電子學一

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September 23, 2021

Course Outline

- Microelectronic Circuits

  Part 1: Devices and Basic Circuits (Chapter 1~6)

  1. Signals, Amplifiers, and Semiconductors
  2. Operational Amplifiers
  3. Diodes
  4. Bipolar Junction Transistors (BJTs)
  5. MOS Field-Effect Transistors (MOSFETs)
  6. Transistor Amplifiers

  Part 2: Analog Integrated Circuits (Chapter 7~13)

  7. Building Blocks of Integrated Circuit Amplifiers

- Handwriting on blackboard for later lectures.

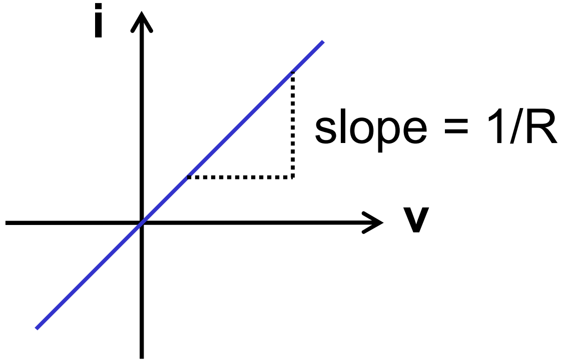
Week 1: Introduction

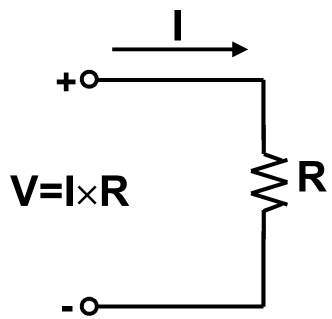
- Review
- Chapter1: Signals, Amplifiers, and Semiconductors
  - learn basic concepts and terminology
    - Signals
    - Frequency spectrum of signals
    - Analog and digital signals
    - Amplifiers
    - Circuit models for amplifiers
    - Frequency response of amplifiers
    - 1.7 ~ 1.12 (Semiconductor, pn junction); move to later part

Basic Device - Resistor

- For a linear resistor:
  - $V = I \times R$ (Ohm's Law)
  - R: resistance, unit: ohm (Ω)
- Conductance (G)
  - $G = 1/R$, unit: mho, siemen (Ω^{-1}, S)
- Power dissipation:
  - $P = V \times I = I^2 \times R = V^2/R$
  - Power consumed by a resistor is dissipated in the form of heat (ohmic heating)
  - e.g. toaster, fuse

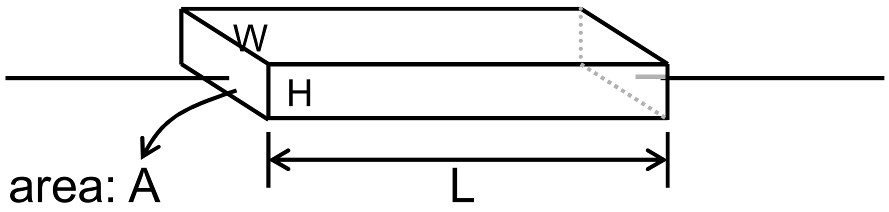
I-V curve of a device





Resistivity

- Resistivity (ρ) is a material property

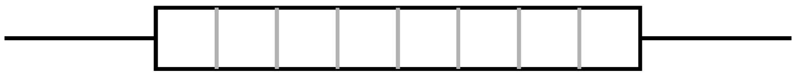


Rubber (insulator) $\rho = 10^{12}$
Silicon (semiconductor) $\rho = 2300$
Copper (conductor) $\rho = 1.7 \times 10^{-8}$
Aluminum (conductor) $\rho = 2.8 \times 10^{-8}$

$$R = \rho \frac{L}{A}$$

- Sheet resistance ($R_\square$)

$$R = \rho \frac{L}{WH} = \frac{\rho}{H}\frac{L}{W} = R_\square \times (number\ of\ squares); \quad R_\square = \frac{\rho}{H}$$



- Sheet resistance and resistivity are important parameters in integrated circuit (IC) designs.
- Resistance varied with temperature (temperature dependent)

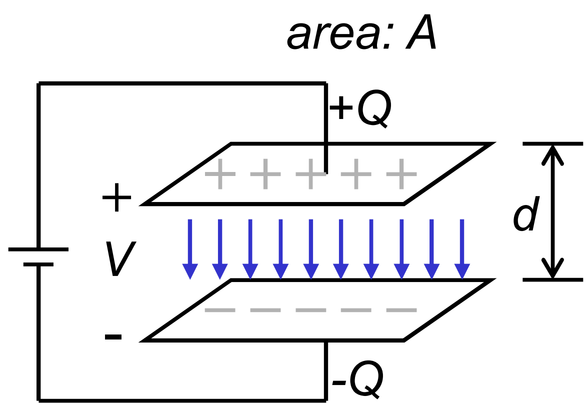
Capacitor

- Passive elements: R, C, L
  - R: dissipate energy
  - C and L: store energy
- A capacitor consists of 2 conducting plates separated by an insulator (dielectric).
- For a linear capacitor:

$$C = \frac{Q}{V}$$

$$i = \frac{dQ}{dt} = \frac{d(CV)}{dt} = C\frac{dV}{dt}$$

$$v(t) = \frac{1}{C}\int_{t_0}^{t} i\,dt + v(t_0)$$



$$C = \varepsilon\frac{A}{d}$$

$\varepsilon = \varepsilon_0\ \varepsilon_r$

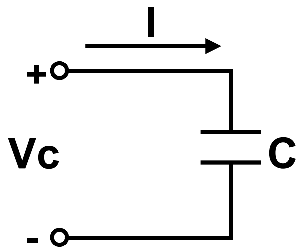
ε_0: free space permittivity
8.854×10^{-12} F/m

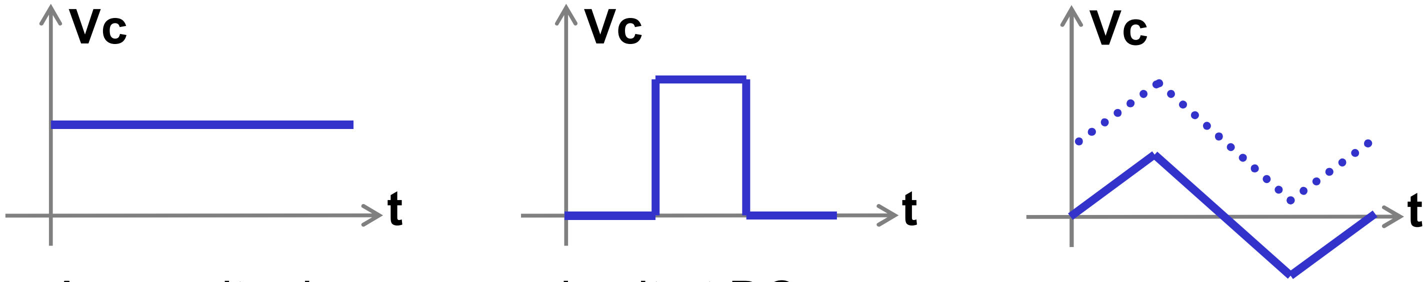
ε_r: relative permittivity
(dielectric constant)

Capacitor

- Three cases:

$$i = C\frac{dV}{dt}$$





- A capacitor is an open circuit at DC.
- The voltage on a capacitor must be continuous.

- Power delivered to a capacitor:

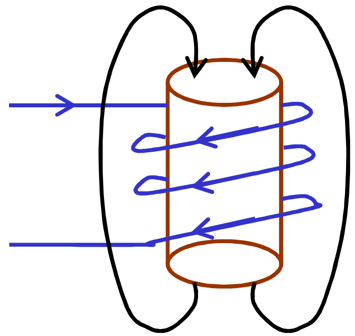
$$P = vi = vC\frac{dv}{dt} \Rightarrow Pdt = Cvdv \Rightarrow W = \int Pdt = \int Cvdv$$

$$W = \frac{1}{2}Cv^2 = \frac{1}{2}\frac{Q^2}{C}$$ (the energy stored in a capacitor)

Inductor

- Capacitors store energy in an electric field, while inductors store energy in a magnetic field.
- Magnetic field is induced by passing current through a coil of wire.
- Faraday's Law: time-varying current induces a voltage in the coil

$$v = L\frac{di}{dt} \qquad (i = C\frac{dv}{dt})$$



- An inductor is a short circuit at DC.
- The current through an inductor must be continuous.

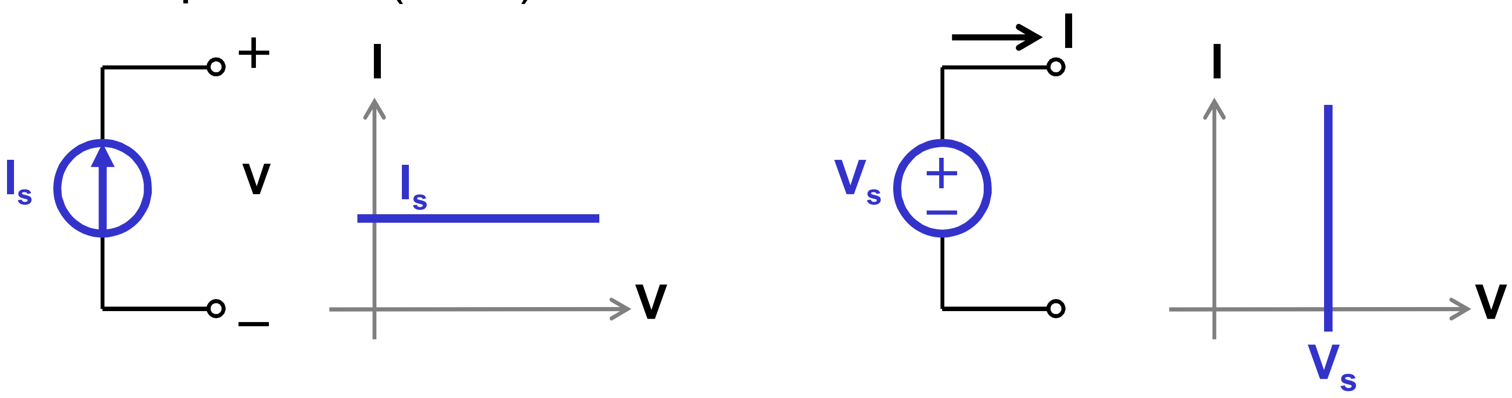
- Power delivered to an inductor:

$$P = vi = L\frac{di}{dt}i \Rightarrow Pdt = Lidi \Rightarrow W = \int Pdt = \int Lidi$$

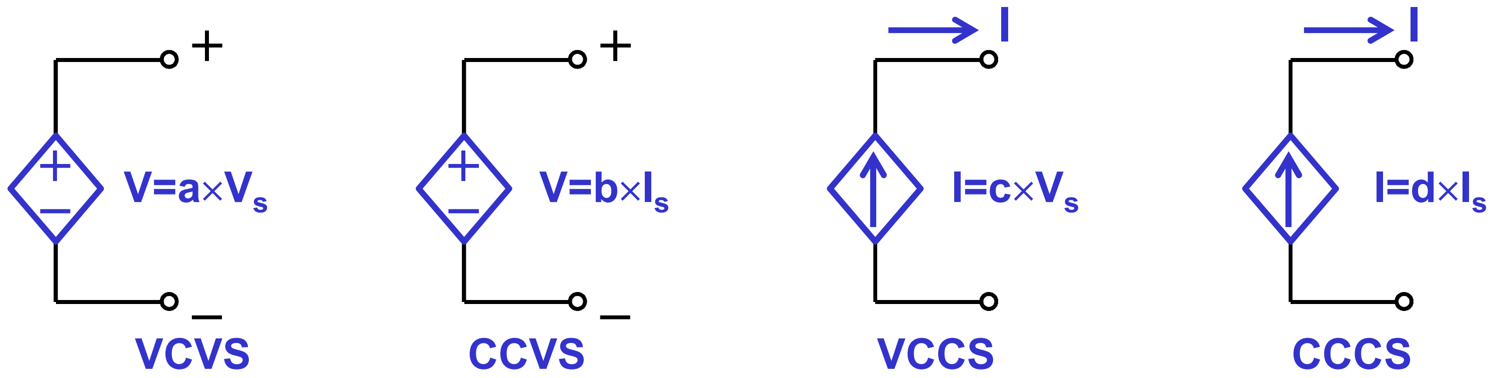
$$W = \frac{1}{2}Li^2$$ (the energy stored in an inductor)

Sources

- Independent (ideal) sources



- Dependent (controlled) sources

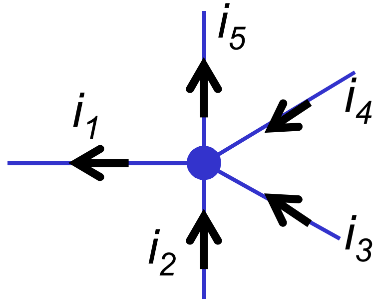


(voltage-controlled voltage source)

(current-controlled current source)

KCL & KVL

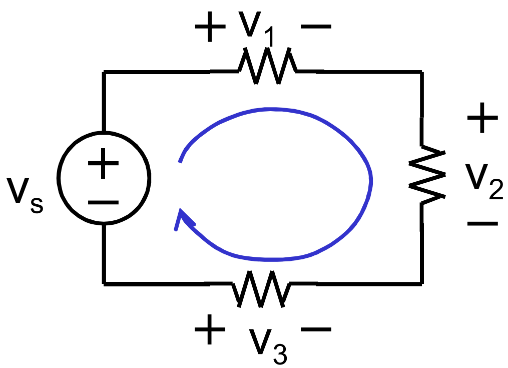
- Kirchhoff's Current Law (KCL): the sum of all currents at a circuit node is zero.



$(-i_1)+i_2+i_3+i_4+(-i_5)=0$

$\sum(i_n) = 0$

- Kirchhoff's Voltage Law (KVL): the sum of all voltages around a closed path (loop) is zero.



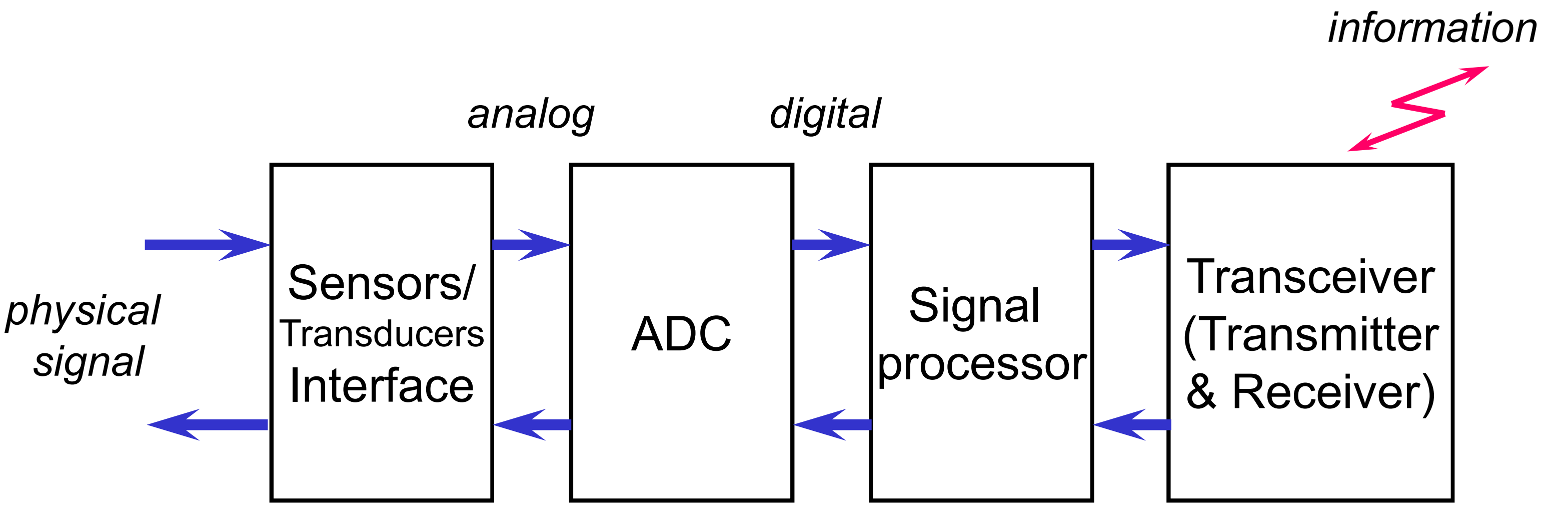
$v_s+(-v_1)+(-v_2)+v_3=0$

$\sum(v_n) = 0$

- Conservation of energy!

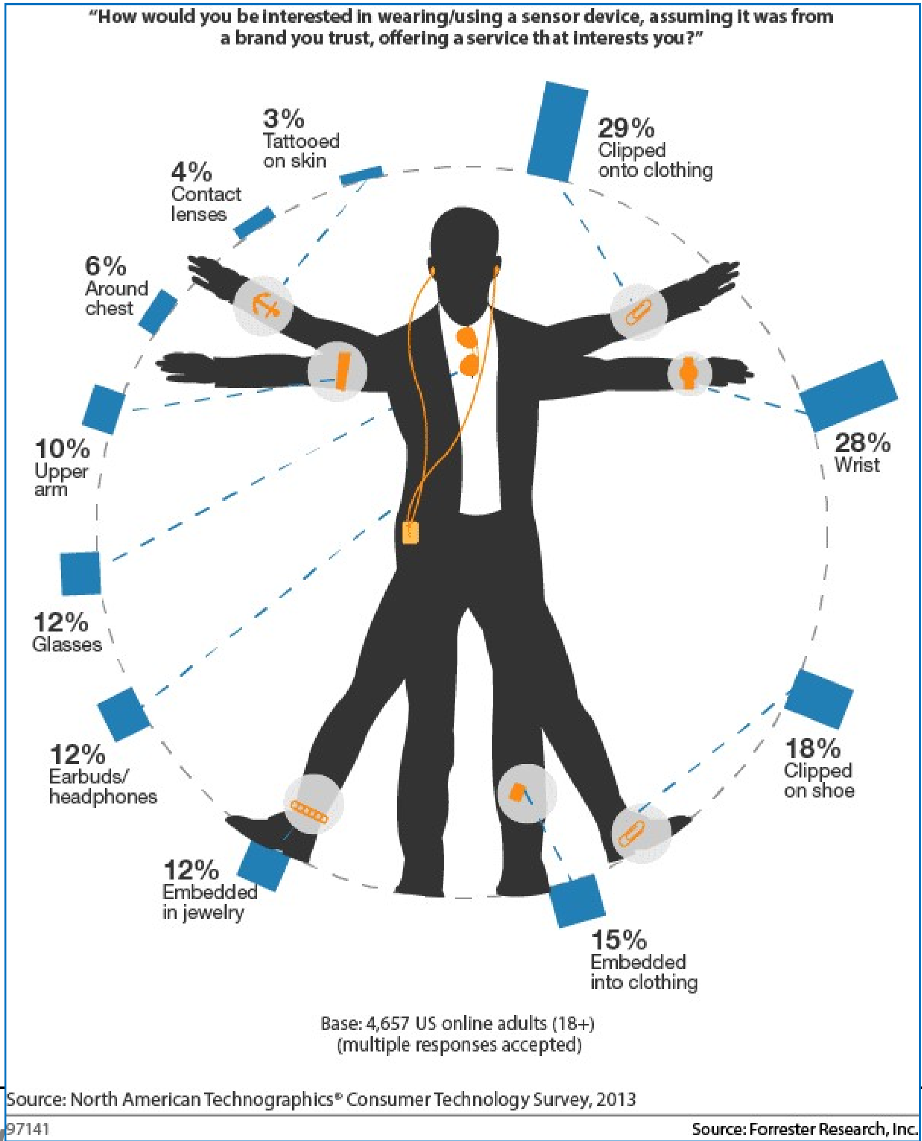
An Electronic System

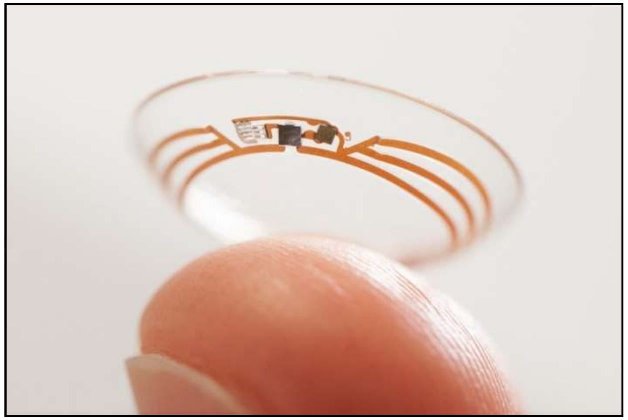
- A generic electronic system (e.g. an ***IoT*** device, or a ***wearable*** device)

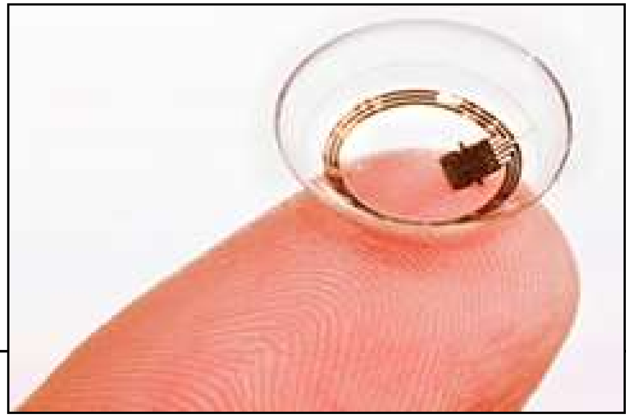


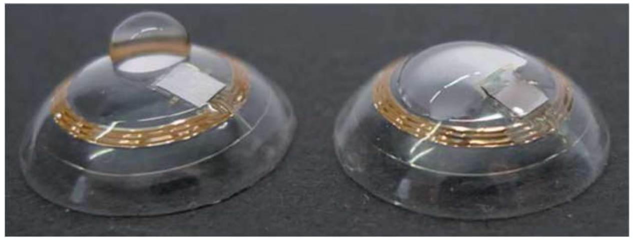
- Electronics and microelectronics
  - From vacuum tubes to discrete transistors, to integrated circuits

Wearable Devices



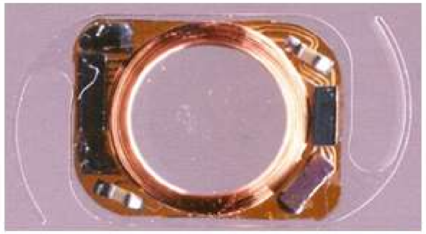


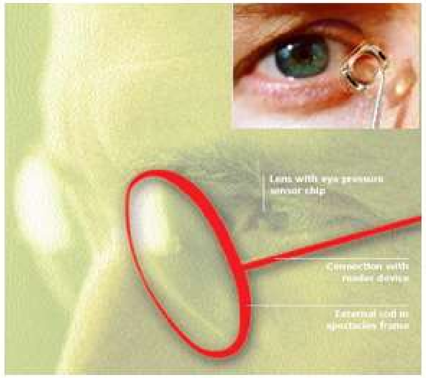




Implanted Device

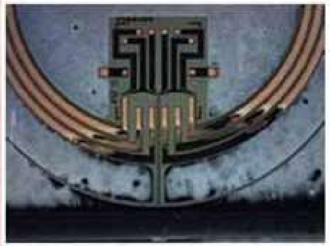
- Glaucoma is one of the common causes for blindness.
- Losing peripheral vision and developing tunnel vision.
- Caused by increased pressure in the eyeball, which impairs the blood supply to the retina.
- Require continuous monitoring of the eye pressure.
- Implanted pressure sensor





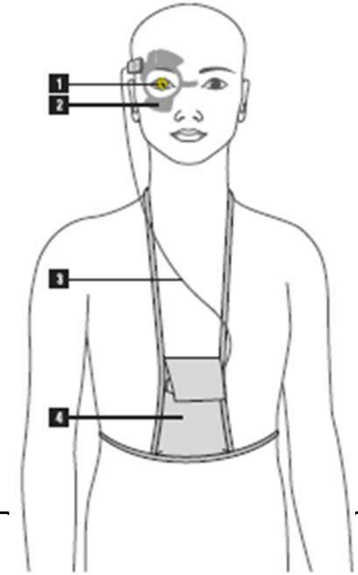
Glaucoma Contact Lens

- Wireless MEMS Sensor-Embedded Contact Lens for Glaucoma Treatment



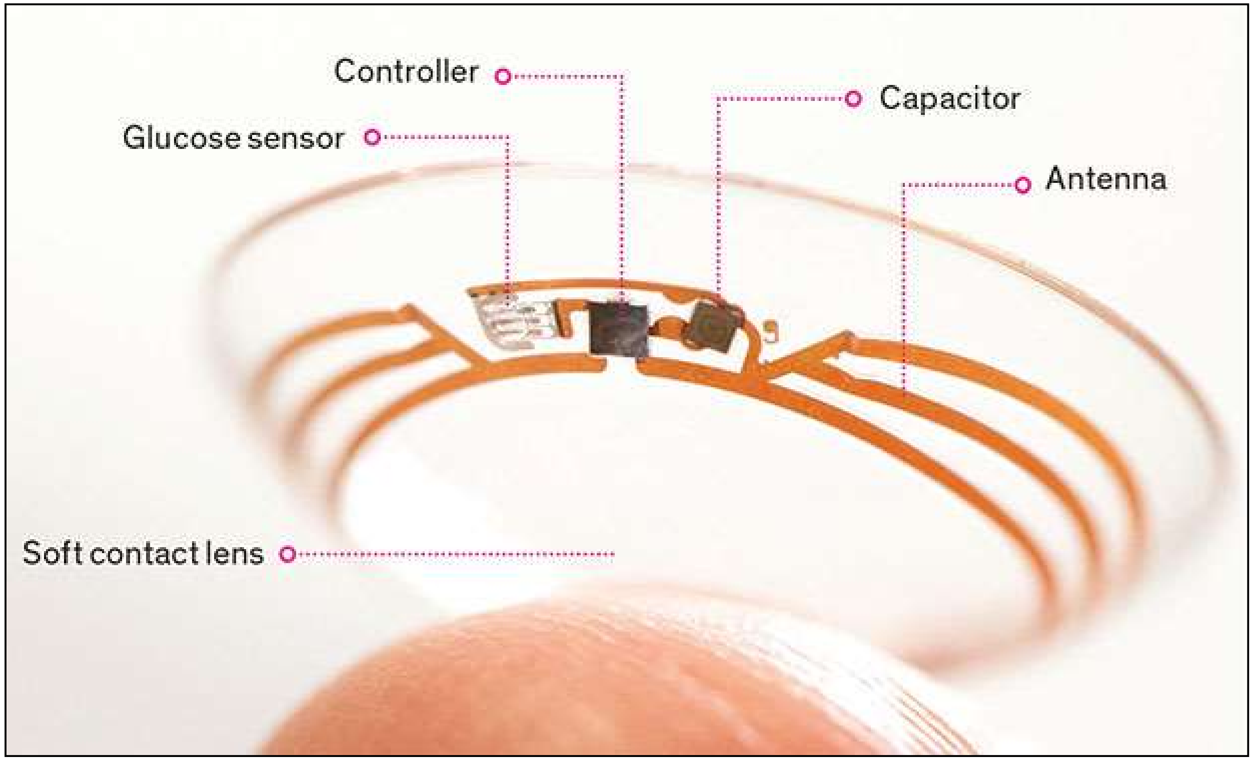
- A two-part system that incorporates a receiver worn by the patient around his neck and the smart contact lens. Besides the strain gauge the lens incorporates an RF transmitter, a miniature processing circuit, and an antenna for conveying measured data to the receiver.

(Sensimed's Triggerfish Lens)



Wearable – Contact Lens

- IEEE Spectrum, July 2017

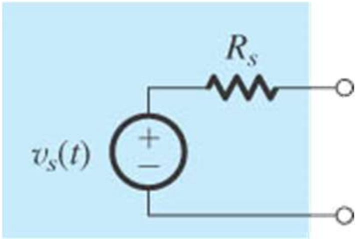


(Verily Life Sciences)

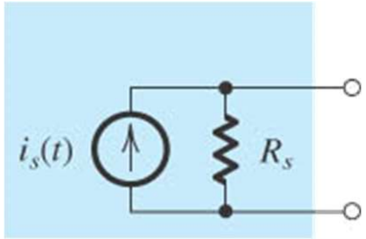
The Greatest Wearable Device ….

Signals

- Physical signal vs. electrical signal
  - Transducers convert physical signals into electrical signals
- Electrical signals:
  - Voltage signal
  - Current signal



Thévenin equivalent circuit

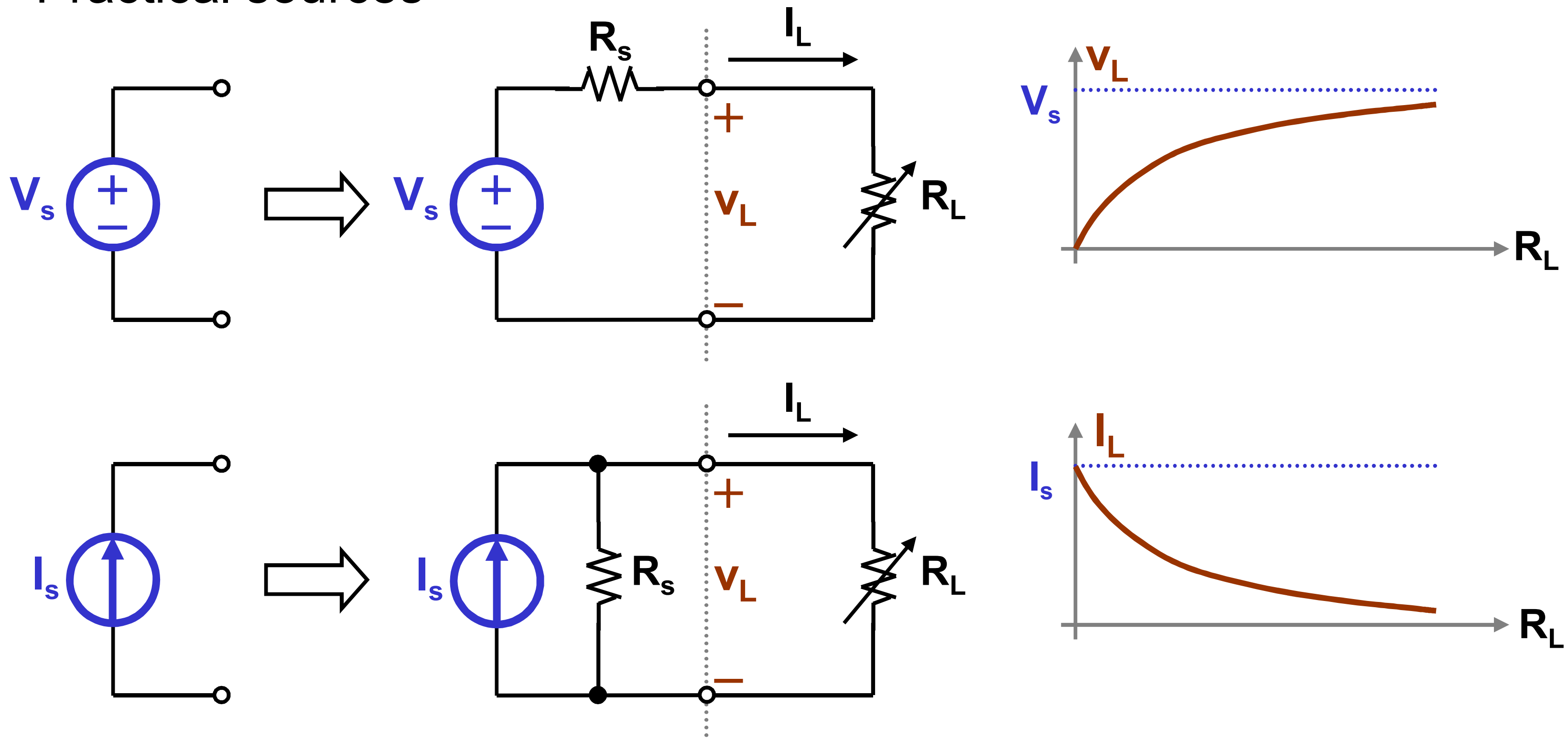


Norton equivalent circuit

- For an ideal voltage/current source, R_s=?
- What is the role of R_s?

Signal Source Modeling

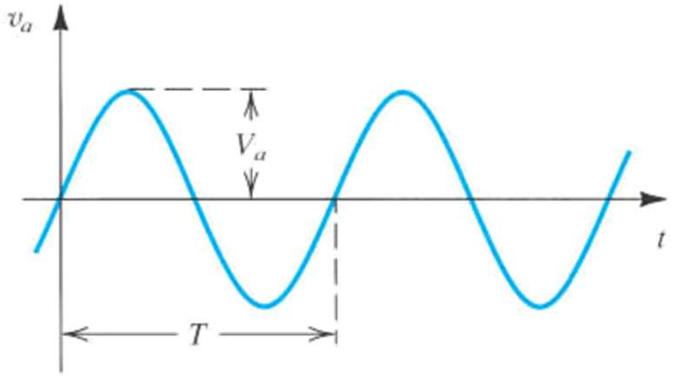
- Practical sources

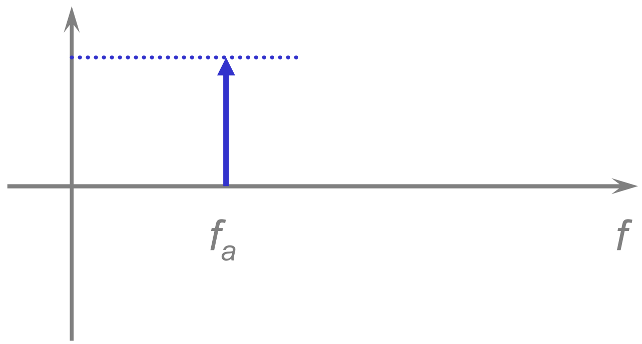


- Considering the load R_L, how to maximize the output voltage (V_L) or current (I_L)?

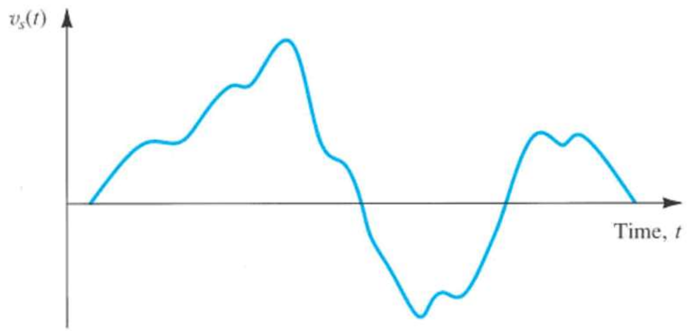
Signals

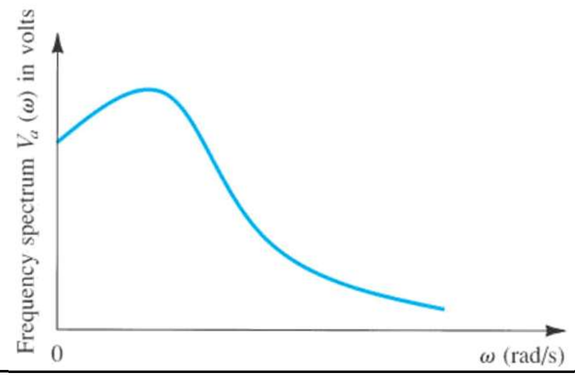
- Time domain vs. Frequency domain
  - $V(t) = V_a \times \sin(\omega t) = V_a \times \sin(2\pi f_a t)$ $\Rightarrow \omega = 2\pi f_a; f_a = 1/T$





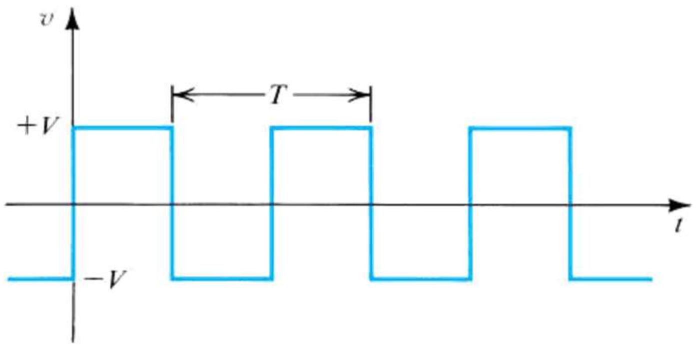
  - For a “random” signal



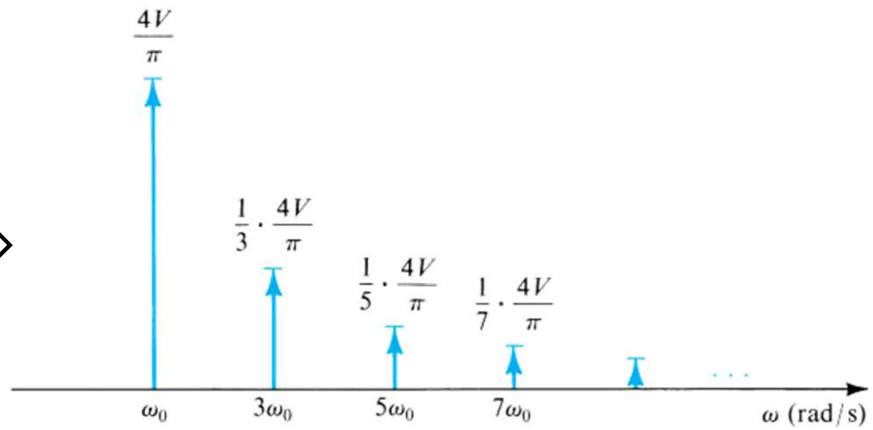


Signals

- Conversion from time domain to frequency domain
  - Fourier transform and Fourier series (will be covered in "Signal and System")
  - For a square wave ⇒ $v(t) = \frac{4V}{\pi}(\sin\omega_0 t + \frac{1}{3}\sin 3\omega_0 t + \frac{1}{5}\sin 5\omega_0 t + ...)$

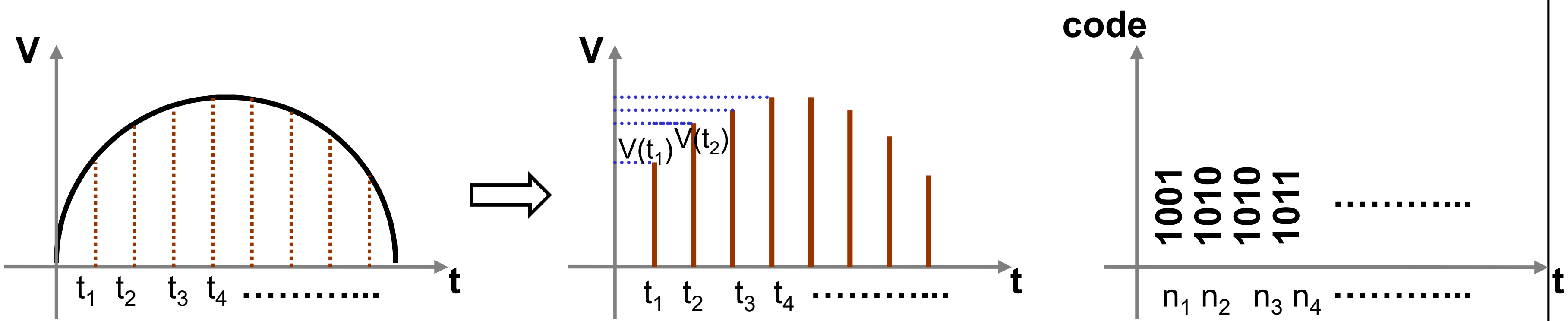


⇒



Analog and Digital Signals

- Analog signals: continuous
- Digital signals: signal represented by a sequence of numbers



Continuous-time analog signal $\xrightarrow{\textbf{sample}}$ **Discrete-time analog signal** $\xrightarrow{\textbf{quantize}}$ **Digital signal**

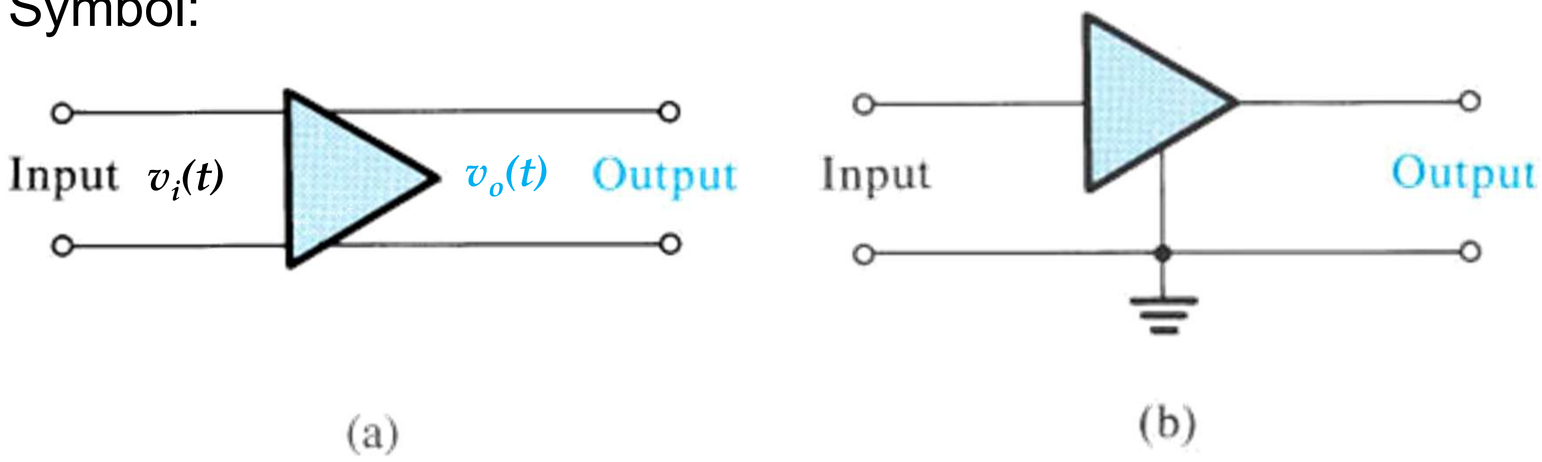
Analog-to-digital converter

Amplifiers

- Amplification

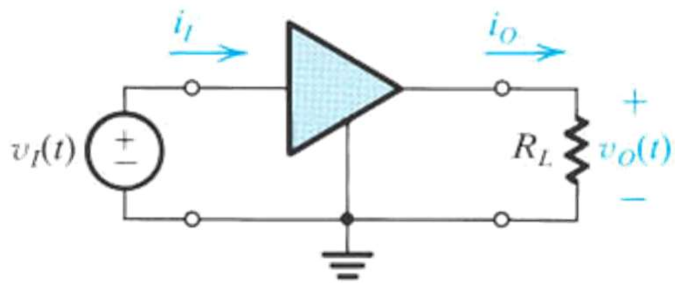
$$v_o(t) = Av_i(t) + Bv_i(t)^2 + Cv_i(t)^3 + ...$$

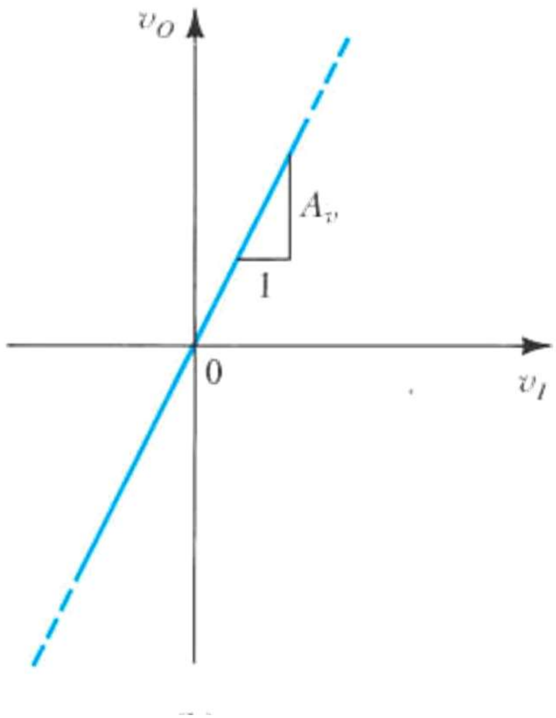
- Linear amplification: B=C= …. =0 (Linear Properties)
- Non-linear amplification $\Rightarrow$ distortion
- Symbol:



Gain

- Voltage, current, and power gains

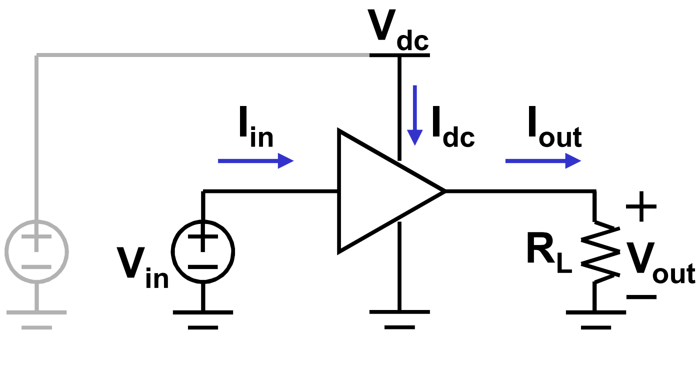


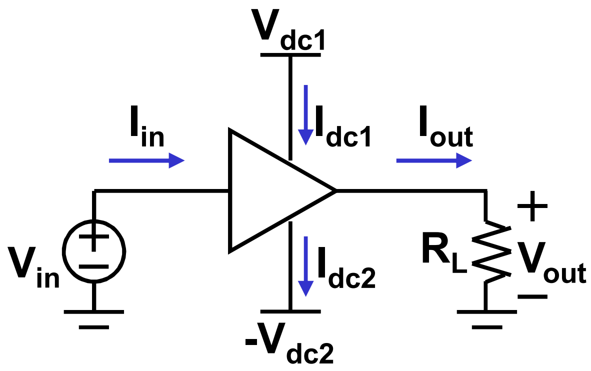


- Voltage gain (A_v) = v_o/v_i (V/V)
- Current gain (A_i) = i_o/i_i (I/I)
- Power gain (A_p) = $v_o i_o/v_i i_i$ (W/W)
- Decibels (dB)
  - $20\times\log|A_v|$
  - $20\times\log|A_i|$
  - $10\times\log|A_p|$

Power Dissipation

- Power consumption





- Single power supply

  $P_{dc}=V_{dc}\times I_{dc}$
  $P_{in}=V_{in}\times I_{in}$
  $P_L=V_{out}\times I_{out}$

- Efficiency

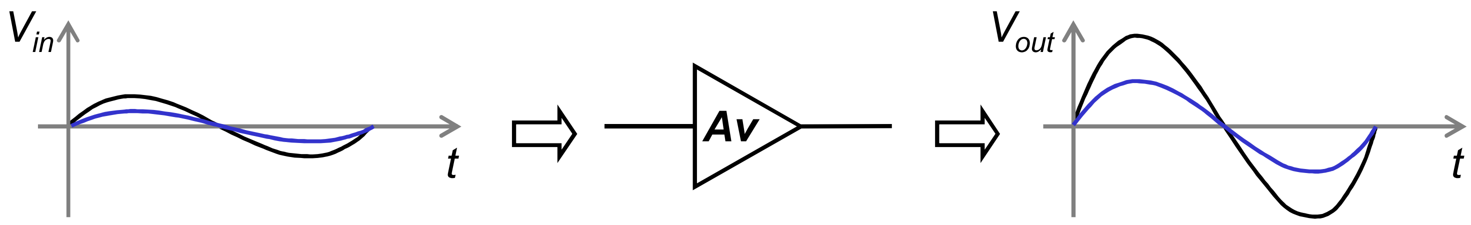
$$\eta \equiv \frac{P_L}{P_{dc}} \times 100\%$$

- Dual power supply

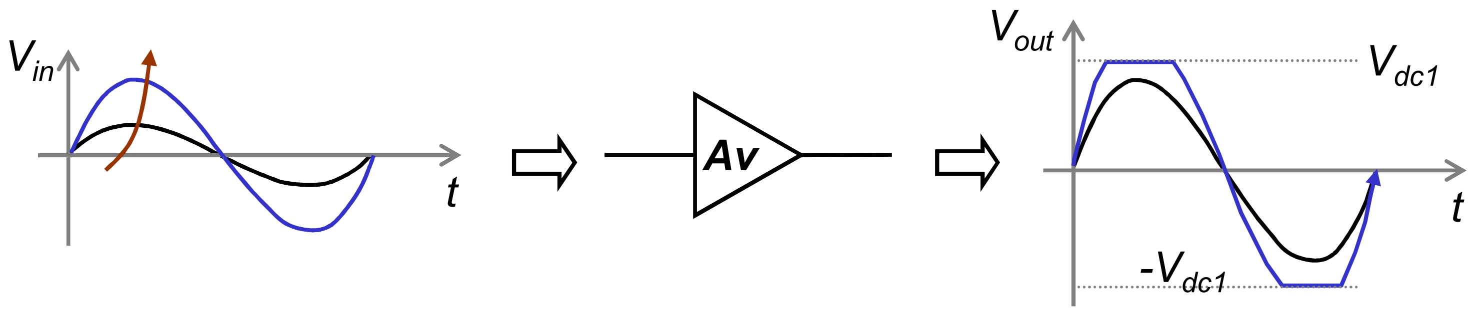
  $P_{dc}=V_{dc1}\times I_{dc1} +(-V_{dc2})\times(-I_{dc2})$
  $P_{in}=V_{in}\times I_{in}$
  $P_L=V_{out}\times I_{out}$

Amplifier Saturation

- Amplify signals (with information)



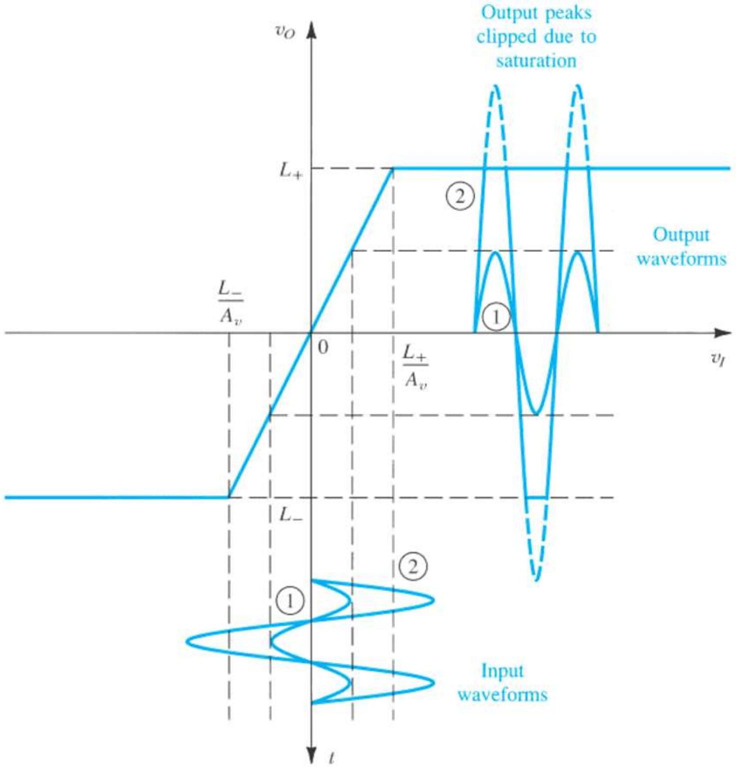
- What if input amplitudes keep increasing?
  - Output waveform is limited by DC power supply voltages

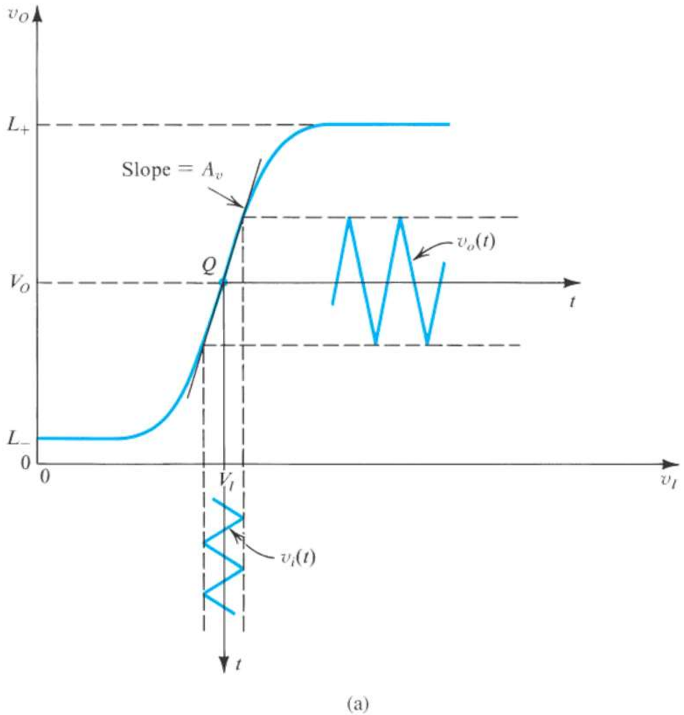


- Saturation (clipping)

Transfer Characteristics

- Transfer characteristic (transfer curve, v_i-v_o curve)
  – Ideal case - practical case



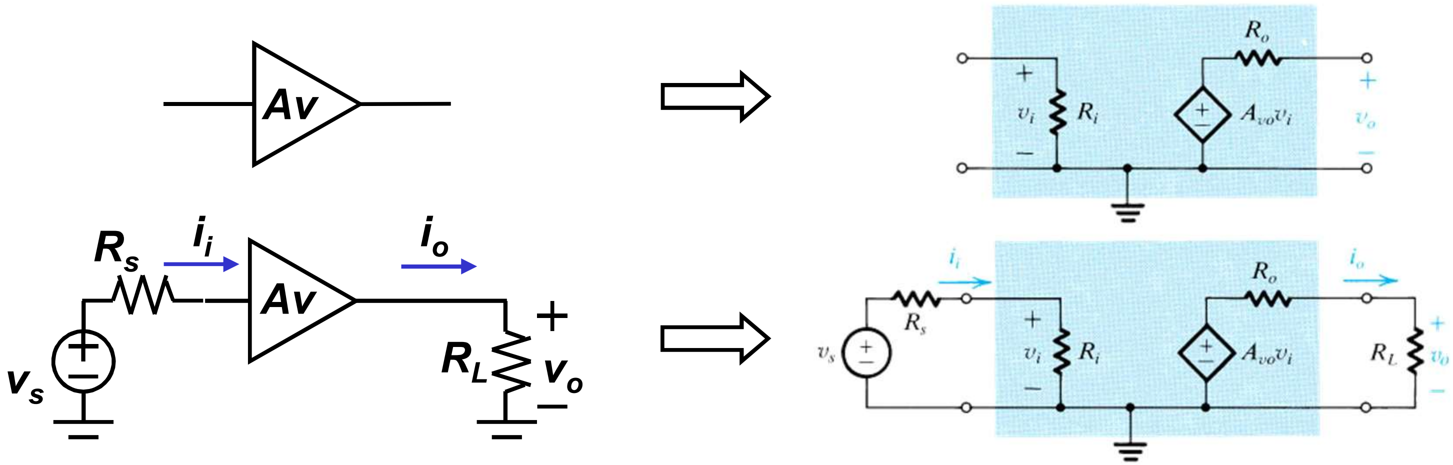


(a)

- Proper biasing and small-signal operation

Amplifier Model

- Model: represent a complex circuit with a simplified version
  - Can have many versions of models, depends on biasing ….
  - Simplify circuit analysis



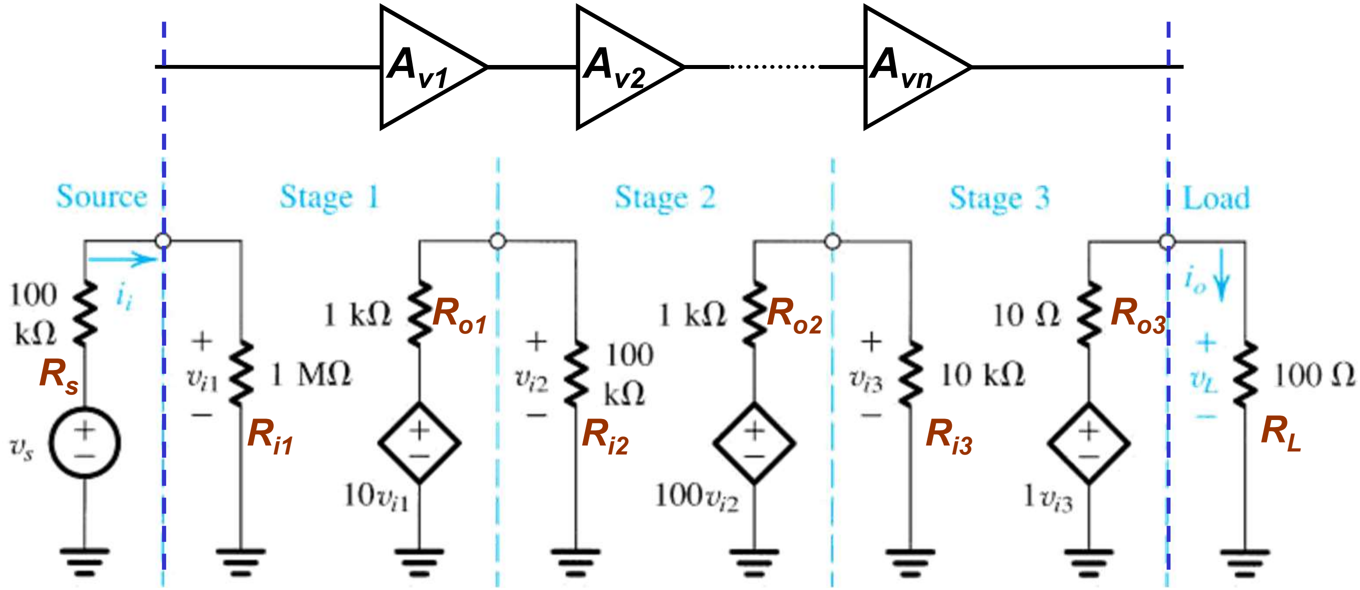
(b)

$$v_o = A_{v0} v_i \frac{R_L}{R_L + R_o}; \quad v_i = v_s \frac{R_i}{R_s + R_i}$$

$$v_o = A_{v0} v_s \frac{R_i}{R_s + R_i} \frac{R_L}{R_L + R_o} \Rightarrow \frac{v_o}{v_s} = A_{v0} \frac{R_i}{R_s + R_i} \frac{R_L}{R_L + R_o}$$

Cascaded Amplifier

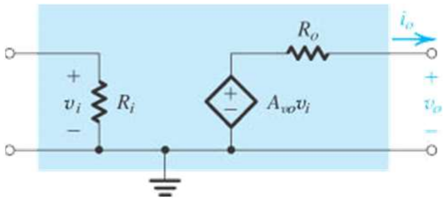
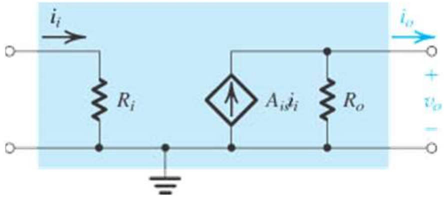
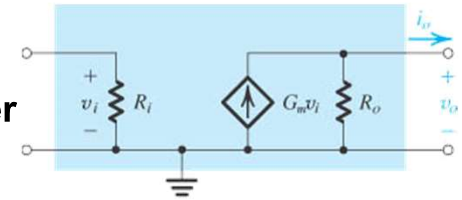
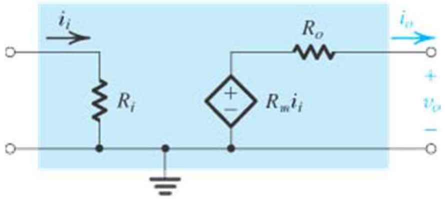
- Allow more flexibility in amplifier design: gain, input/output impedance, etc.



$$v_L = A_{v3} v_{i3} \frac{R_L}{R_{o3} + R_L}; \quad v_{i3} = A_{v2} v_{i2} \frac{R_{i3}}{R_{o2} + R_{i3}}; \quad v_{i2} = A_{v1} v_{i1} \frac{R_{i2}}{R_{o1} + R_{i2}}; \quad v_{i1} = v_s \frac{R_{i1}}{R_s + R_{i1}}$$

$$v_o = v_s A_{v3} A_{v2} A_{v1} \frac{R_L}{R_{o3} + R_L} \frac{R_{i3}}{R_{o2} + R_{i3}} \frac{R_{i2}}{R_{o1} + R_{i2}} \frac{R_{i1}}{R_s + R_{i1}}$$

Four Amplifier Types

Type	Model	Gain Expression	Ideal Case
Voltage Amplifier		$A_{vo} \equiv \left.\frac{v_o}{v_i}\right\|_{i_o=0} \quad (V/V)$	$R_i = \infty, R_o = 0$
Current Amplifier		$A_{is} \equiv \left.\frac{i_o}{i_i}\right\|_{v_o=0} \quad (A/A)$	$R_i = 0, R_o = \infty$
Transconductance Amplifier		$G_m \equiv \left.\frac{i_o}{v_i}\right\|_{v_o=0} \quad (A/V)$	$R_i = \infty, R_o = \infty$
Transresistance Amplifier		$R_m \equiv \left.\frac{v_o}{i_i}\right\|_{i_o=0} \quad (V/A)$	$R_i = 0, R_o = 0$

Amplifier Type

- These four types are equivalent

$$A_{vo} = \frac{v_o}{v_i} = \frac{i_o R_o}{i_i R_i} = A_{is}\left(\frac{R_o}{R_i}\right)$$

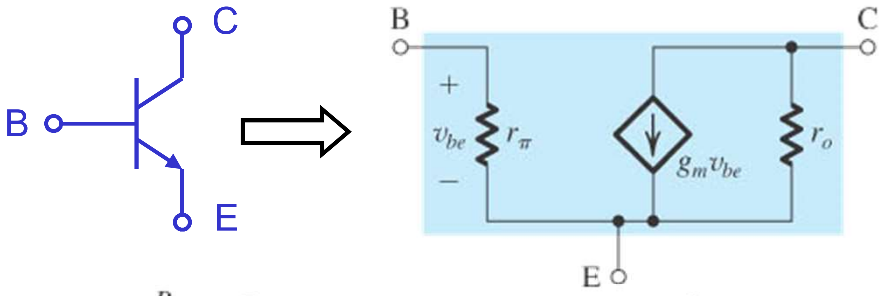
$$= \frac{v_o}{i_i R_i} = \frac{R_m}{R_i}$$

$$= \frac{i_o R_o}{v_i} = G_m R_o$$

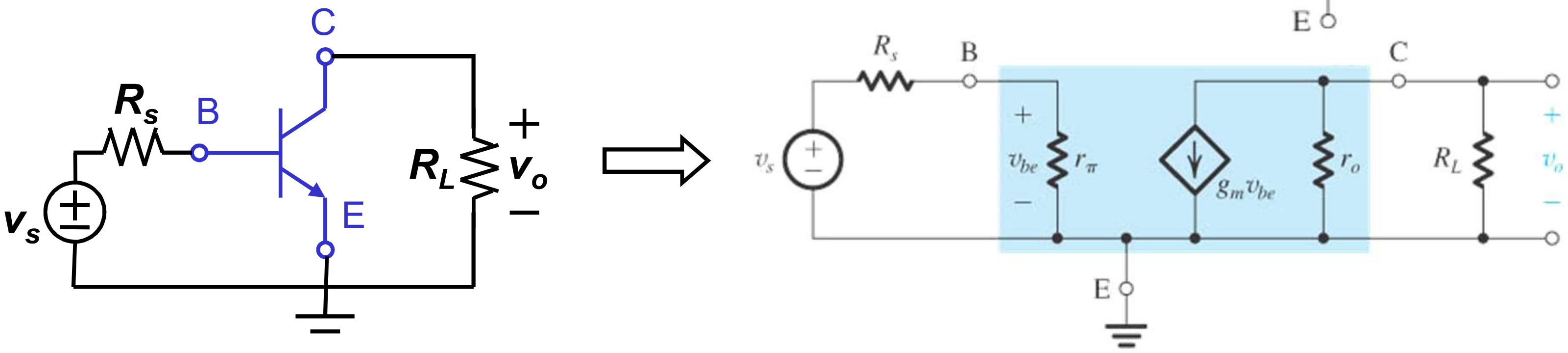
- These models are two-port networks
- These models are unilateral

Example 1.4

- BJT (bipolar junction transistor)



- Equivalent circuit



(b)

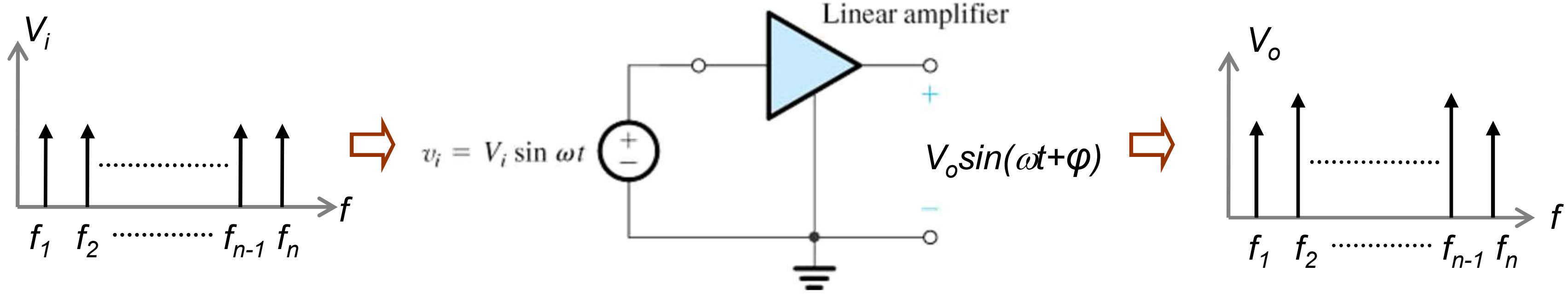
- Find v_o and A_v

$$v_o = (-g_m v_{be})(R_L \| r_o)$$

$$v_{be} = v_s \frac{r_\pi}{R_s + r_\pi} \quad \Rightarrow v_o = -g_m v_s \frac{r_\pi}{R_s + r_\pi}(R_L \| r_o) \quad \Rightarrow A_v = \frac{v_o}{v_s} = -g_m \frac{r_\pi}{R_s + r_\pi}(R_L \| r_o)$$

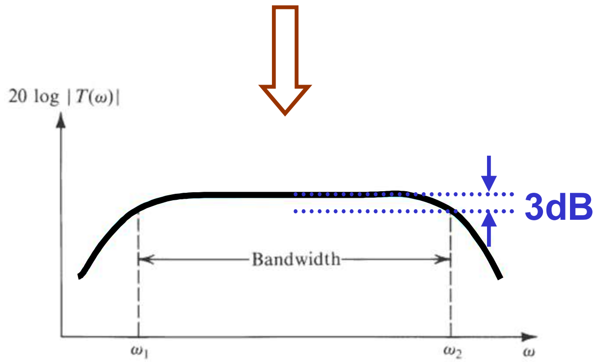
Frequency Response

- Different amplifications at different frequencies



$$A_v = \frac{V_o}{V_i} \Rightarrow A_v(\omega) = \frac{V_o(\omega)}{V_i(\omega)}$$ (Transfer function)

$$\angle A_v(\omega) = \phi$$



- Only frequency-dependent components cause frequency response
  - R, L, C: ???

Frequency Dependence of Devices

- Describing devices in time-domain can be quite complicated

$$i = C\frac{dv}{dt}; \quad if\ v = v_A \sin(\omega t) \Rightarrow i = C\omega v_A \cos(\omega t)$$

For a certain ***v*** (amplitude v_A), ***i*** grows as ω increases.

$$\Rightarrow \frac{v_A}{i} \propto \frac{1}{C\omega}$$

$$v = L\frac{di}{dt}; \quad if\ i = i_A \sin(\omega t) \Rightarrow v = L\omega i_A \cos(\omega t)$$

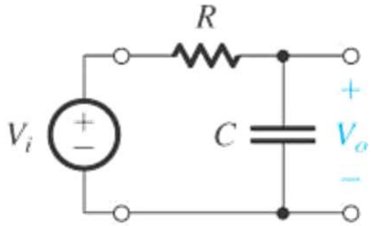
For a certain ***i*** (amplitude i_A), ***v*** grows as ω increases.

$$\Rightarrow \frac{v}{i_A} \propto L\omega$$

- Define "impedance" in the frequency domain
  - Why impedance? (recall basic circuit analysis techniques: KCL, KVL, and Ohm's Law)
  - $Z_L = j\omega L = sL$ (reactance or impedance); ***$s = j\omega$***
  - $Z_C = 1/j\omega C = 1/sC$ (reactance or impedance)
  - $Z_R = R$ (resistance or impedance)

STC Network

- A STC network: a RC or RL circuit
  - Time constant τ=RC or L/R
- ***RC low pass (LP) network***

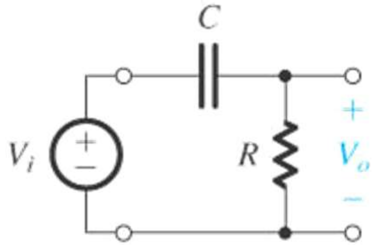


$$T(s)=\frac{v_o}{v_i}=\frac{1/sC}{R+1/sC}=\frac{1}{1+sRC}=\frac{1}{1+s/\omega_0}\qquad \omega_0=1/RC$$

$$T(\omega)=\frac{1}{1+j\omega/\omega_0}\Rightarrow\left|T(\omega)\right|=\frac{1}{\sqrt{1+(\omega/\omega_0)^2}}$$

$$\angle T(\omega)=-\tan^{-1}(\omega/\omega_0)$$

- ***RC high pass (HP) network***



$$T(s)=\frac{v_o}{v_i}=\frac{R}{R+1/sC}=\frac{sRC}{1+sRC}=\frac{s}{\omega_0+s}\qquad \omega_0=1/RC$$

$$T(\omega)=\frac{j\omega}{\omega_0+j\omega}\Rightarrow\left|T(\omega)\right|=\frac{1}{\sqrt{(\omega_0/\omega)^2+1}}$$

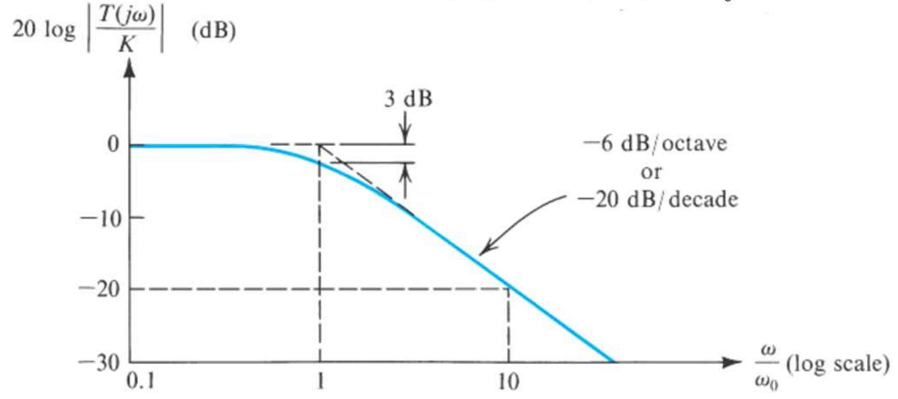
$$\angle T(\omega)=\tan^{-1}(\omega_0/\omega)$$

STC Circuit Bode Plots

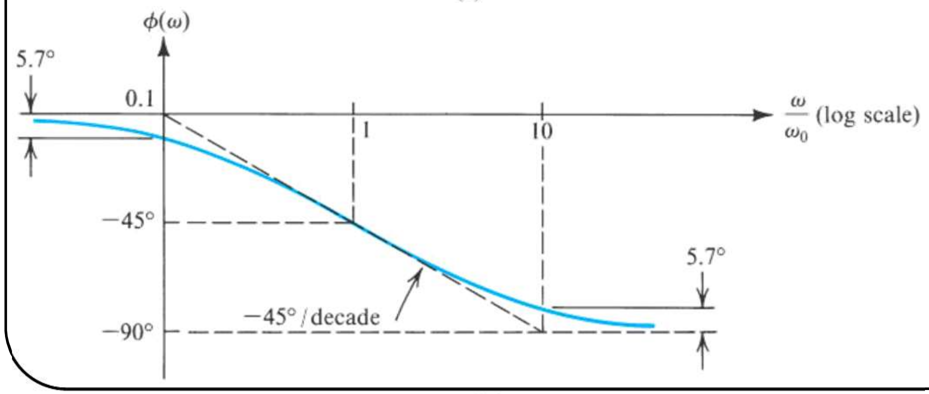
- ***LPF***

$$T(\omega)=\frac{1}{1+j\omega/\omega_0}\Rightarrow\left|T(\omega)\right|=\frac{1}{\sqrt{1+(\omega/\omega_0)^2}}$$

$$\angle T(\omega)=-\tan^{-1}(\omega/\omega_0)$$



(a)

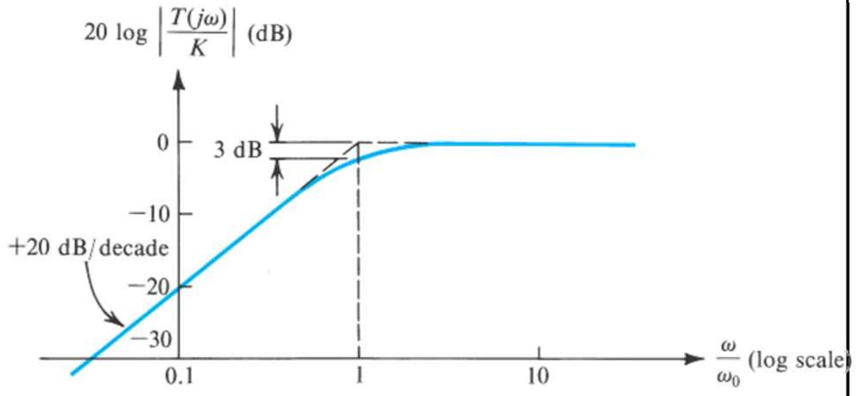


(b)

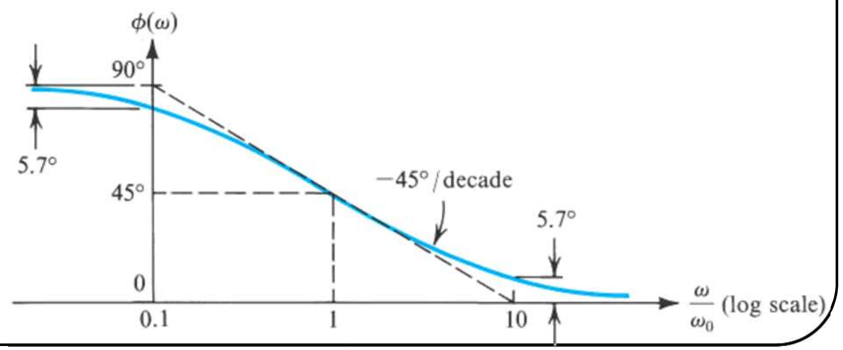
- ***HPF***

$$T(\omega)=\frac{j\omega}{\omega_0+j\omega}\Rightarrow\left|T(\omega)\right|=\frac{1}{\sqrt{(\omega_0/\omega)^2+1}}$$

$$\angle T(\omega)=\tan^{-1}(\omega_0/\omega)$$



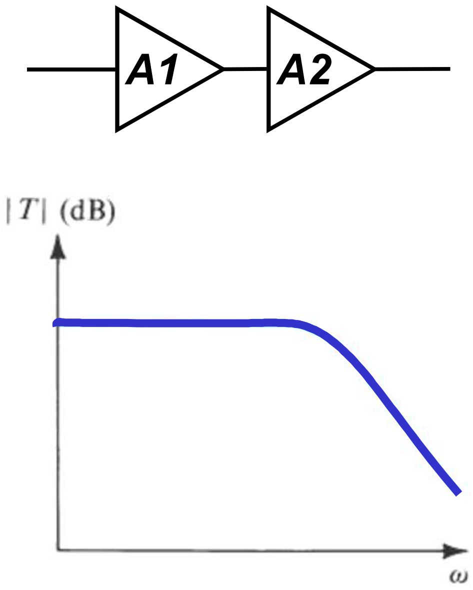
(a)



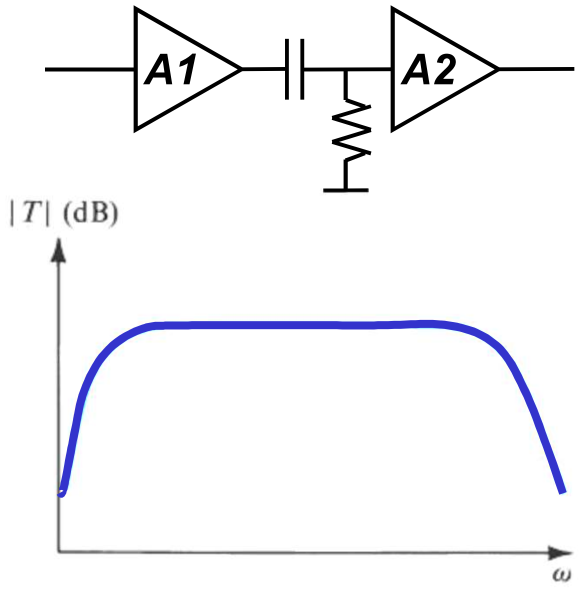
(b)

Amplifier Classifications

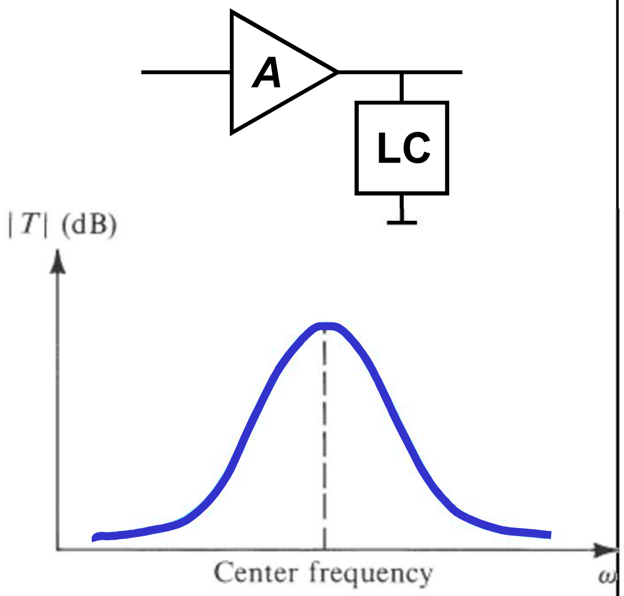
Direct coupled amplifier



Capacitively coupled amplifier (ac coupled)



Tuned amplifier (bandpass)



Problem Solving and Analysis

- Understand the problem
  - **Learn to ask questions**
  - **"Asking the right question is half the answer"**
- Divide the problem into modules
- Represent each module with equivalent model
- Plug in the models to simplify the problem
- Solve the problem with **reasonable approximation**
  - **Gain insight**

武林高手

- 劍招 vs. 劍意

- 張三豐 傳授 張無忌 太極劍
- 風清揚 傳授 令狐沖 獨孤九劍

- 劍招: equation, calculation ⇒ practice
- 劍意: intuition, insight ⇒ “feel” and “see” how circuits work