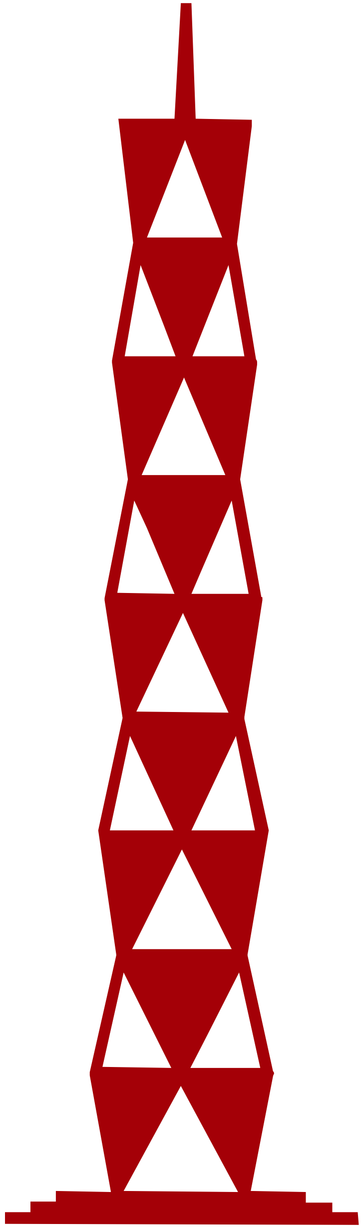


SI100B
Introduction to Information Science and Technology (Part 3: Electrical Engineering)

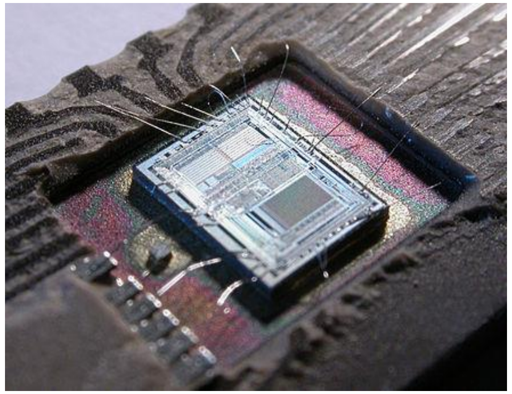
Lecture #6 Analog Circuits

Instructor: Junrui Liang (梁俊睿)

Nov. 27th, 2020

The Theme Story

Devices (1)



Circuits (4/4)

Systems ~~(2)~~ (1)

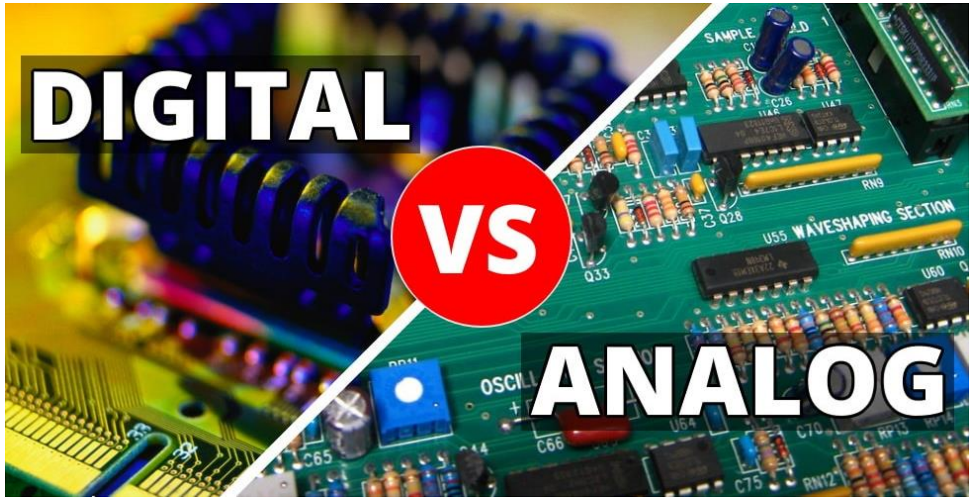
(Pictures are from the Internet)

Study Purpose of Lecture #6

- 哲学（bao'an）三问
  - Who are you?
  - Where are you from?
  - Where are you going?

To answer those questions throughout your life

- In this lecture, we ask
  - How to connect a discrete digital machine to the physical world?
  - What are the purpose and basic principle of an analog circuit 模拟电路?
  - How to convert analog (continuous) signal into digital (discrete) signal?



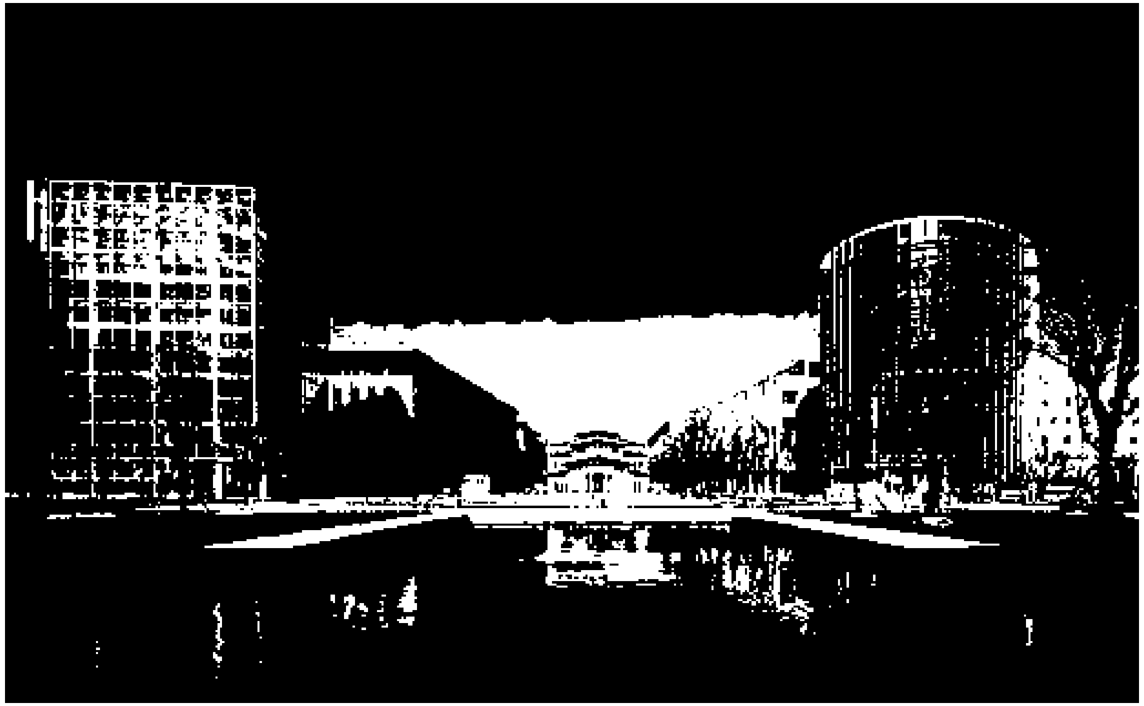
(Pictures are from the Internet)

Lecture Outline

- The real world vs. a binary world
- Fundamentals of analog (linear) circuit 模拟电路
  - Amplification 放大的原理
  - Operational amplifier 运算放大器
- Basic MOS amplifier 单MOS管放大器
  - Voltage range and frequency limitations 电压范围和频率限制
- Analog to digital conversion (ADC) 模数转换
- Digital to analog conversion (DAC) 数模转换

What if a real world becomes binary (black or white)?

The colorful real world



A binary world

every pixel can only be either 1 (black) or 0 (white)

How to approximate the real world?

The colorful real world

A gray scale world

every pixel can only be a number between 1 (black) or 0 (white)

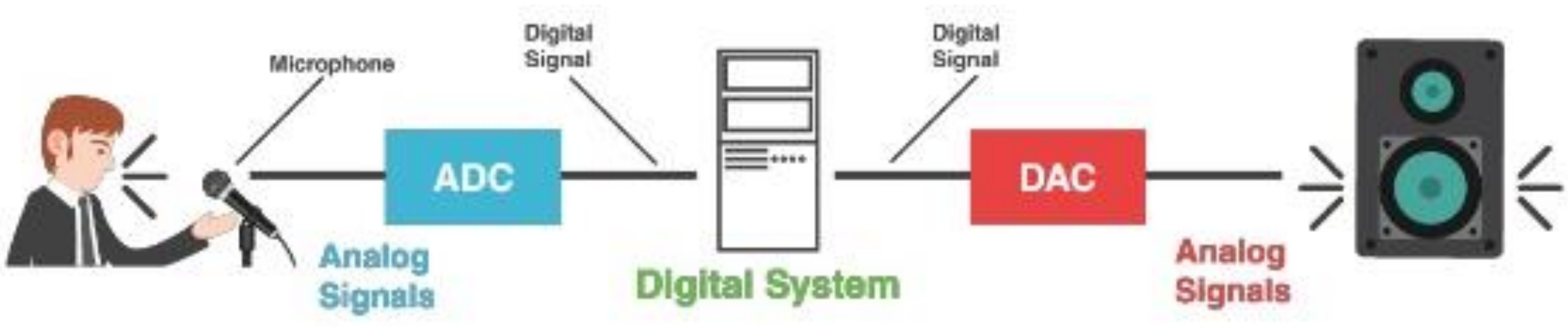
How to approximate the real world?

The colorful real world

A colorful approximation

You must understand both
the optics (physics of light) &
its digital approximation

The real world vs. a binary world



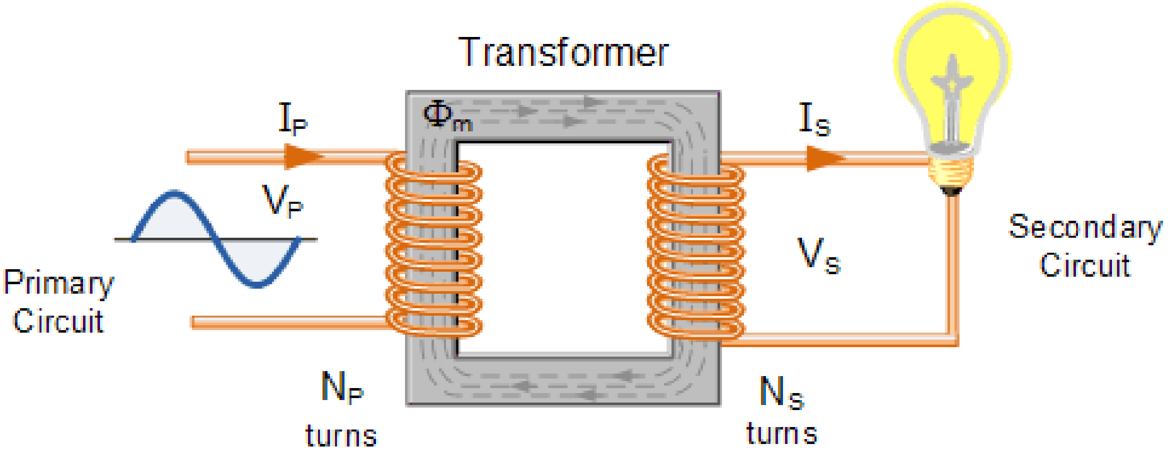
Real-world signal

Digital data

Real-world approximation

The importance of amplification

- In the mechanical domain
  - What is amplified?
  - What is reduced?
- In the electrical domain
  - What is amplified?
  - What is reduced?



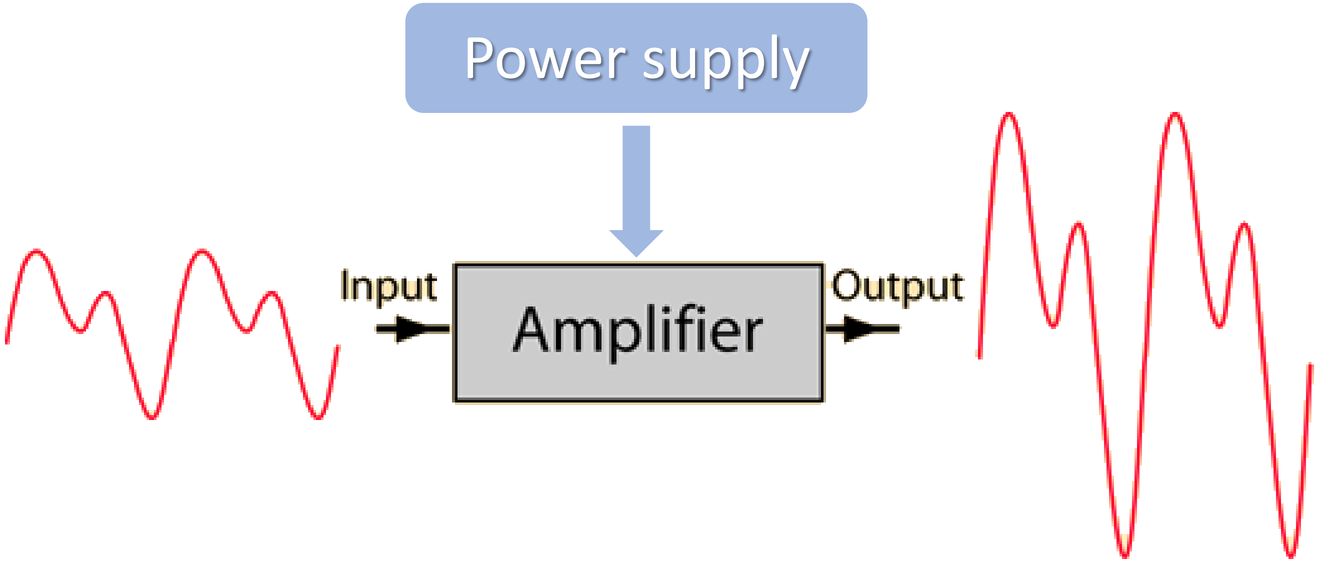
How about these?

- In the mechanical domain
  - What is amplified?
  - What is reduced?

- In the electrical domain
  - What is amplified?
  - What is reduced?

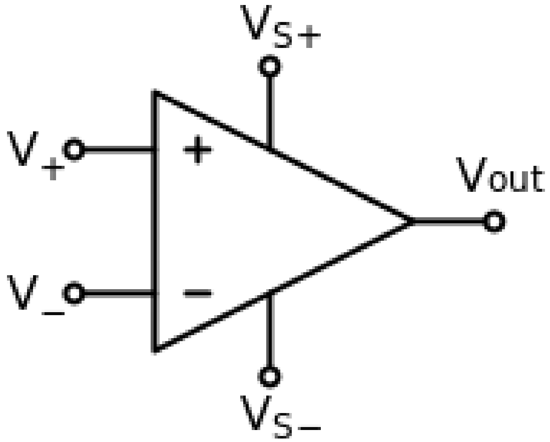
(Electronic) amplifier

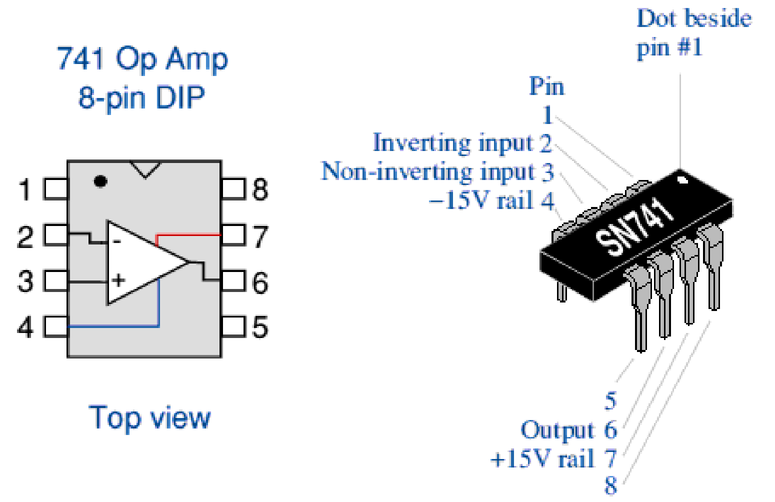
- An electronic device that increases the power of a signal
  - Taking energy from a power supply
  - controlling the output to match the input signal shape but with a larger amplitude
  - The opposite of an attenuator
  - An amplifier provides gain, an attenuator provides loss



- One of the most widely used electronic devices
- Originally from analog computers for doing mathematical operations
- Characteristics
  - DC-coupled
  - Voltage amplifier
  - High gain ($A \to \infty$)
  - A differential input ($V_+ - V_-$)
  - A single-ended output (V_{out})

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

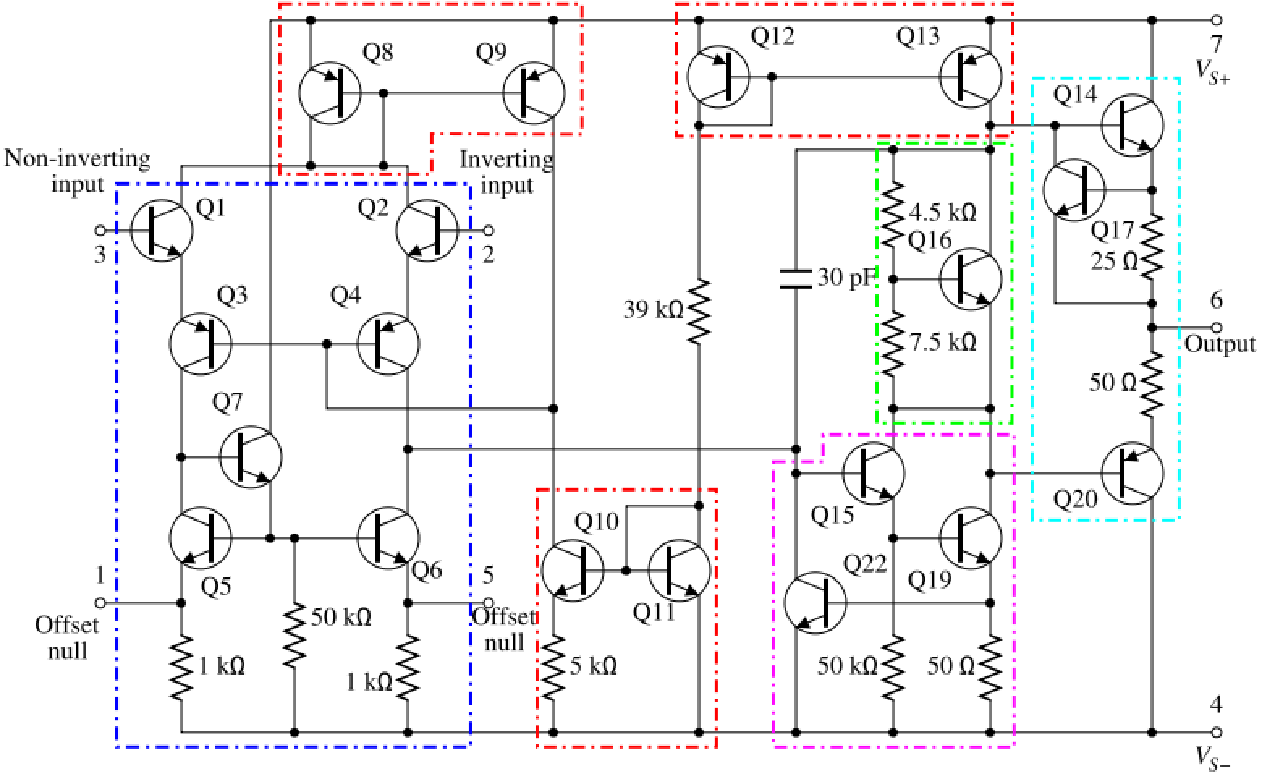




The most usual 741 package

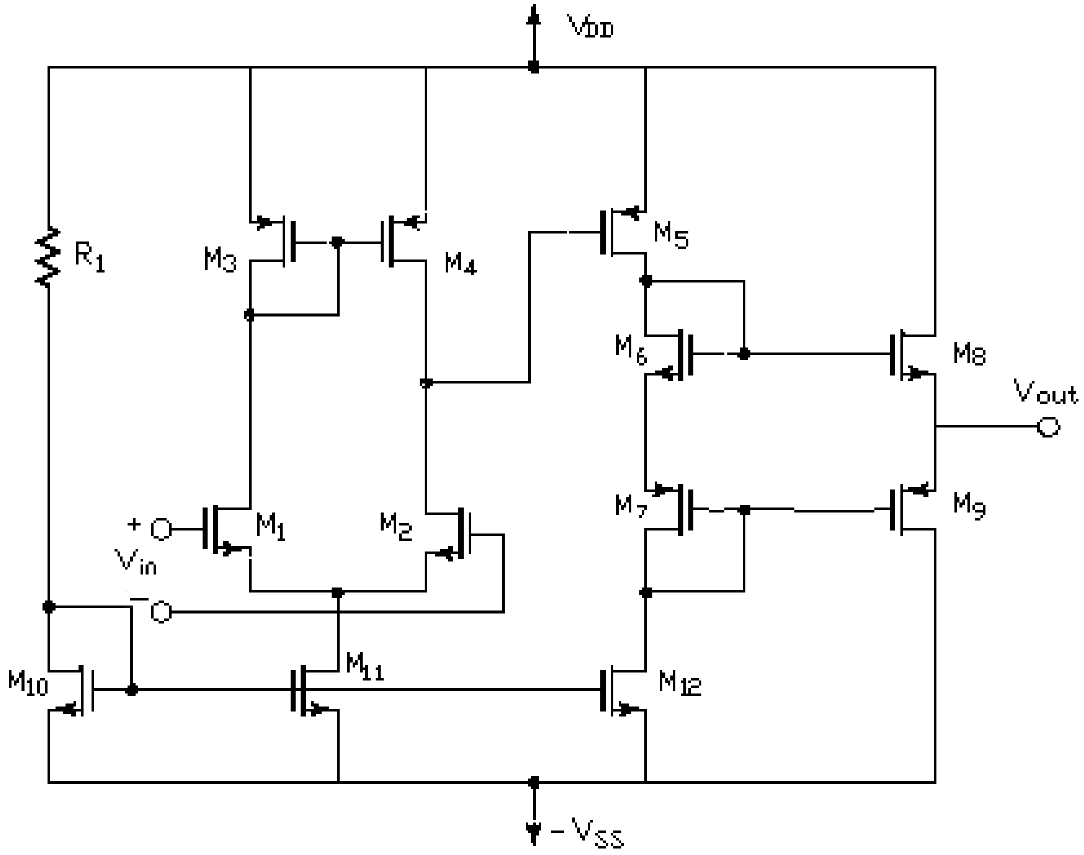
Realization

- BJT Technology



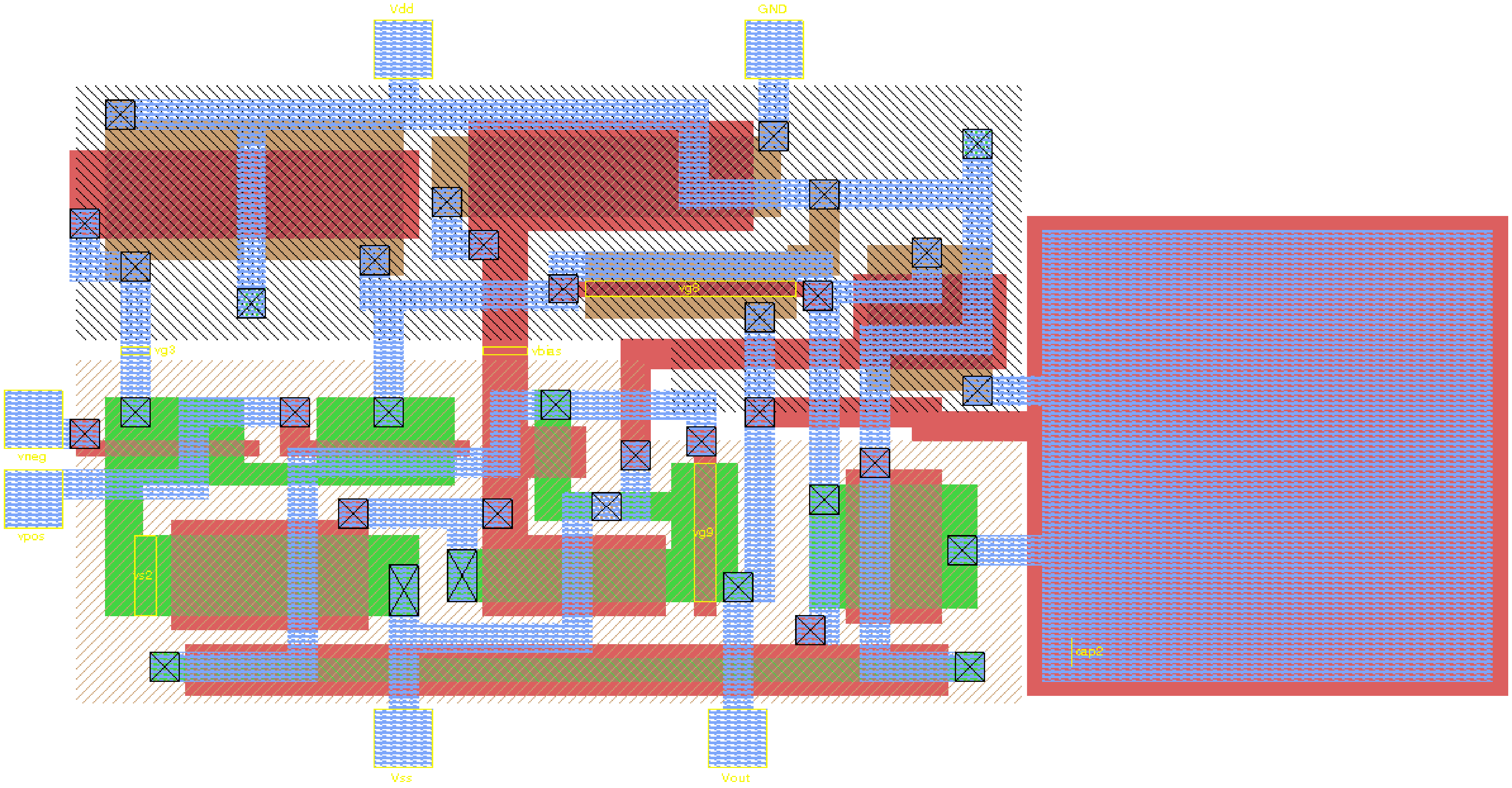
A component-level diagram of the common 741 op-amp. Dotted lines outline: current mirrors (red); differential amplifier (blue); class A gain stage (magenta); voltage level shifter (green); output stage (cyan).

- CMOS Technology



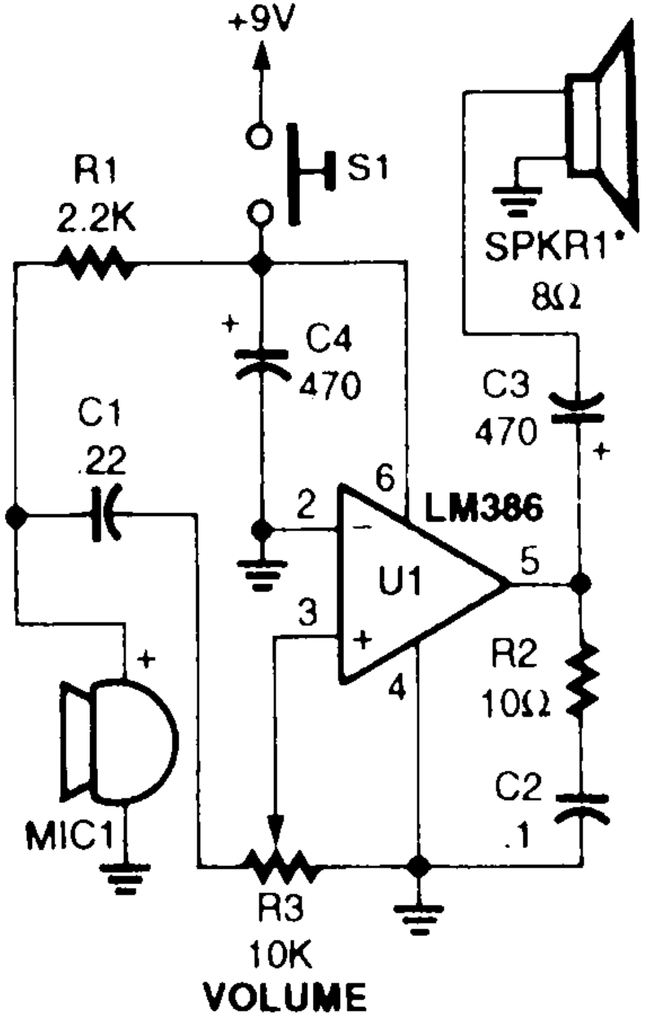
Realization

- Layout view of a simple CMOS operational amplifier

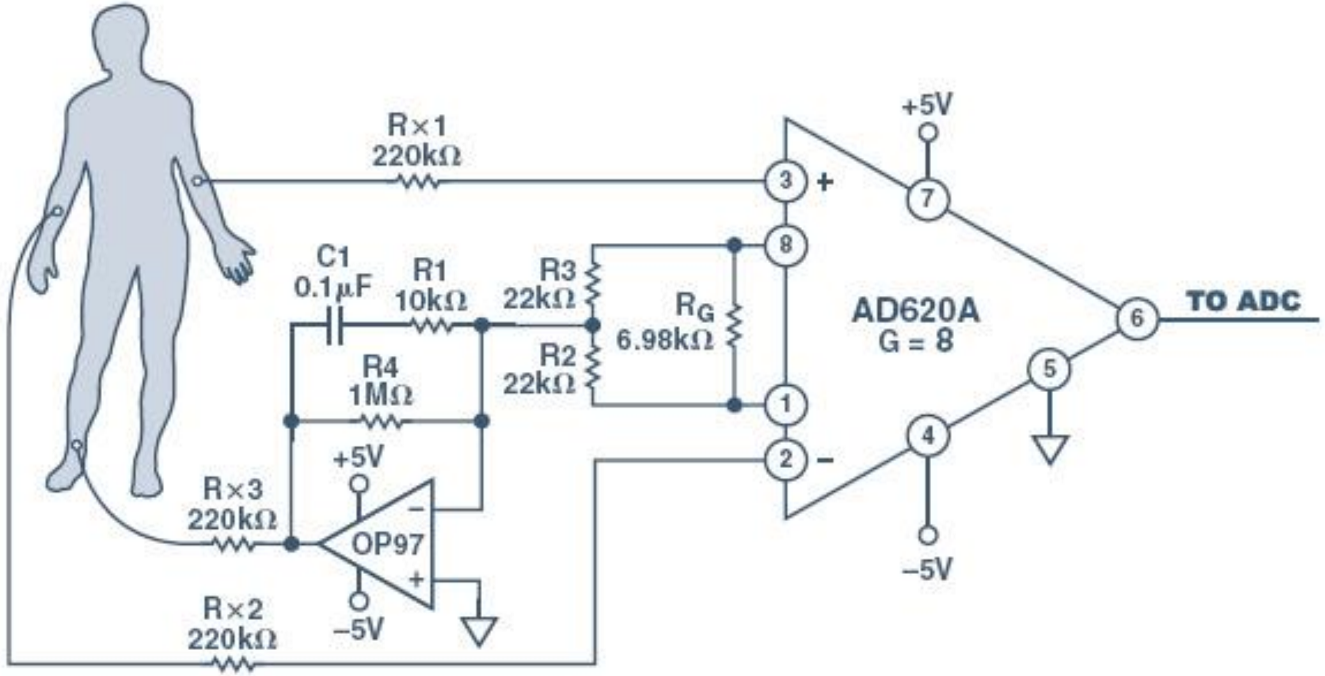


Applications

- Audio system



- Bio-electric signal



Ideal op amp

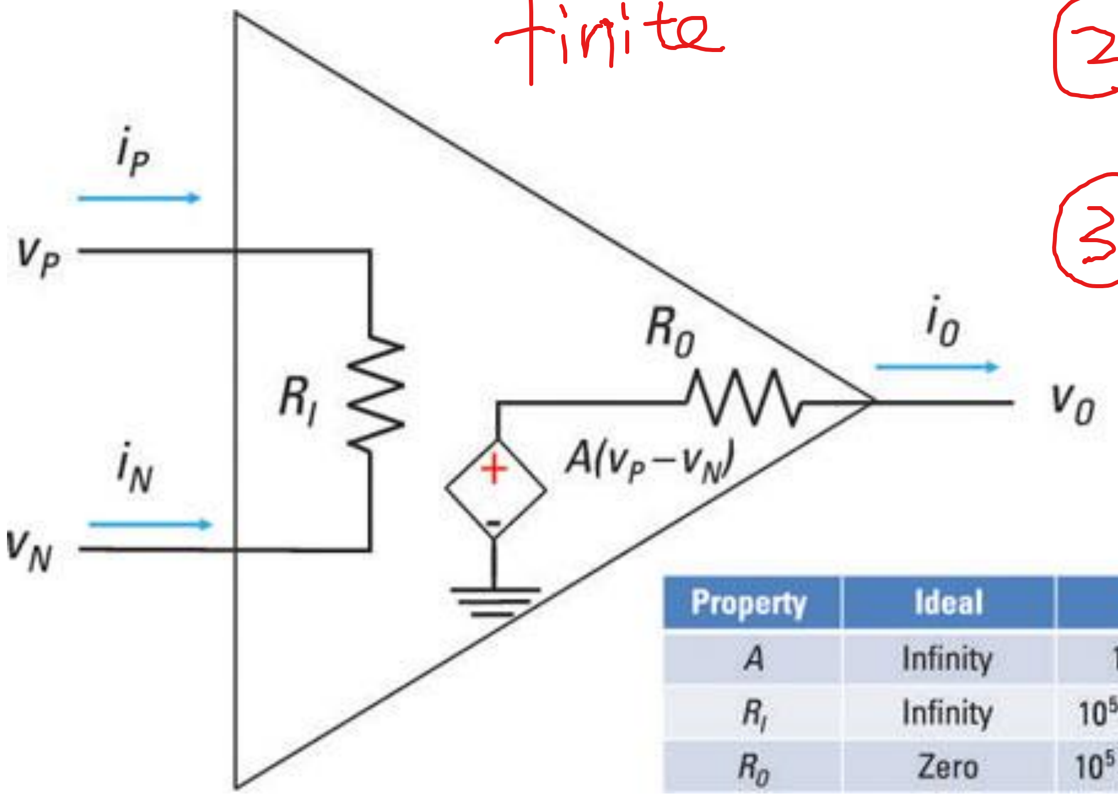
$(V_p - V_n)$

finite

① $R_I \to \infty \Rightarrow \underline{i_p = 0}$ 虚断

② $A \to \infty \Rightarrow V_p - V_n = 0$

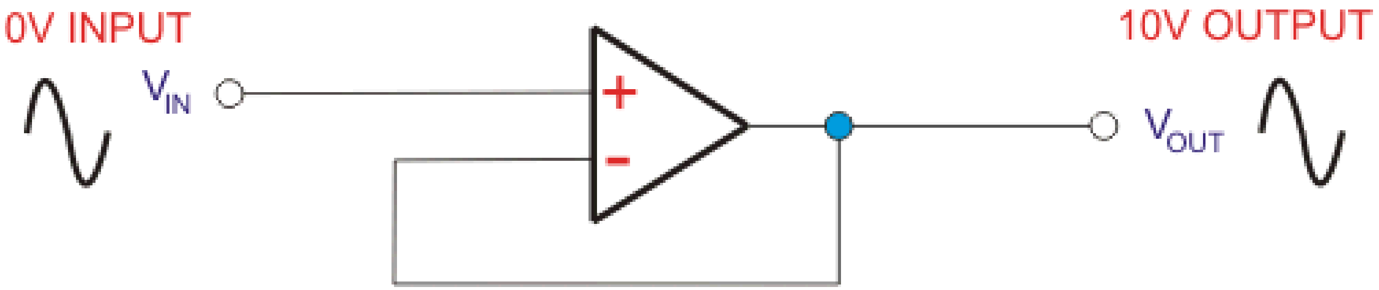
③ $R_o = 0 \Longrightarrow$ 带负载强



Property	Ideal	Typical
A	Infinity	$10^5 < A < 10^8$
R_I	Infinity	$10^5\,\Omega < R_I < 10^8\,\Omega$
R_O	Zero	$10^5\,\Omega < R_O < 10^8\,\Omega$

Voltage follower 电压跟随器

- A voltage follower is a op-amp circuit which has a voltage **gain of 1**



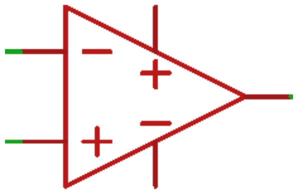
$$V_{out} = A(V_+ - V_-)$$

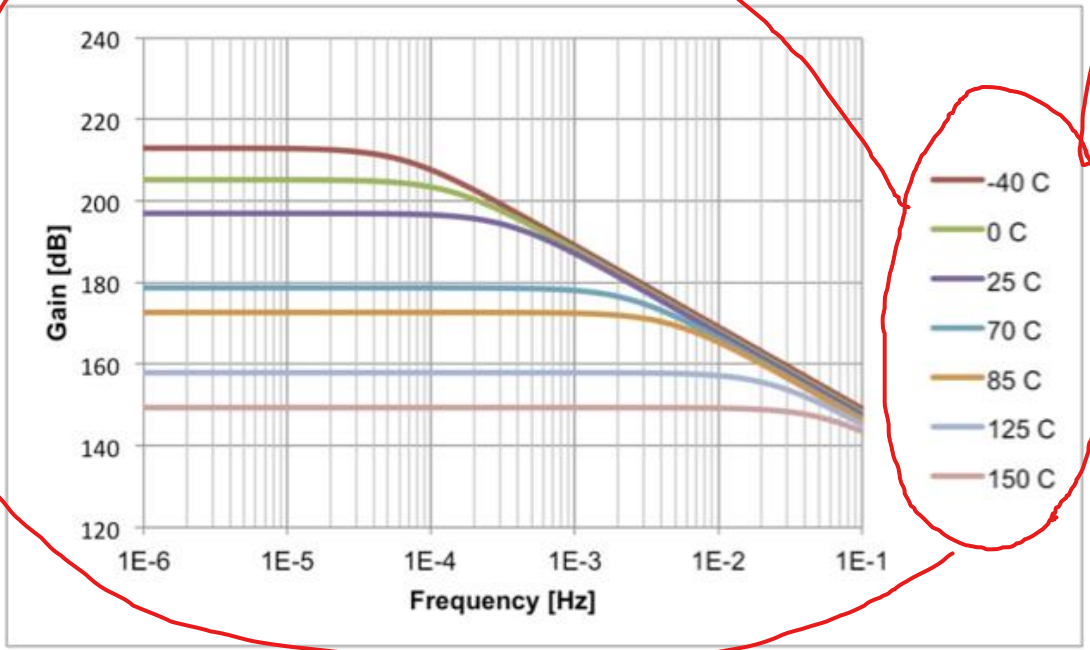
带负载

$$\frac{V_{out}}{V_{in}} = \frac{A}{1+A} \xrightarrow{A\to\infty} = 1$$

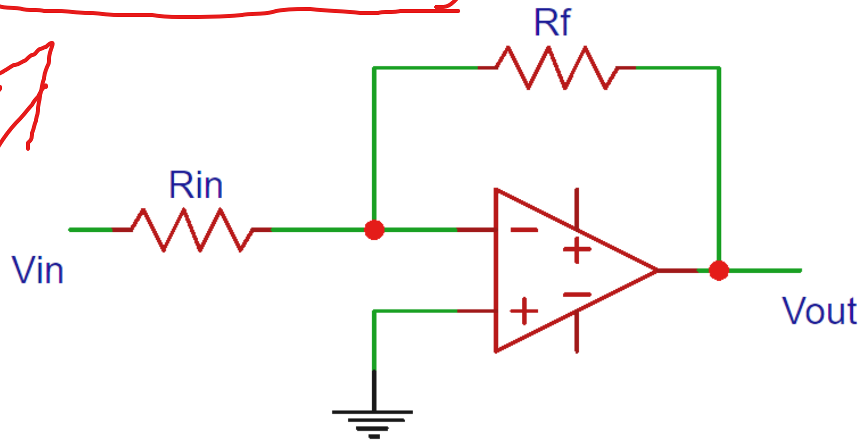
Open-loop and close-loop gain

- Open-loop gain 开环增益
  - Large but finite
  - Instable subjected to the manufacturing process, temperature, etc.





- Close-loop gain 闭环增益



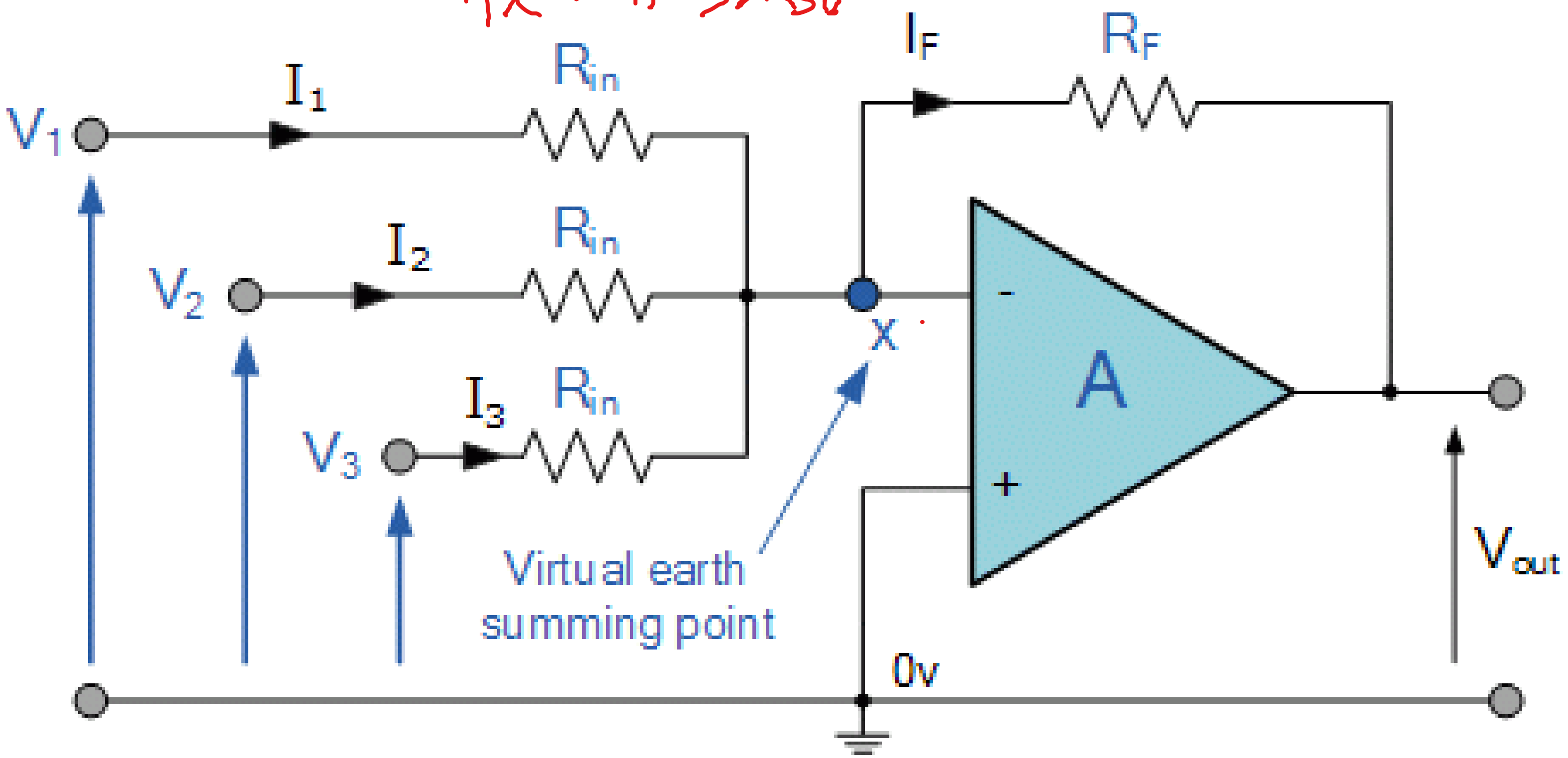
Gain = Vout/Vin = -Rf/Rin

$$I_1 = \frac{V_{in} - 0}{R_{in}} = I_2 = \frac{0 - V_{out}}{R_f}$$

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

Summing amplifier circuit

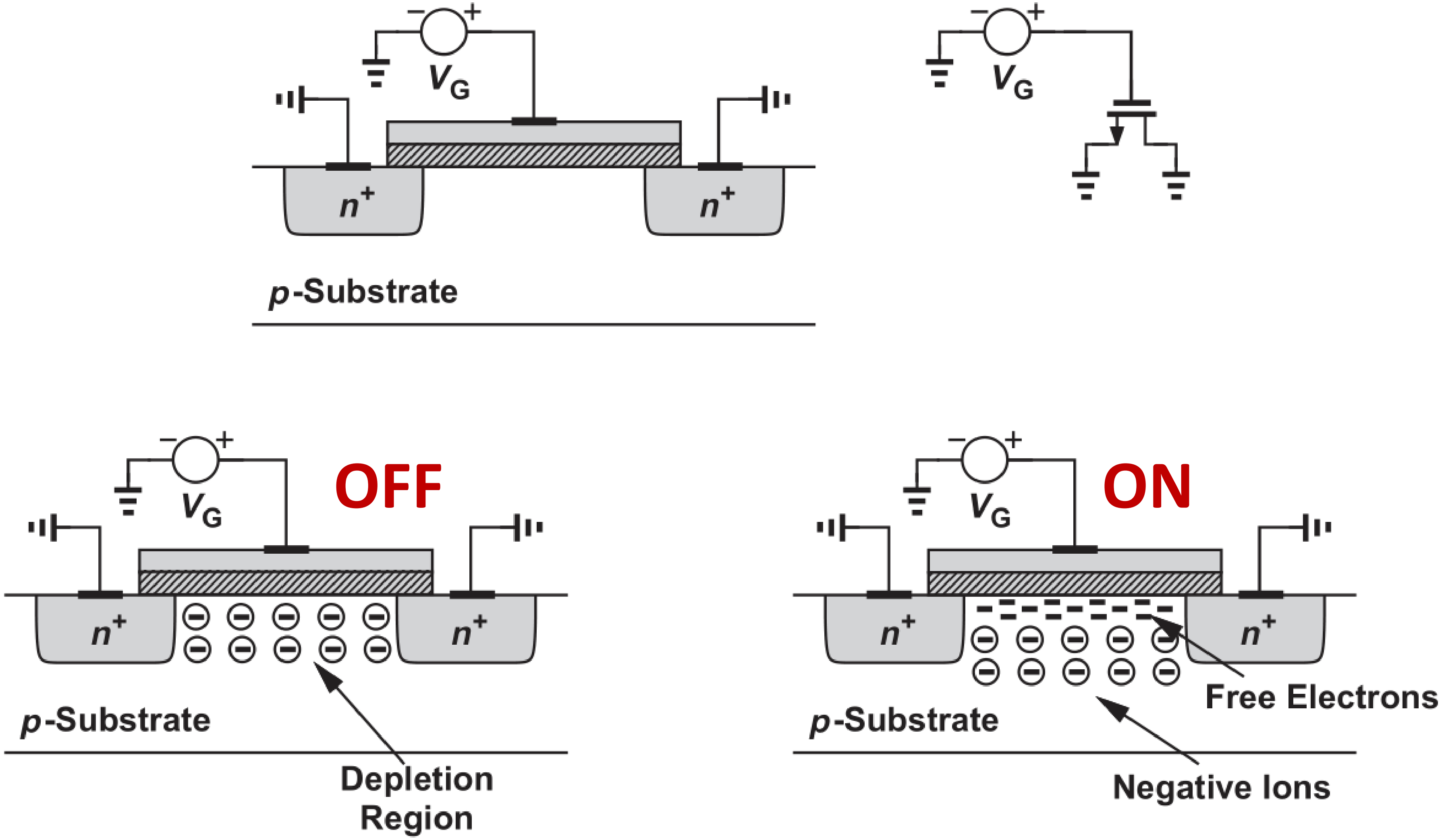
模拟加法器



$$I_F = I_1 + I_2 + I_3$$

$$\frac{V_1}{R_{in}} + \frac{V_2}{R_{in}} + \frac{V_3}{R_{in}} = \frac{0 - V_{out}}{R_f} \Rightarrow V_1 + V_2 + V_3 = -V_{out}$$

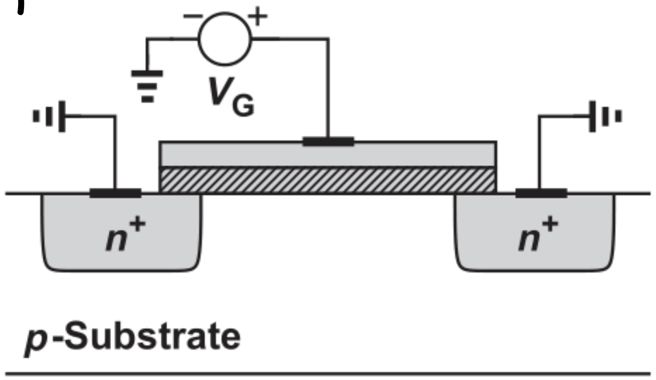
MOSFET in digital applications: a review



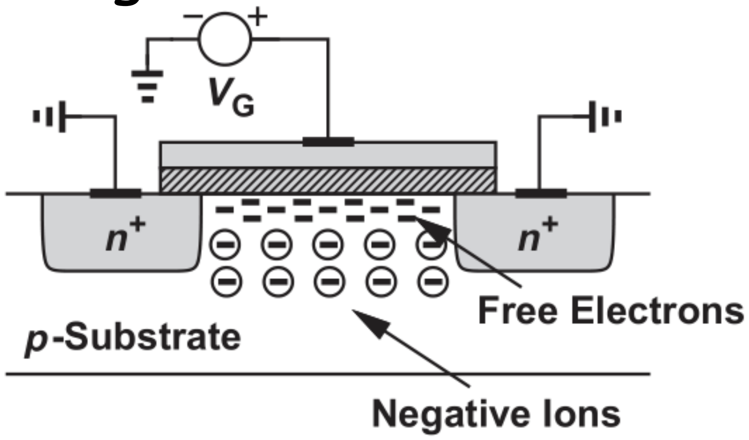
(Razavi, Fundamentals of Microelectronics)

Beyond the on/off states

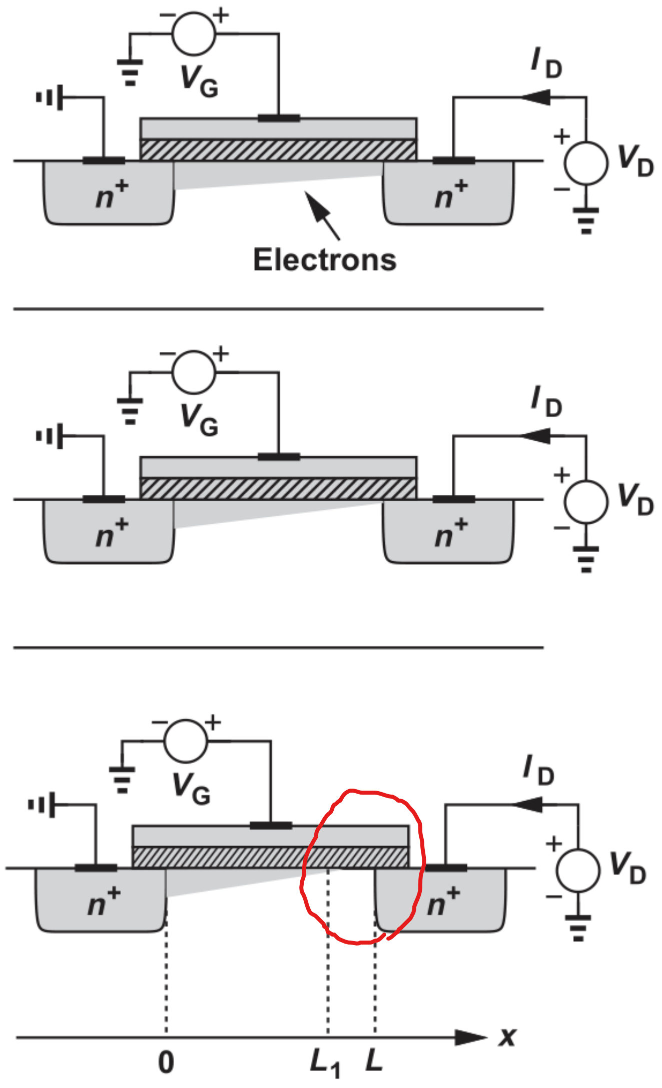
- For digital electronics
  - Cut off



  - Conducting

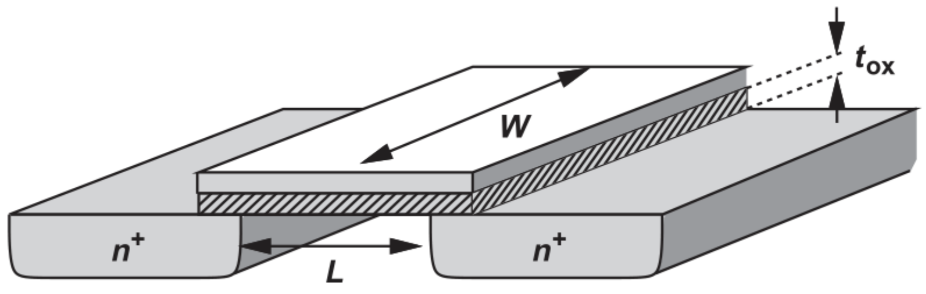


- For analog electronics



(Razavi, Fundamentals of Microelectronics)

I/V characteristics



Linear region:

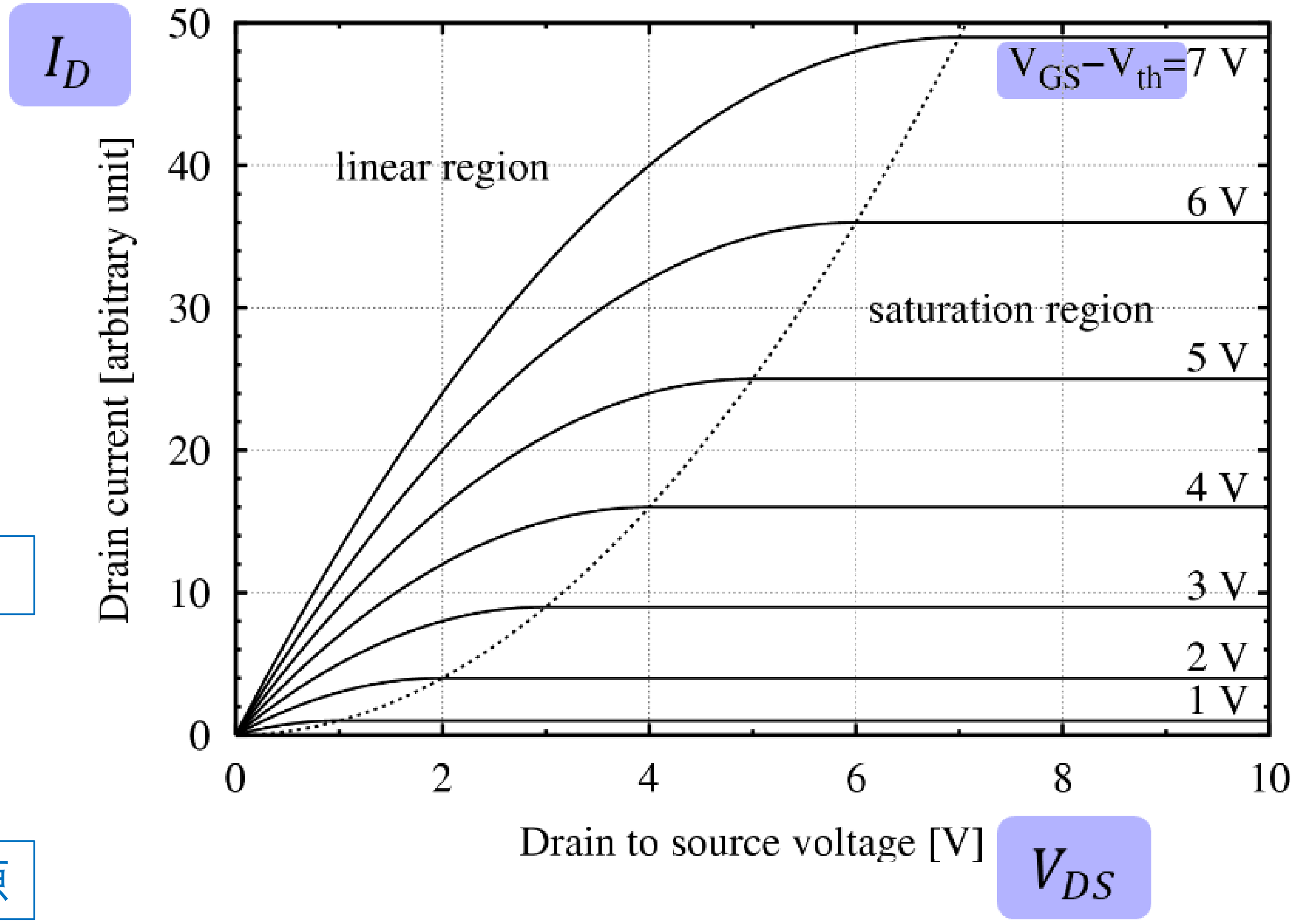
$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}[2(V_{GS} - V_{TH})V_{DS} - V_{DS}^2]$$

A voltage-controlled resistor 压控电阻

Saturation region:

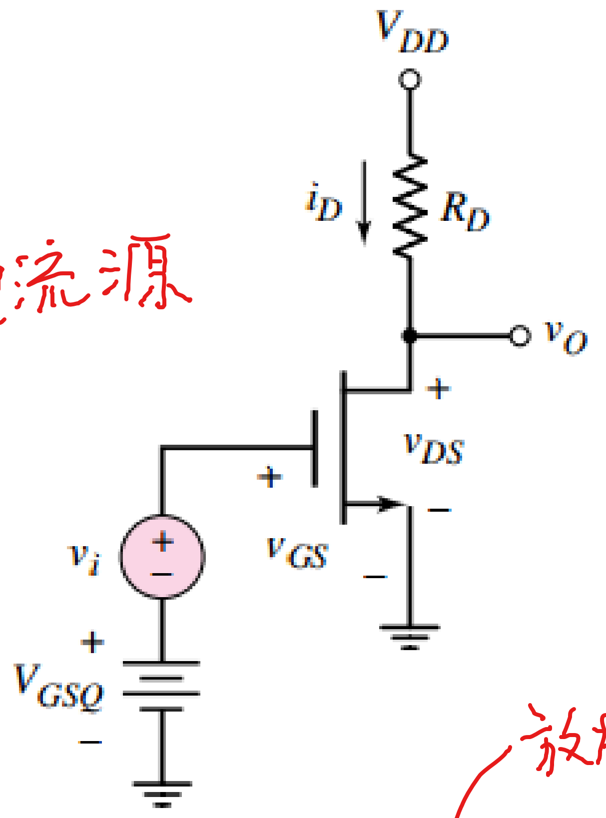
$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS} - V_{TH})^2(1 + \lambda V_{DS})$$

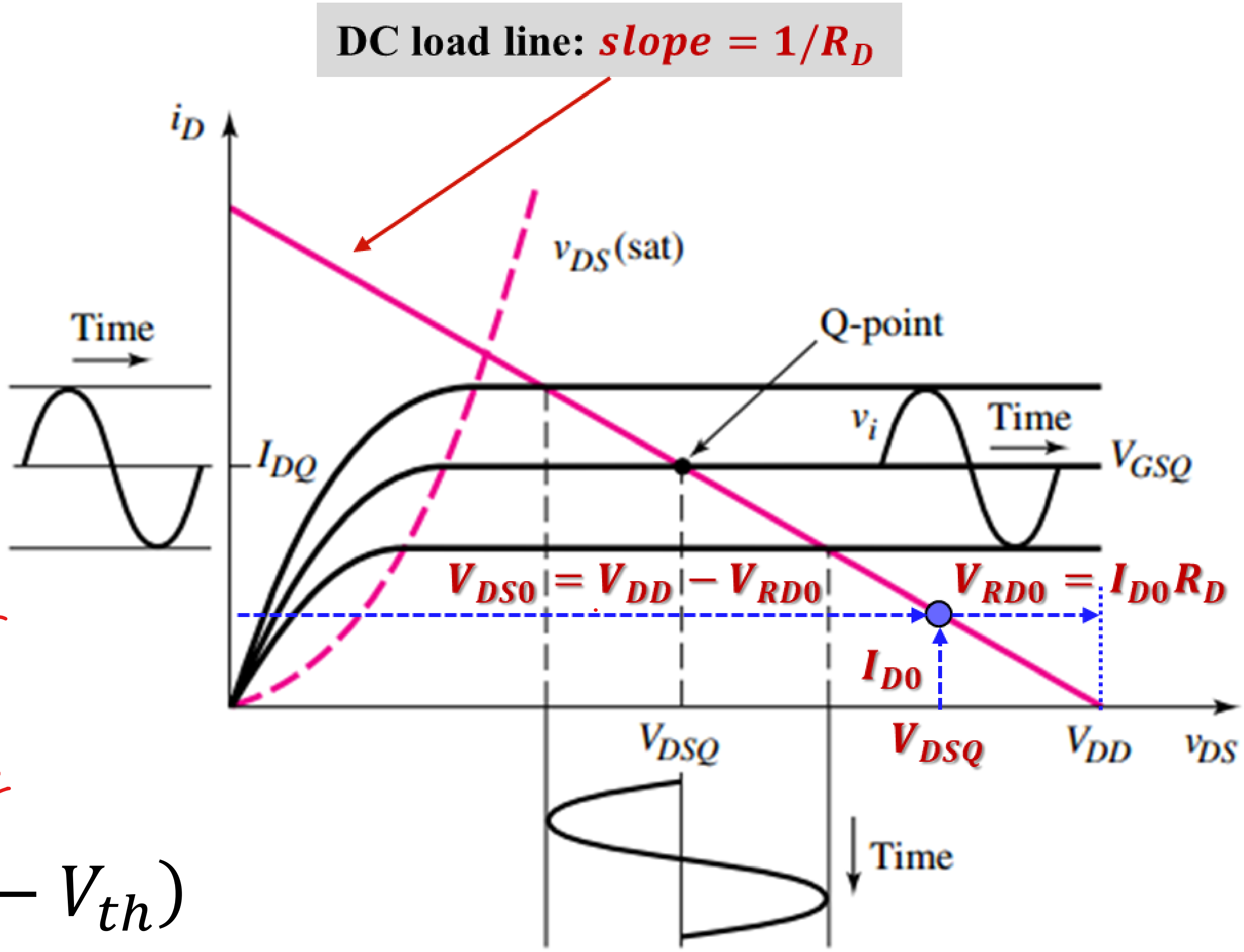
A voltage controlled current source 压控电流源



(Razavi, Fundamentals of Microelectronics)

Basic MOS amplifier





放大倍数

$$V_0 = V_{DD} - R_D i_D$$

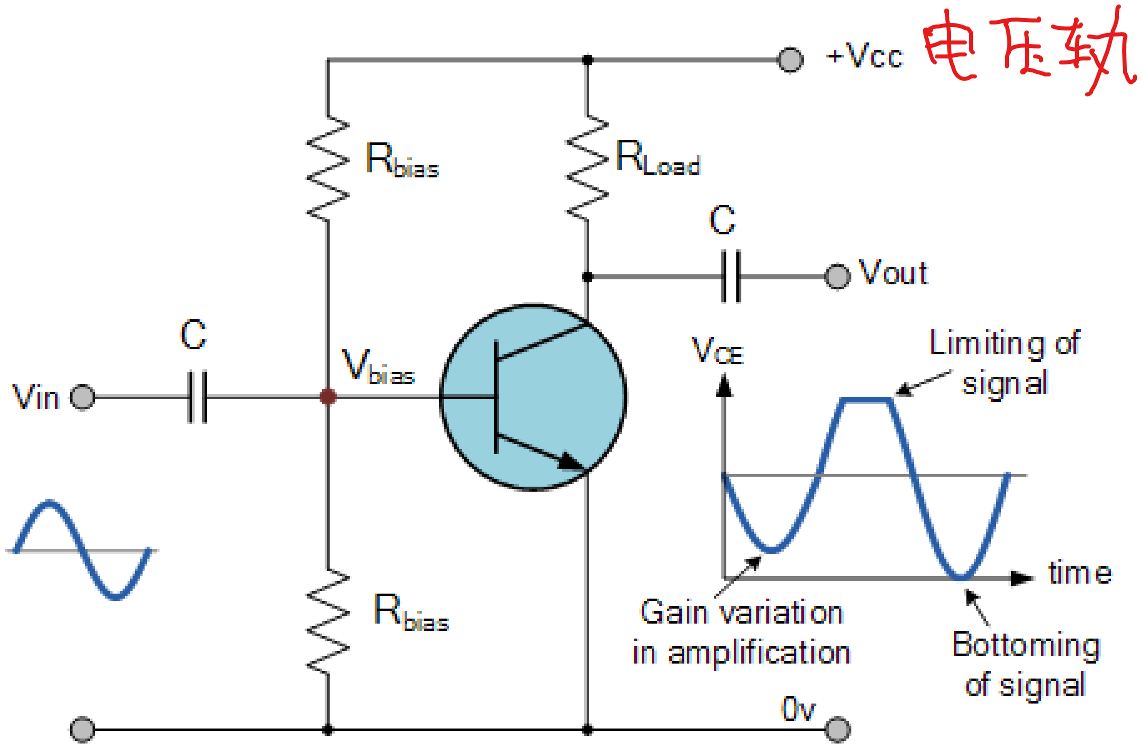
跨导

$$= V_{DD} - R_D g_m (V_{GS} - V_{th})$$

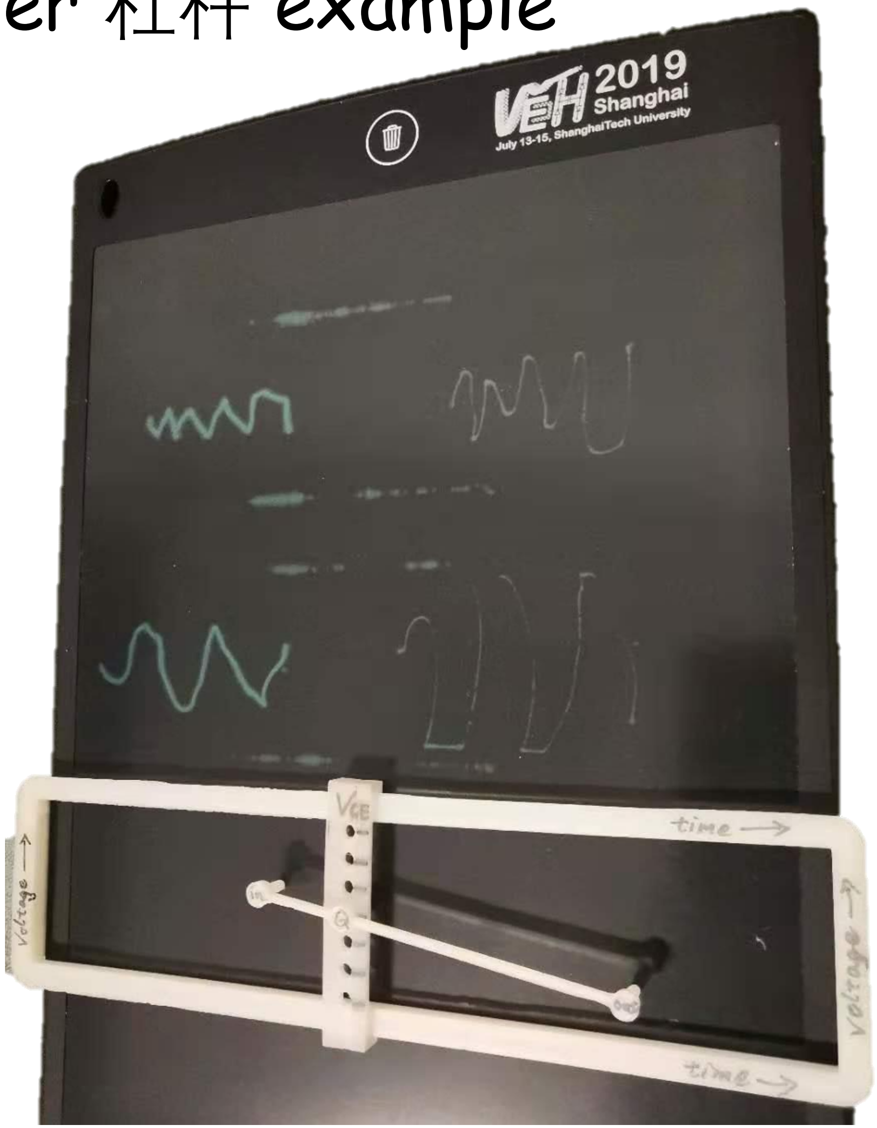
(Neamen, Electronic Circuit Analysis and Design)

Voltage range limitations

- In a real transistor circuit

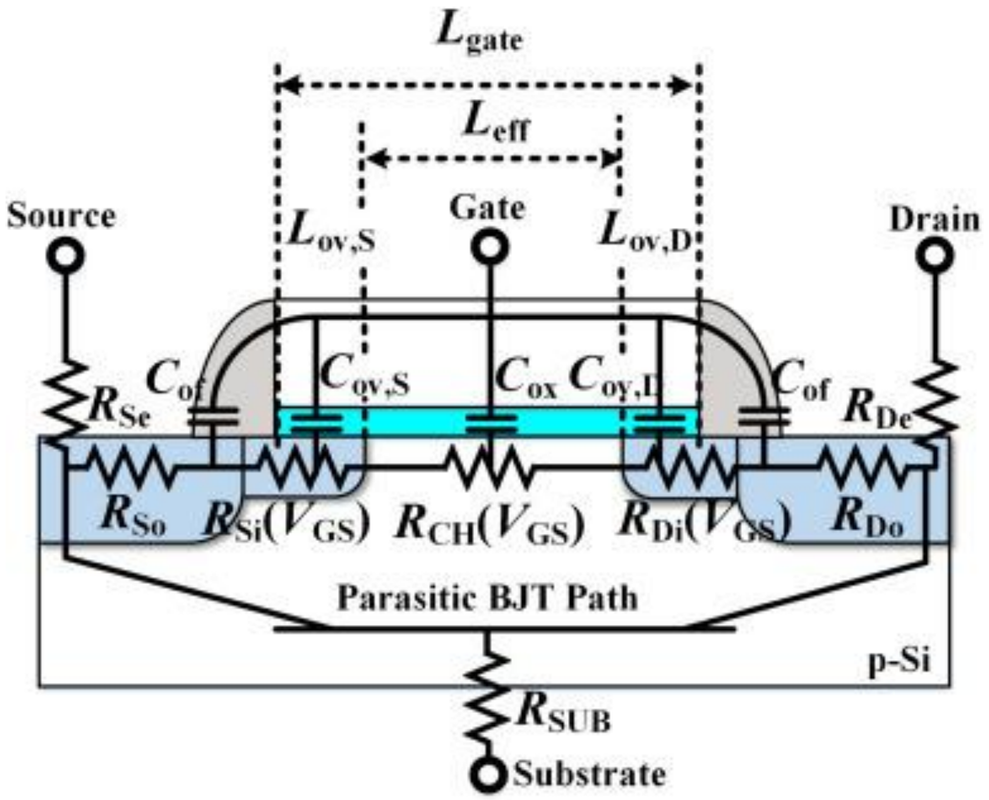


- A lever 杠杆 example

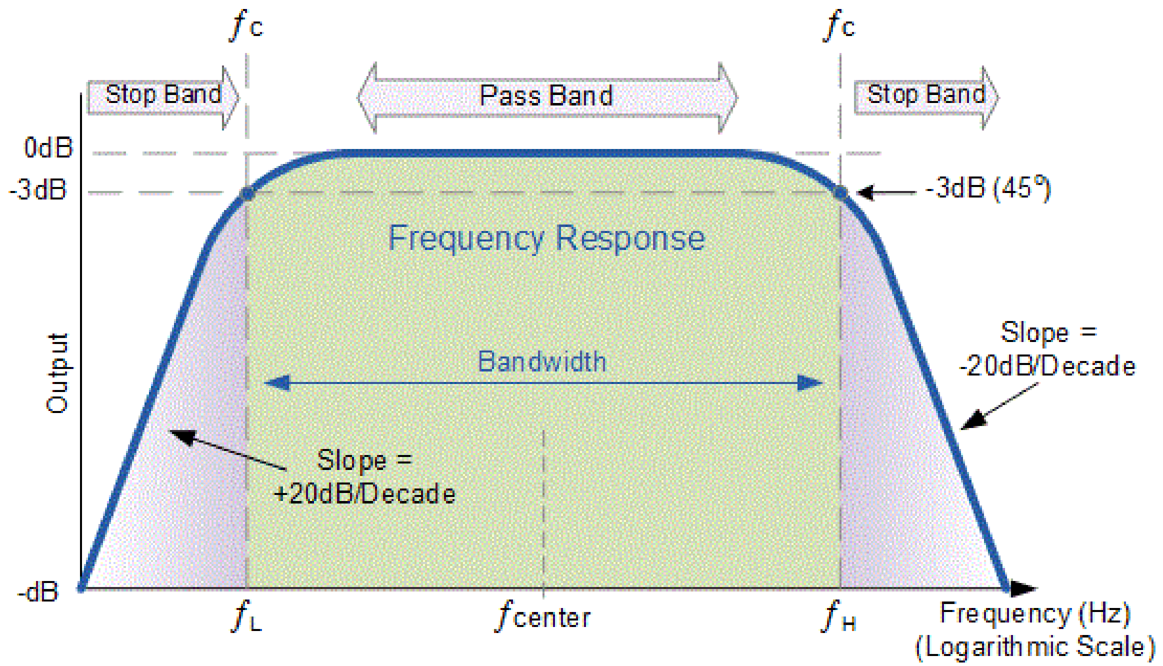


Frequency limitations

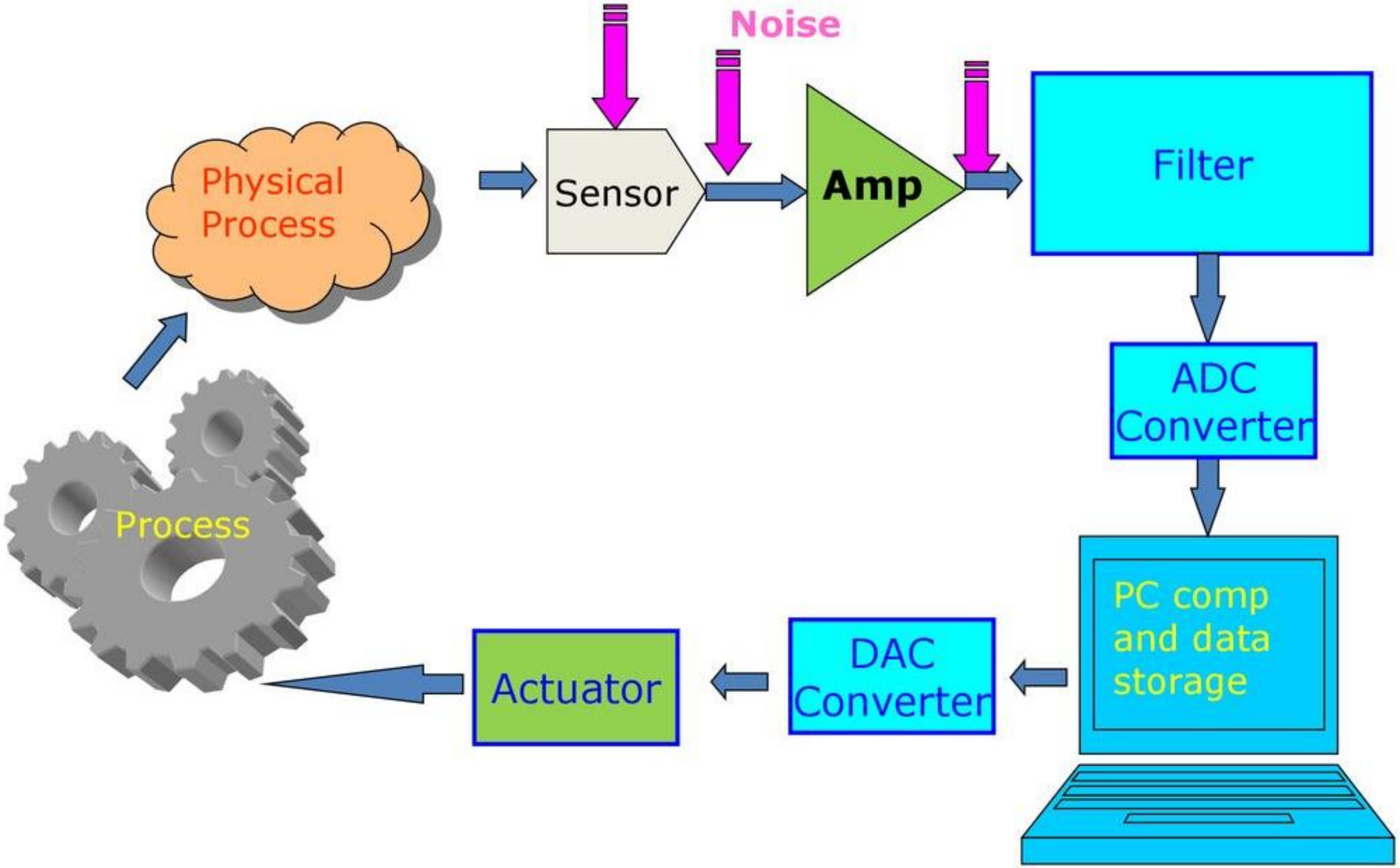
- Parasitic components of a MOSFET



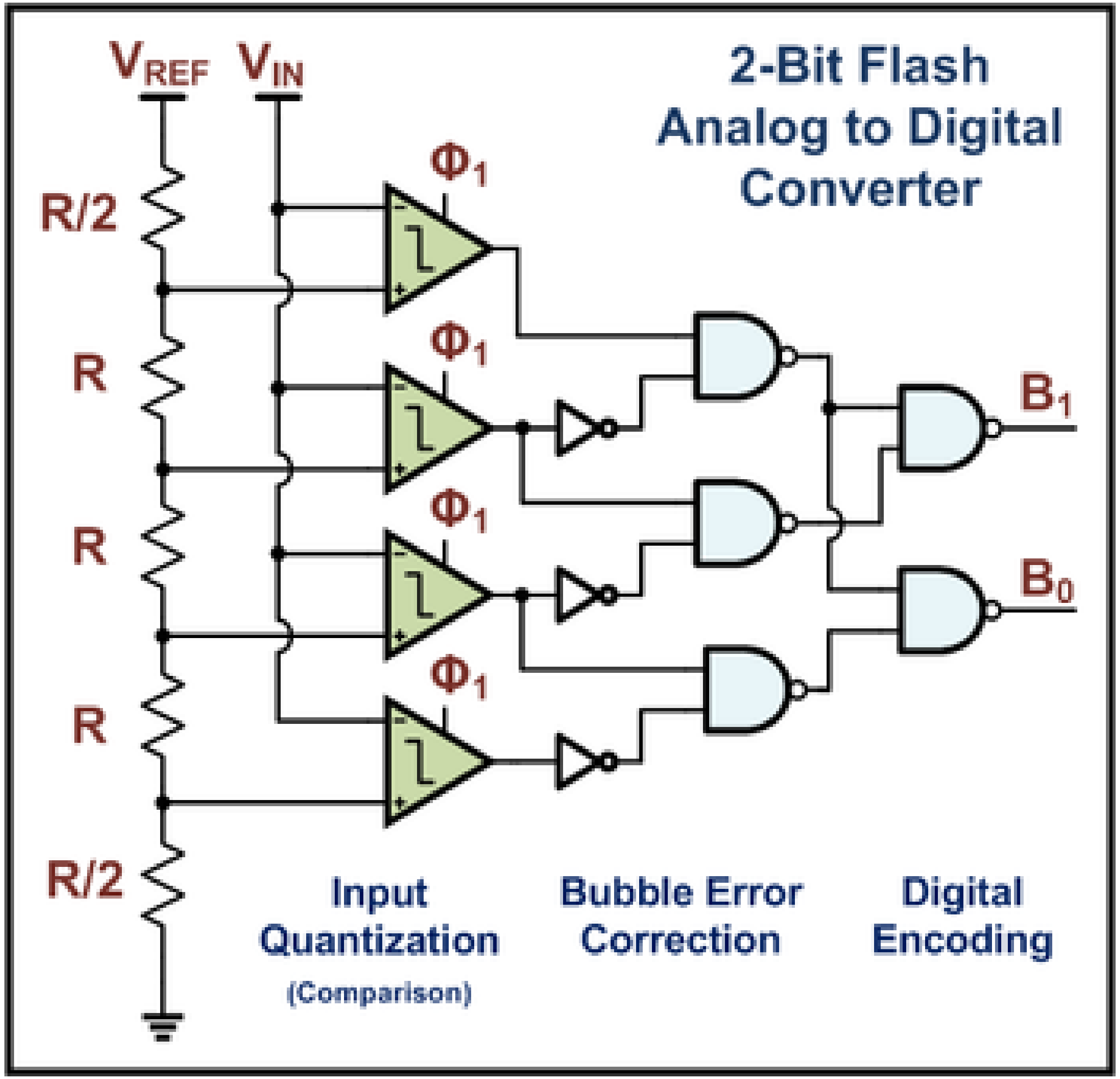
- Frequency response



ADC & DAC


Noise
Physical Process
Sensor
Amp
Filter
ADC Converter
PC comp and data storage
DAC Converter
Actuator
Process

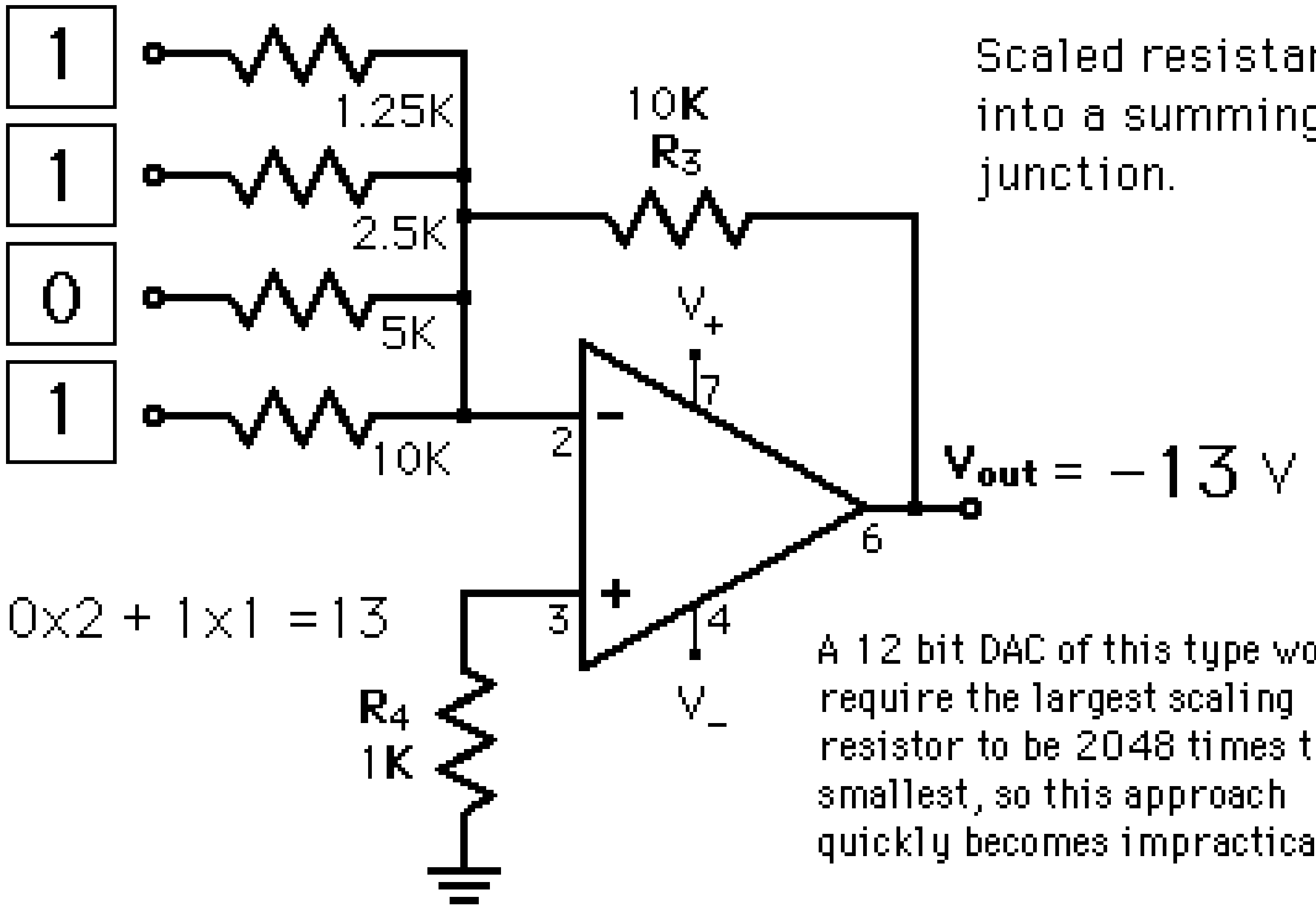
ADC example: Flash ADC (direct-conversion ADC)



Digital-to-analog converter (DAC)

- The simplest form

Inputs in volts are weighted in the summing amplifier to produce the corresponding analog voltage.



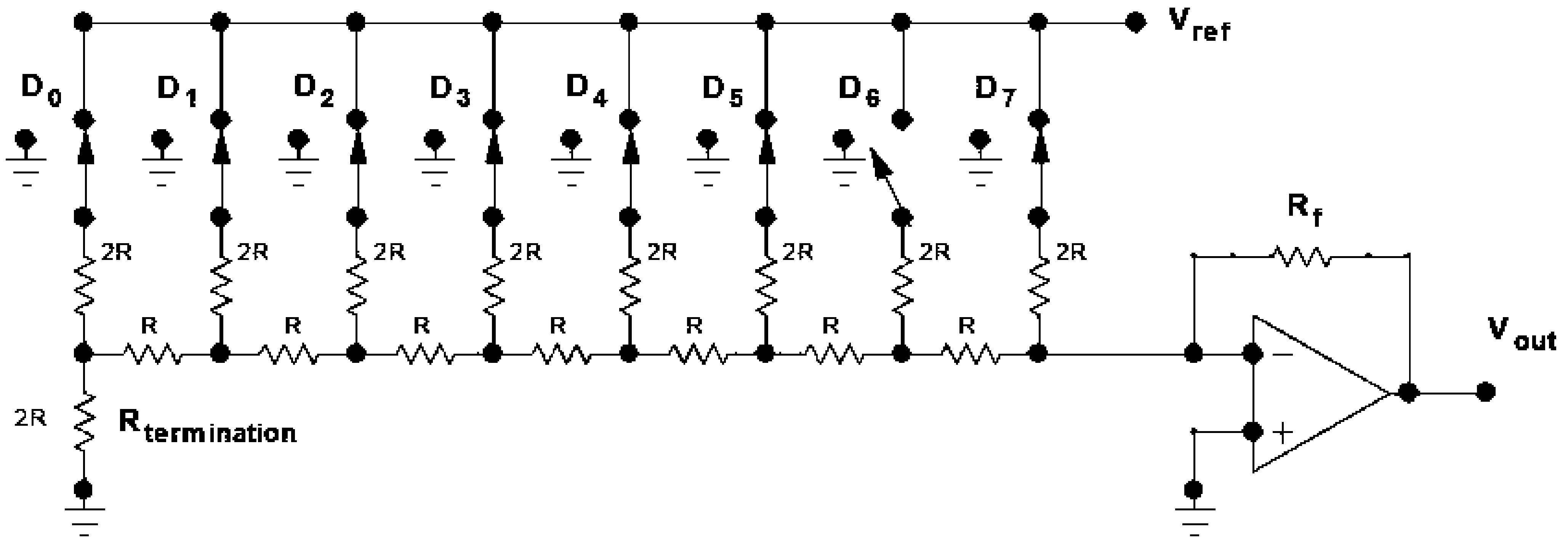
1x8 + 1x4 + 0x2 + 1x1 = 13

Scaled resistances into a summing junction.

A 12 bit DAC of this type would require the largest scaling resistor to be 2048 times the smallest, so this approach quickly becomes impractical.

Digital-to-analog converter (DAC)

- The R-2R ladder



$$V_{out} = -\frac{R_f}{R}\left(\frac{D_7}{2}+\frac{D_6}{4}+\frac{D_5}{8}+\frac{D_4}{16}+\frac{D_3}{32}+\frac{D_2}{64}+\frac{D_1}{128}+\frac{D_0}{256}\right)$$

$D = 0$ or 1