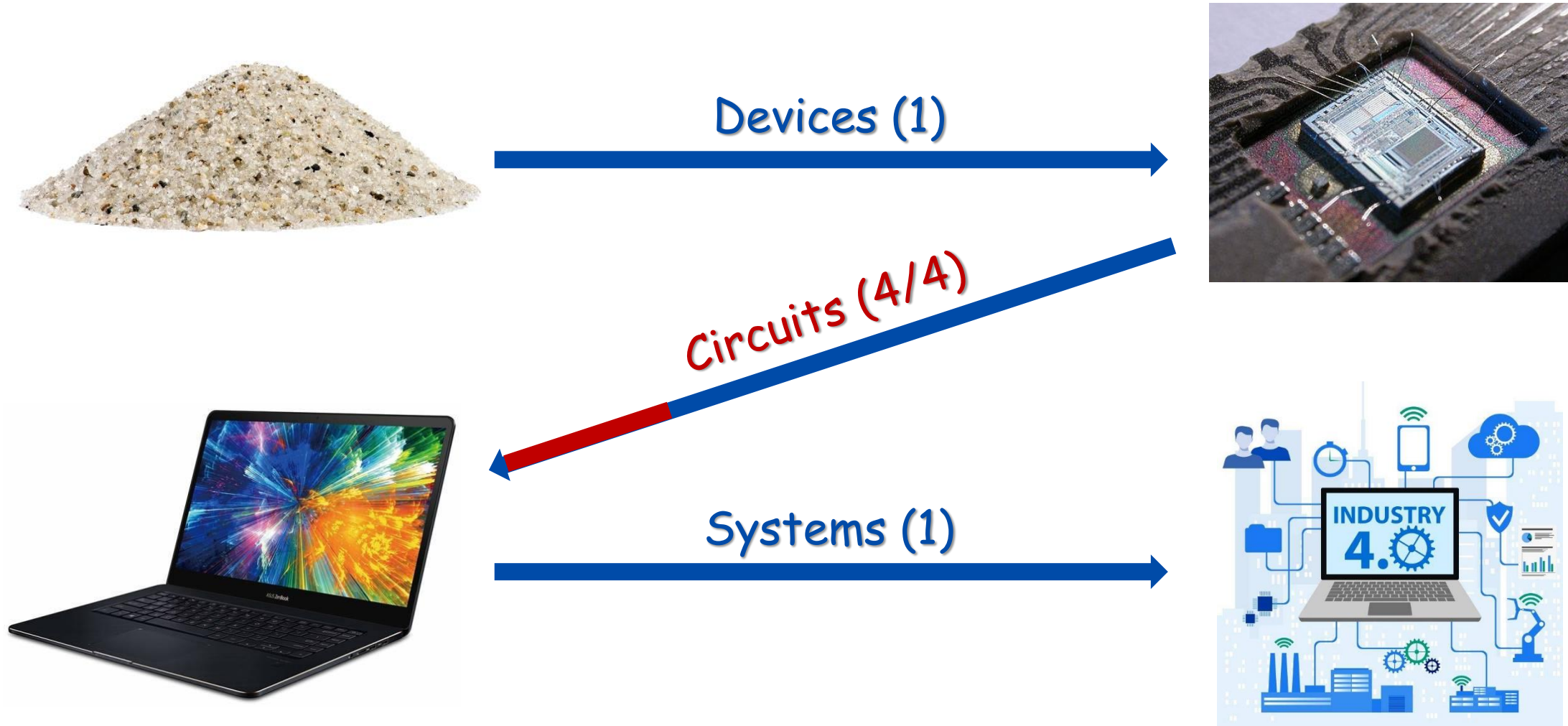# SI100B
Introduction to Information Science and Technology (Electrical Engineering)

Lecture #6 Analog Circuits

Instructor: Junrui Liang (梁俊睿)

Oct. 21st, 2022

The Theme Story

Devices (1)

Circuits (4/4)

Systems (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

(Pictures are from the Internet)

- 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?
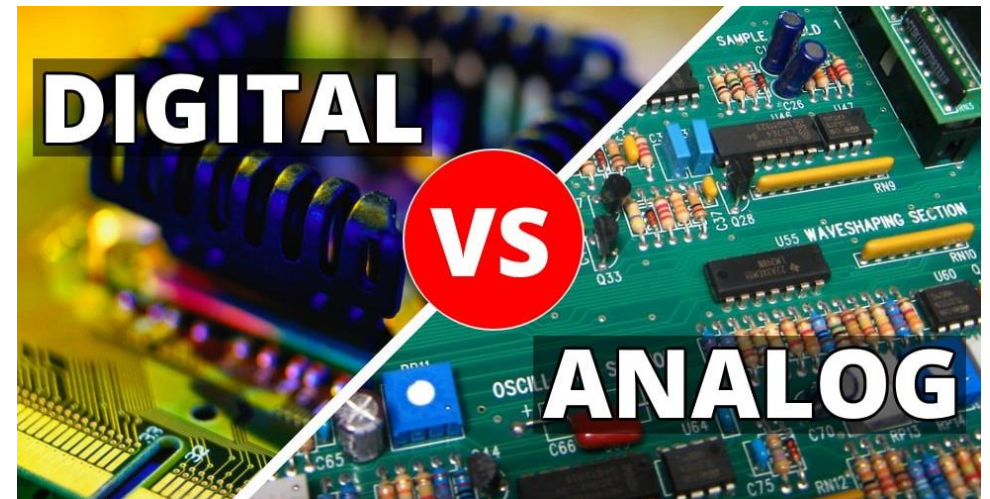
Lecture Outline

- 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
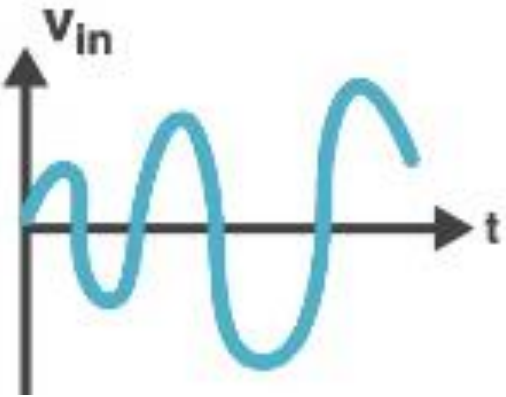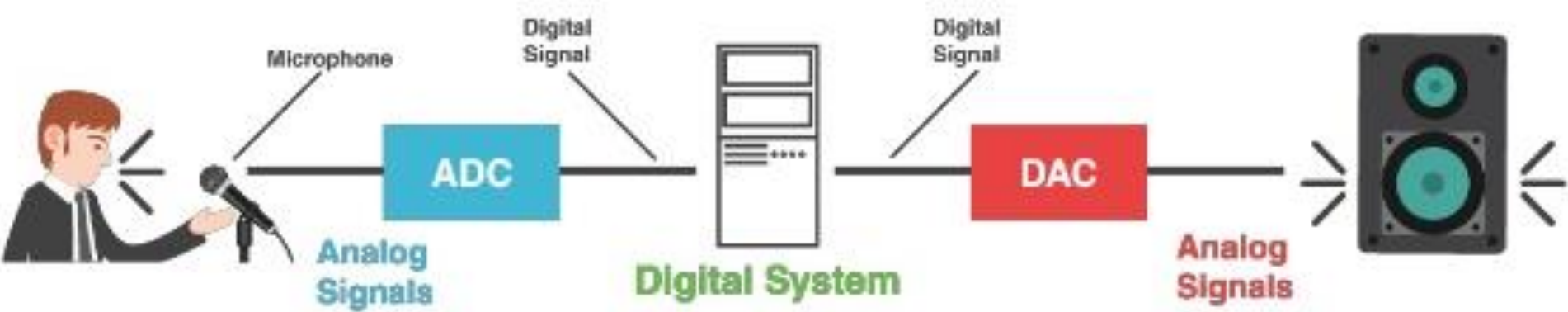1 (black) or 0 (white)

How to approximate the real world?

The colorful real world

A colorful approximation

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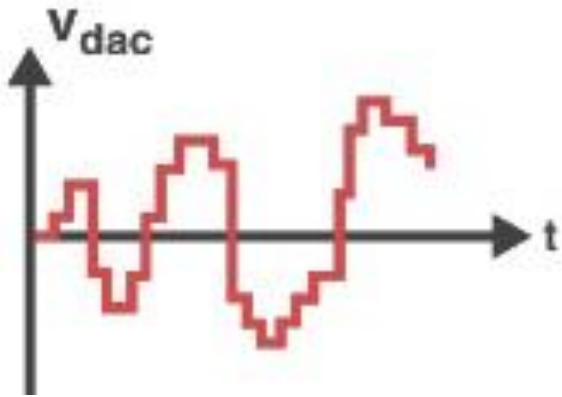the optics (physics of light) &
its digital approximation

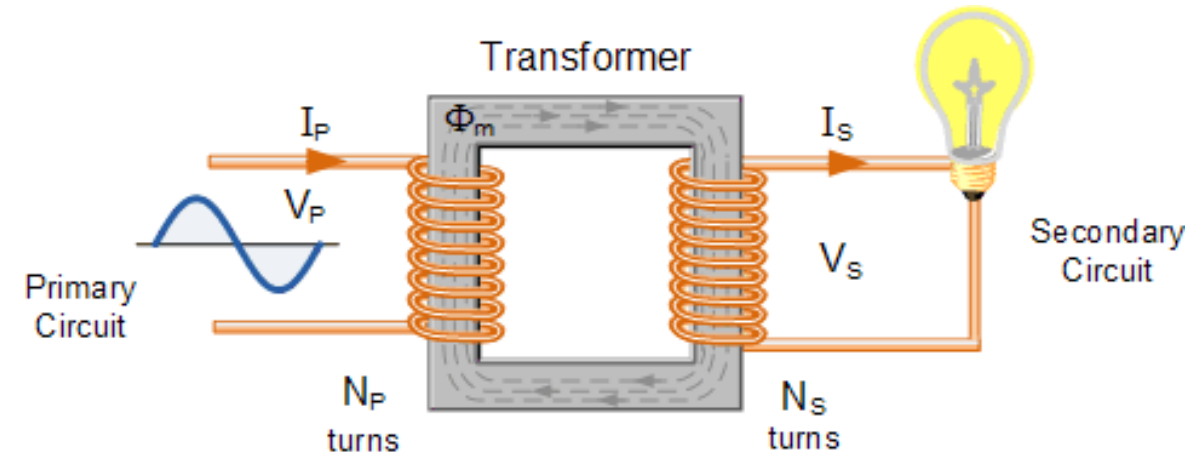# The real world vs. a binary world

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
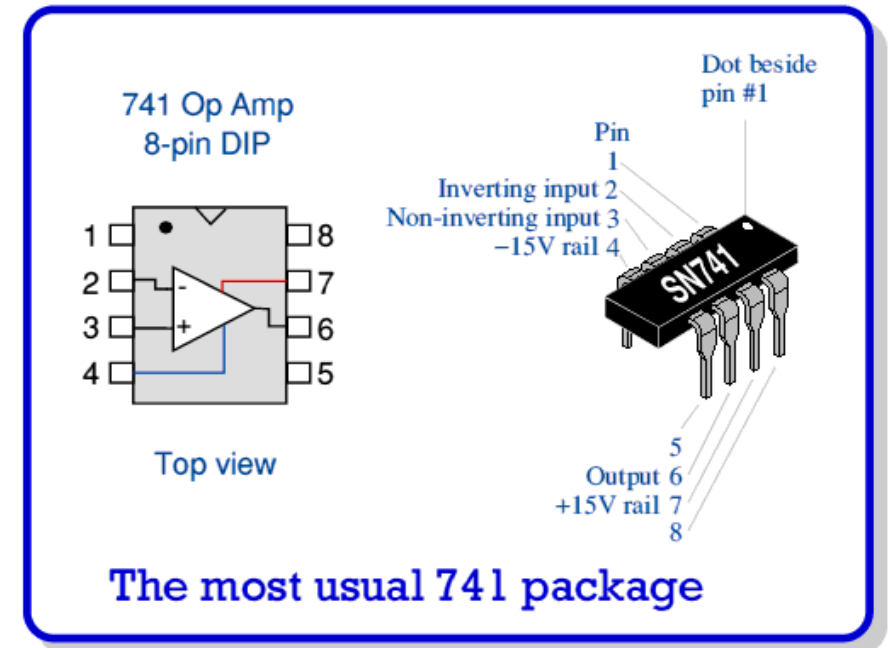 - What is amplified?
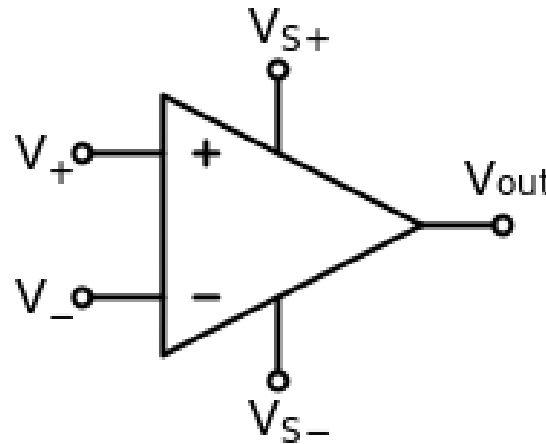 - What is reduced?

(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
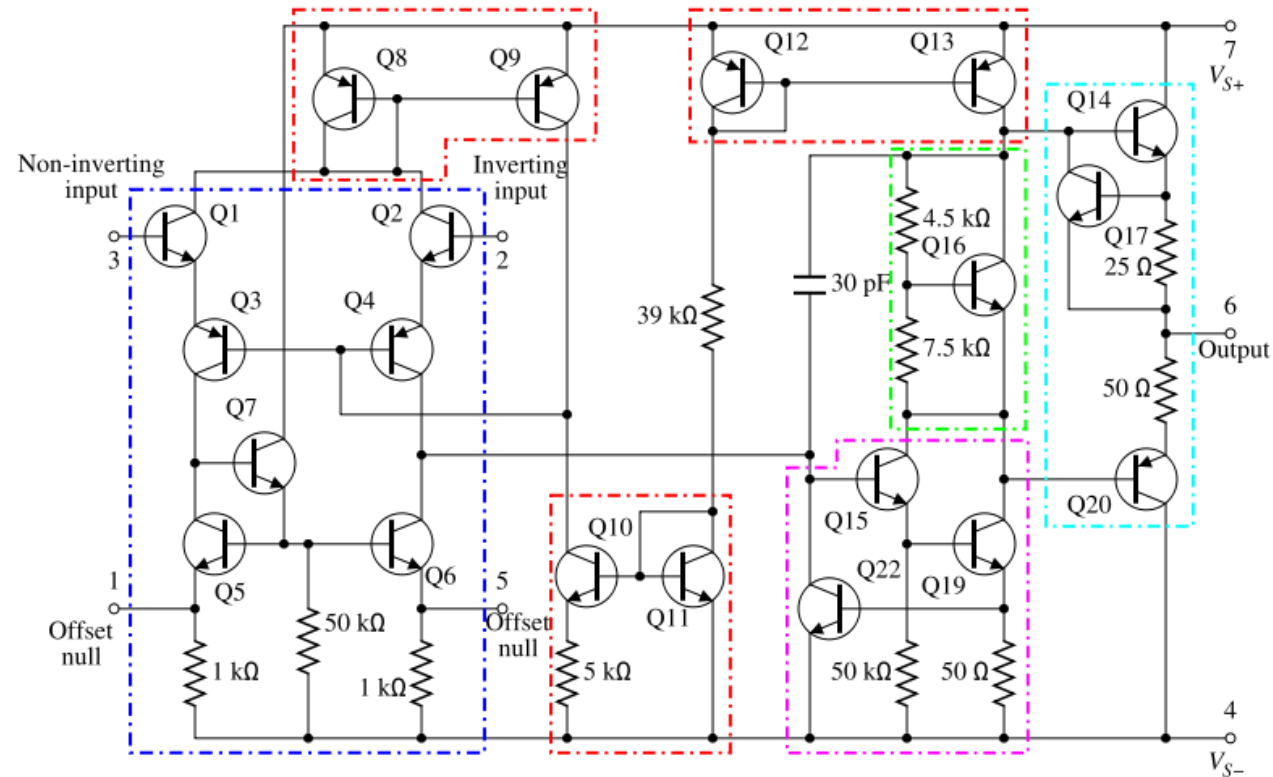 - An amplifier provides gain, an attenuator provides loss
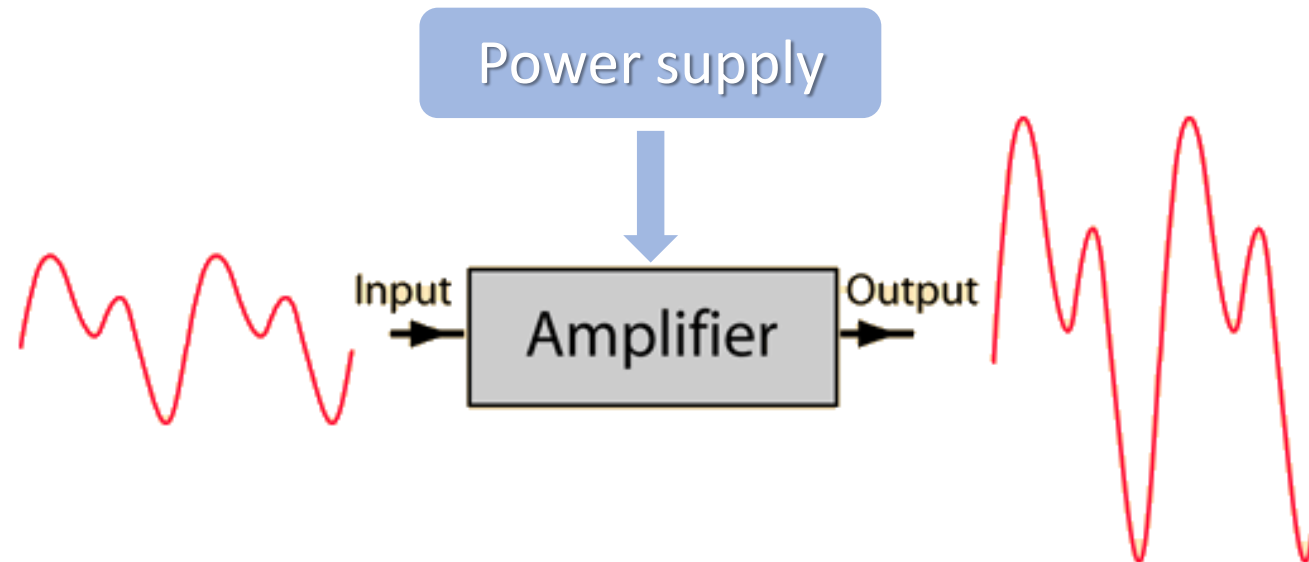
- One of the most widely used electronic devices

- 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})

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

741 Op Amp
8-pin DIP

1
2
3
4

8
7
6
5

Top view

Dot beside pin #1

Pin 1
Inverting input 2
Non-inverting input 3
−15V rail 4

SN741

5
Output 6
+15V rail 7
8

The most usual 741 package

Realization

- ## BJT Technology

- ## CMOS 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
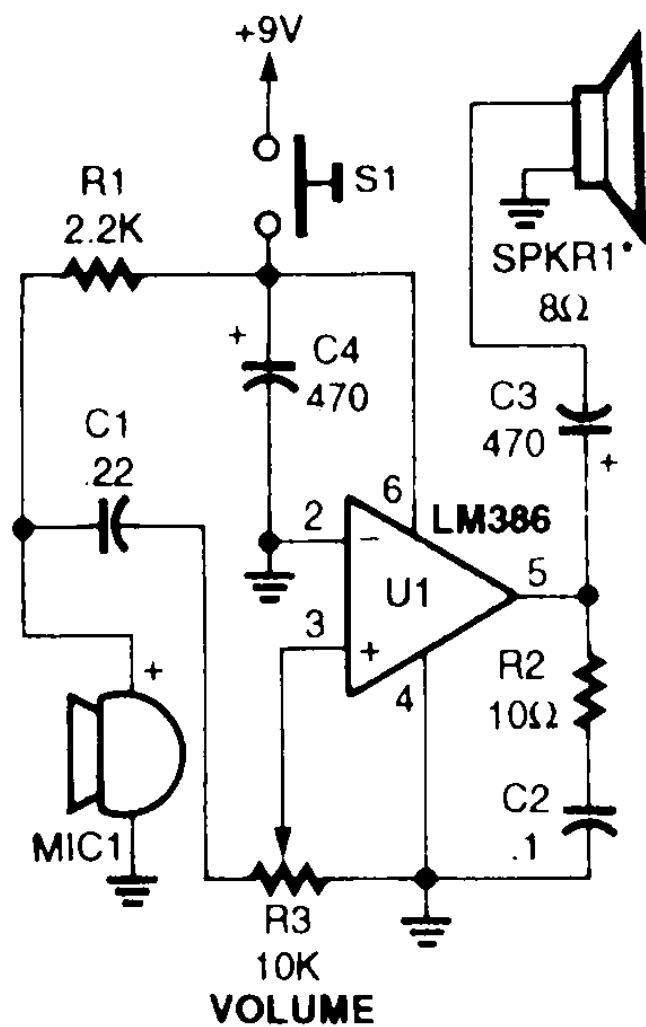level shifter (green); output stage (cyan).
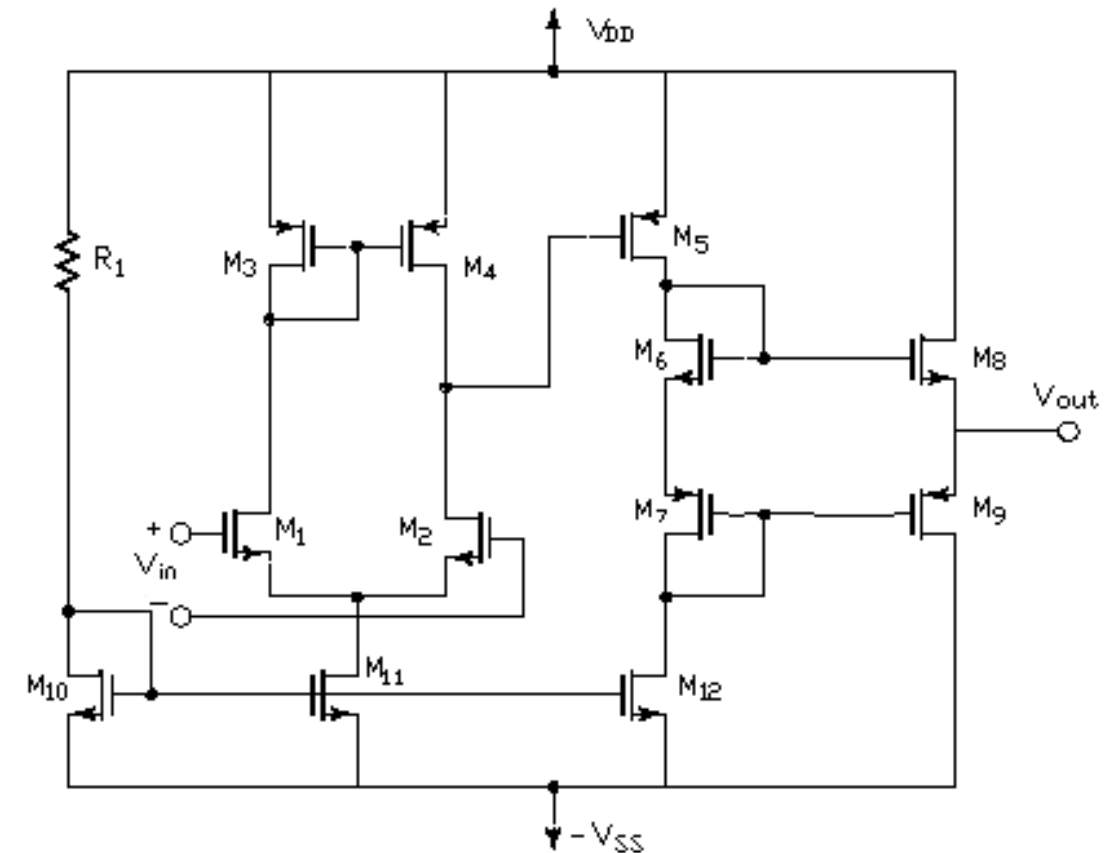
Realization

- Layout view of a simple CMOS operational amplifier
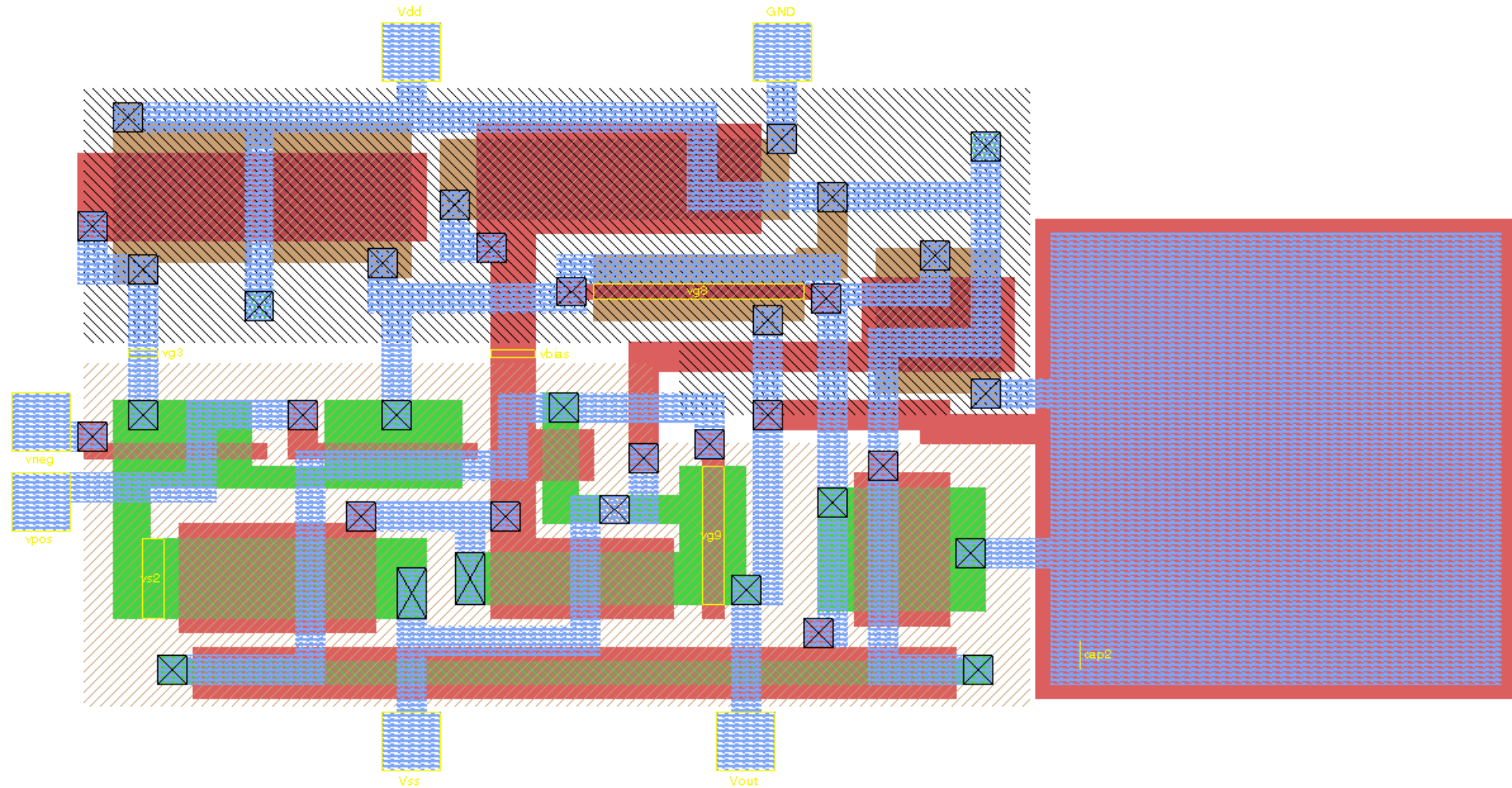
Applications
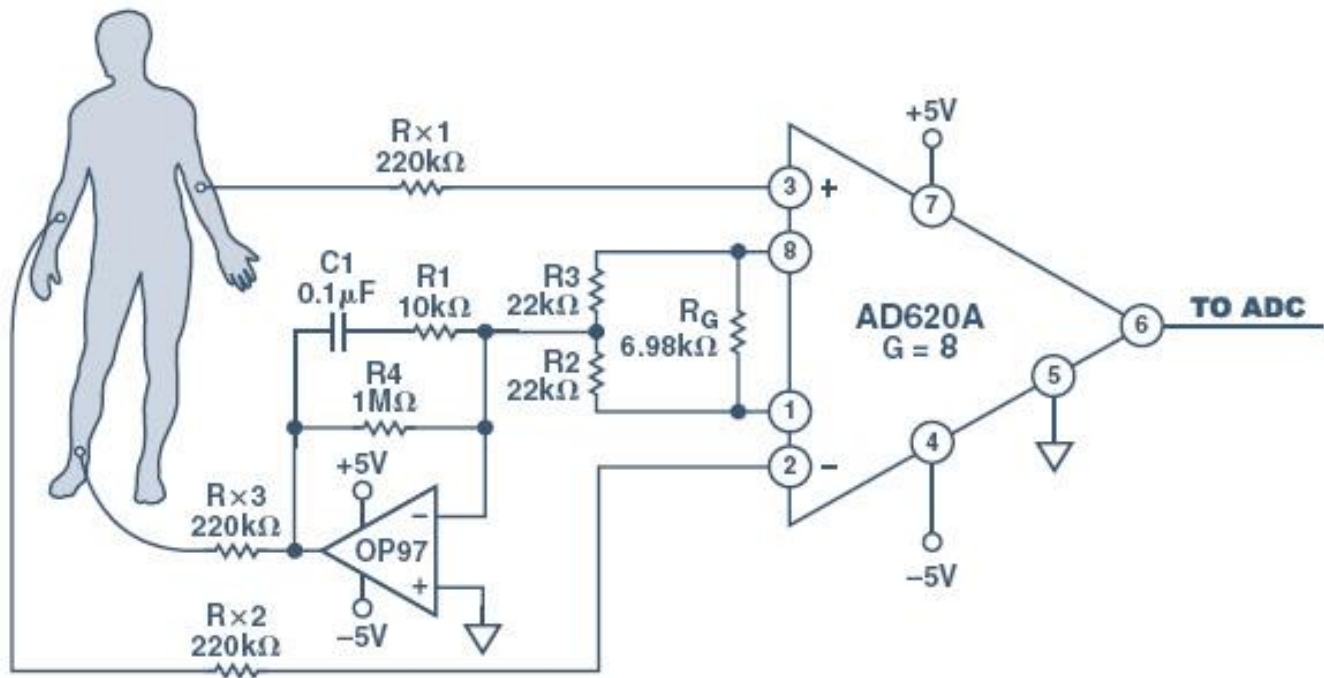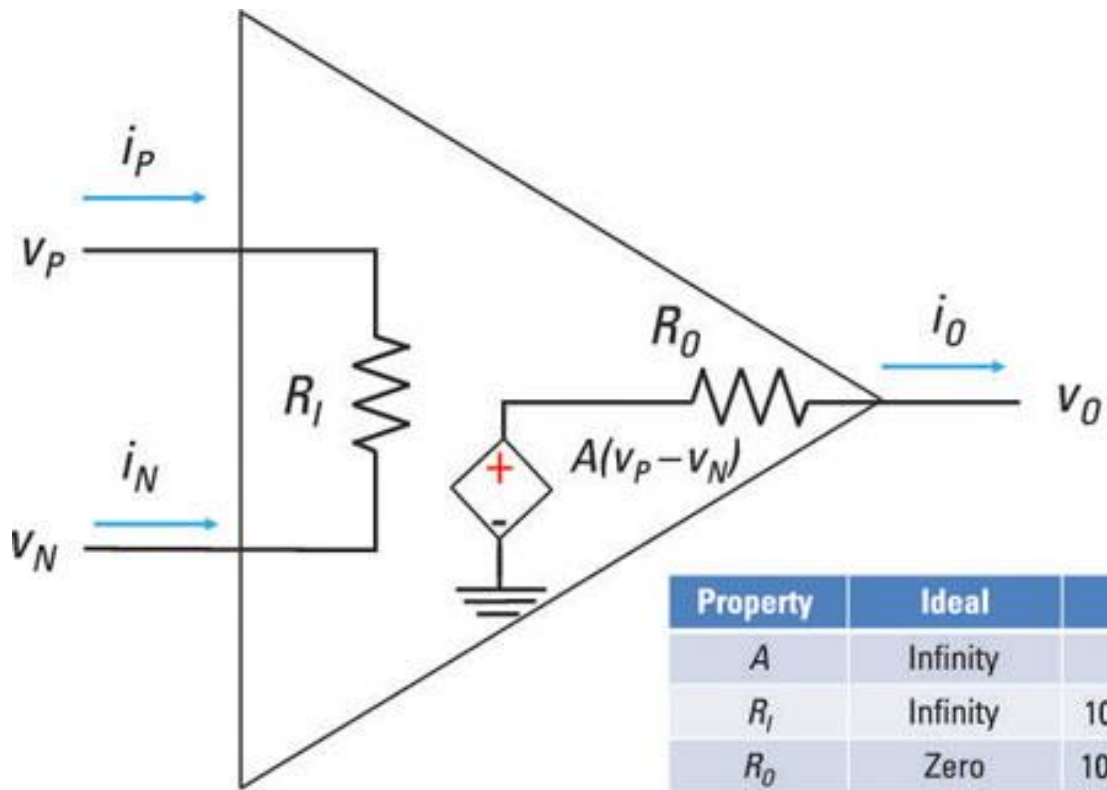
• Audio system

• Bio-electric signal

Ideal op amp

Property	Ideal	Typical
A	Infinity	$10^5 < A < 10^8$
R_I	Infinity	$10^5\,\Omega < R_I < 10^8\,\Omega$
R_0	Zero	$10^5\,\Omega < R_0 < 10^8\,\Omega$

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

10V INPUT

V_{IN}

10V OUTPUT
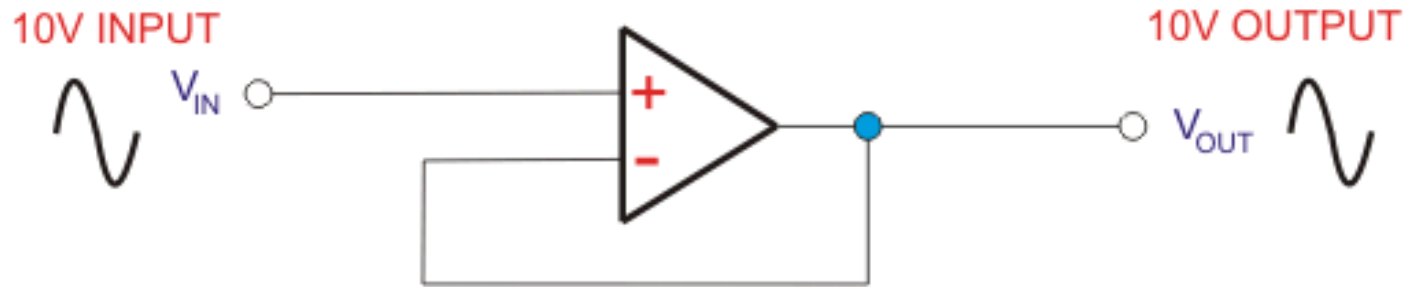
V_{OUT}

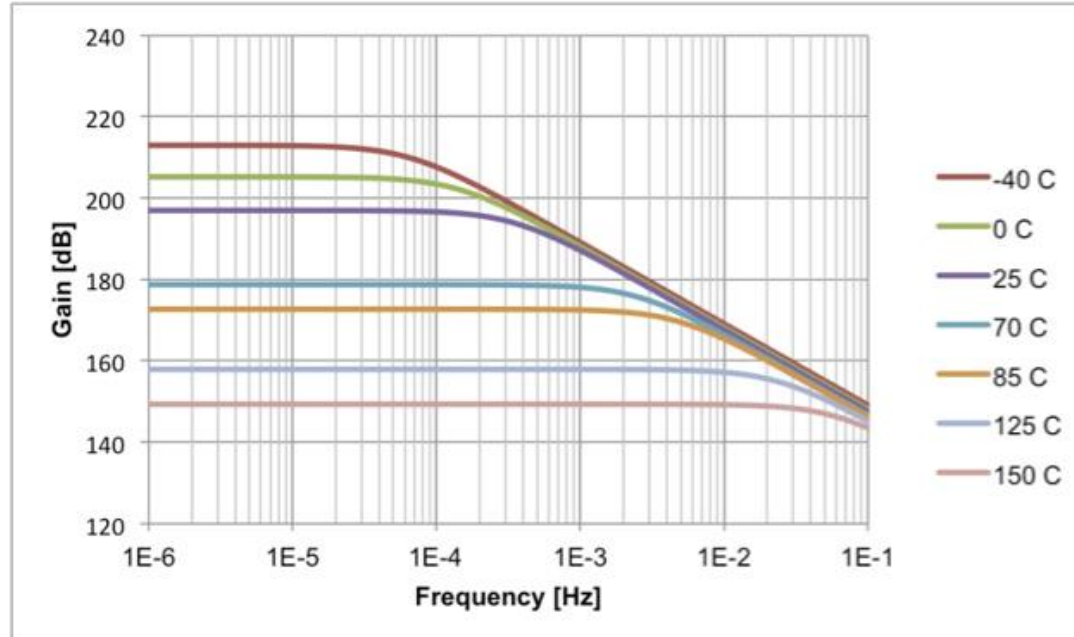$$V_{out} = A(V_+ - V_-)$$

Open-loop and close-loop gain

- ## Open-loop gain 开环增益
  - Large but finite
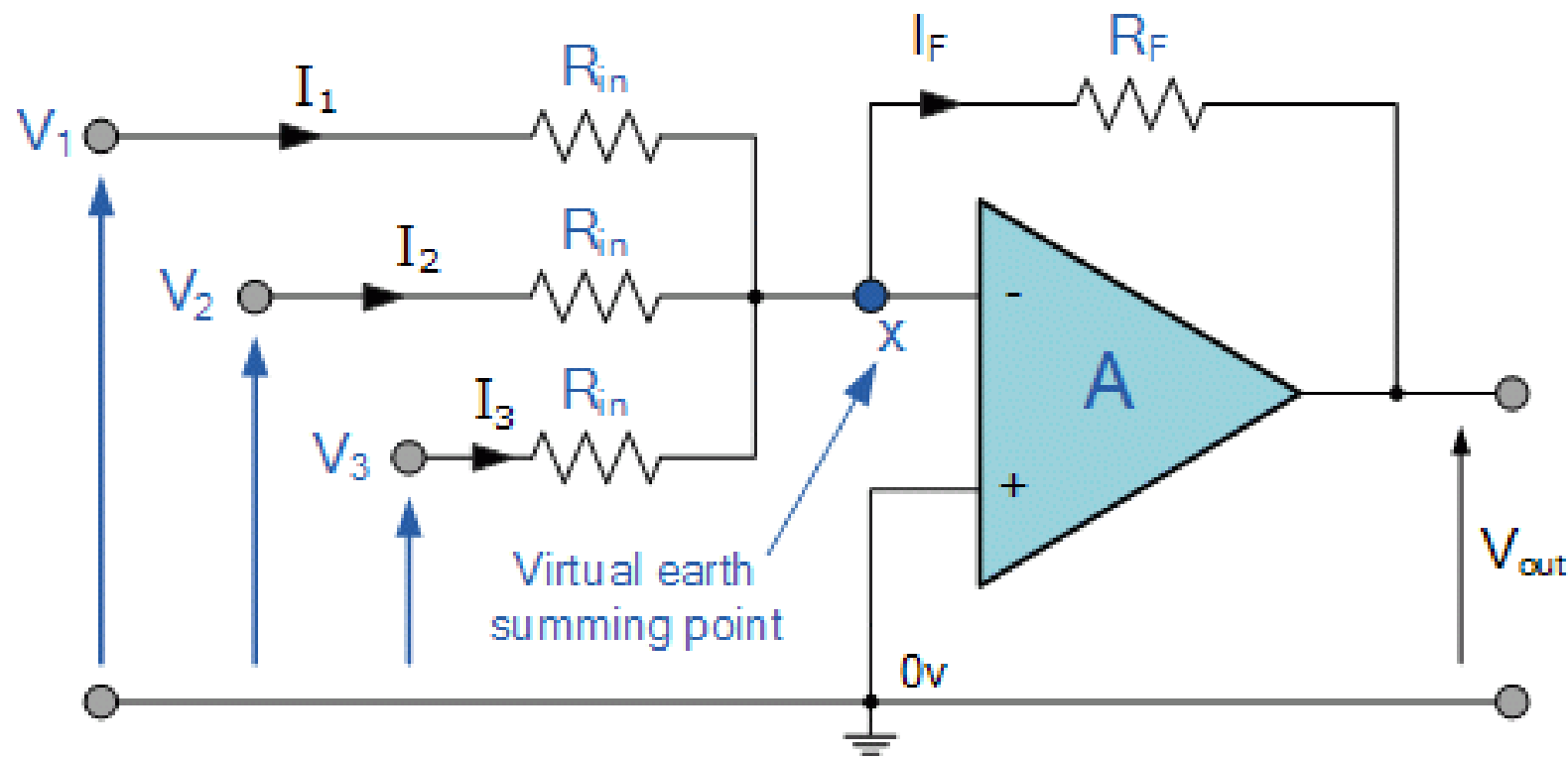 - Instable subjected to the manufacturing process, temperature, etc.
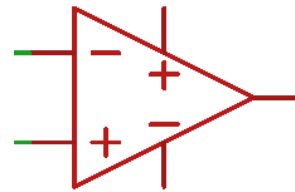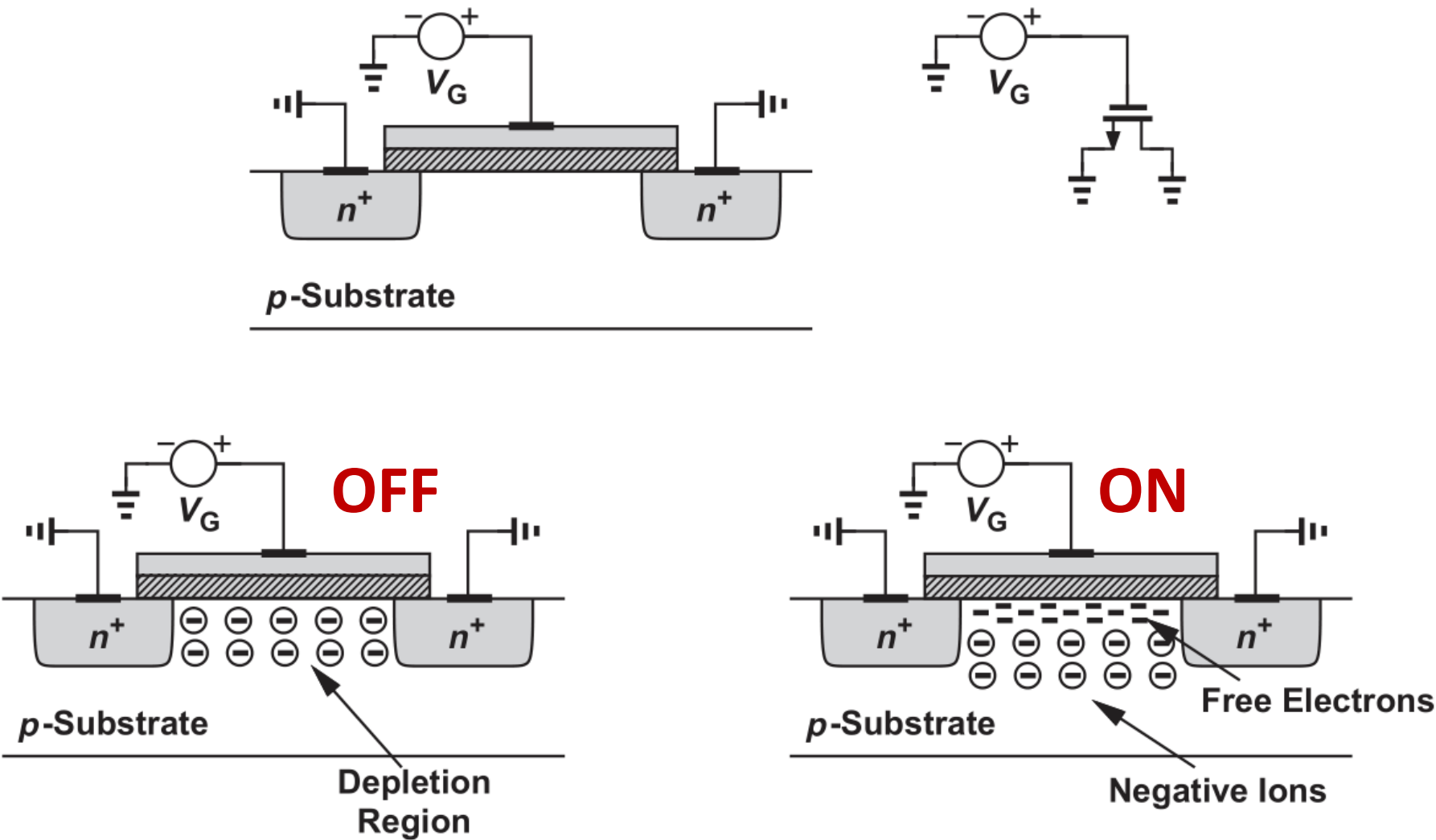
- ## Close-loop gain 闭环增益
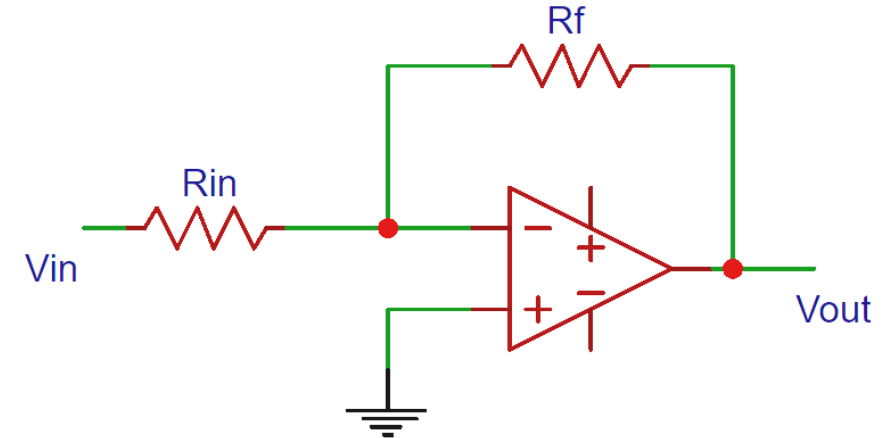
Gain = Vout/Vin = Rf/Rin

Summing amplifier circuit
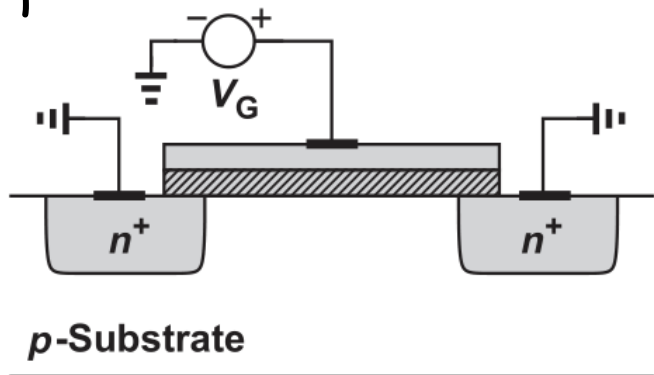

Virtual earth summing point

MOSFET in digital applications: a review
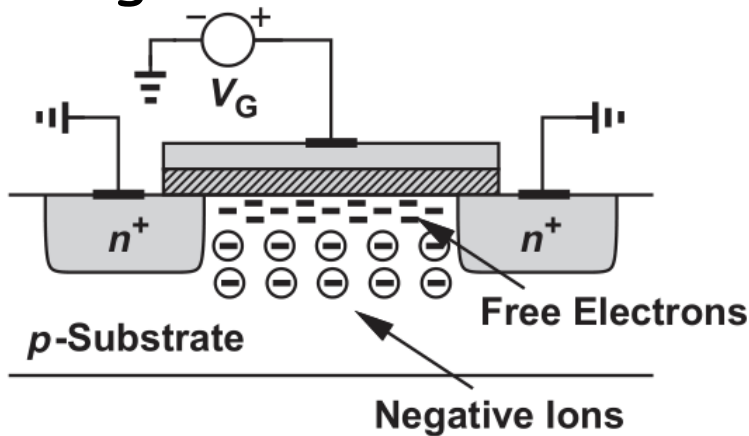

OFF

ON

(Razavi, Fundamentals of Microelectronics)

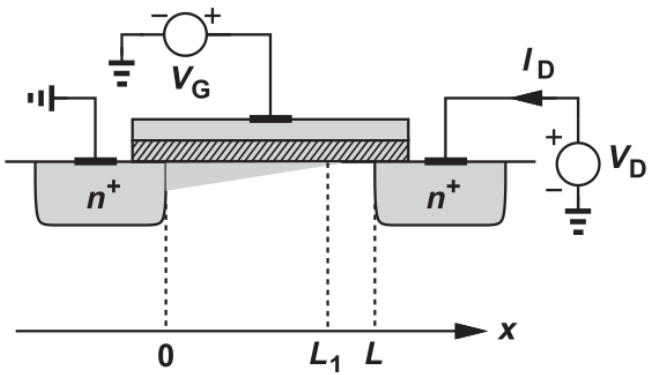# Beyond the on/off states
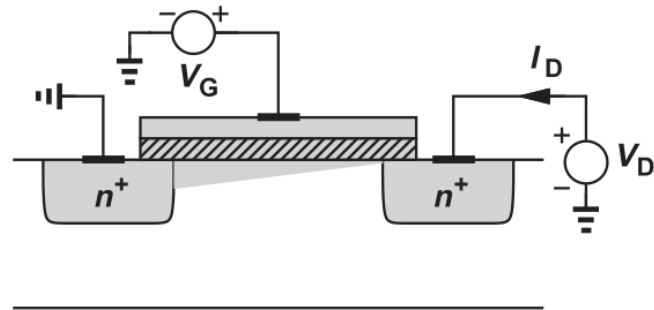
- For digital electronics
  - Cut off

  - Conducting

- For analog electronics
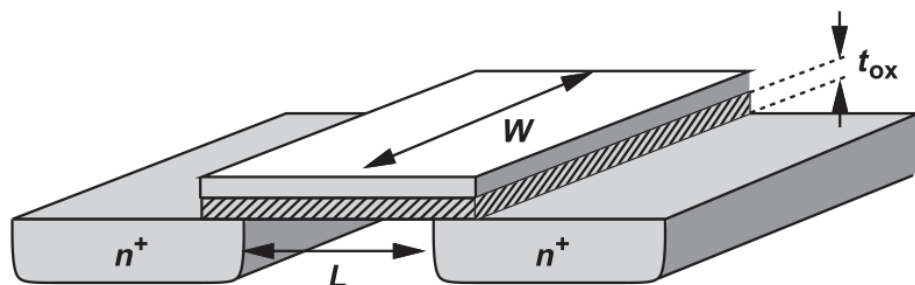

(Razavi, Fundamentals of Microelectronics)
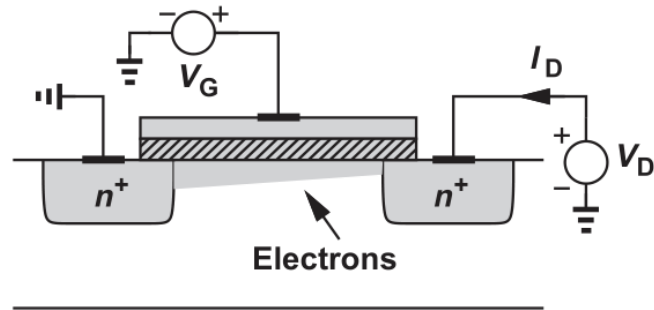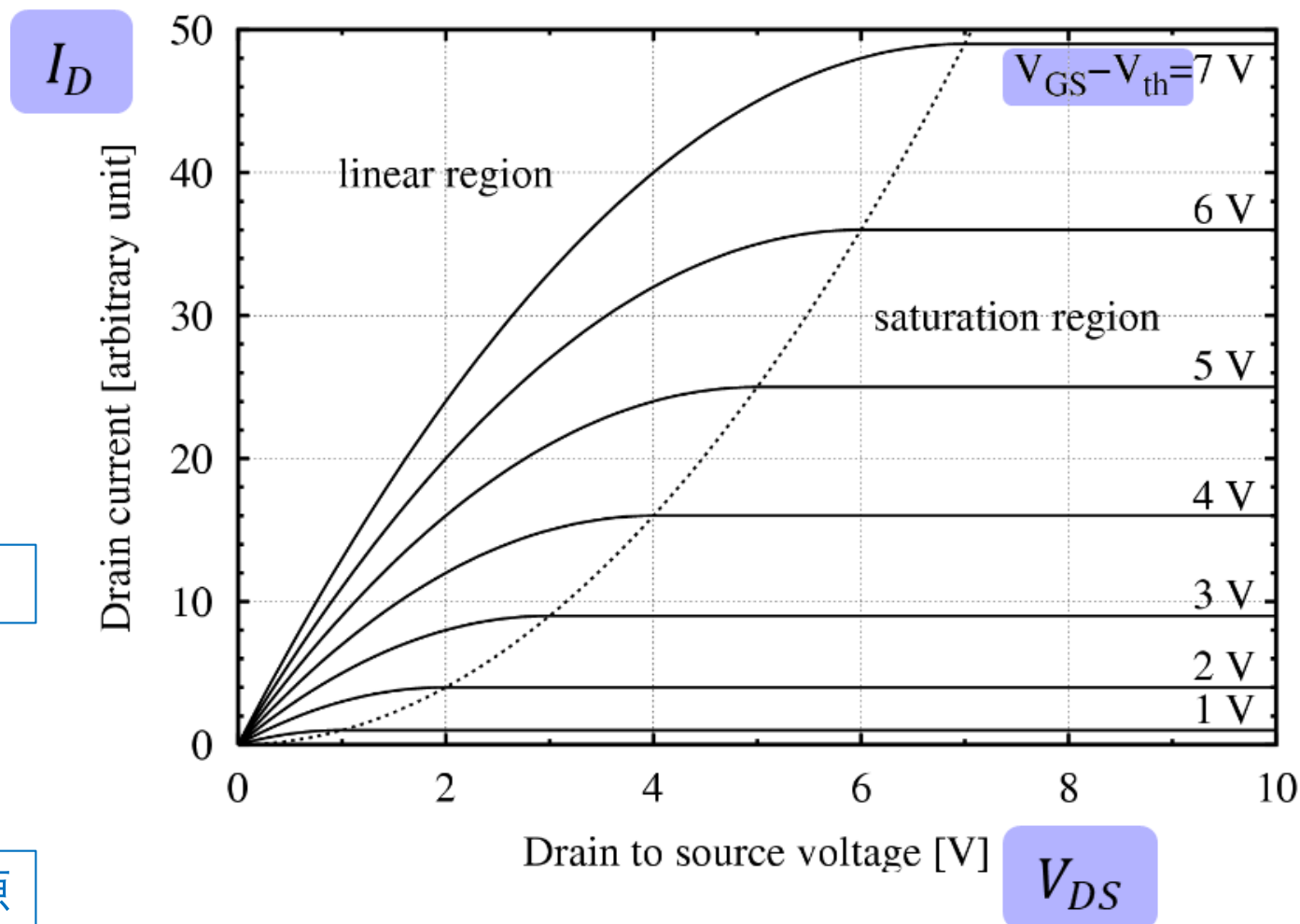
I/V characteristics

Linear region:

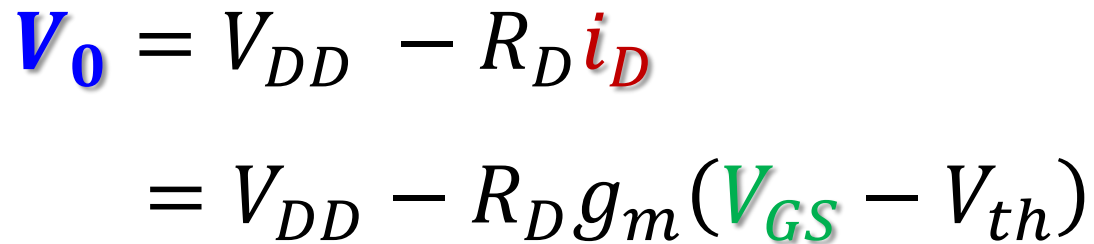$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}[2(V_{GS} - V_{TH})V_{DS} - V_{DS}^2]$$

A voltage-controlled resistor 压控电阻

Saturation region:

$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS} - V_{TH})^2(1 + \lambda V_{DS})$$
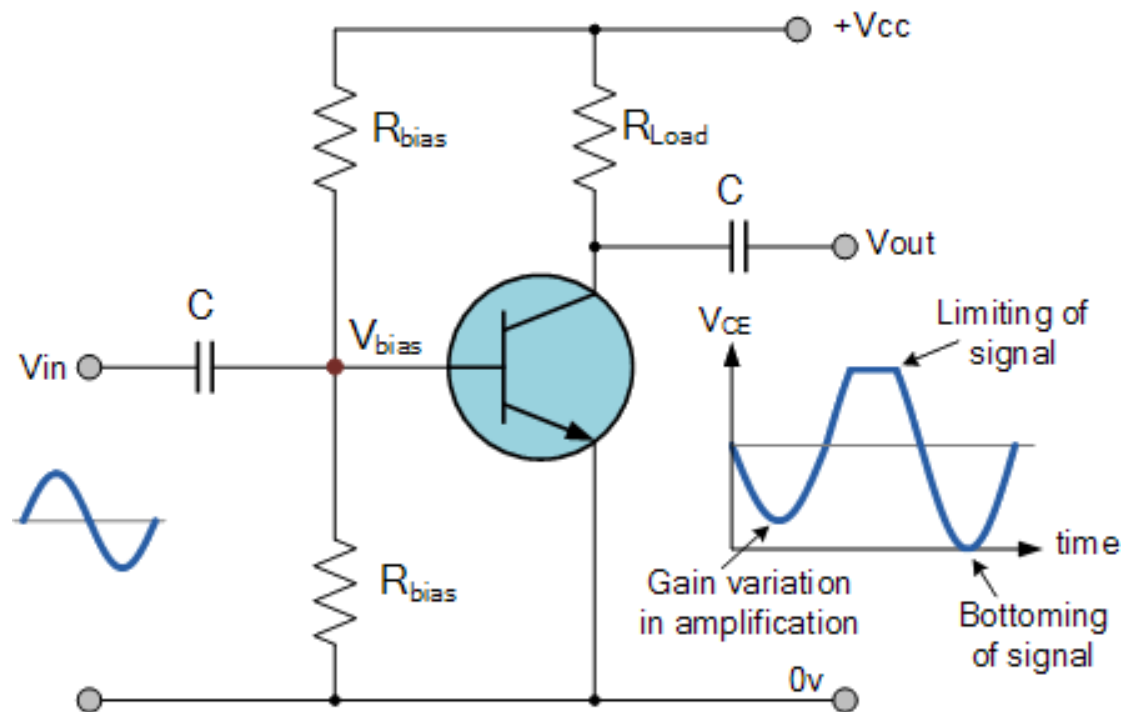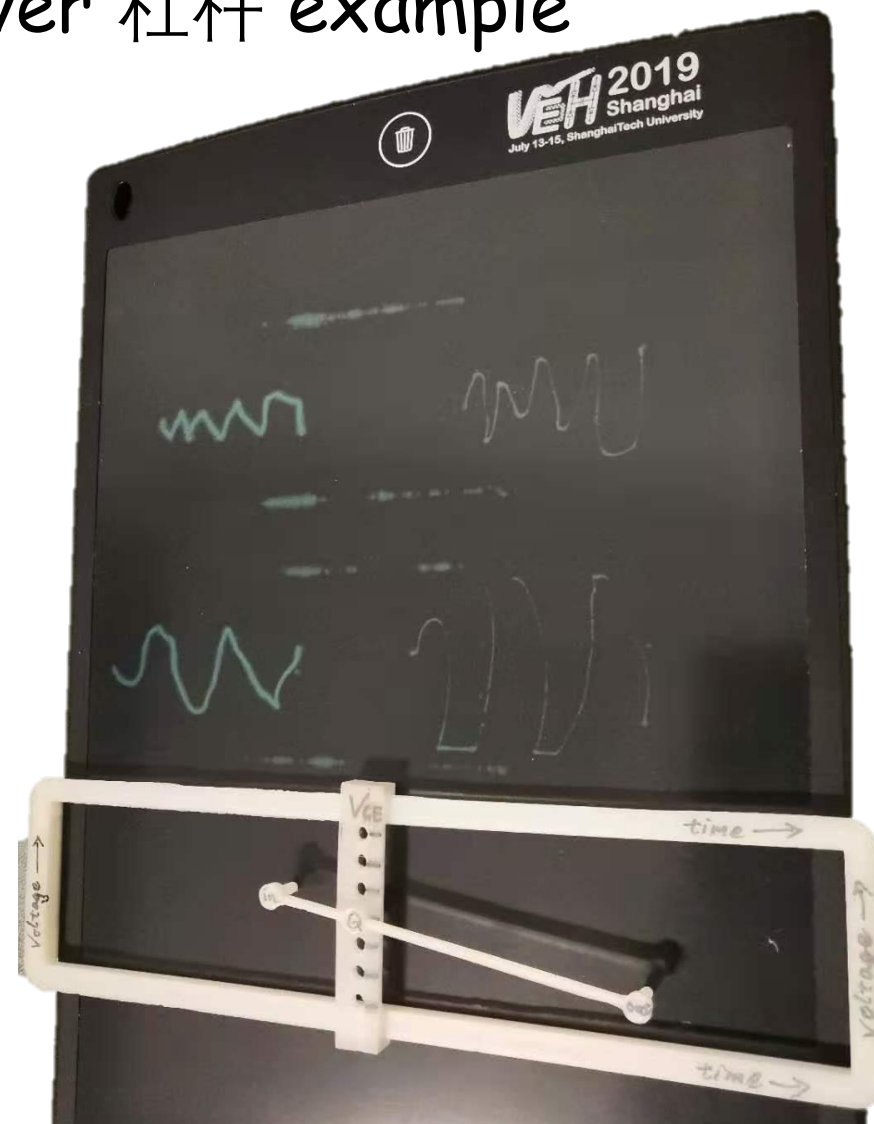
A voltage controlled current source 压控电流源

(Razavi, Fundamentals of Microelectronics)

Basic MOS amplifier

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

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

(Neamen, Electronic Circuit Analysis and Design)

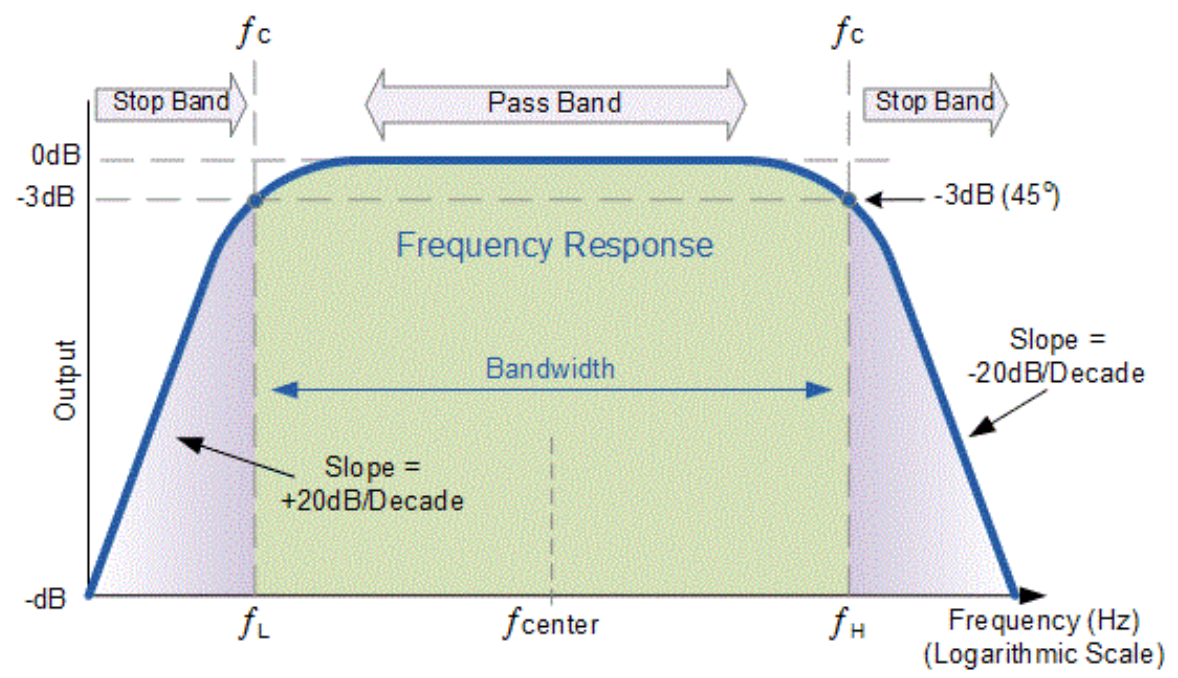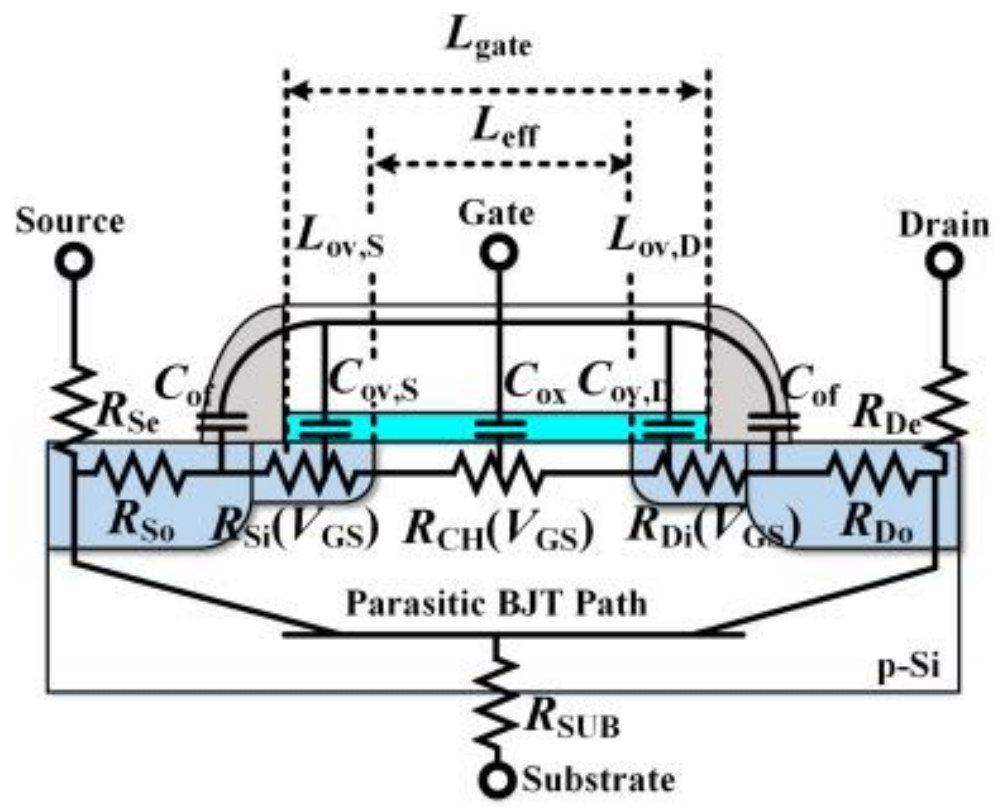# Voltage range limitations

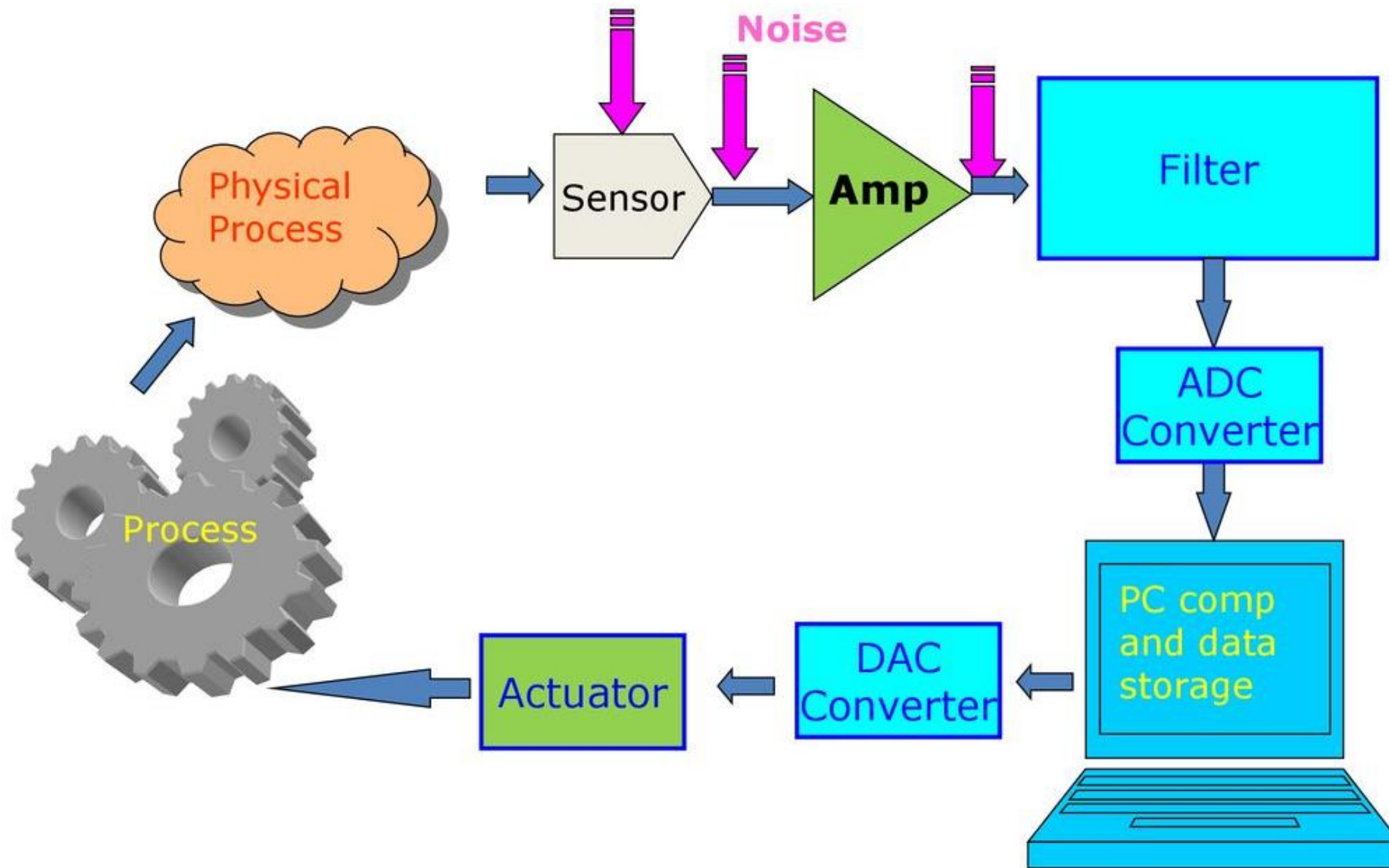- In a real transistor circuit
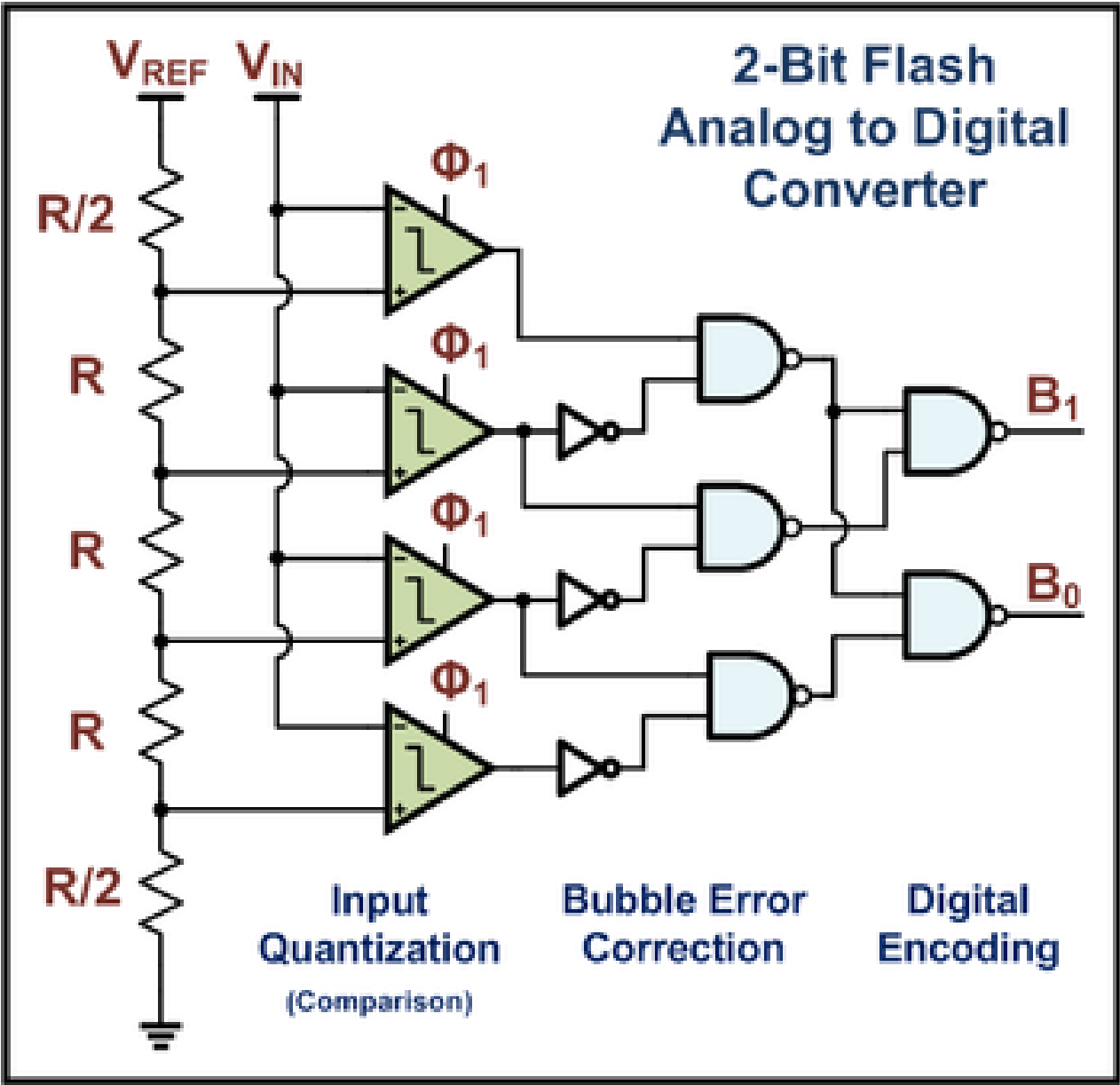
- A lever 杠杆 example

Frequency limitations

- Parasitic components of a MOSFET

- Frequency response

ADC & DAC

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.

Scaled resistances into a summing junction.

1

1

0

1

1.25K

2.5K

5K

10K

10K
R_3

V_+

7

2

−

+

3

4

6

V_-

R_4
1K

$\mathbf{V_{out}} = -13$ V

$$1 \times 8 + 1 \times 4 + 0 \times 2 + 1 \times 1 = 13$$

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.
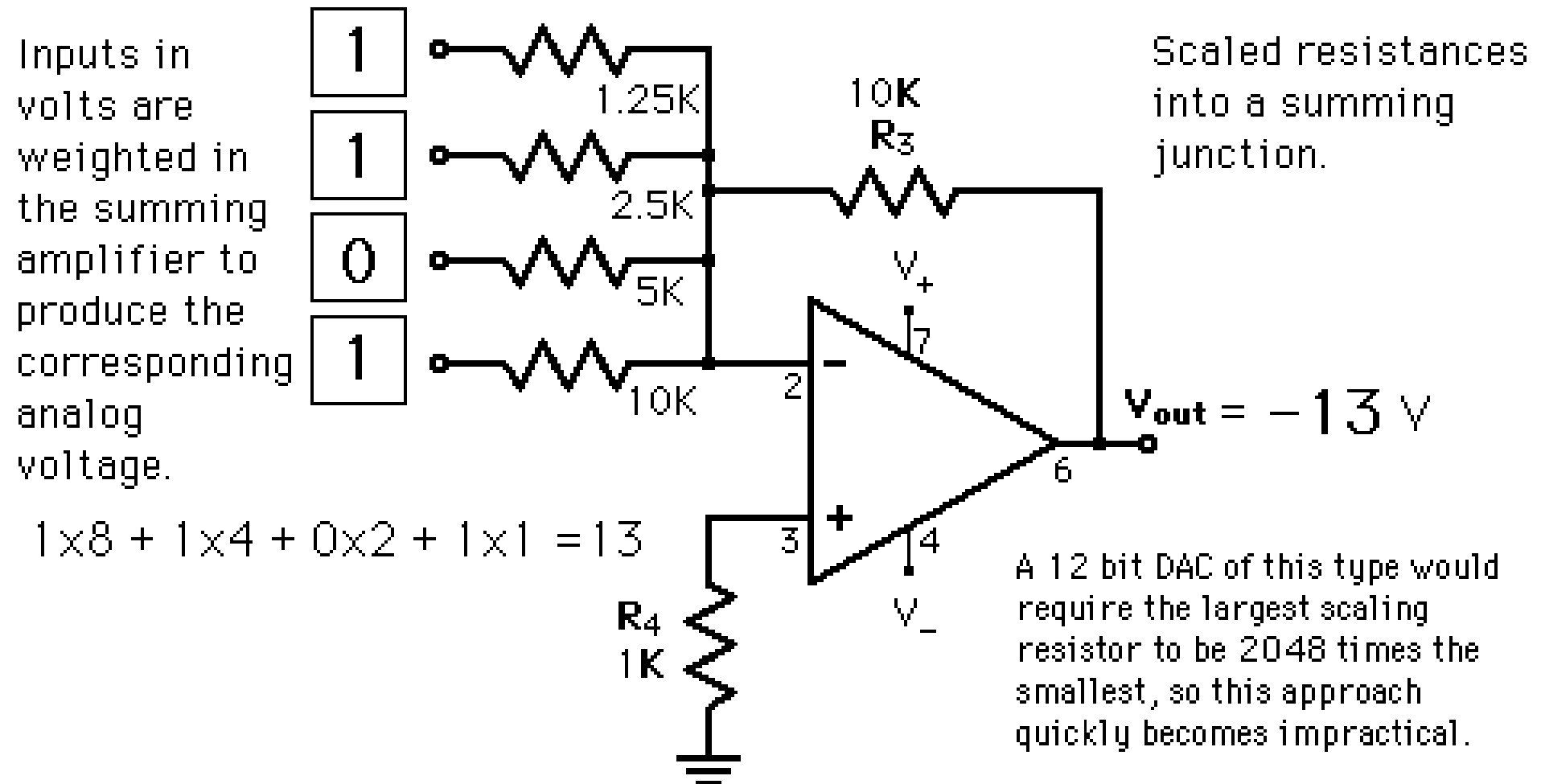
Digital-to-analog converter (DAC)

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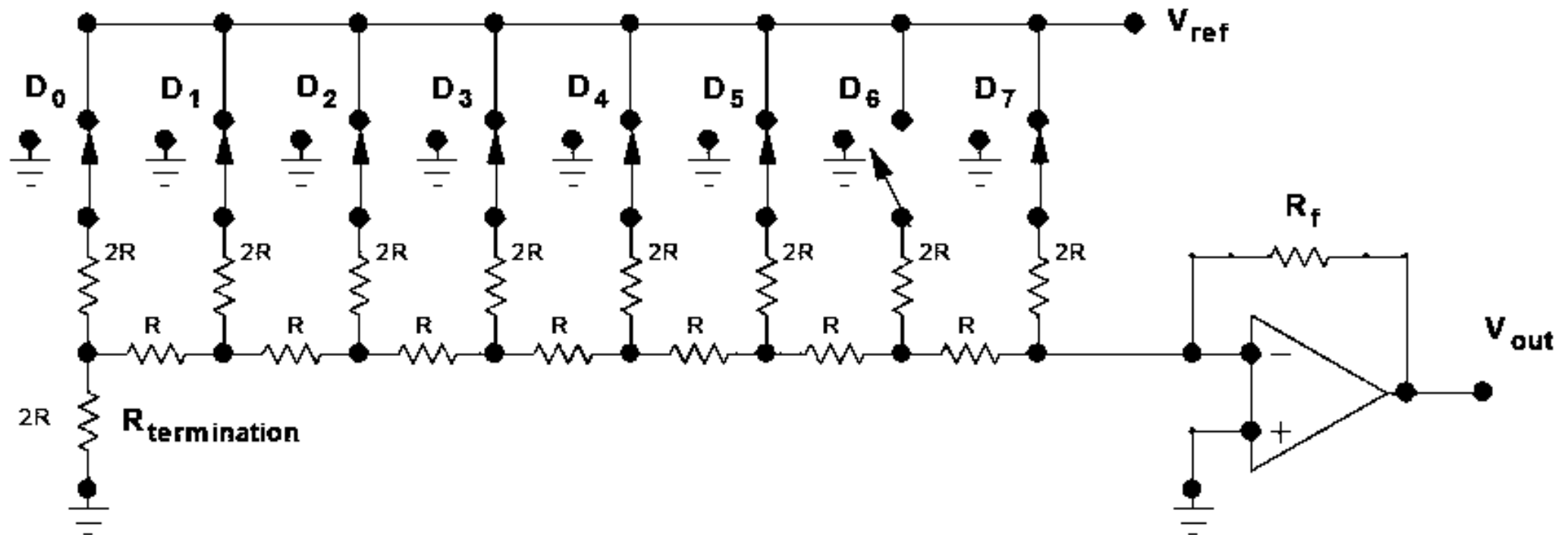
$$V_{out} = -\frac{R_f}{R}\left(\frac{D_7}{2} + \frac{D_6}{4} + \frac{D_5}{8} + \frac{D_4}{16} + \frac{D_3}{32} + \frac{D_2}{64} + \frac{D_1}{128} + \frac{D_0}{256}\right)$$

$$D = 0 \text{ or } 1$$