Fundamentals of Microelectronics

- **CH1 Introduction to Microelectronics**
- **CH2 Basic Physics of Semiconductors**
- **CH3 Diode Models and Circuits**
- **CH4 Physics of Bipolar Transistors**
- **CH5 Bipolar Amplifiers**
- CH6 Physics of MOS Transistors
- CH7 CMOS Amplifiers
- CH8 Operational Amplifier As A Black Box

Chapter 1 Introduction to Microelectronics

- **1.1 Electronics versus Microelectronics**
- **1.2 Example of Electronic System: Cellular Phone**
- **1.3 Analog versus Digital**

Microelectronics Revolution

- Microelectronics has revolutionized our lives with cellphones, digital cameras, laptop computers, tablets and many other electronic products.
- Learning microelectronics *can* be fun.
- We will learn
  - how each device operates,
  - how devices comprise circuits that perform interesting and useful functions, and
  - how circuits form sophisticated systems.
- We will see the beauty of microelectronics and appreciate the reasons for its explosive growth.

device: 元件
circuit: 電路
function: 功能
system: 系統
product: 產品

Electronics versus Microelectronics

- The general area of electronics began about a century ago and used in the radio and radar communications during the two world wars.
- Early systems incorporated "vacuum tubes," amplifying devices that operated with the flow of electrons between plates in a vacuum chamber. 真空管
- However, the finite lifetime and the large size of vacuum tubes motivated researchers to seek an electronic device with better properties.
- The first ***transistor*** was invented in the end of 1940s and rapidly displaced vacuum tubes. 電晶體
- Until 1960s began the integration of many transistors on a ***chip***. 晶片
- Early chips contained only a handful of devices, but … .
- Advances in "***integrated circuits***" (***IC***s) technology soon made possible to dramatically increase the complexity of "microchips."

積體電路

Example 1.1

Today's microprocessors contain about 100 million transistors in a chip area of approximately 3 cm x 3 cm. (The chip is a few hundred microns thick.) Suppose integrated circuits were not invented and we attempted to build a processor using 100 million "discrete" transistors. If each device occupies a volume of 3 mm x 3 mm x 3 mm, determine the minimum volume for the processor. What other issues would arise in such an implementation?

Solution

The minimum volume is given by 27 mm^3 x 10^8 , i.e., a cube 1.4 m on each side! Of course, the wires connecting the transistors would increase the volume substantially.

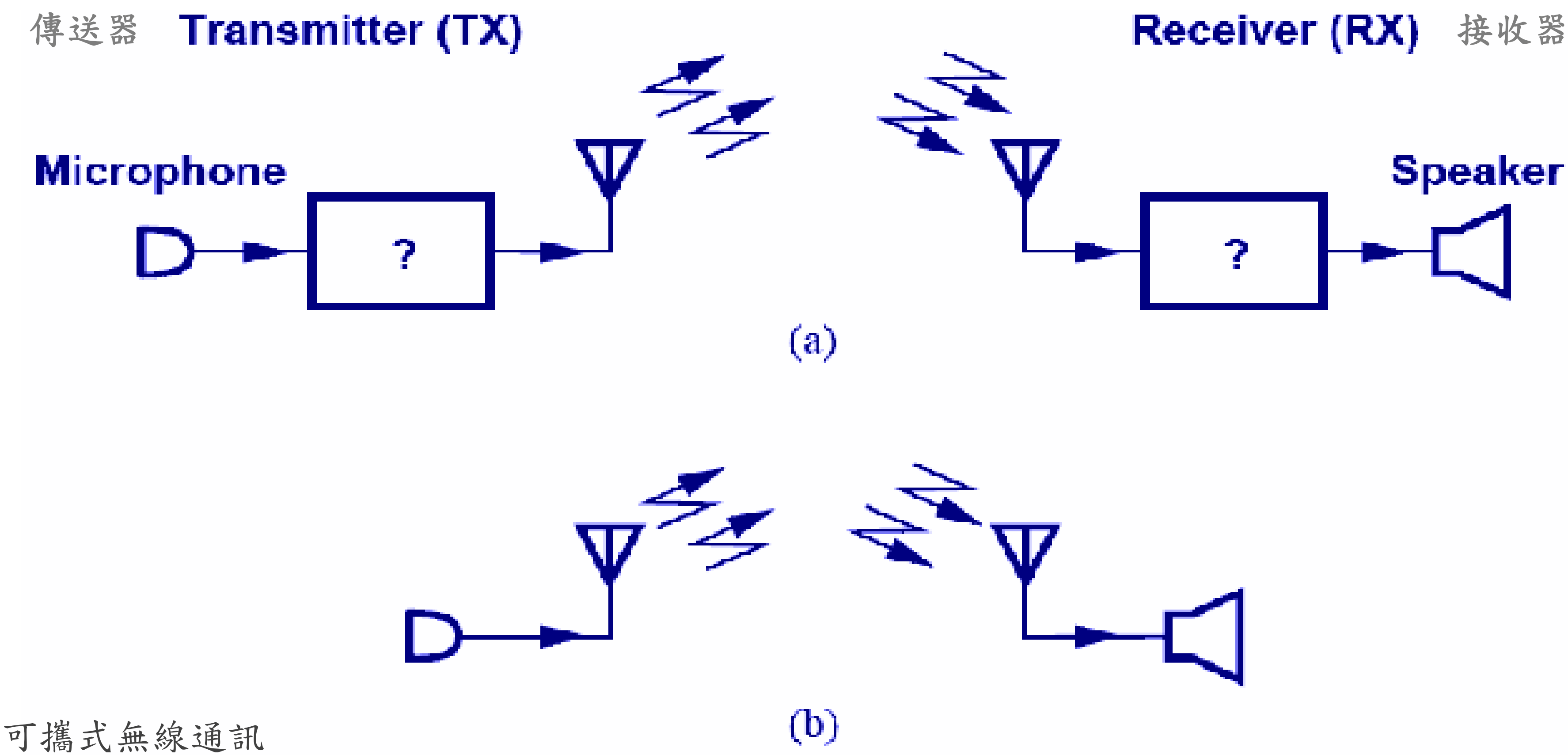
In addition to occupying a large volume, this discrete processor would be extremely *slow*; the signals would need to travel on wires as long as 1.4 m! Furthermore, if each discrete transistor costs 1 cent and weighs 1 g, each processor unit would be priced at one million dollars and weigh 100 tons!

Exercise: How much power would such a system consume if each transistor dissipates 10 μW?

microprocessor: 微處理器;
micron: 微米, $\mu = 10^{-6}$;
power: 功率;

million: 百萬, $M = 10^6$
wire: 連接線
discrete: 分立式, 個別

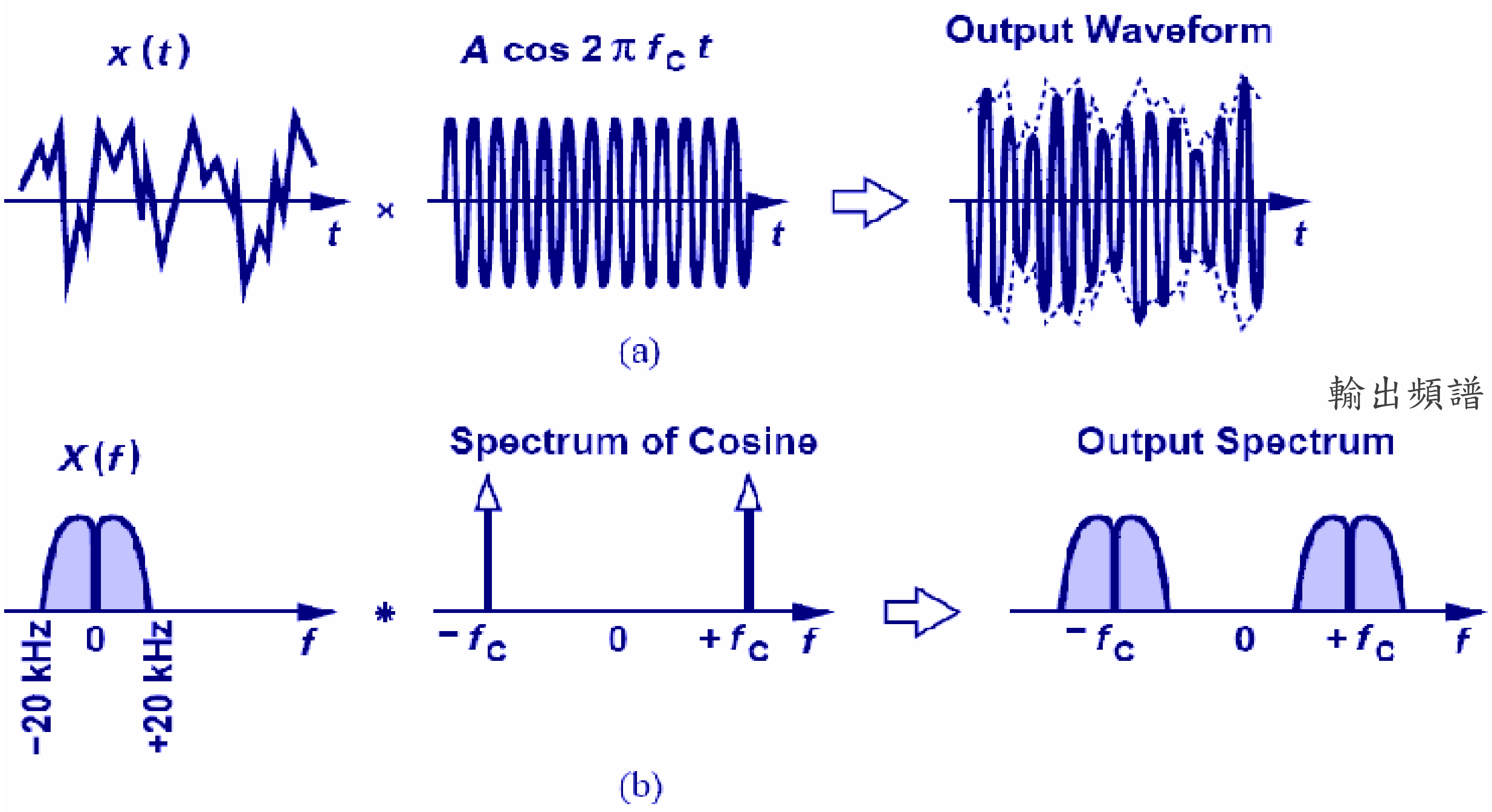
Cellular Technology



可攜式無線通訊

- Portable wireless communication: an important example of microelectronics.
- Microelectronics exist in black boxes that process the received and transmitted voice signals.

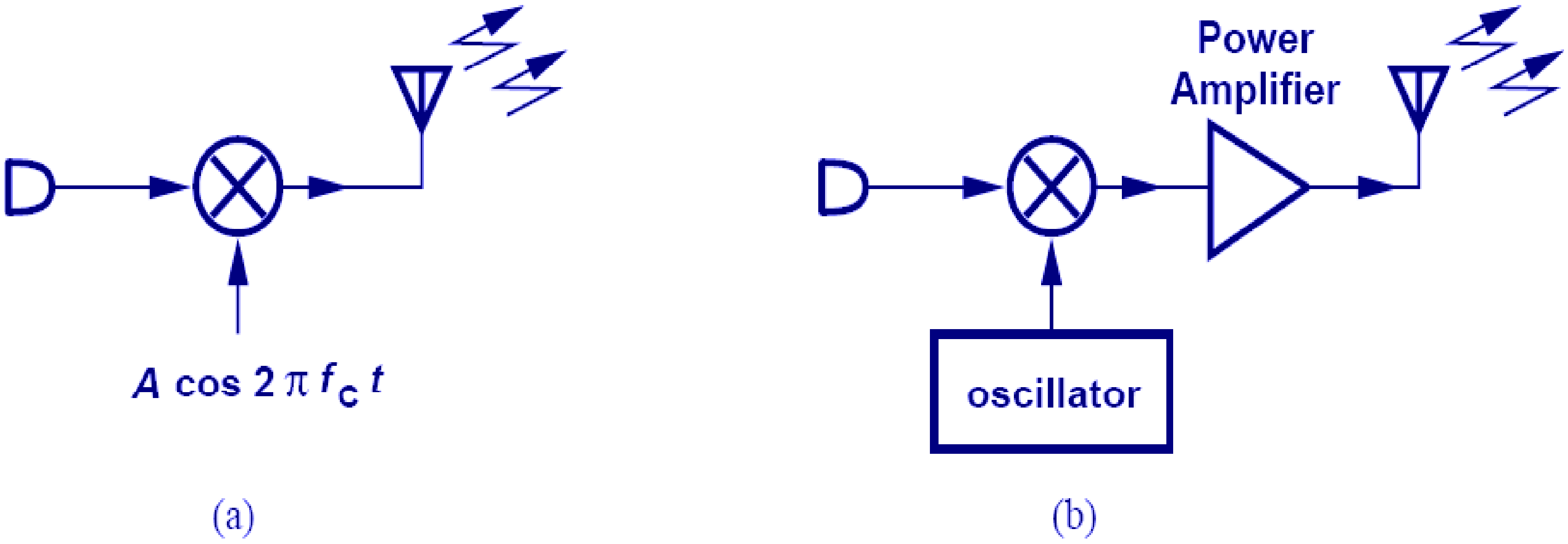
Frequency Up-conversion



- Voice is "up-converted" by multiplying two sinusoids.
- When multiplying two sinusoids in time domain, their spectra are convolved in *frequency domain*.

頻域

Transmitter

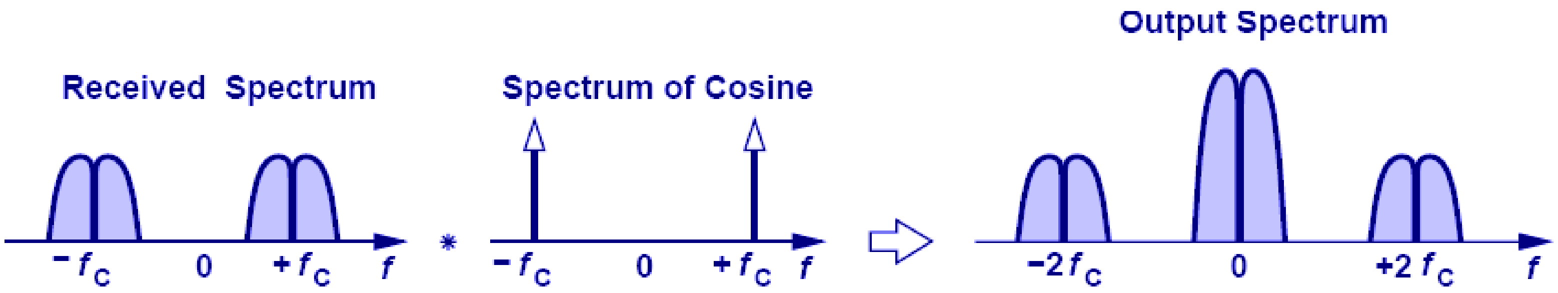


混頻器

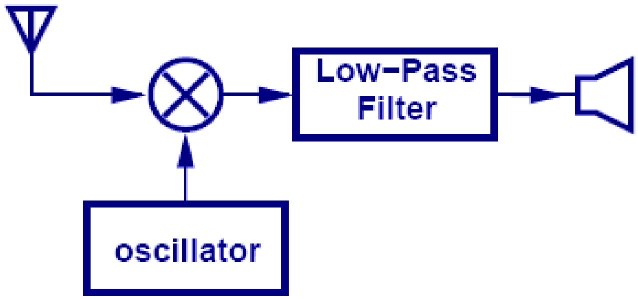
天線

- Two frequencies are multiplied by a ***mixer*** and radiated by an ***antenna*** in (a).
- ***Power amplifier*** is added in (b) to boost the signal. 功率放大器
- ***Oscillator*** generates the required high frequency sinusoid signal. 震盪器
- Higher frequency means smaller antenna size.

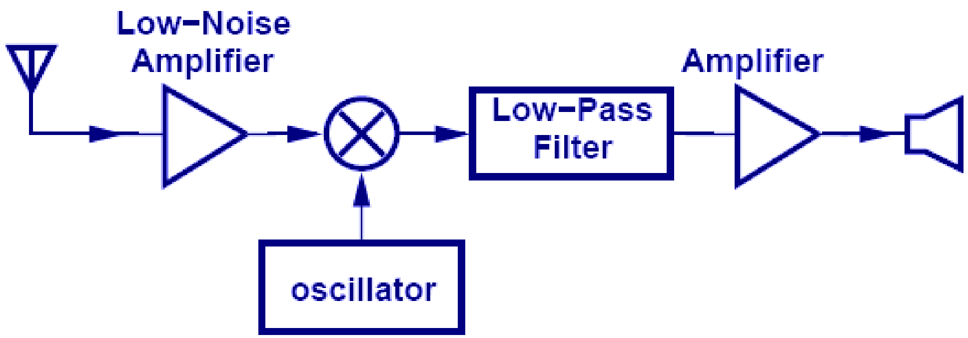
Receiver



(a)



(b)



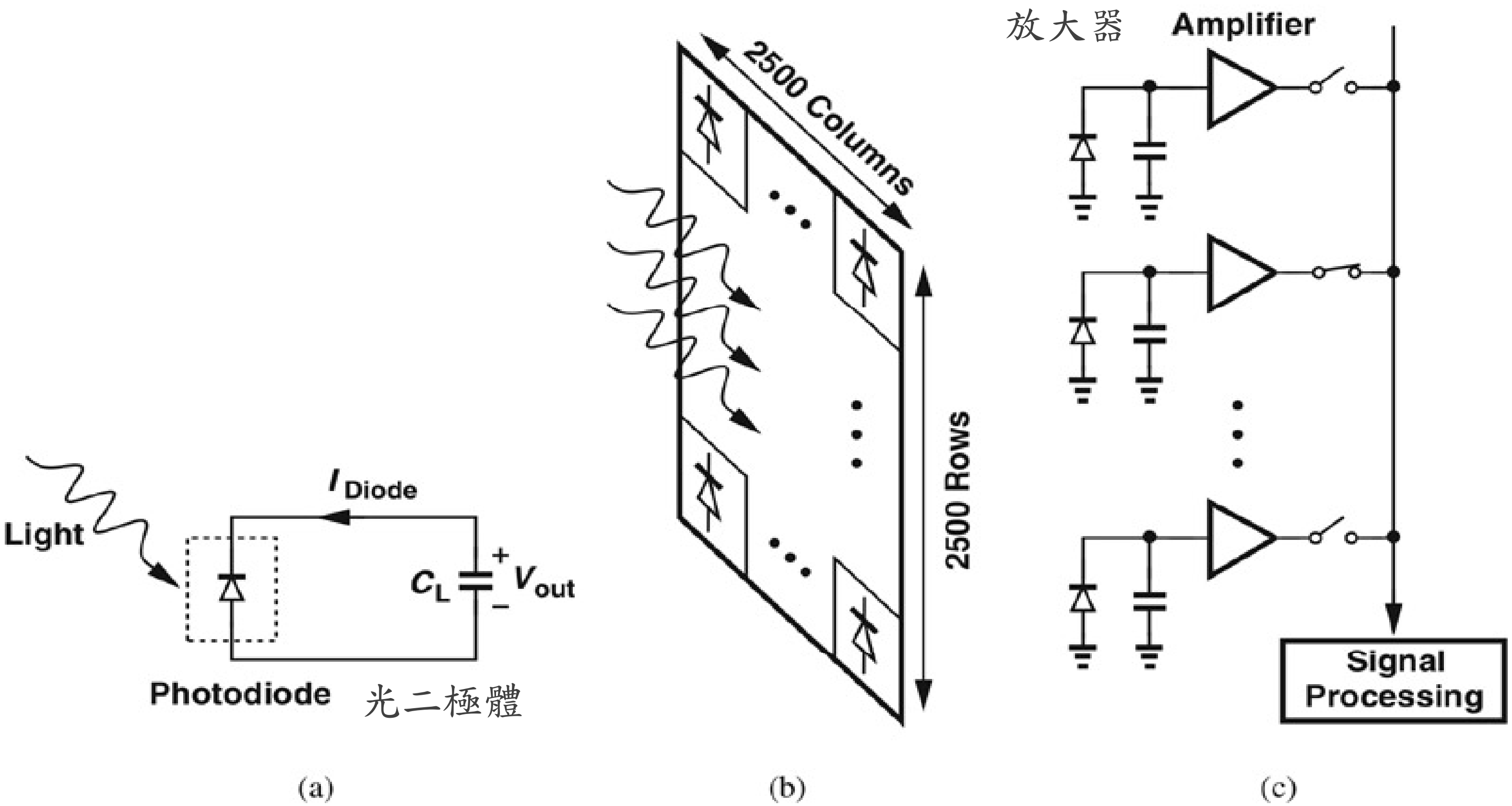
(c)

直流

- High frequency is translated to ***DC*** by multiplying by f_C. 低雜訊放大器
- ***Low-noise amplifier*** is needed for signal boosting without excessive noise.
- ***Low-pass filter*** can reject unwanted high frequency signals.

低通濾波器

Front-end of Digital Camera



- An array (matrix) of pixels with ***photodiode*** convert light to electricity.
- Each ***pixel*** produces a current proportional to the intensity of the received light, and then charges through a capacitance, for a certain period of time, developing a proportional voltage across it.

像素

訊號處理

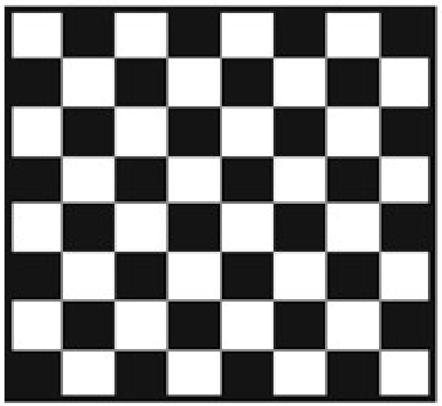
- The ***amplifier*** enlarge the voltage for subsequent ***signal processing***.

Example 1.2

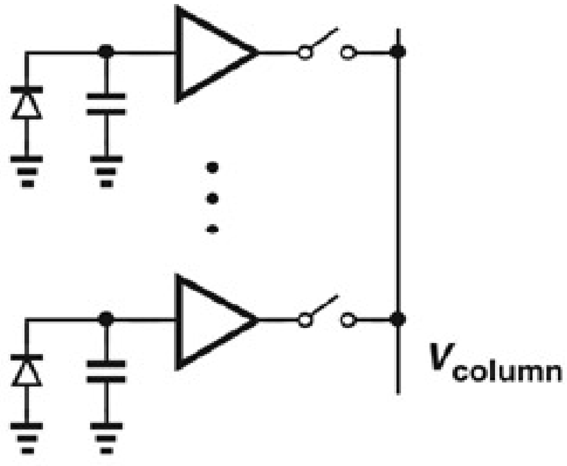
A digital camera is focused on a chess board. Sketch the voltage produced by one column as a function of time.

Solution

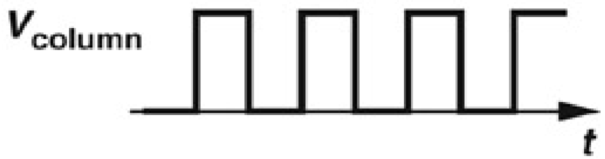
The pixels in each column receive light only from the white squares [Fig. (a)]. Thus, the column voltage alternates between a maximum for such pixels and zero for those receiving no light. The resulting waveform is shown in Fig. (c).



(a)



(b)

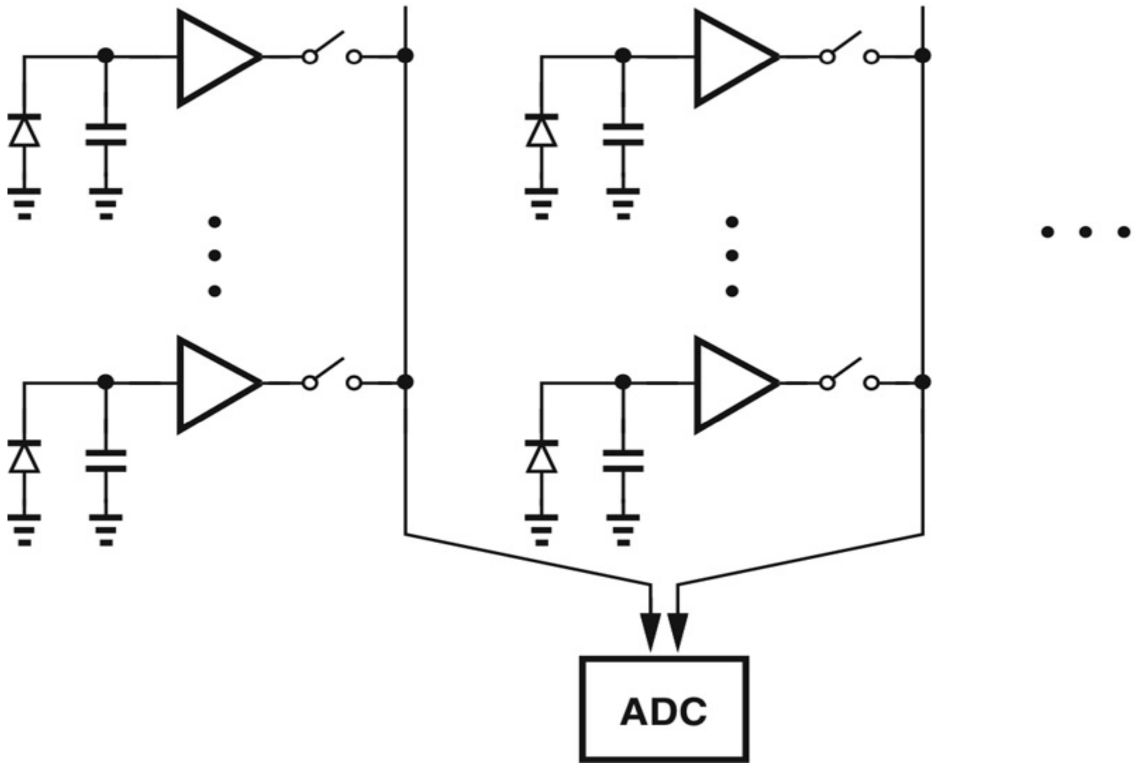


(c)

Different voltage level of V_{column} will be generated for grey pattern.

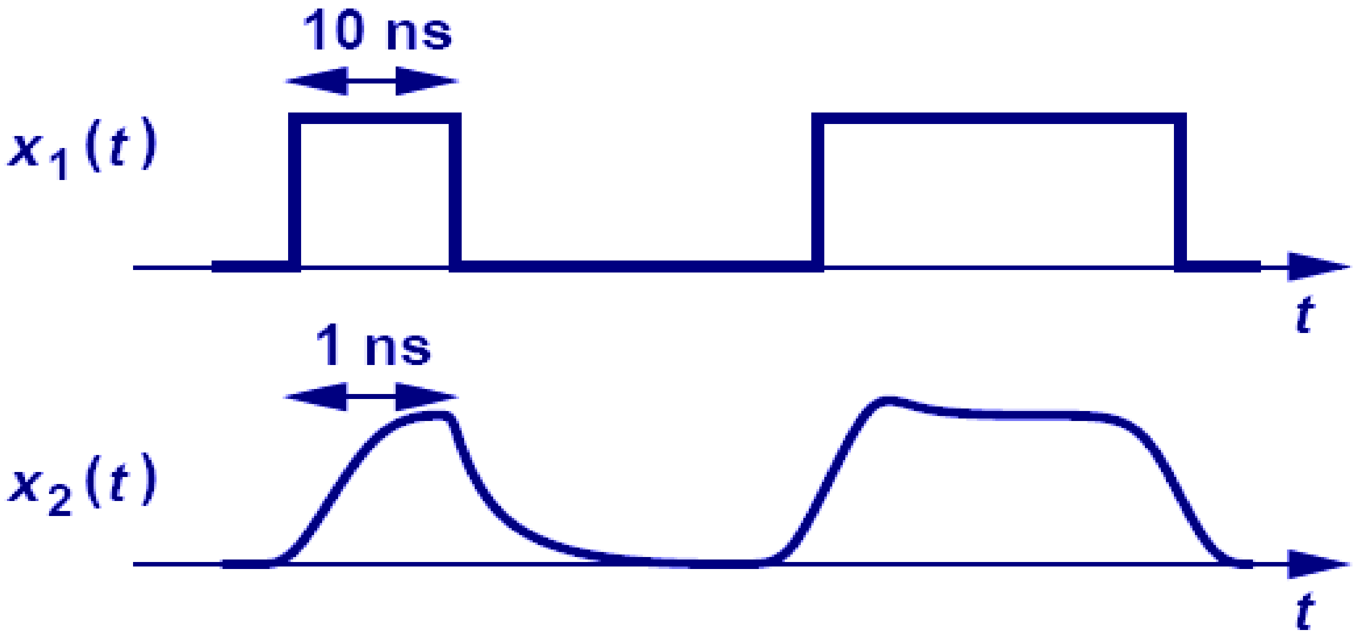
Analog-to-digital Converter

- The voltage produced by each pixel is an analog signal and can assume all values within a range, we must first "digitize" it by means of an "***analog-to-digital converter***" (***ADC***). 類比至數位轉換器



Sharing one ADC between two columns

Digital or Analog?



- $x_1(t)$ is operating at 100Mb/s and $x_2(t)$ is operating at 1Gb/s.
- A ***digital*** signal operating at very high frequency is very "***analog***".

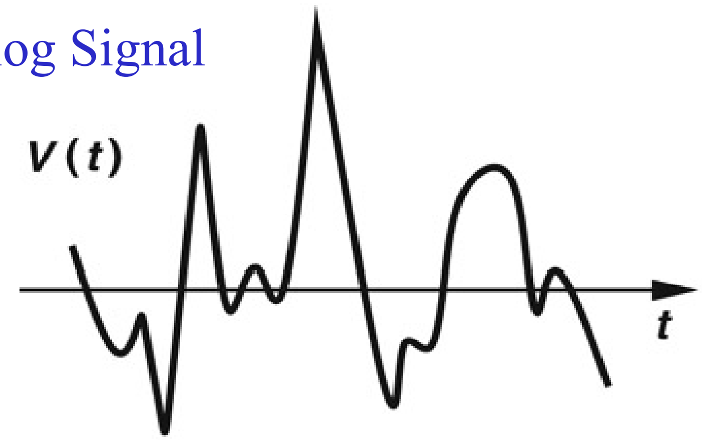
數位 類比

Analog: the signal magnitude can take on any value within limits and may vary continuously with time

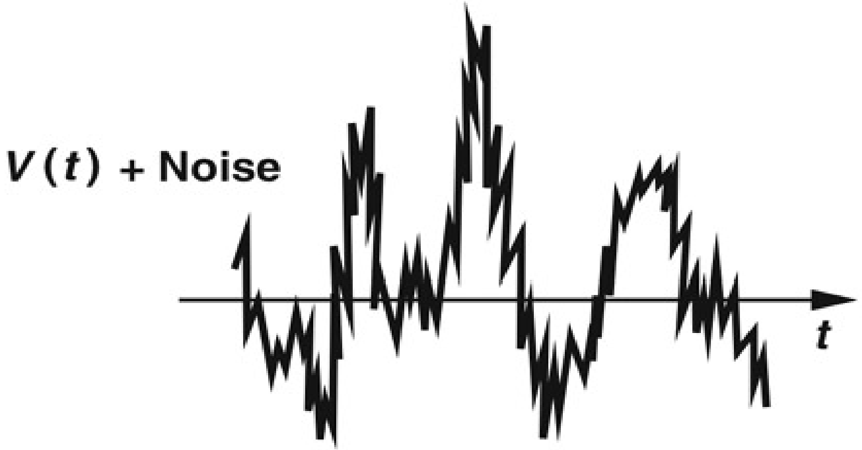
Digital: the signal magnitude has discrete values, generally two distinct levels (high and low)

Analog and Digital Signals

Analog Signal

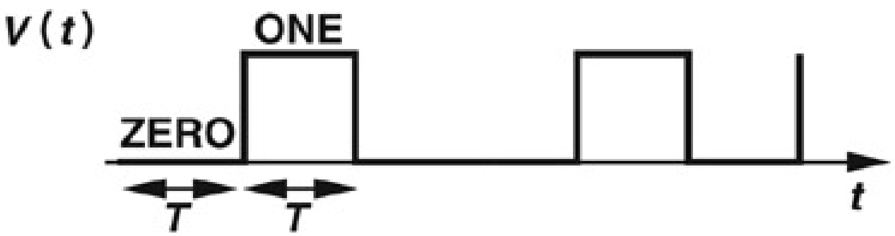


(a)

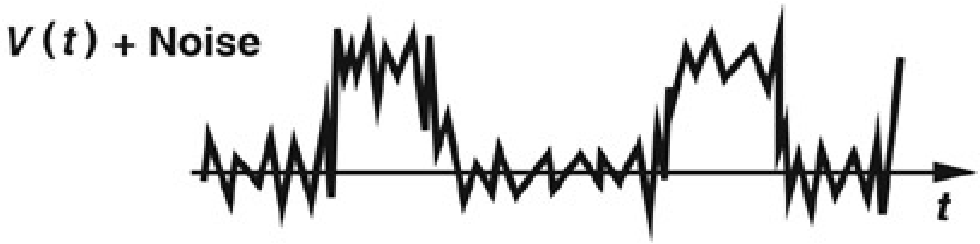


(b)

Digital Signal



(a)



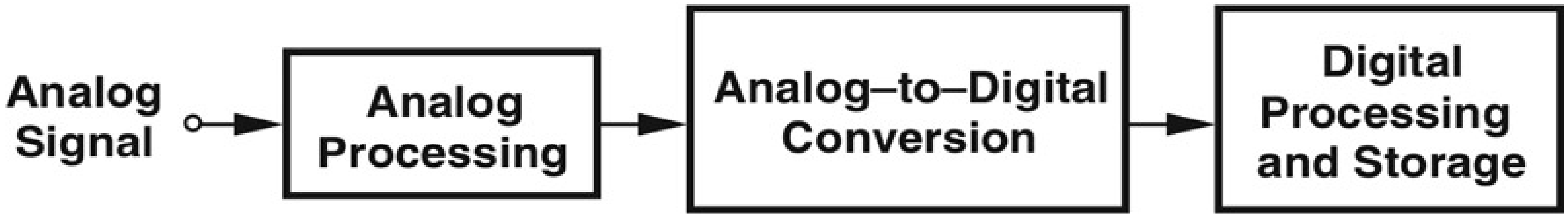
(b)

Noise (雜訊) is everywhere!

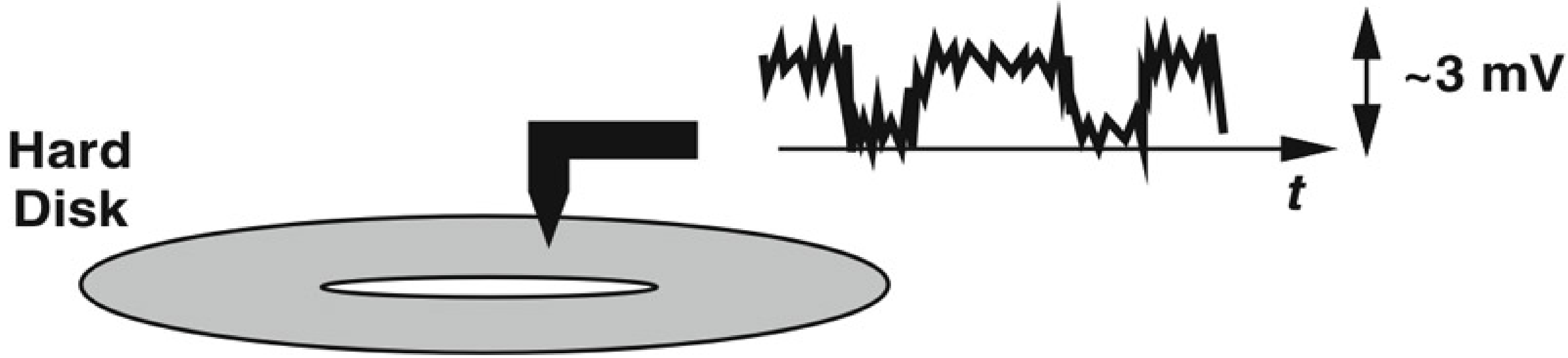
It can be reduced or filtered to a negligible level, if treated properly.

Typical Signal Processing

Processing of signals in the digital domain is favored



Digital signal picked up from a hard disk
must be viewed and processed as analog



Analog Circuits

- Microelectronic systems incorporate many analog functions, which often limit the performance of the overall system.
- The most commonly-used analog function is amplification, which is necessary to raise the signal swing to acceptable levels.
- The performance of an amplifier is characterized by a number of parameters, e.g., gain, speed, and power dissipation.
- The voltage ***gain*** is defined as

$$A_v = \frac{v_{out}}{v_{in}}.$$

signal swing: 訊號擺幅
performance: 性能
gain: 增益
decibel (dB): 分貝

- In some cases, we prefer to express the gain in decibels (dB)

$$A_v\,|_{dB} = 20\log\frac{v_{out}}{v_{in}}.$$

- For example, a voltage gain of 10 translates to 20 dB.
- The gain of typical amplifiers falls in the range of 10^1 to 10^5. (20 ~ 100 dB)

Example 1.3

A cellphone receives a signal level of 20μV, but it must deliver a swing of 50 mV to the speaker that reproduces the voice. Calculate the required voltage gain in decibels.

Solution

We have

$$A_v = 20\log\frac{50\text{mV}}{20\mu\text{V}}$$

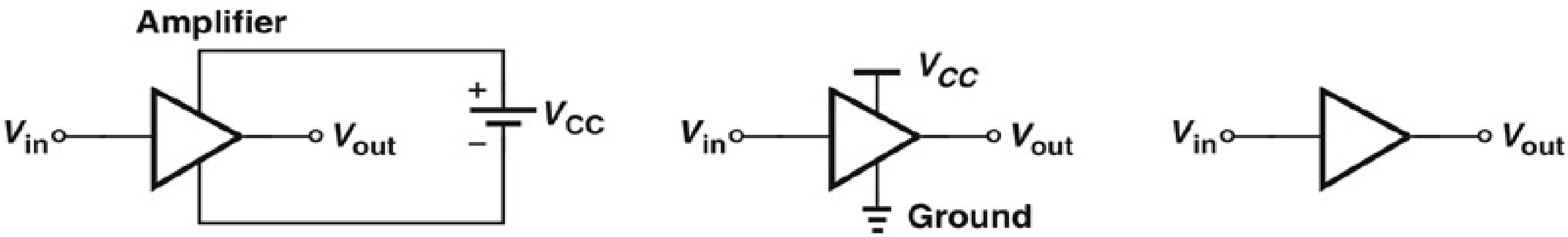
$$\approx 68\text{dB}.$$

Exercise: What is the output swing if the gain is 50 dB?

$$50 = 20\log\frac{V_{out}}{V_{in}} \qquad V_{out} = 10^{(50/20)}V_{in} = 316 \text{ x } 20\ \mu\text{V} = 6.32\text{ mV}$$

General Amplifier Symbol

- An amplifier must draw power from a voltage source, e.g., a battery or a charger, called the "***power supply***." 電源供應
- The notation can be simplify to that shown in Fig. (b), where the "***ground***" terminal signifies a reference point with zero potential. 接地
- The supply terminals can even be omitted [Fig. (c)].
- Typical supply voltages are in the range of 1 V to 10 V.

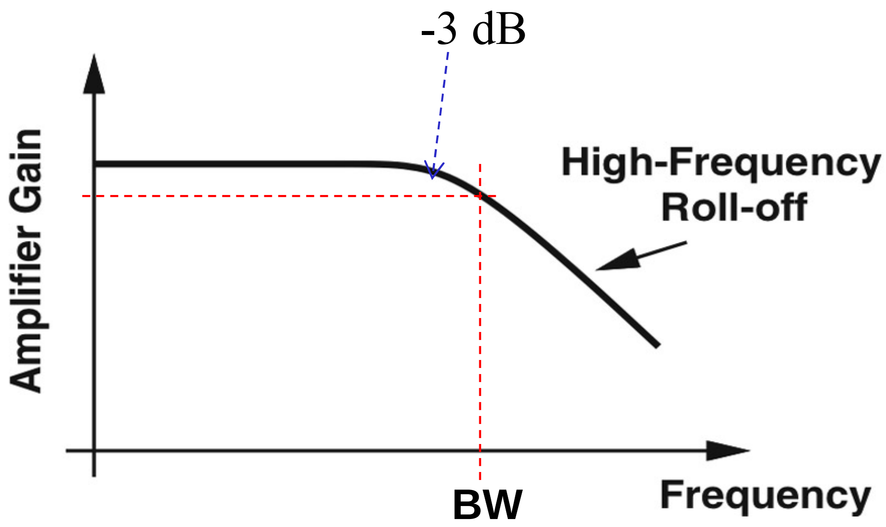


(a) (b) (c)

Energy is transferred in current flowing from high voltage to low voltage.
Current is a flow of charges.
Circuit must setup a current loop for proper operation.

Amplifier's Gain vs. Frequencies

- The *frequency response* of amplifiers.
- Capacitances in the circuit, manifested at high frequencies thereby lowering the gain, result the gain rolls off at high frequencies, limiting the (usable) "***bandwidth (BW)***" of the circuit.
- Amplifiers (and other analog circuits) suffer from trade-offs between gain, speed and power dissipation.
- Today's microelectronic amplifiers achieve bandwidths as large as tens of gigahertz.



frequency response: 頻率響應

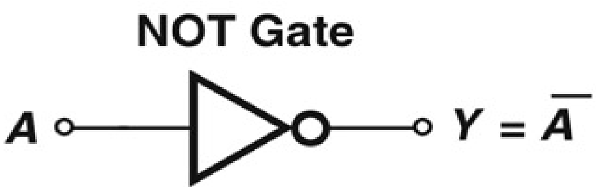
bandwidth: 頻寬

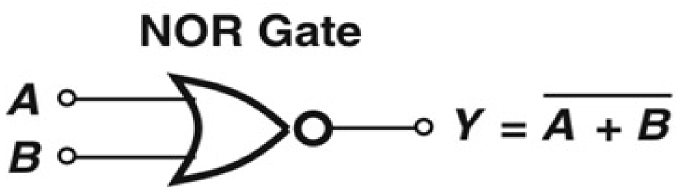
trade-off: 折衷, 取捨

giga-hertz (GHz): 10^9 Hz

Digital Circuits

- More than 80% of the microelectronics industry deals with digital circuits, including microprocessors (μP), static and dynamic memories (SRAM, DRAM), and digital signal processors (DSP).
- Basic logic gates form "combinational" circuits, and latches and flip-flops constitute "sequential" machines. They are AND, OR, INV (NOT), NAND, NOR, XOR, XNOR, DFF, SR-FF, … .
- The *complexity*, *speed*, and *power dissipation* of these building blocks play a central role in the overall system performance.





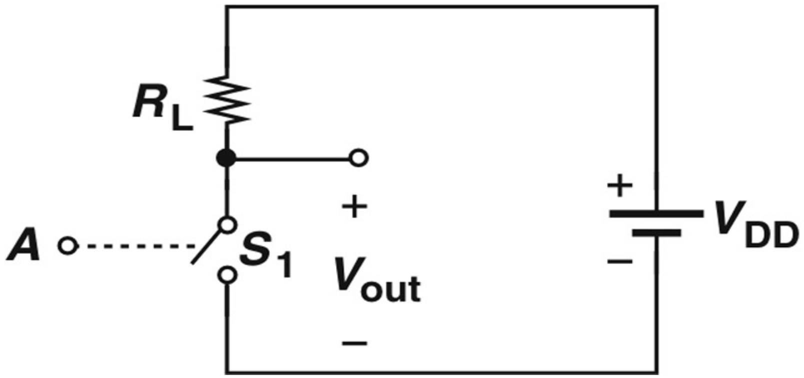
RAM (random access memory): 隨取記憶體

DSP: 數位訊號處理

complexity: 複雜度

Example 1.4

Consider the circuit shown in the Figure, where switch S_1 is controlled by the digital input. That is, if A is high, S_1 is on and vice versa. Prove that the circuit provides the NOT function.



switch: 開關

Solution

If A is high, S_1 is on, forcing to zero. On the other hand, if A is low, S_1 remains off, drawing no current from R_L. As a result, the voltage drop across R_L is zero and hence $V_{out} = V_{DD}$; i.e., the output is high. We thus observe that, for both logical states at the input, the output assumes the opposite state.

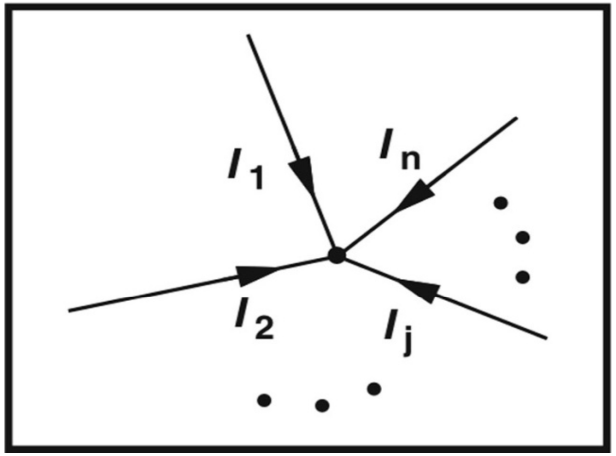
Exercise: Determine the logical function if S_1 and R_L are swapped and V_{out} is sensed across R_L.

Kirchoff Current Law (KCL)

- The sum of all currents flowing *into* a ***node*** is zero:

$$\sum_j I_j = 0.$$

- KCL in fact results from conservation of *charge*: a nonzero sum would mean that either some of the charge flowing into a node *vanishes* or this node *produces* charge.



KCL: 克西荷夫電流定律

KVL: 克西荷夫電壓定律

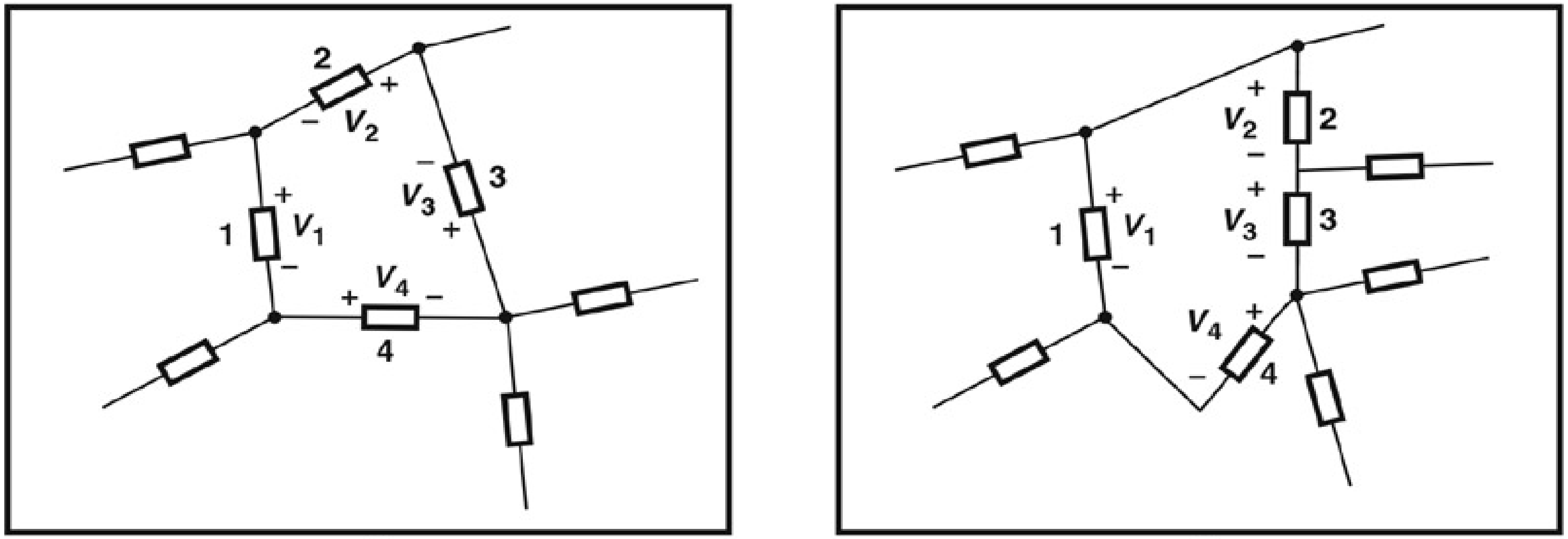
charge: 電荷

Kirchoff Voltage Law (KVL)

- The sum of voltage drops around any ***closed loop*** in a circuit is zero:

$$\sum_j V_j = 0,$$

- KVL arises from the conservation of the "*electromotive force*."
- In the example illustrated in Fig. (a), we may sum the voltages in the loop to zero: $V_1+V_2+V_3+V_4=0$.
- Alternatively, as shown in Fig. (b), we can say $V_1=V_2+V_3+V_4$.



(a) (b)

Example 1.5

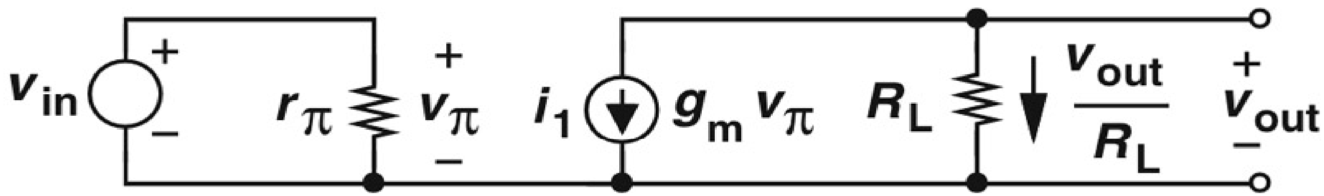
The topology depicted in the Fig. represents the equivalent circuit of an amplifier. The dependent current source i_1 is equal to a constant, g_m, multiplied by the voltage drop across r_π. Determine the voltage gain of the amplifier, v_{out}/v_{in}.

Solution

dependent: 相依;　independent: 獨立

We must compute v_{out} in terms of v_{in}, i.e., we must eliminate v_π from the equations. Writing a KVL in the "input loop," we have $v_{in} = v_\pi$, and hence $g_m v_\pi = g_m v_{in}$. A KCL at the output node yields

$$g_m v_\pi + \frac{v_{out}}{R_L} = 0.$$



It follows that

$$\frac{v_{out}}{v_{in}} = -g_m R_L.$$

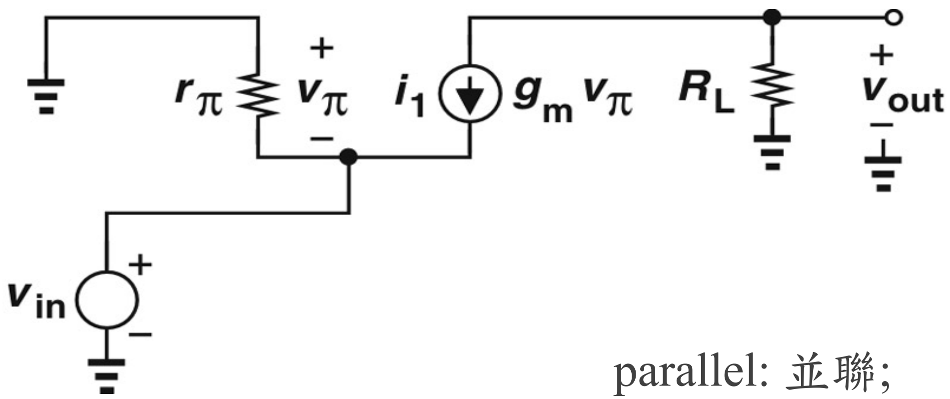
Note that the circuit amplifies the input if $g_m R_L > 1$. Unimportant in most cases, the negative sign simply means the circuit "*inverts*" the signal.

Exercise: Repeat the above example if $r_\pi \rightarrow \infty$.

invert: 反相

Example 1.6

The following figure shows another amplifier topology. Compute the gain.



Solution

parallel: 並聯; series: 串聯

Noting that r_π in fact appears in parallel with v_{in}, we write a KVL across these two components: $v_{in}= - v_\pi$. The KCL at the output node is similar to example 1.5. Thus,

$$\frac{v_{out}}{v_{in}} = g_m R_L .$$

Interestingly, this type of amplifier does not invert the signal.

Exercise: Repeat the above example if $r_\pi \rightarrow \infty$.

Example 1.7

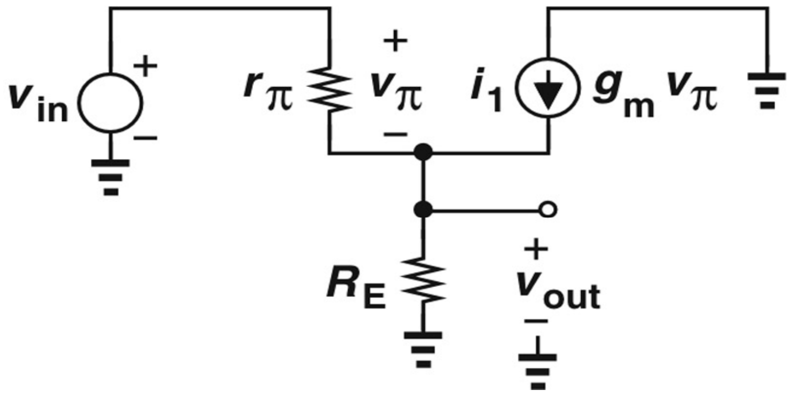
A third amplifier topology is shown in the Fig.. Determine the voltage gain.

Solution

We first write a KVL around the loop consisting of v_{in}, r_π, and R_E: $v_{in} = v_\pi + v_{out}$

That is, $v_\pi = v_{in} - v_{out}$. Next, noting that the currents v_π/r_π and $g_m v_\pi$ flow *into* the output node, and the current v_{out}/R_E flows *out* of it, we write a KCL:

$$\frac{v_\pi}{r_\pi} + g_m v_\pi = \frac{v_{out}}{R_E}.$$



Substituting $v_{in} - v_{out}$ for v_π gives

$$v_{in}\left(\frac{1}{r_\pi} + g_m\right) = v_{out}\left(\frac{1}{R_E} + \frac{1}{r_\pi} + g_m\right),$$

and hence

$$\frac{v_{out}}{v_{in}} = \frac{\dfrac{1}{r_\pi} + g_m}{\dfrac{1}{R_E} + \dfrac{1}{r_\pi} + g_m} = \frac{(1 + g_m r_\pi)R_E}{r_\pi + (1 + g_m r_\pi)R_E}.$$

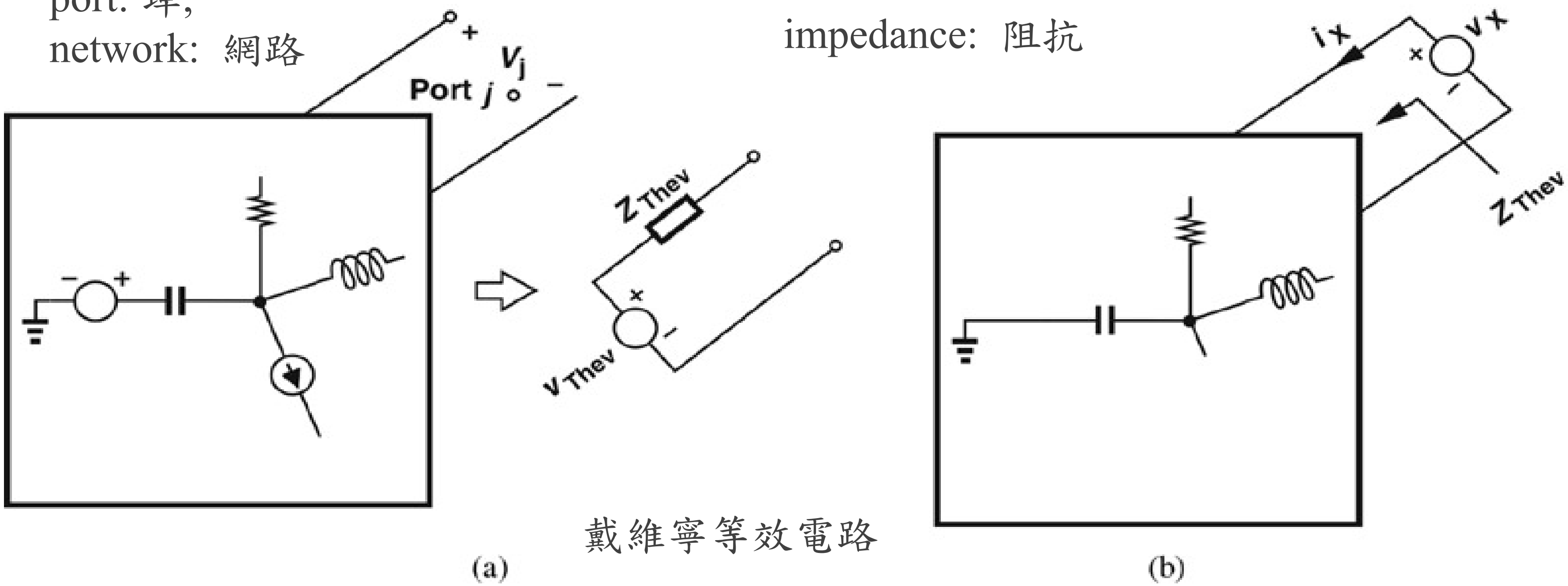
Note that the voltage gain always remains *below* unity. Would such an amplifier prove useful at all?

Thevenin Equivalent Circuit

- A (linear) one-*port network* can be replaced with an *equivalent* circuit consisting of one voltage source in series with one impedance.
- The equivalent voltage, V_{Thev}, is obtained by leaving the port *open* and computing the voltage created by the actual circuit at this port.
- The equivalent *impedance*, Z_{Thev}, is determined by setting all independent voltage and current sources in the circuit to zero and calculating the impedance between the two nodes.

port: 埠;
network: 網路

equivalent: 等效
impedance: 阻抗



戴維寧等效電路

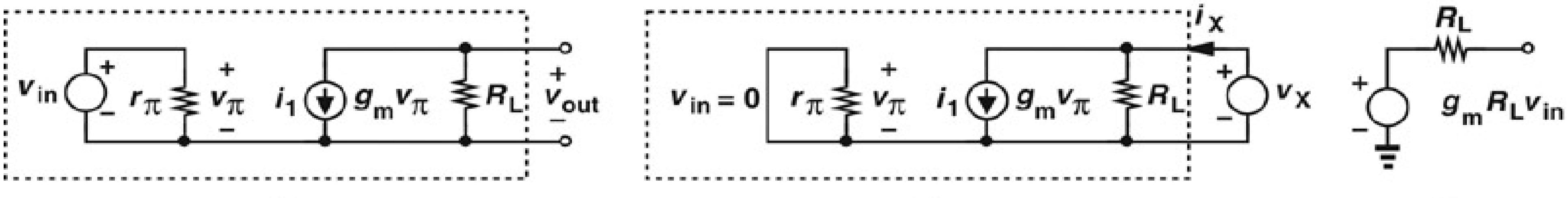
Example 1.8

Suppose the input voltage source and the amplifier shown in Example 1.5 are placed in a box and only the output port is of interest [Fig. (a)]. Determine the Thevenin equivalent of the circuit.

Solution

We must compute the *open-circuit* output voltage and the impedance seen when looking into the output port. The Thevenin voltage is obtained from Fig. (a) and

$$v_{Thev} = v_{out} = -g_m R_L v_{in}.$$



(a) (b) (c)

To calculate Z_{Thev}, we set v_{in} to zero, apply a voltage source, v_x, across the output port, and determine the current drawn from the voltage source, i_x. As shown in Fig. (b), setting v_{in} to zero means replacing it with a *short circuit*. Also, note that the current source $g_m v_\pi$ remains in the circuit because it depends on the voltage across r_π, whose value is not known a priori.

open circuit: 開路, 斷路; short circuit: 短路, 通路

Example 1.8 [cnt'd]

How do we solve the circuit of Fig. (b)? We must again eliminate v_π. Fortunately, since both terminals of r_π are tied to ground, $v_\pi = 0$ and $g_m v_\pi = 0$. The circuit thus reduces to R_L and

$$i_X = \frac{v_X}{R_L}.$$

That is,

$$R_{Thev} = R_L.$$

Figure (c) depicts the Thevenin equivalent of the input voltage source and the amplifier. In this case, we call R_{Thev} ($=R_L$) the "output impedance" of the circuit.

Exercise: Repeat the above example if $r_\pi \rightarrow \infty$.

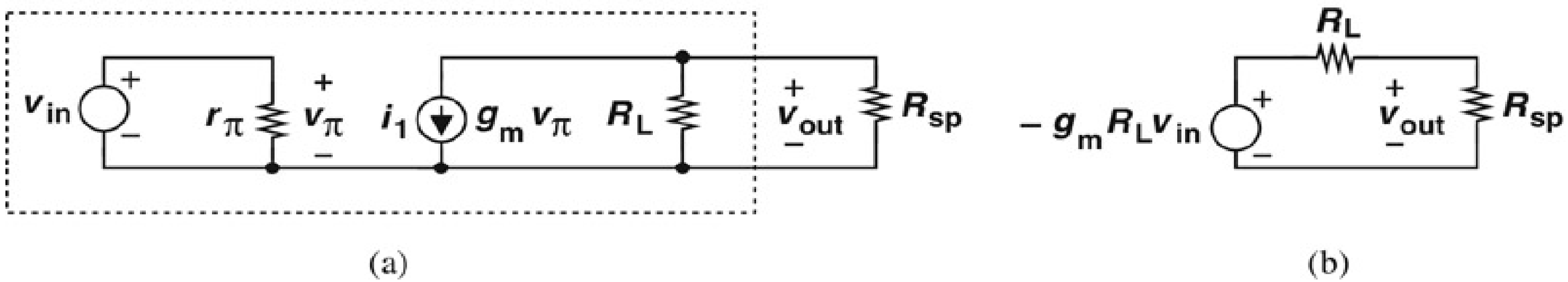
Example 1.9

The amplifier of Example 1.5 must drive a speaker having an impedance of R_{sp}. Determine the voltage delivered to the speaker.

Solution

Shown in Fig. (a) is the overall circuit arrangement that must solve. Replacing the section in the dashed box with its Thevenin equivalent from Fig. (c) in Example 1.8, we greatly simplify the circuit [Fig. (b)], and write

$$v_{out} = -g_m R_L v_{in} \frac{R_{sp}}{R_{sp} + R_L} = -g_m v_{in} (R_L \parallel R_{sp}).$$

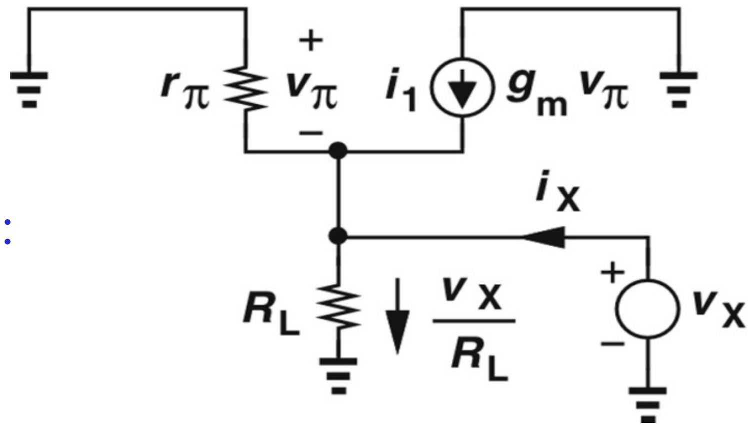


Exercise: Repeat the above example if $r_\pi \rightarrow \infty$.

Example 1.10

Determine the Thevenin equivalent of the circuit shown in Example 1.7 if the output port is of interest.

Solution



The open-circuit output voltage is simply obtained from:

$$v_{Thev} = \frac{(1+g_m r_\pi)R_L}{r_\pi + (1+g_m r_\pi)R_L} v_{in}.$$

To calculate the Thevenin impedance, we set v_{in} to zero and apply a voltage source across the output port as depicted in the Fig. To eliminate v_π, we recognize that the two terminals of r_π are tied to those of v_x and hence $v_\pi = - v_x$

Example 1.10 [cnt'd]

We now write a KCL at the output node. The currents v_π/r_π, $g_m v_\pi$, and i_x flow *into* this node and the current v_x/R_L, flows out of it. Consequently,

$$\frac{v_\pi}{r_\pi} + g_m v_\pi + i_X = \frac{v_X}{R_L},$$

or

$$\left(\frac{1}{r_\pi} + g_m\right)(-v_X) + i_X = \frac{v_X}{R_L}.$$

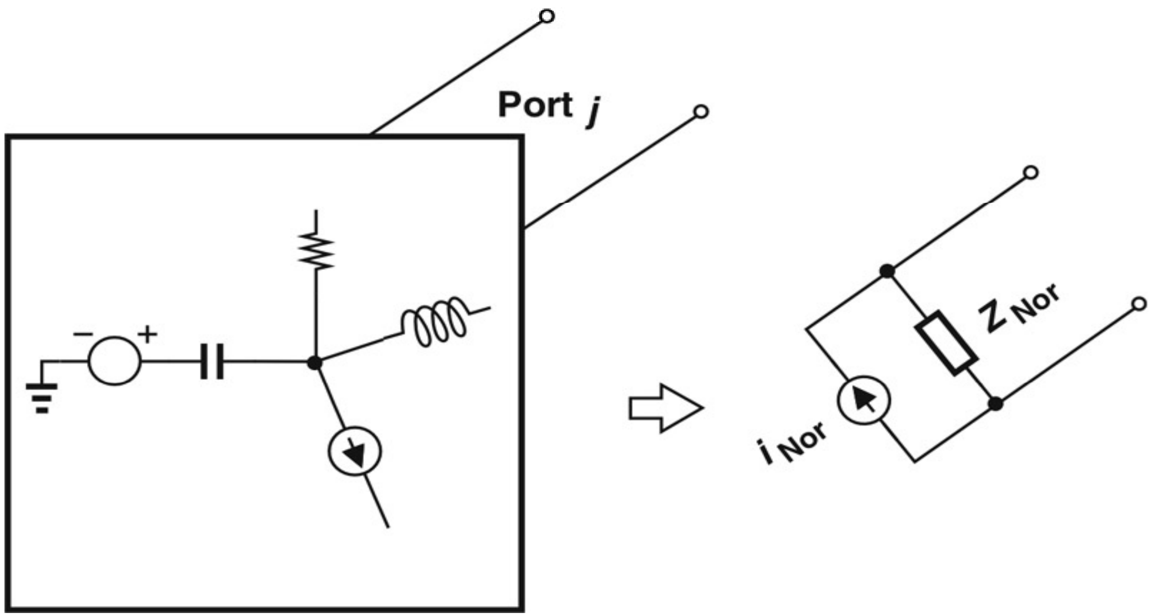
That is,

$$R_{Thev} = \frac{v_X}{i_X} = \frac{r_\pi R_L}{r_\pi + (1 + g_m r_\pi) R_L}.$$

Exercise What happens if $R_L = \infty$?

Norton's Theorem

- A (linear) one-port network can be represented by one current source, i_{Nor}, in parallel with one impedance, Z_{Nor}.
- i_{Nor} is obtained by shorting the port of interest and computing the current that flows through it.
- Z_{Nor} is determined by setting all independent voltage and current sources in the circuit to zero and calculating the impedance seen at the port.
- Of course, $Z_{Nor} = Z_{Thev}$



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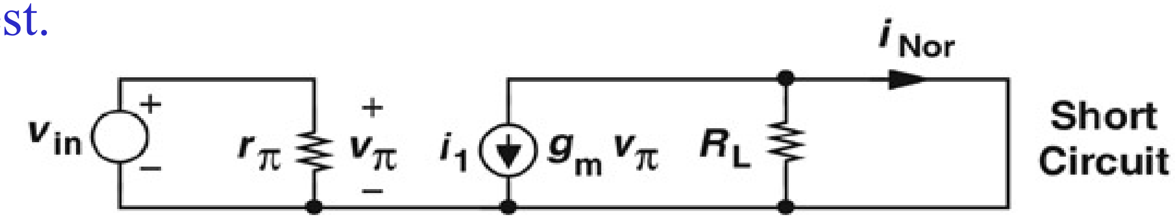
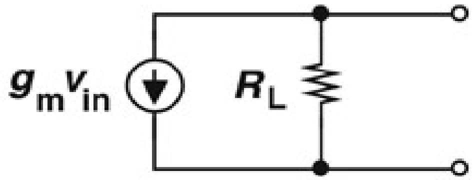
Example 1.11

Determine the Norton equivalent of the circuit shown in Example 1.7 if the output port is of interest.



(a)



(b)

Solution

As depicted in Fig. (a), we short the output port and seek the value of i_{Nor}. Since the voltage across R_L is now forced to zero, this resistor carries no current. A KCL at the output node thus yields

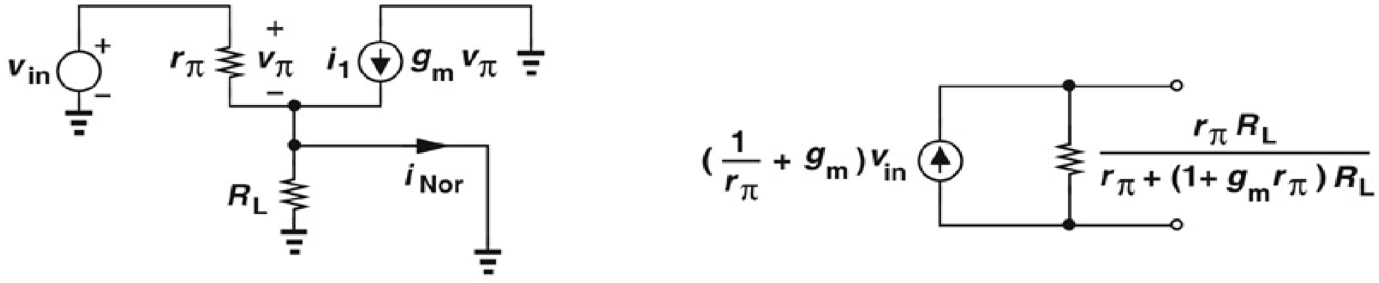
$$i_{\text{Nor}} = -g_m v_\pi = -g_m v_{in}.$$

Also, from Example 1.8, R_{Nor} (= R_{Thev}) = R_L. The Norton equivalent therefore emerges as shown in Fig. (b). To check the validity of this model, we observe that the flow of i_{Nor} through R_L produces a voltage of $-g_m R_L v_{in}$, the same as the output voltage of the original circuit.

Exercise Repeat the above example if a resistor of value R_1 is added between the top terminal of v_{in} and the output node.

Example 1.12

Determine the Norton equivalent of the circuit shown in Example 1.7 if the output port is interest.



(a) (b)

Solution

Shorting the output port as illustrated in Fig. (a), we note that R_L carries no current. Thus,

$$i_{\mathrm{Nor}} = \frac{v_\pi}{r_\pi} + g_m v_\pi .$$

Also, $v_{in} = v_\pi$ (why?), yielding

$$i_{\mathrm{Nor}} = \left(\frac{1}{r_\pi} + g_m\right) v_{in} .$$

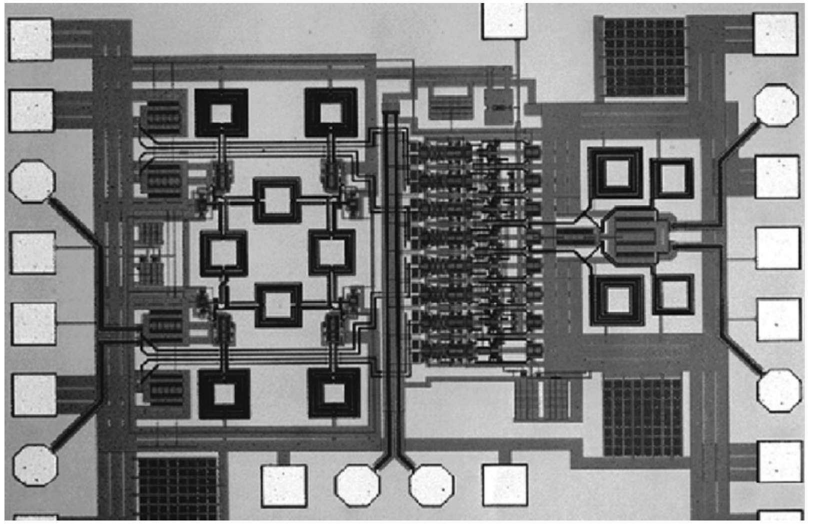
With the aid of found in Example 1.8, we construct the Norton equivalent depicted in Fig. (b).

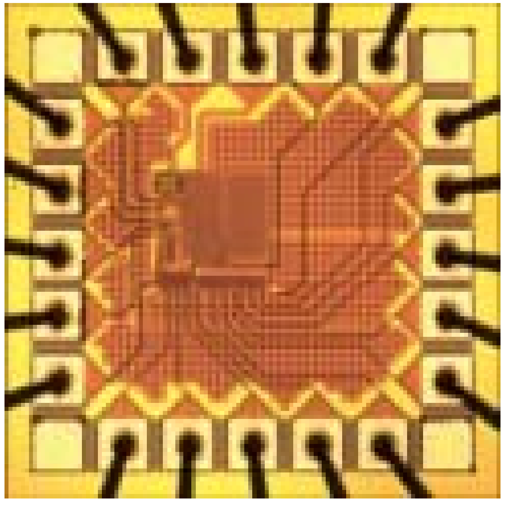
Exercise What happens if $r_\pi = \infty$?

Chapter Summary

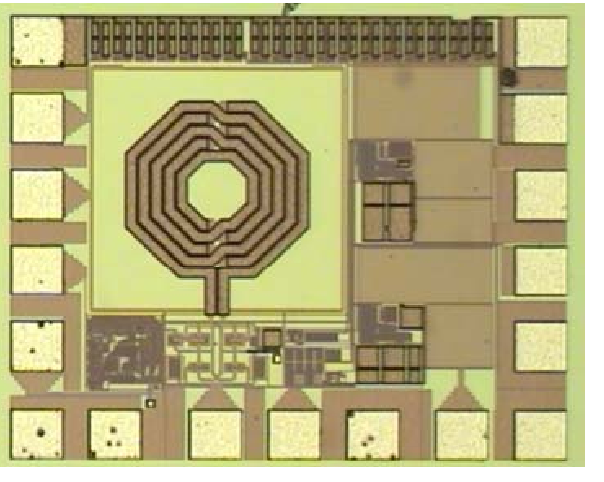
- Electronic functions appear in many devices, including cellphones, digital cameras, laptop computers, etc.
- Amplification is an essential operation in many analog and digital systems.
- Analog circuits process signals that can assume various values at any time. By contrast, digital circuits deal with signals having only two levels and switching between these values at known points in time.
- Despite the “digital revolution,” analog circuits find wide application in most of today’s electronic systems.
- The voltage gain of an amplifier is defined as v_{out}/v_{in} and sometimes expressed in decibels (dB) as $20\log(v_{out}/v_{in})$.
- Kirchoff’s current law (KCL) states that the sum of all currents flowing into any node is zero. Kirchoff’s voltage law (KVL) states that the sum of all voltages around any loop is zero.
- Norton’s theorem allows simplifying a one-port circuit to a current source in parallel with an impedance. Similarly, Thevenin’s theorem reduces a one-port circuit to a voltage source in series with an impedance.

Micro-chip Photo





10-bit ADC



2.45 GHz RFID Tag