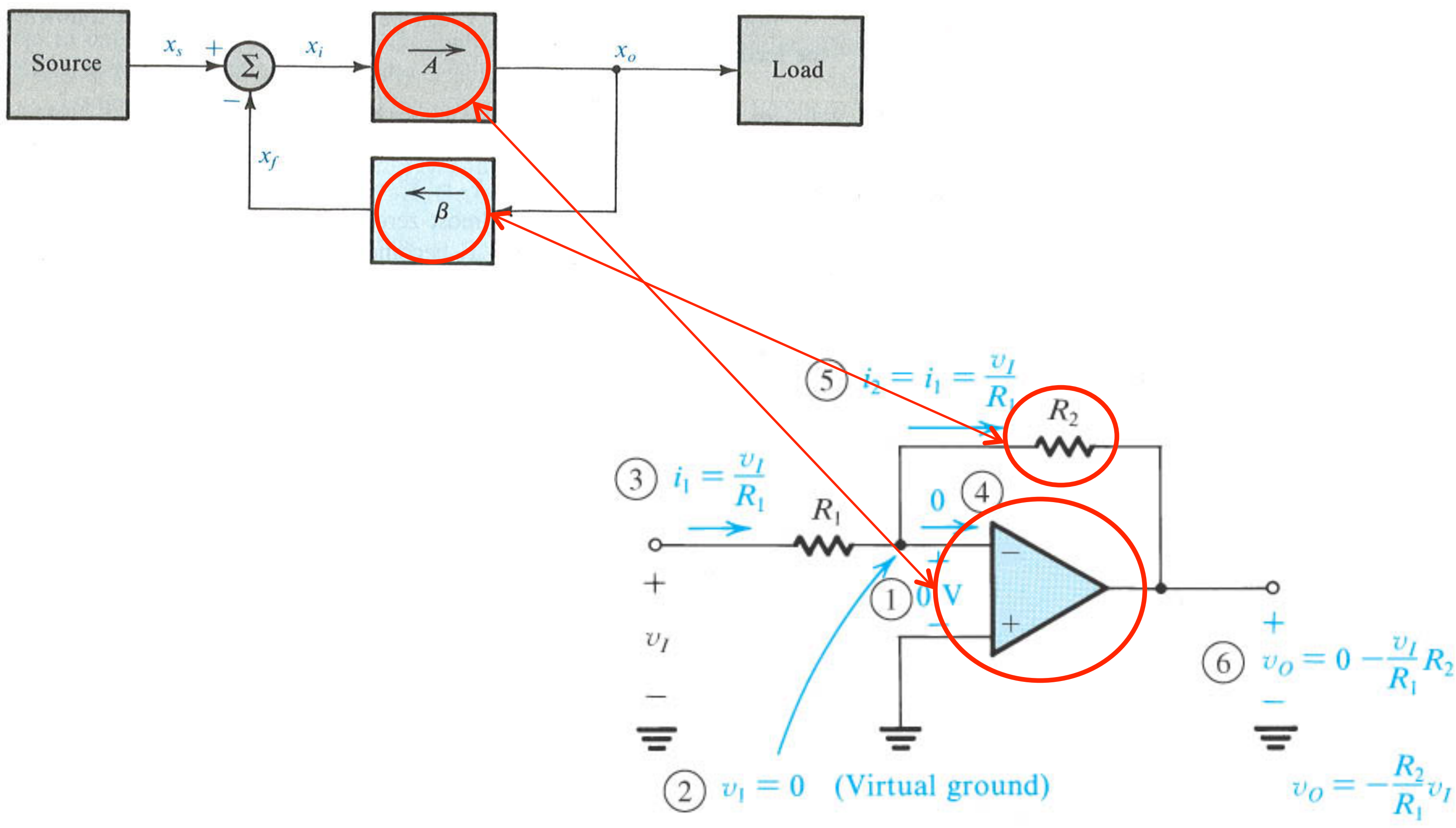
- If Aβ >> 1 then $$A_f = \frac{x_0}{x_s} = \frac{A}{1 + A\beta} \rightarrow \frac{1}{\beta}$$

  The output depends only on the feedback, not on the op amp characteristics

- It can be demonstrated also that negative feedback:
  - Reduce nonlinear distortion
  - Reduce the effect of noise
  - Control the input and output impedance
  - Extend the bandwidth of the amplifier
- All of these properties can be achieved by trading off gain



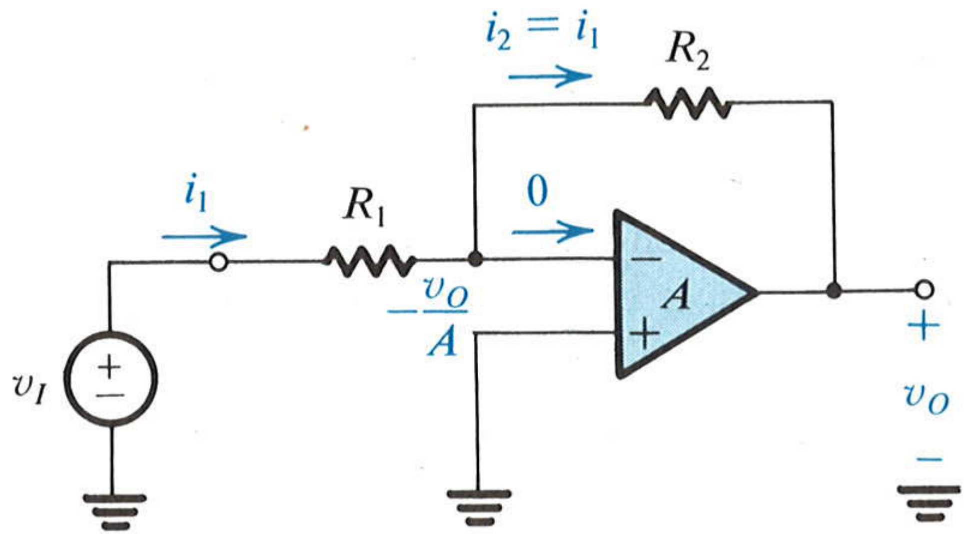
Negative feedback in Ideal OP-AMPS: The Inverting Configuration (ideal Op-Amp)



(b)

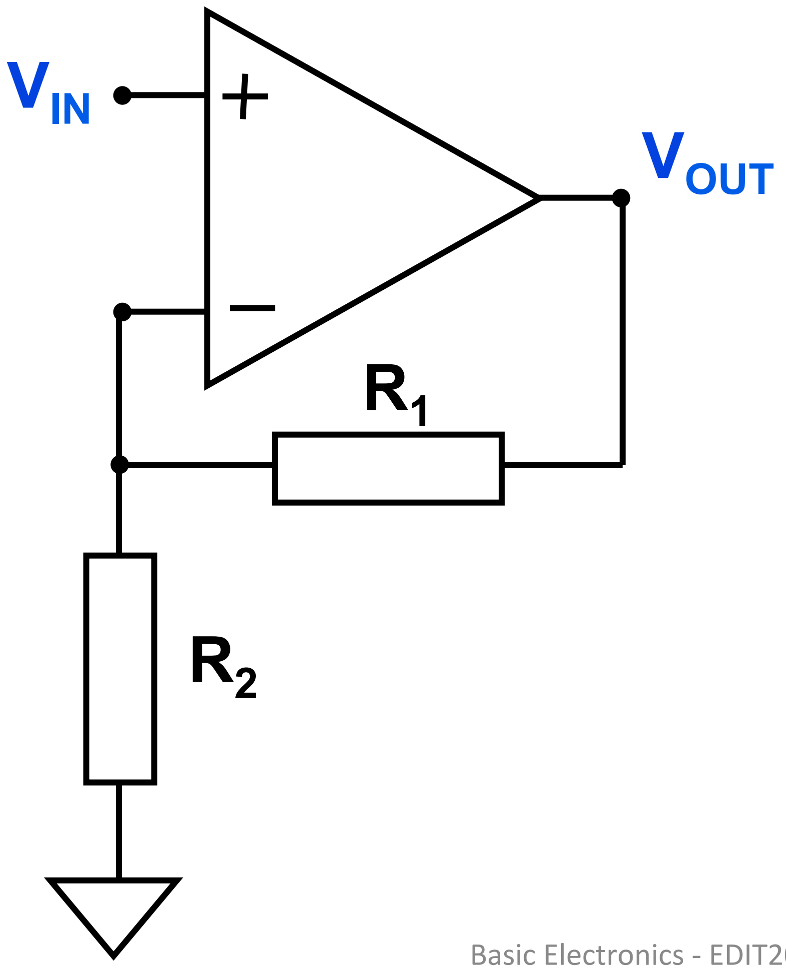
Effect of a Finite Open-loop Gain

$$\frac{V_{out}}{V_{in}} = \frac{-R2/R1}{1+\frac{1+R2/R1}{A}}$$



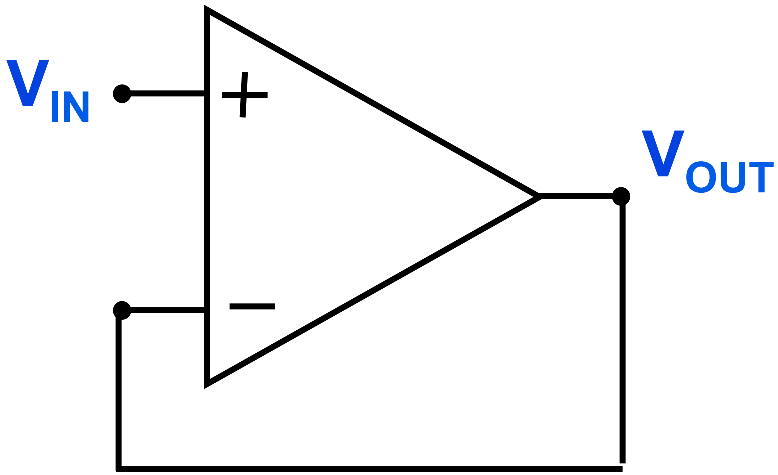
$$1+\frac{R2}{R1} << A$$ → Minimizes the dependence of the open loop gain (A) in the close loop Gain !

Basic OA configurations: Non-inverting configuration



$$\frac{V_{out}}{V_{in}} = 1 + \frac{R1}{R2}$$

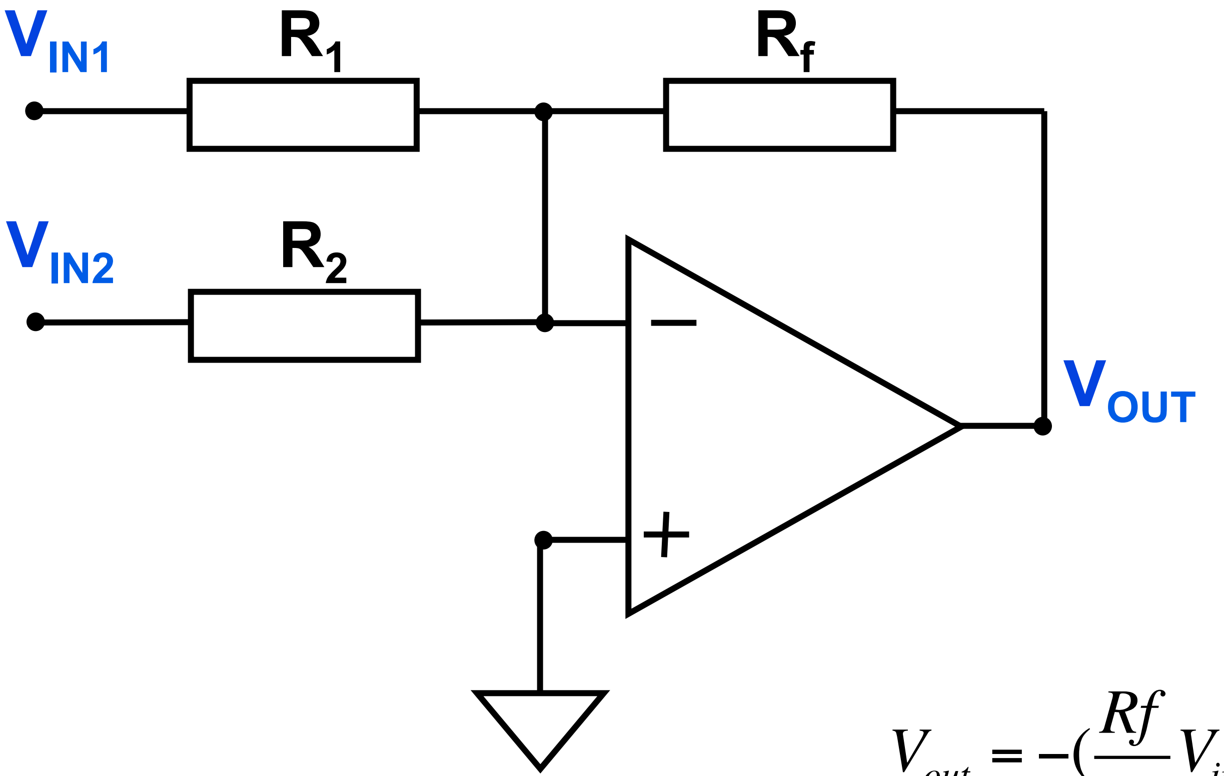
Basic OA configurations: Voltage follower (Analog buffer)



$$\frac{V_{out}}{V_{in}} = 1$$

- Since in the voltage-follower circuit the entire output is fed back to the inverting input, the circuit is said to have 100% negative feedback

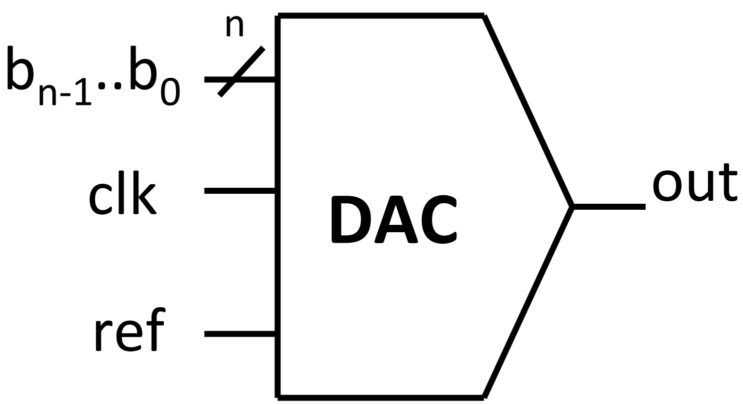
Basic OA configurations: A Weighted summer

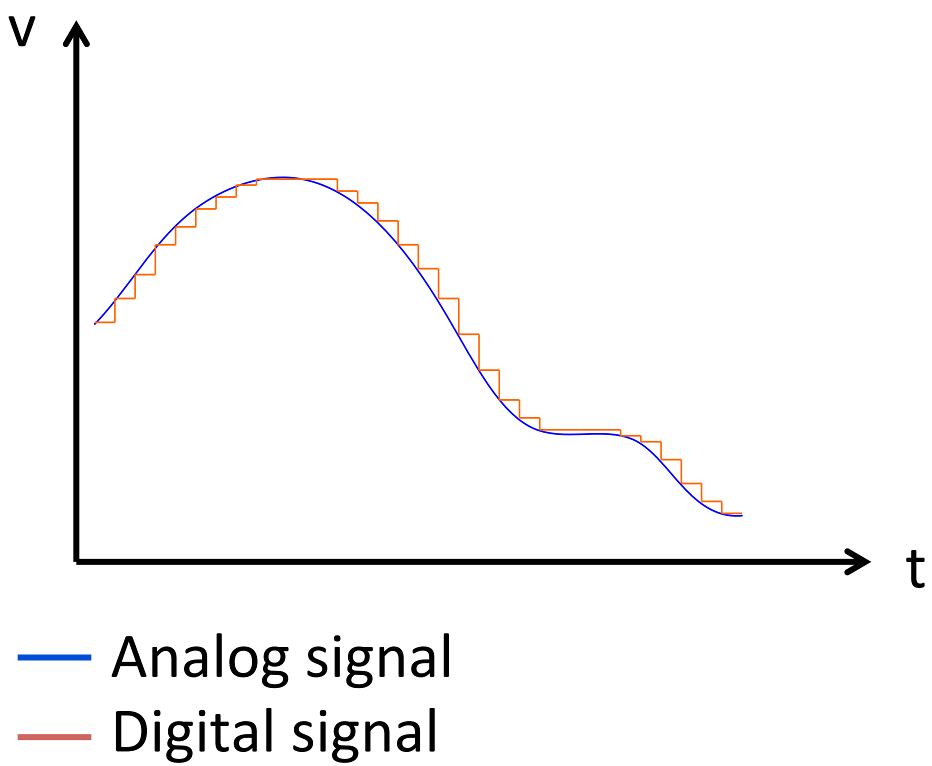


$$V_{out} = -\left(\frac{Rf}{R1}V_{in1} + \frac{Rf}{R2}V_{in2}\ldots\ldots\right)$$

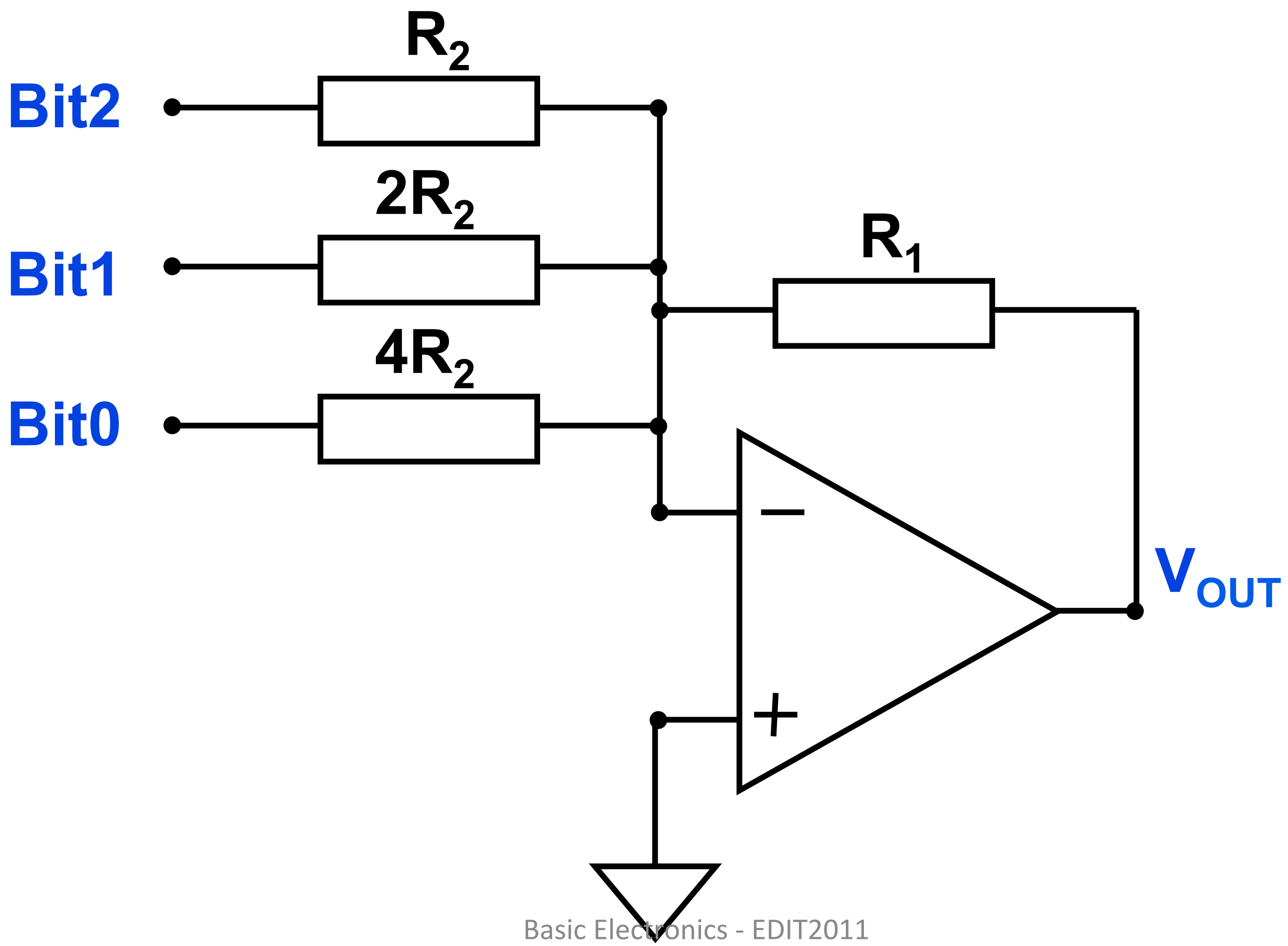
Example: Analog to Digital Converter

- A **Digital to Analog Converter** (**DAC**) generates an analog output which corresponds to an digital input

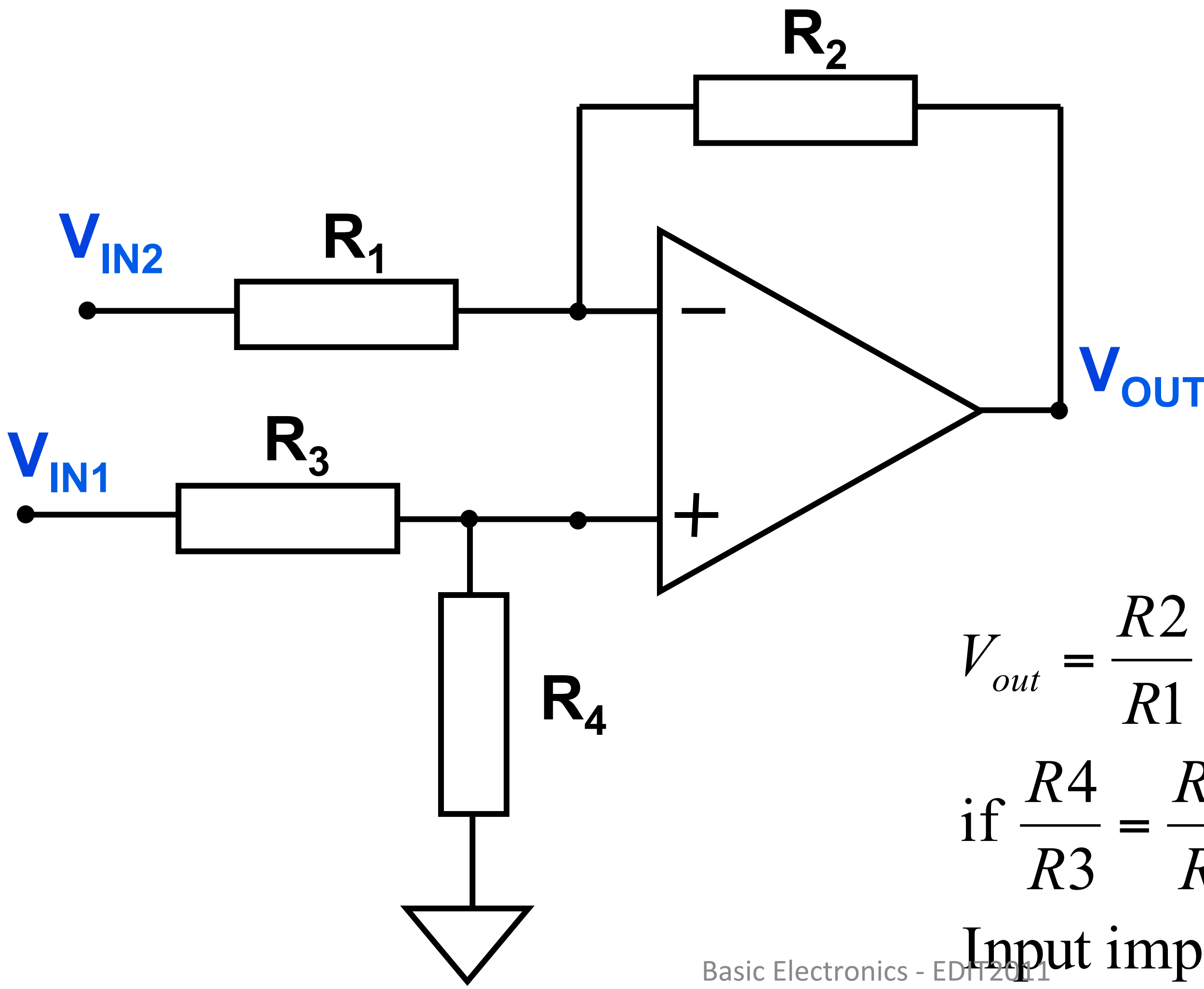




Example: 3-bit Analog to Digital Converter (II)



Basic OA configurations: A difference amplifier

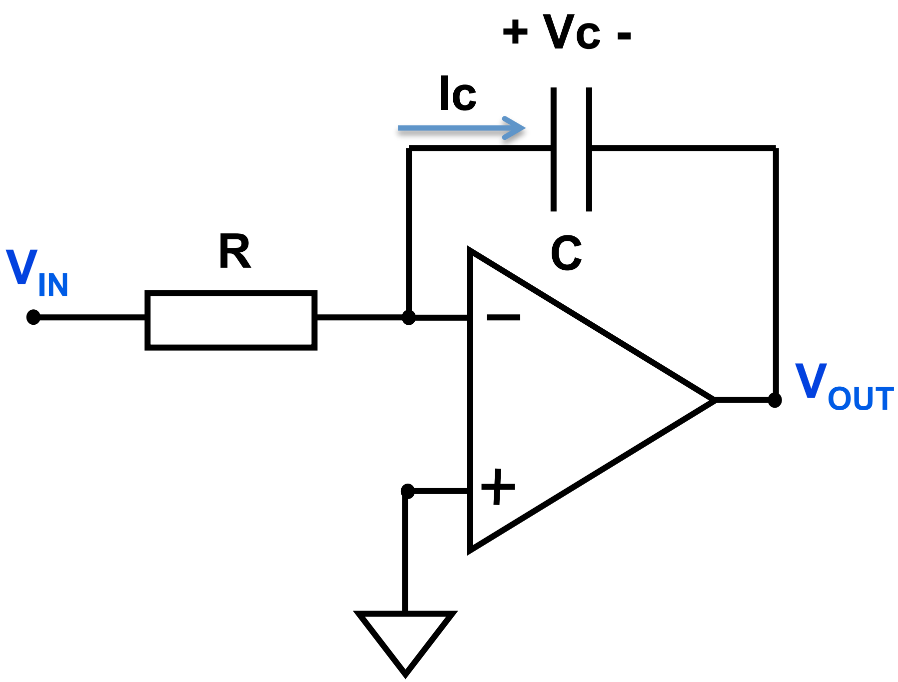


$$V_{out} = \frac{R2}{R1}(V_{in1} - V_{in2})$$

$$\text{if } \frac{R4}{R3} = \frac{R2}{R1}$$

$$\text{Input impedance}: Zin = 2R1$$

The Inverting Integrator: temporal response



$$Vc(t) = Vc + \frac{1}{C}\int_0^t i_c(t)\,dt$$

$$V_{out}(t) = -\frac{1}{RC}\int_0^t V_{in}(t)\,dt - Vc$$

- This circuit provides an output voltage that is proportional to the time integral of the input
- Vc is the initial condition of integration and CR the **integrator time constant**

The inverting integrator: Frequency response

Transfert function (S domain)

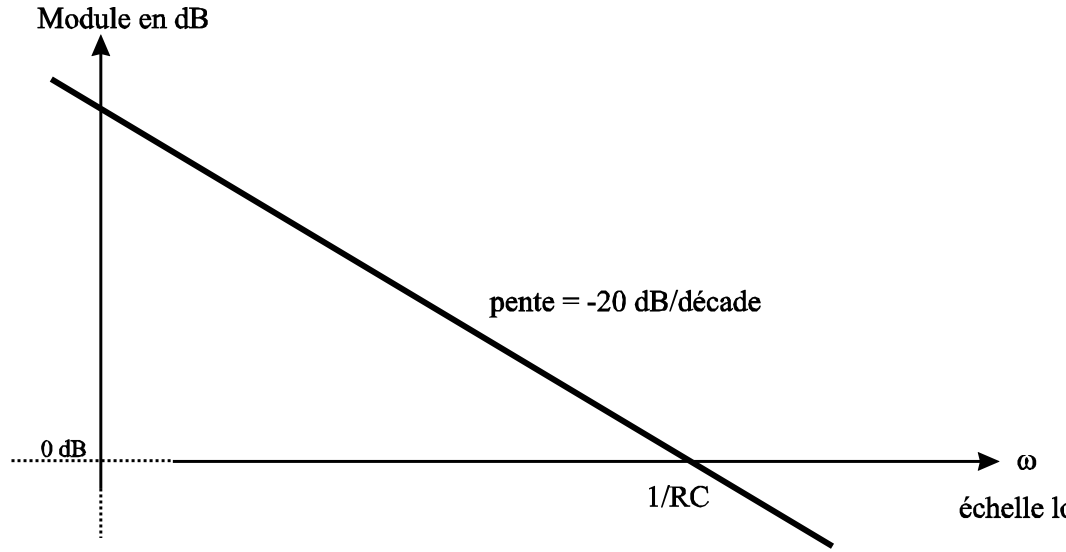
$$\frac{Vout(s)}{Vin(s)} = -\frac{1}{sRC}$$

Transfert function (physical frequencies)

$$\frac{Vout(jw)}{Vin(jw)} = -\frac{1}{jwRC}$$

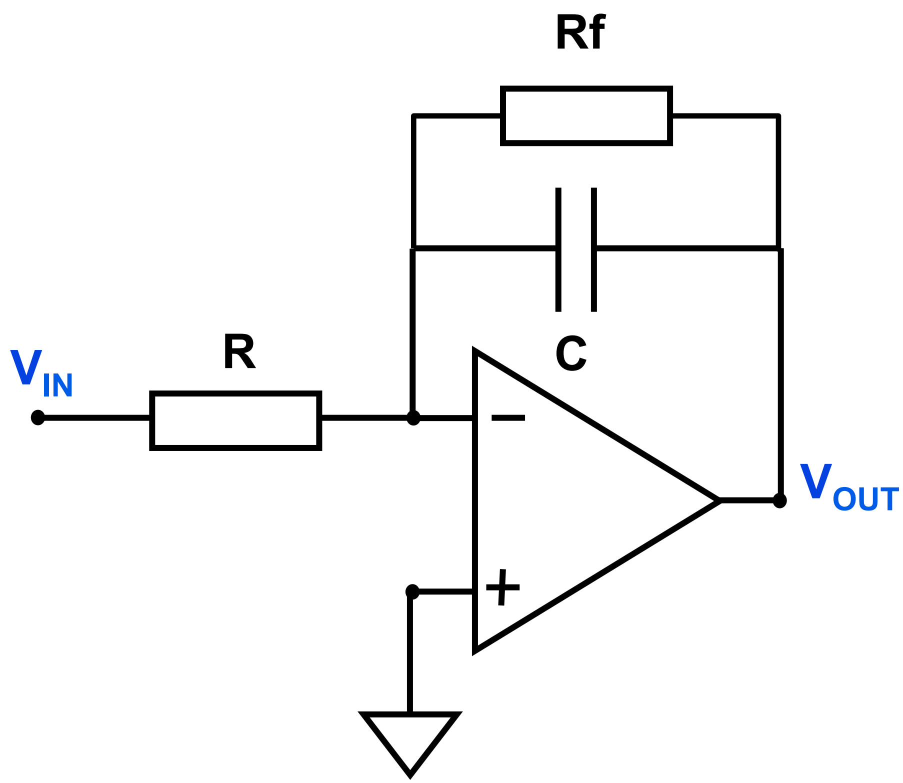
Magnitude

$$\left|\frac{Vout}{Vin}\right| = \frac{1}{wRC}$$



- Integrator operates as an open-loop amplifier for DC inputs (w=0)

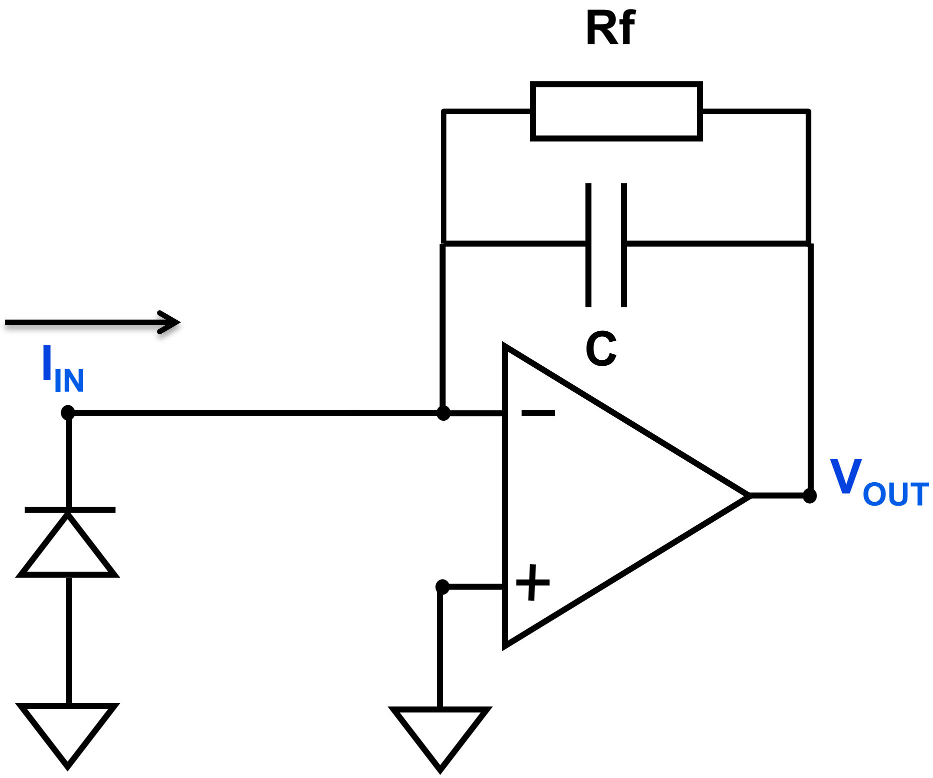
The inverting integrator: finite DC response



$$\frac{Vout(s)}{Vin(s)} = -\frac{R_F / R}{1 + sCR_F}$$

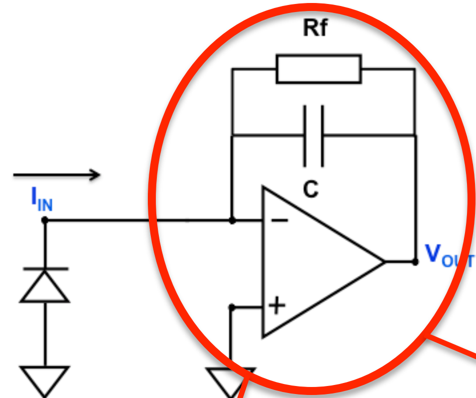
- The gain at DC is now –Rf/R

A charge amplifier

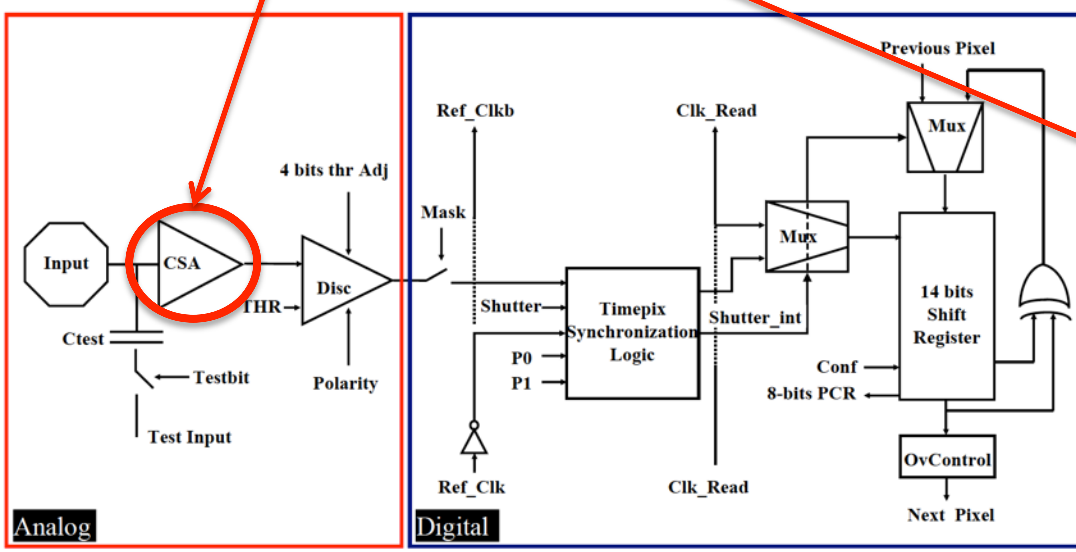


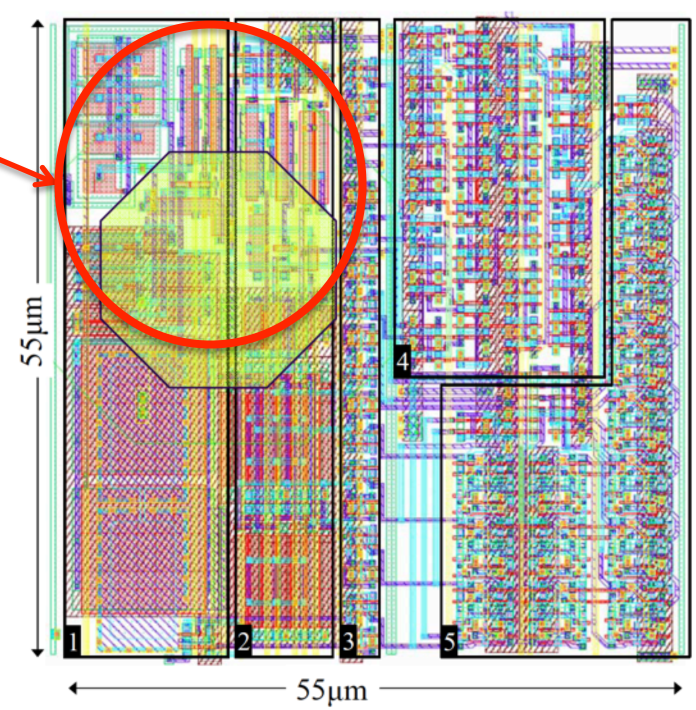
$$\frac{Vout(s)}{Iin(s)} = -\frac{R_F}{1 + sCR_F}$$

A charge amplifier in HEP



$$\frac{Vout(s)}{Iin(s)} = -\frac{R_F}{1 + sCR_F}$$

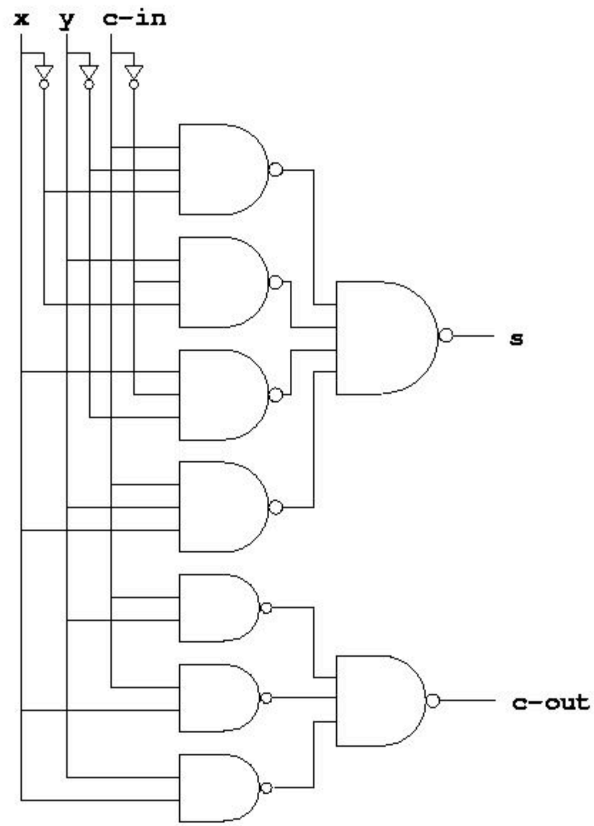




Summary

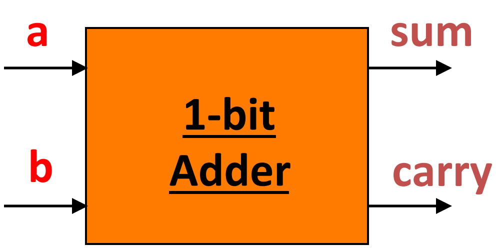
- Analog signals are representation of physical quantities
- Different mathematical tools used in analog circuit design have been shown (KVL,KCL, Fourier/Laplace…)
- Operational Amplifier (Op Amps) are the basic components used to build analog circuits
- Negative feedback is very useful in order to desensitize the OA characteristics to affect the circuit performance

DIGITAL CIRCUITS



Digital Circuits

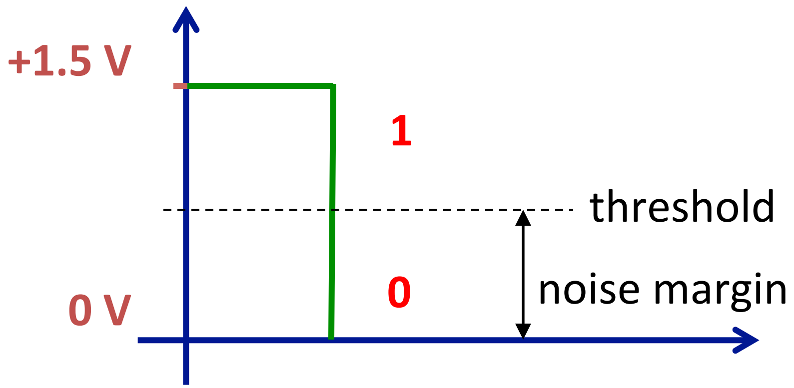
- It is an electronic subsystem which operates entirely on numbers (using, for instance, binary representation)

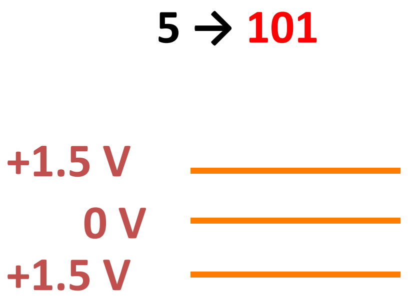


a	b	sum	carry
0	0	0	0
0	1	1	0
1	0	1	0
1	1	0	1

Encoding of Digital Signals

- We use binary digits
  - Two values: {**0 , 1**}
- Positional system
- Encoded by two voltage levels
  - **+1.5 V → 1 , 0 V → 0**





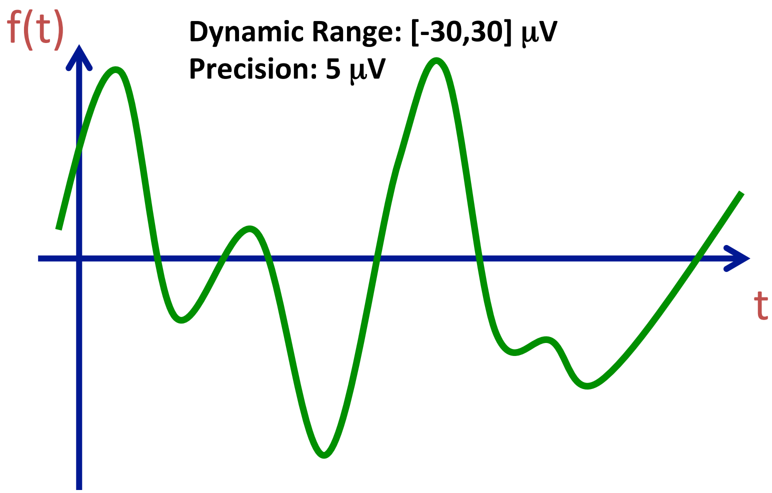
Why binary Digital?

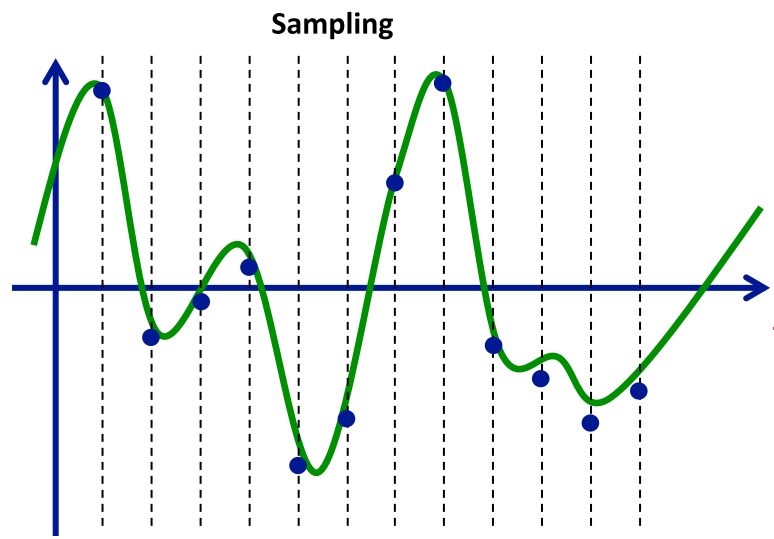
- Digital signals are easy and cheap to store
- Digital signals are insensible to noise
- Boolean algebra can be used to represent, manipulate, minimize logic functions
- Digital signal processing is easier and relatively less expensive than analog signal processing

Digital Representation of Analog Signals

- Problem: represent f(t) using a finite number of binary digits
- Example: A key stroke using 6 bits
  - Only 64 possible values, hence not all values can be represented
- Quantization error: due to finite number of digits
- Time sampling: time is continuous but we want a finite sequence of numbers

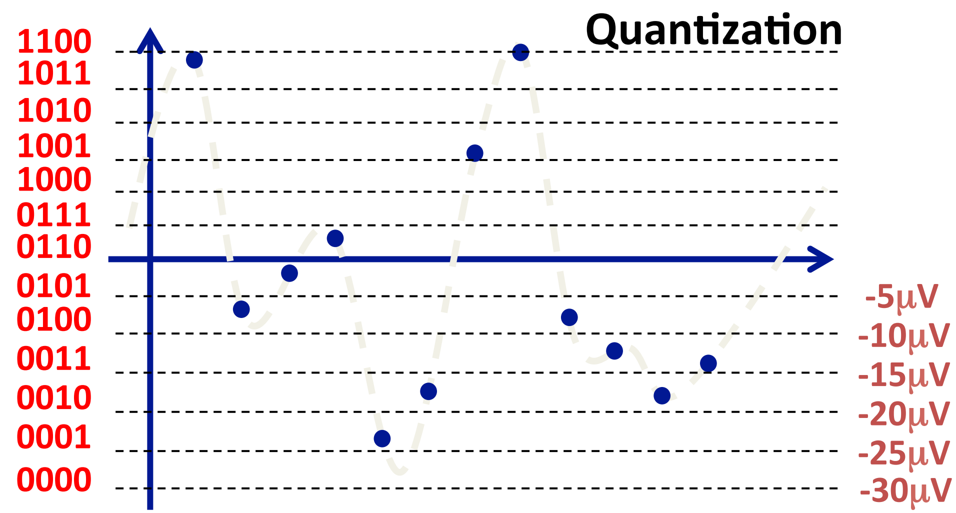
Digital Representation of Analog Signals





1011
0100
0101
0110
0001
0010
1001
1100
0100
0011
0010
0011

Result ←



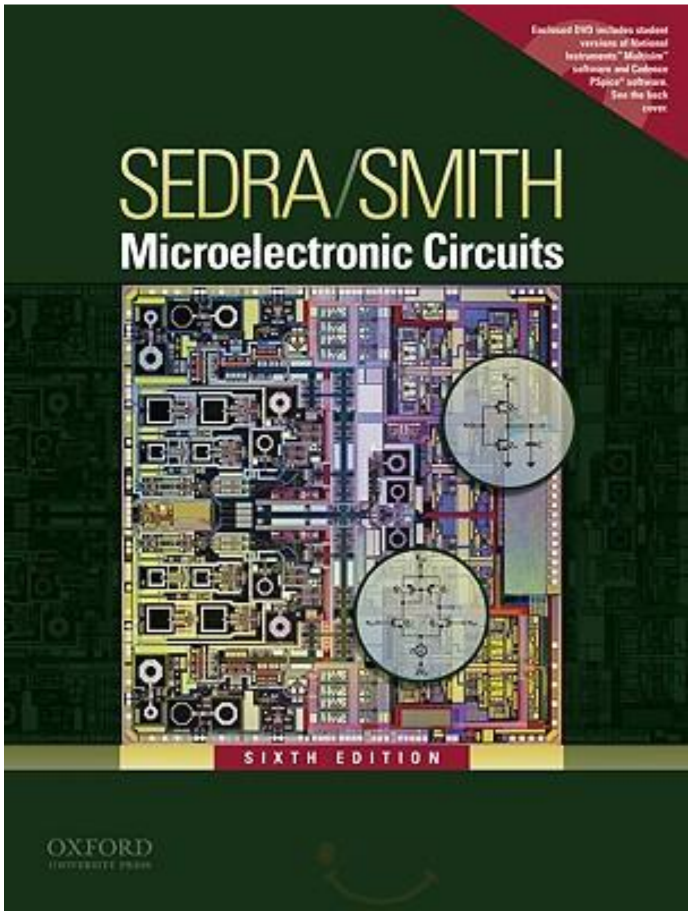
Digital Representation of Logic Functions

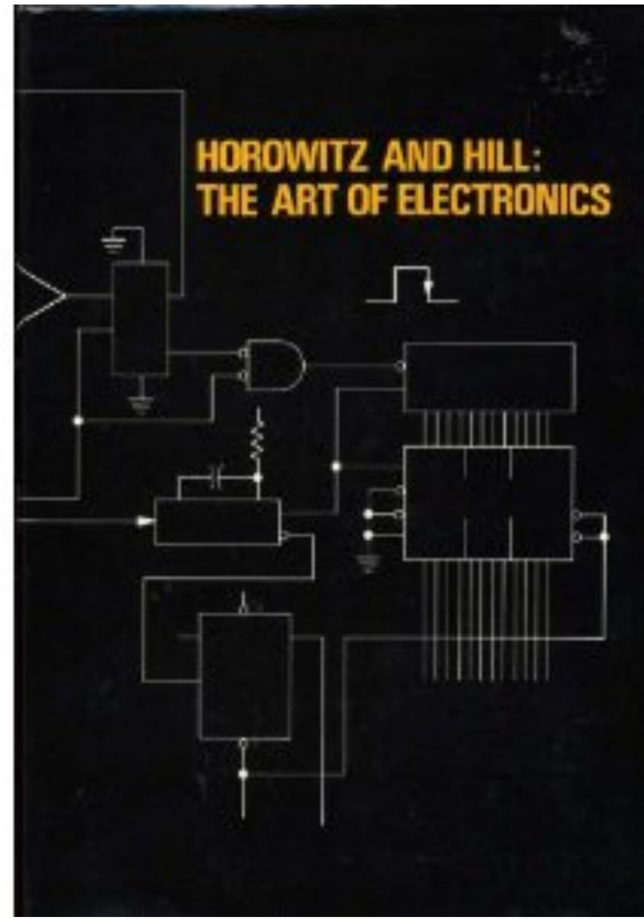
- Boolean Algebra:
  - Variables can take values **0 or 1** (true or false)
  - Operators on variables:
    - a AND b $a \cdot b$
    - a OR b $a+b$
    - NOT b $\sim b$
- Any logic expression can be built using these basic logic functions
- Example: exclusive OR

Summary

- Analog signals are representation of physical quantities
- Digital signals are less sensible to noise than analog signals
- Digital signals can represent analog signals with arbitrary precision (at the expense of digital circuit cost)
- Boolean algebra is a powerful mathematical tool for manipulating digital circuits

Recommended references

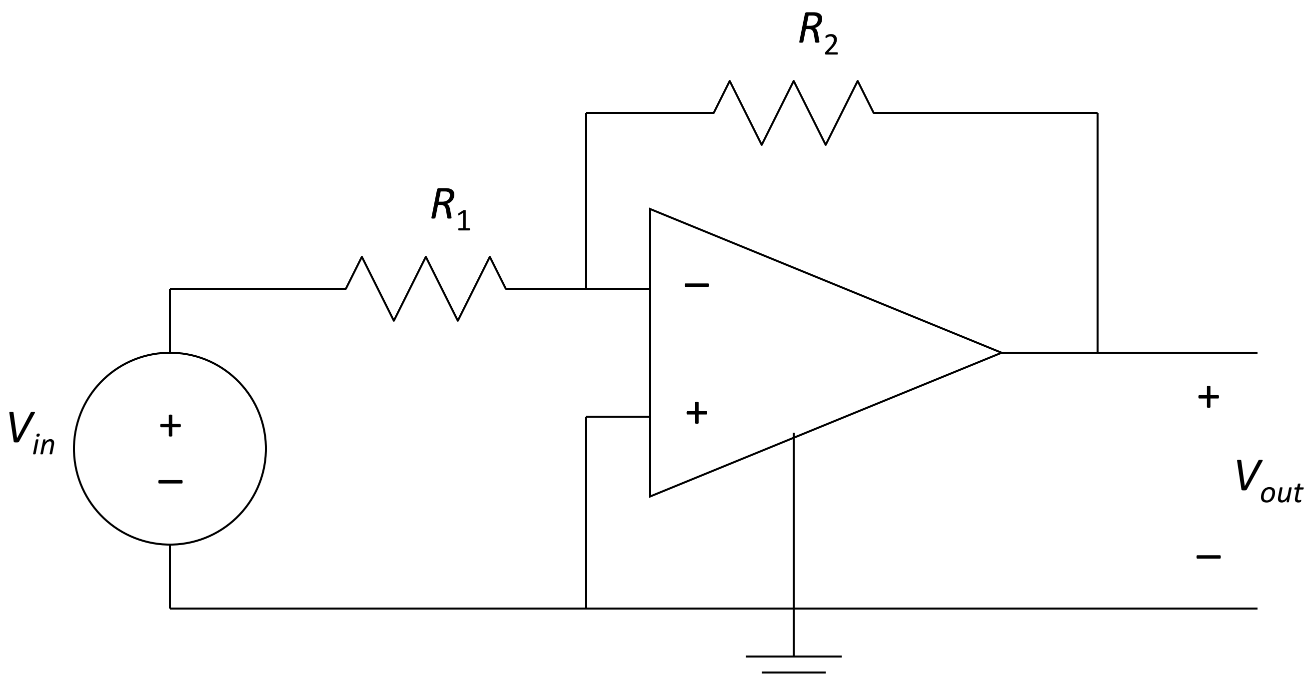




Apendix

Calculation using KCL of Inverting OA

The Basic Inverting Amplifier



Consequences of the Ideal OA

- Infinite input resistance means the current into the inverting input is zero:

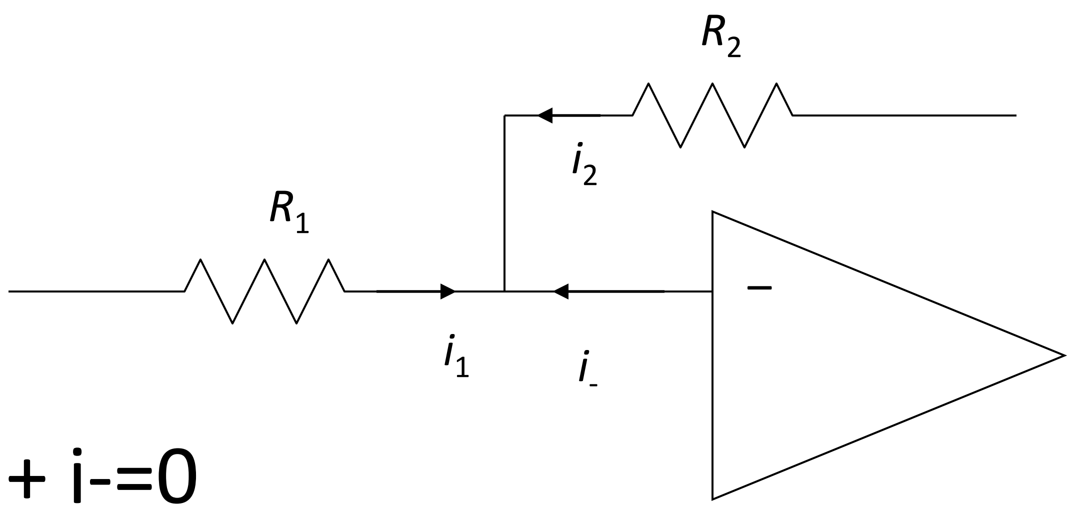
  $i- = 0$

- Infinite gain means the difference between v+ and v- is zero:

  $v+ - v- = 0$

Solving the Amplifier Circuit

- Apply KCL at the inverting input:



- i1 + i2 + i-=0

KCL

$$i_- = 0$$

$$i_1 = \frac{v_{in} - v_-}{R_1} = \frac{v_{in}}{R_1}$$

$$i_2 = \frac{v_{out} - v_-}{R_2} = \frac{v_{out}}{R_2}$$

Solve for vout

$$\frac{v_{in}}{R_1} = -\frac{v_{out}}{R_2}$$

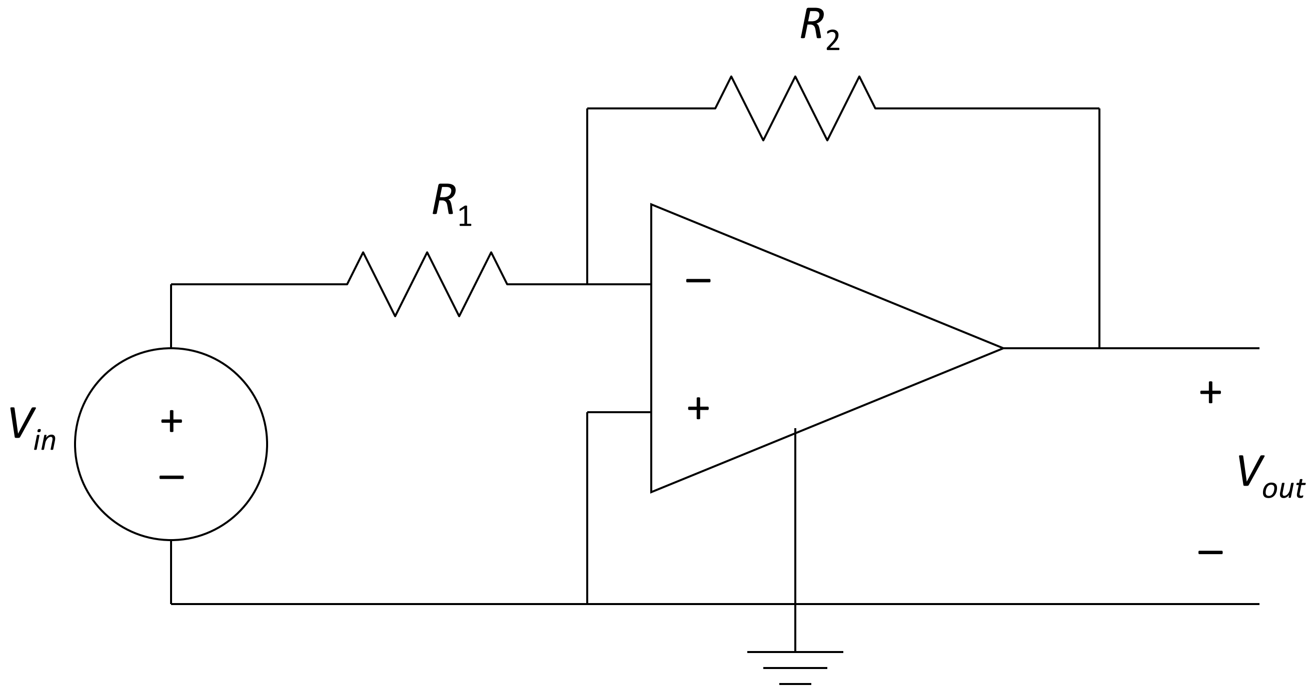
- Amplifier gain:

$$\frac{v_{out}}{v_{in}} = -\frac{R_2}{R_1}$$

Recap

- The ideal op-amp model leads to the following conditions:
- i- = 0 = i+
- v+ = v-
- These conditions are used, along with KCL and other analysis techniques, to solve for the output voltage in terms of the input(s).

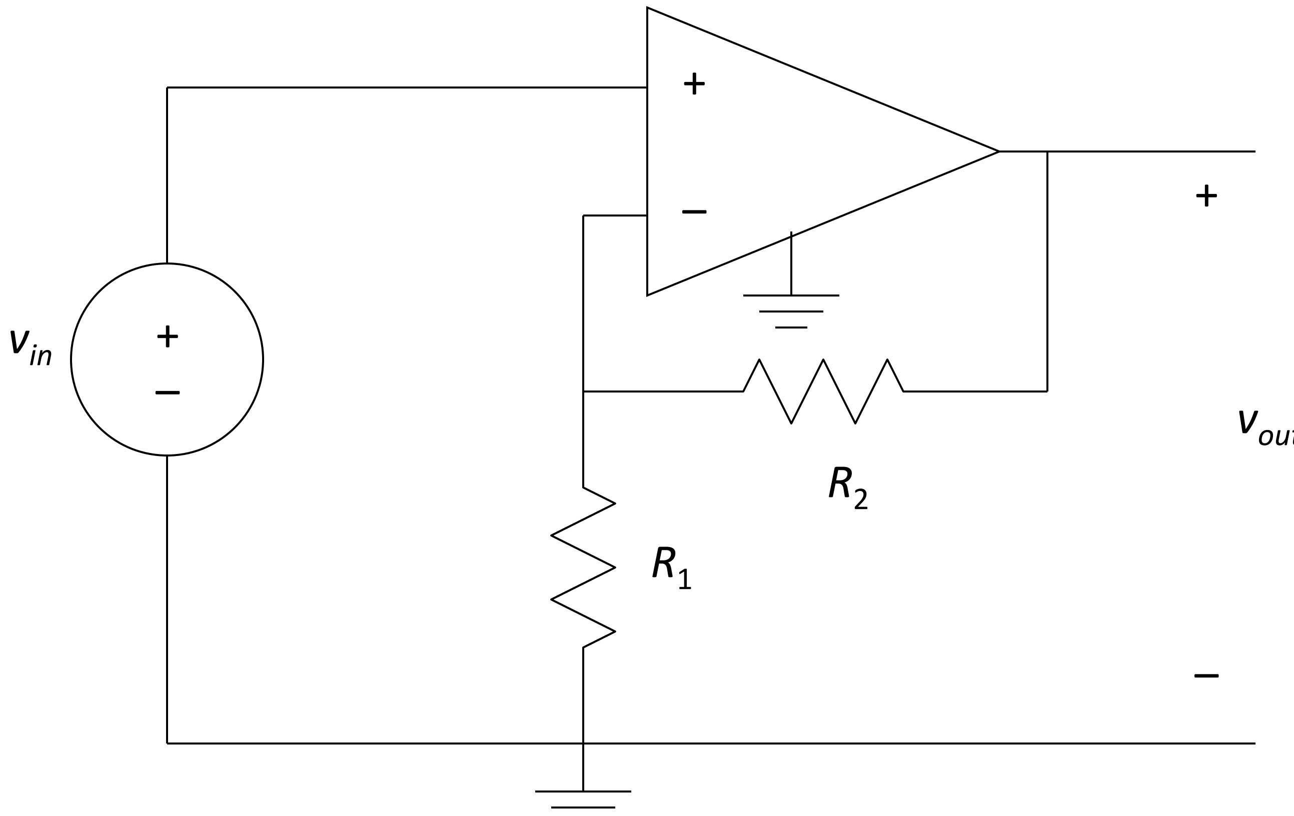
Where is the Feedback?



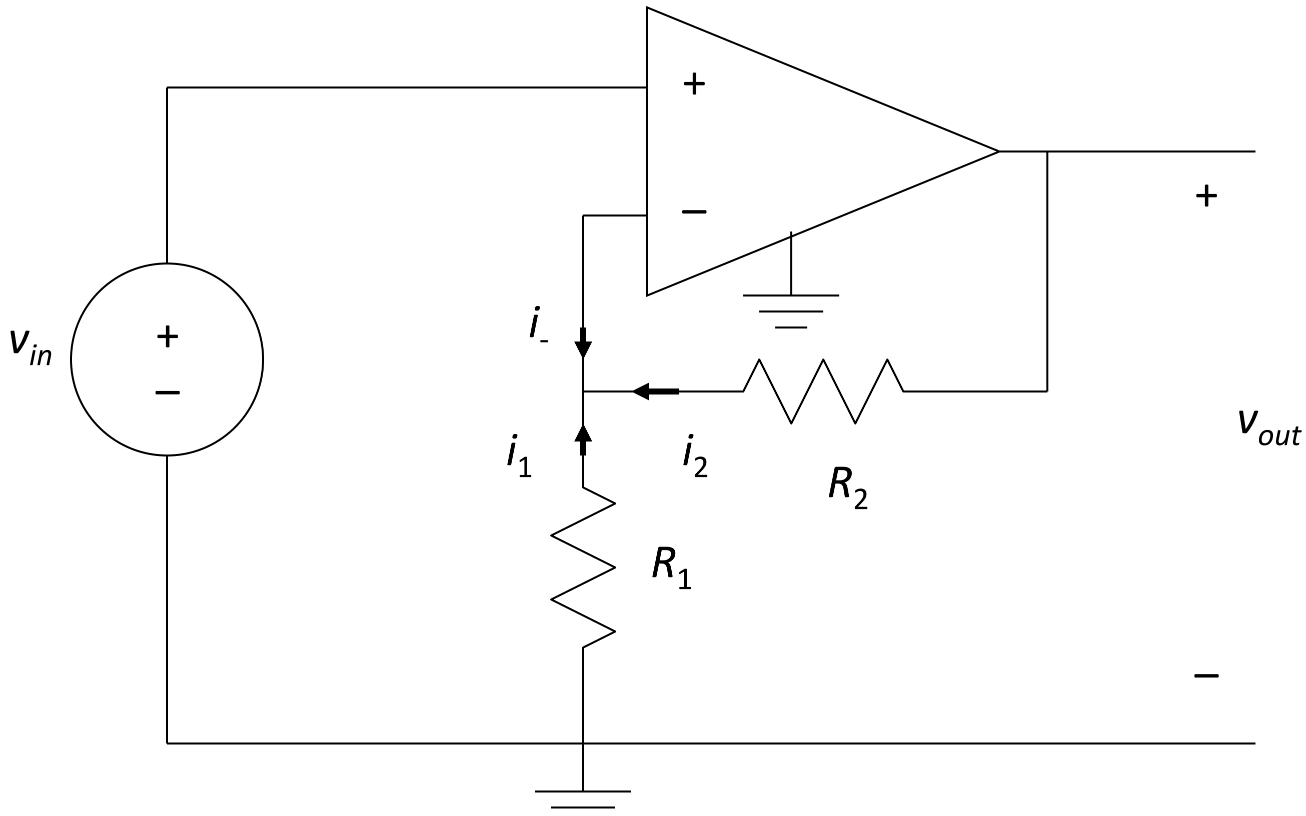
Review

- To solve an op-amp circuit, we usually apply KCL at one or both of the inputs.
- We then invoke the consequences of the ideal model.
  – The op amp will provide whatever output voltage is necessary to make both input voltages equal.
- We solve for the op-amp output voltage.

The Non-Inverting Amplifier



KCL at the Inverting Input



KCL

$$i_- = 0$$

$$i_1 = \frac{-v_-}{R_1} = \frac{-v_{in}}{R_1}$$

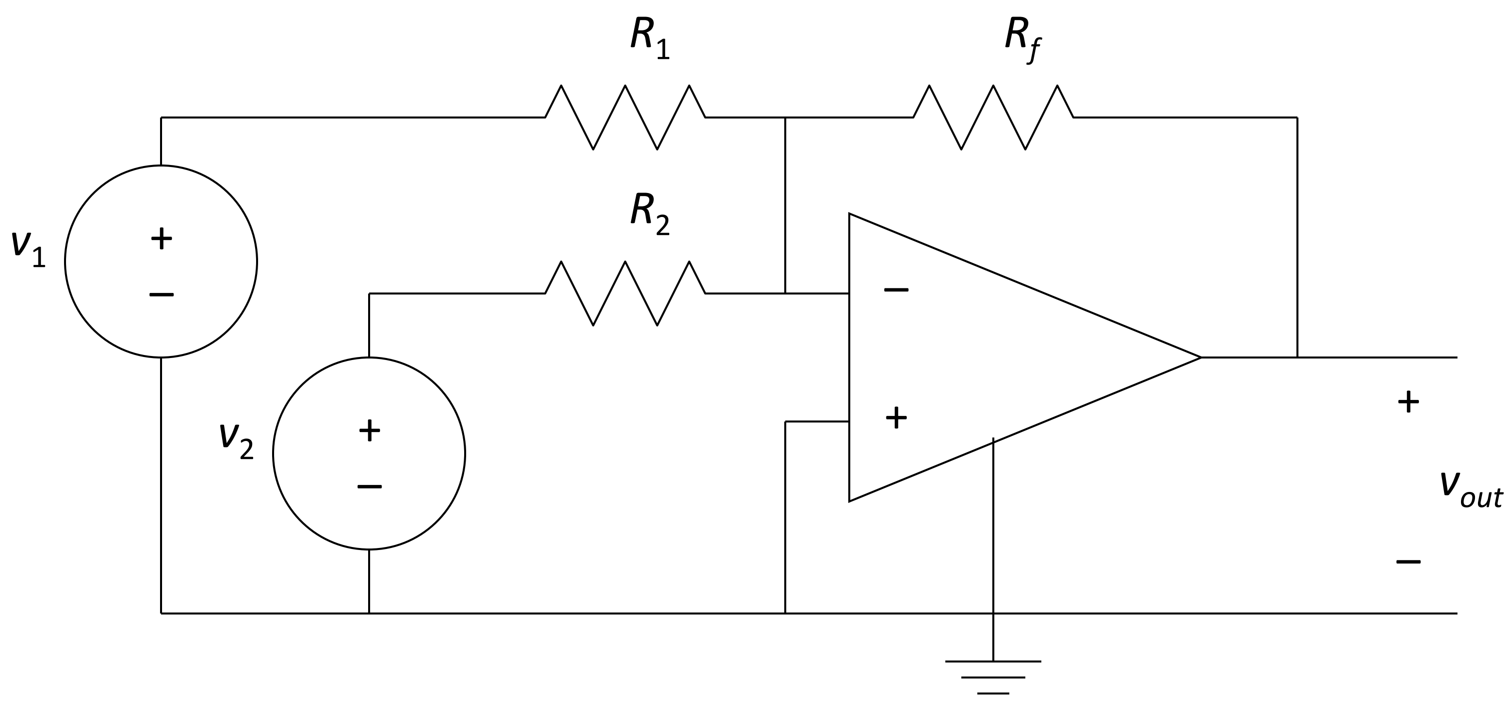
$$i_2 = \frac{v_{out} - v_-}{R_2} = \frac{v_{out} - v_{in}}{R_2}$$

Solve for Vout

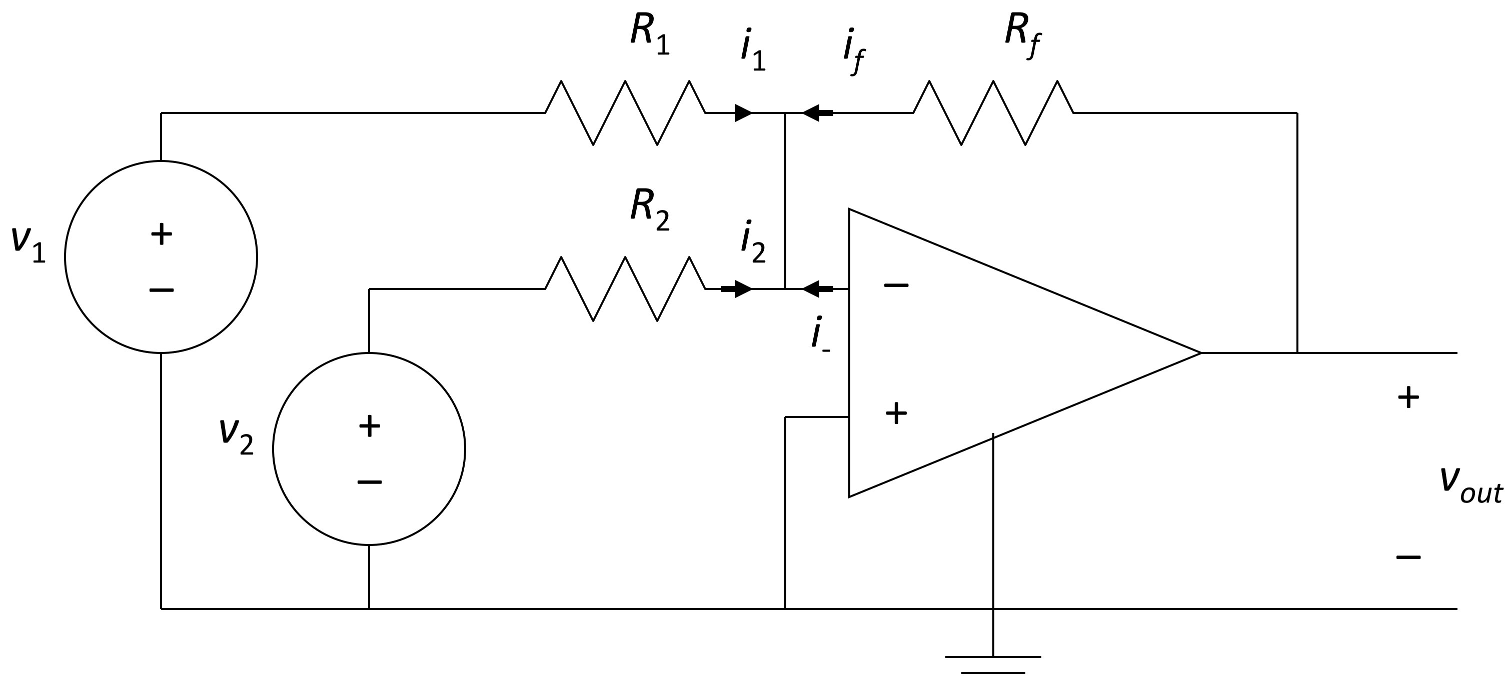
$$\frac{-v_{in}}{R_1} + \frac{v_{out} - v_{in}}{R_2} = 0$$

$$v_{out} = v_{in}\left(1 + \frac{R_2}{R_1}\right)$$

A Mixer Circuit



KCL at the Inverting Input



KCL

$$i_1 = \frac{v_1 - v_-}{R_1} = \frac{v_1}{R_1}$$

$$i_2 = \frac{v_2 - v_-}{R_2} = \frac{v_2}{R_2}$$

KCL

$$i_- = 0$$

$$i_f = \frac{v_{out} - v_-}{R_f} = \frac{v_{out}}{R_f}$$

Solve for Vout

$$\frac{v_1}{R_1} + \frac{v_2}{R_2} + \frac{v_{out}}{R_f} = 0$$

$$v_{out} = -\frac{R_f}{R_1} v_1 - \frac{R_f}{R_2} v_2$$