模拟与数字电路

Analog and Digital Circuits

第 二十 讲：**运算放大器与负反馈原理**

Lecture 20: **Operational Amplifiers**

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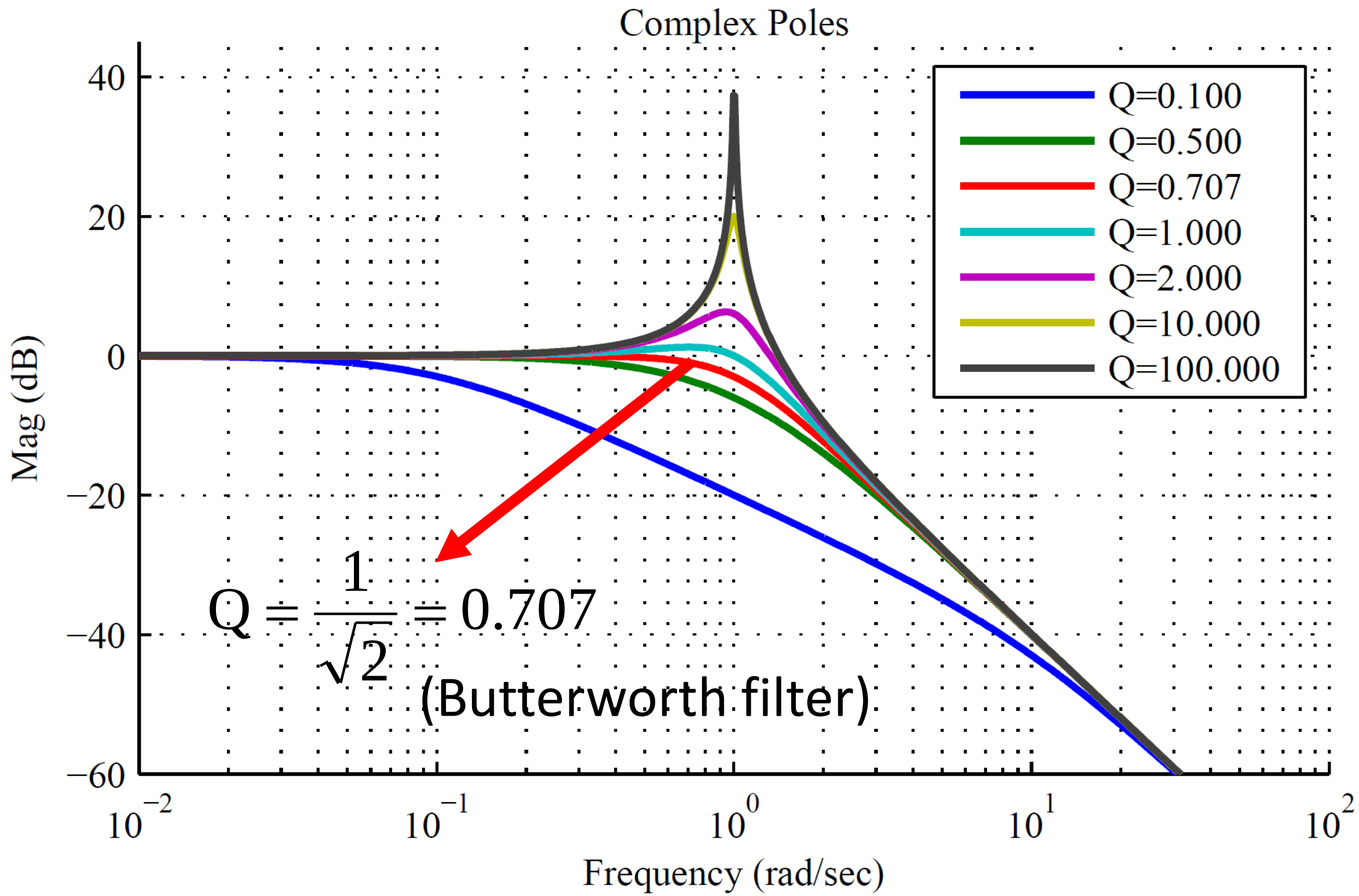
课程主页 扫一扫

提纲

- 复习
  - 从低通、高通、带通滤波器的零极点变化?

  - （续）滤波器
  - 负反馈
  - 运算放大器
  - 运算放大器的应用

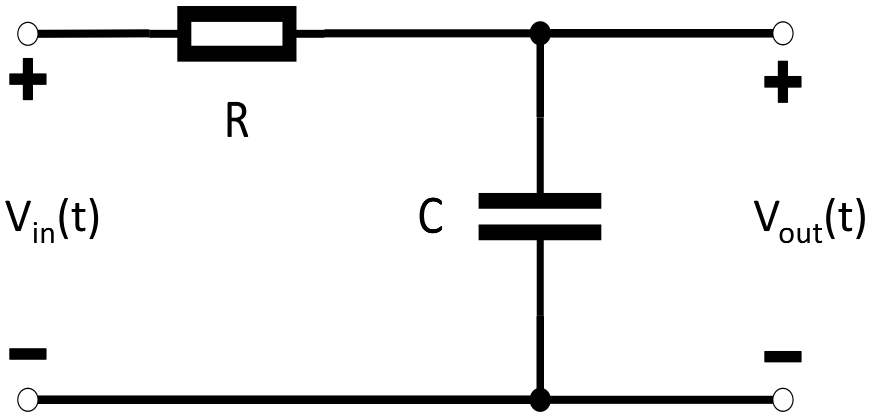
复习：二阶滤波器的品质因数

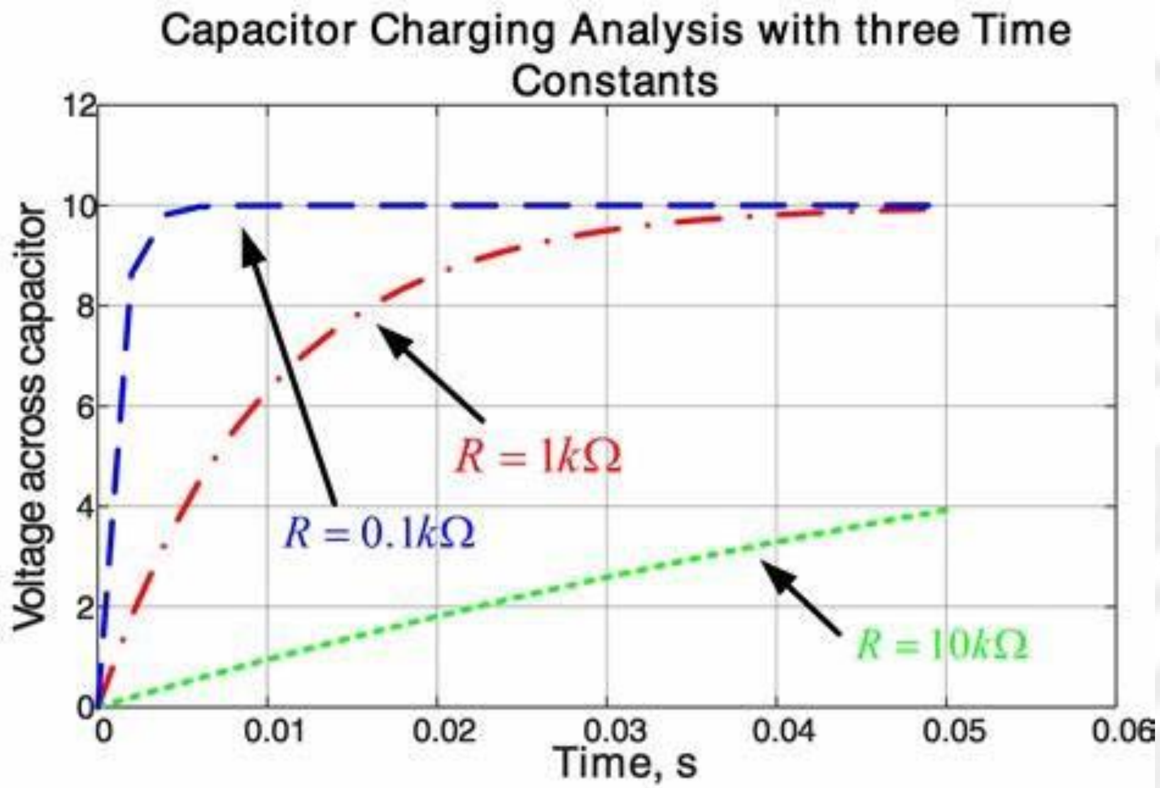


$$H(s) = \frac{K}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2}$$

$Q > 0.707$ Peaking

时间常数 time constant





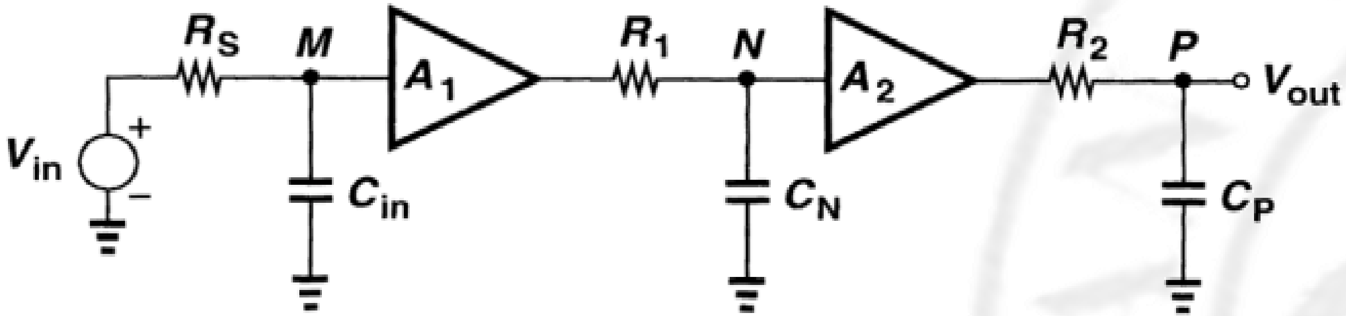
$$C \cdot \frac{dV_{out}(t)}{dt} + \frac{1}{R} \cdot V_{out}(t) = \frac{1}{R} \cdot V_{in}(t)$$

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

$$\frac{V_o(jw)}{V_i(jw)} = \frac{\frac{1}{jwC}}{R + \frac{1}{jwC}} = \frac{1}{1 + jwRC}$$

高阶有源滤波器

- 对于一个电路的结点，如果有电容和电阻连接在这个结点上，那么通常这个结点会给最终的表达式贡献一个极点：



$$\frac{V_{out}}{V_{in}}(s)=\frac{1}{1+R_S C_{in} s}\cdot\frac{A_1}{1+R_1 C_N s}\cdot\frac{A_2}{1+R_2 C_p s}$$

$$=1\cdot A_1 A_2 \frac{1}{1+s/\omega_{pM}}\cdot\frac{1}{1+s/\omega_{pN}}\cdot\frac{1}{1+s/\omega_{pP}}$$

放大器的非线性

- 典型建模方案：泰勒展开

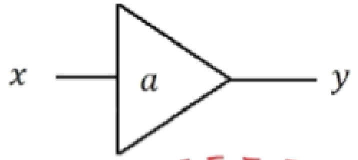
Non-Linear Amplifier

- x = input
- y = output

$$y = a.x + b.x^2 + c.x^3 + \ldots$$

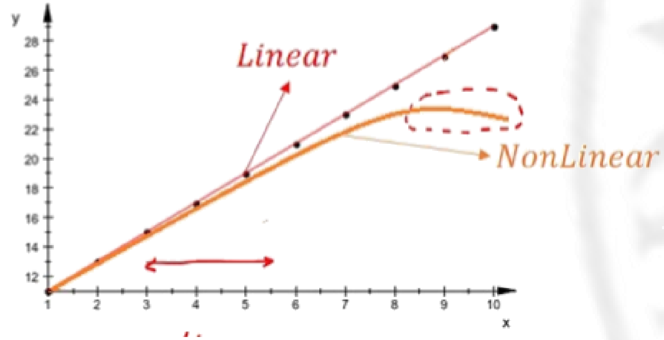
- Generally c<0

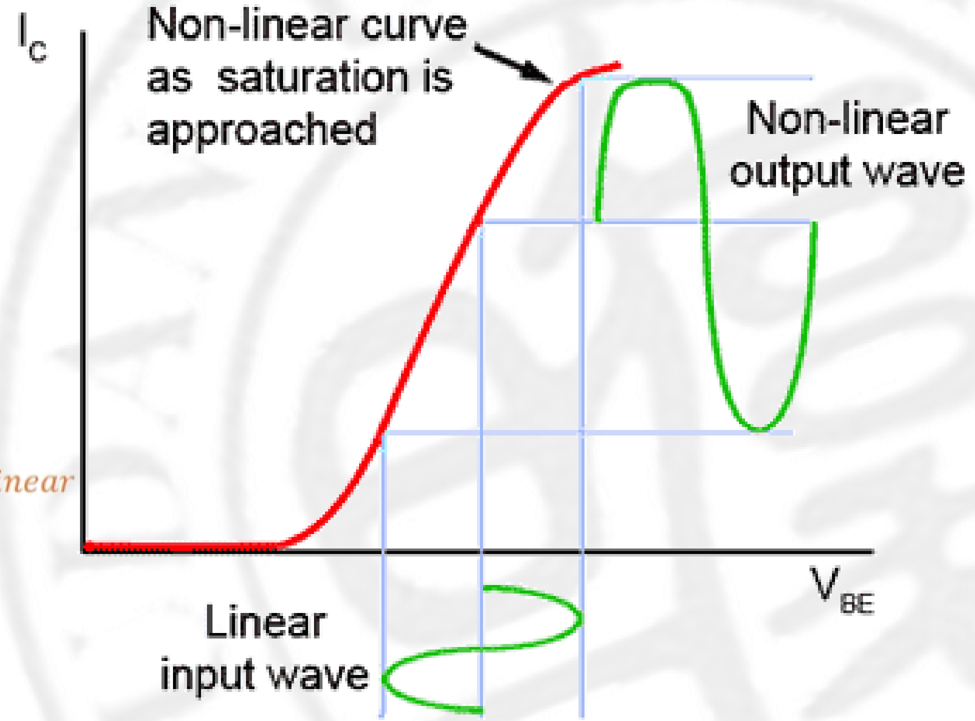
$x \rightarrow$ low



$b = 0$
$c = 0$

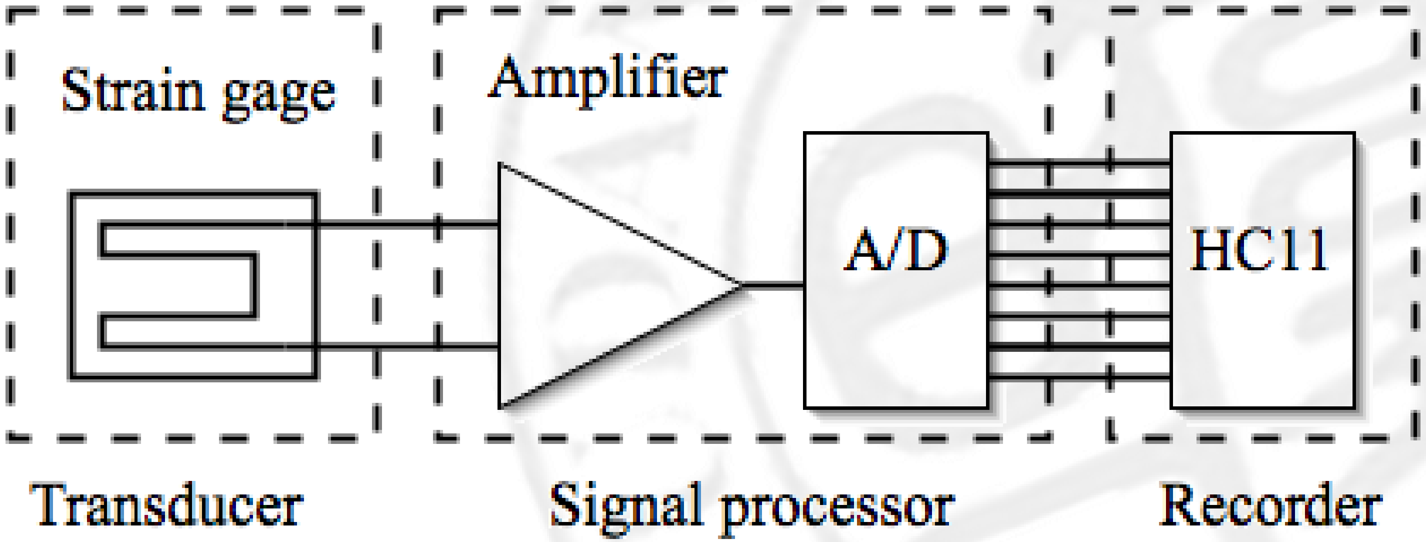
$$y = \underbrace{a.x}_{\text{Linear}} + b.x^2 + c.x^3 + \ldots$$





运算放大器

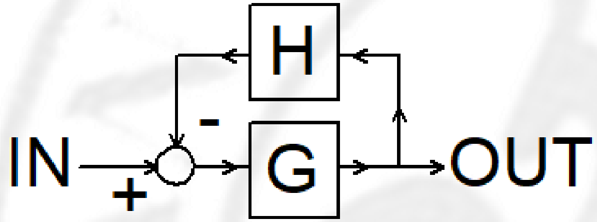
- Sensor signals are often too weak or too noisy
- 目标1：以固定的比列线性放大信号
- 目标2：将某些频率滤去



负反馈原理

- 负反馈：将输出按一定比例反馈到输入
- 通过信号流图得到负反馈的表达式
- 当增益G不恒定，但保持远远大于1时
- 增益由H的大小决定
- 实际上当，GH>>1时

  G的输入摆幅非常小



$$\text{Gain} = \frac{G}{1+GH}$$

$$\text{Gain} = \frac{1}{H} \times \frac{GH}{1+GH}$$

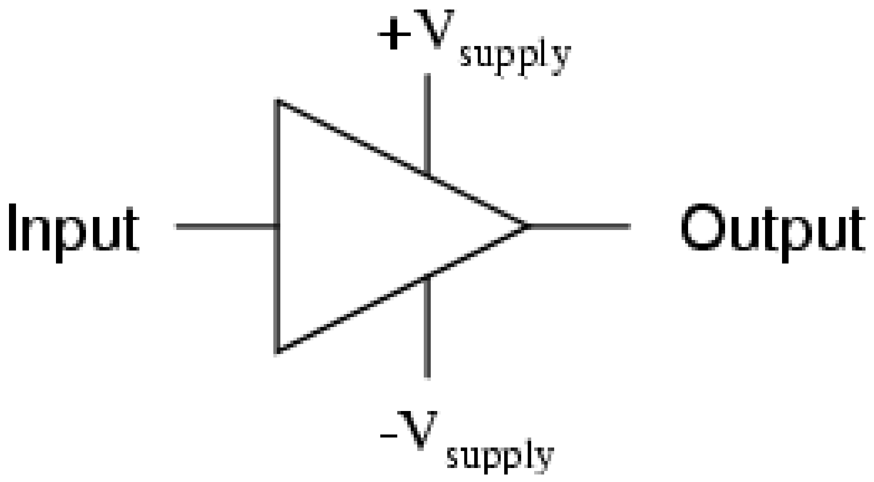
Loop gain is <u>not</u> GH.

Loop gain <u>is</u> -GH.

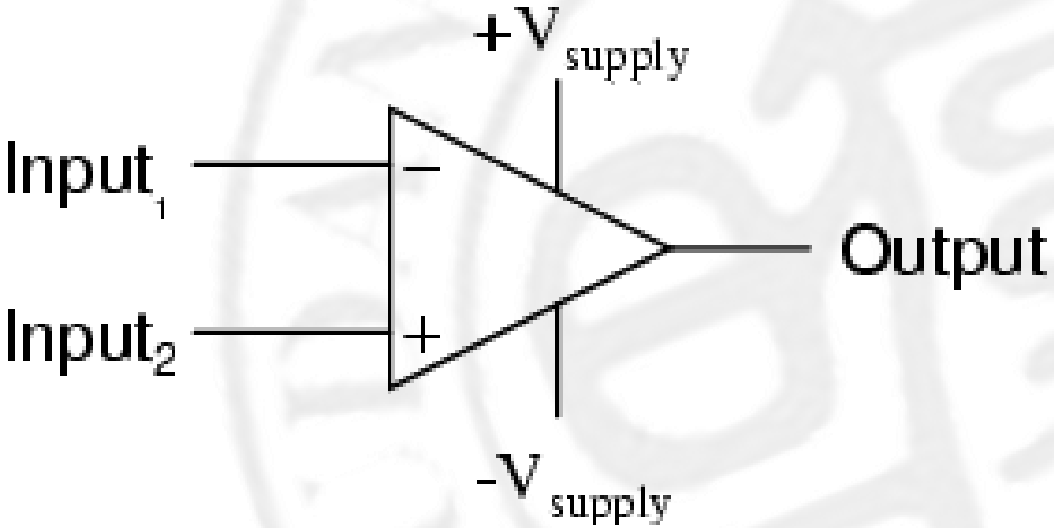
如何实现减法？

- 单端放大器
- 差分放大器

General amplifier circuit symbol

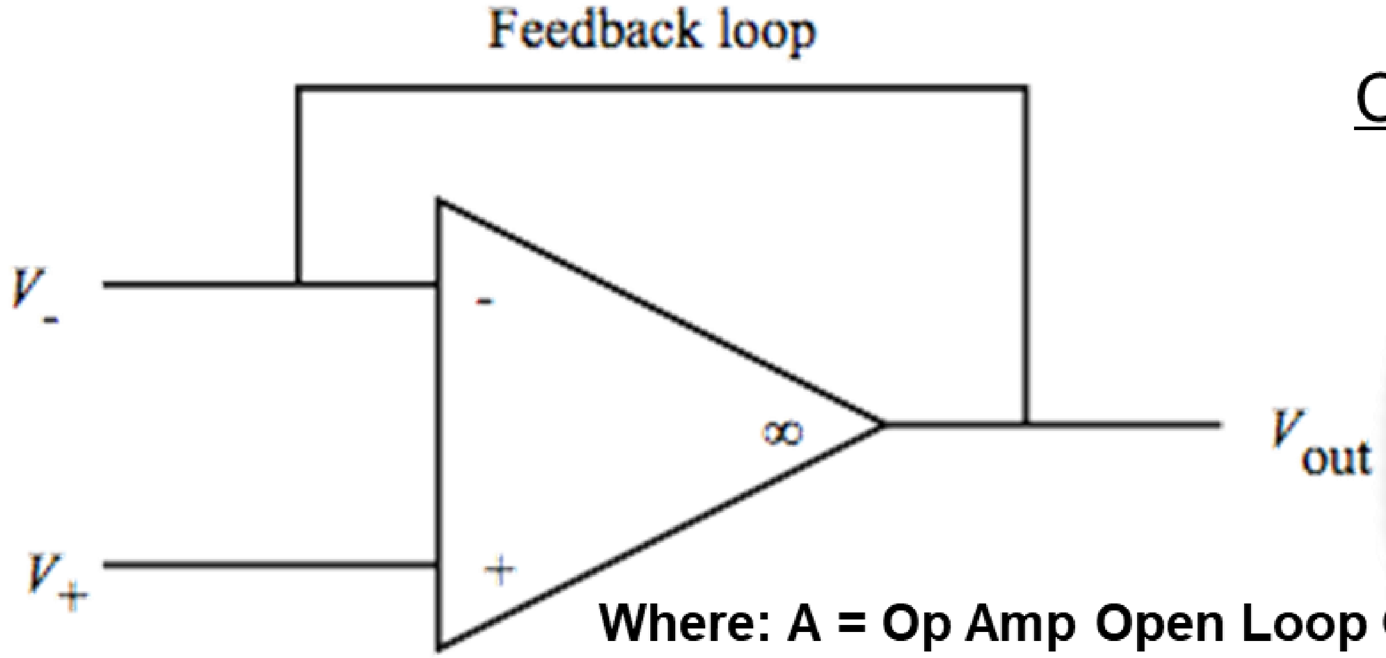


Differential amplifier



放大电路 应用实例

- 将输出直接连接到负端输入



Where: A = Op Amp Open Loop Gain

F = Feedback Loop Gain

<u>Closed Loop Transfer Function</u>

H(s) = **A** / (1 + **AF**)

<u>When AF >> 1…</u>

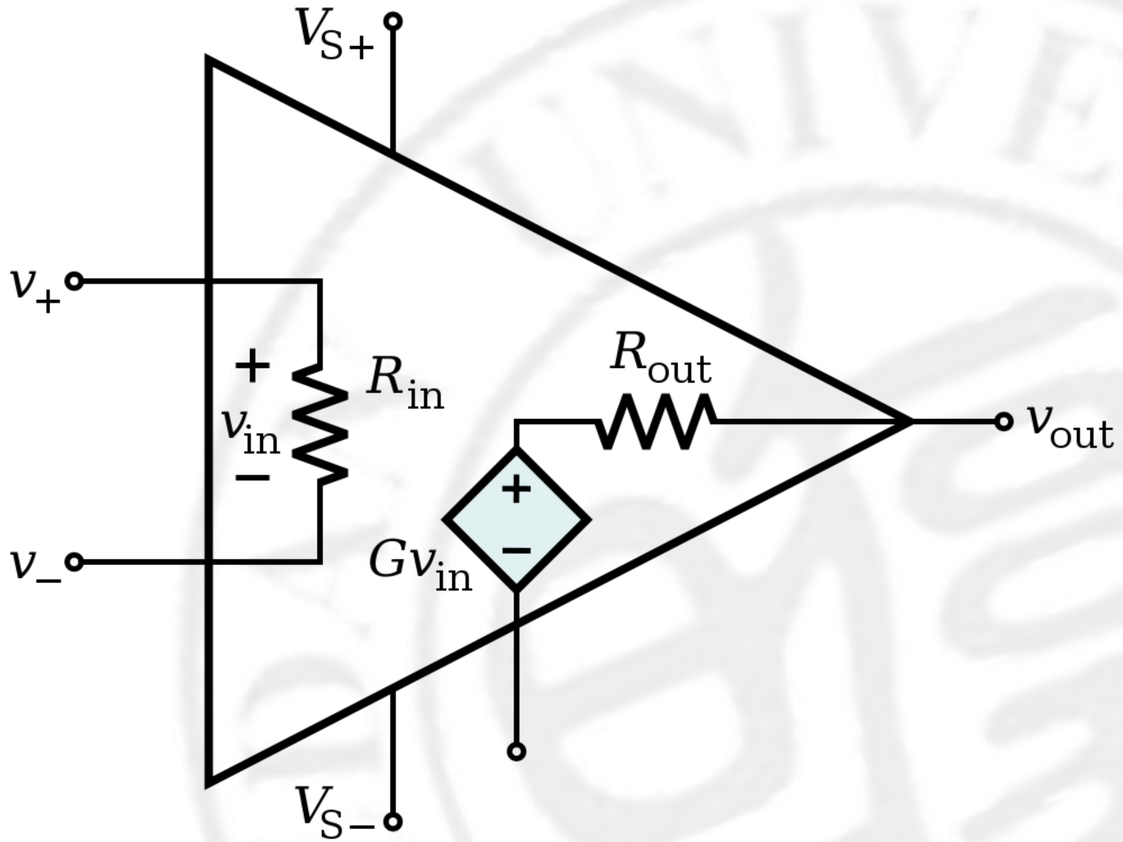
H(s) = 1 / **F**

理想运算放大器 参数

- 电压增益：无限大（大于 10000）
- 输入阻抗：无限大（开路）
- 输出等效电阻：零（实际上如果负载也是无线大可以不满足）
- 频率响应为固定值

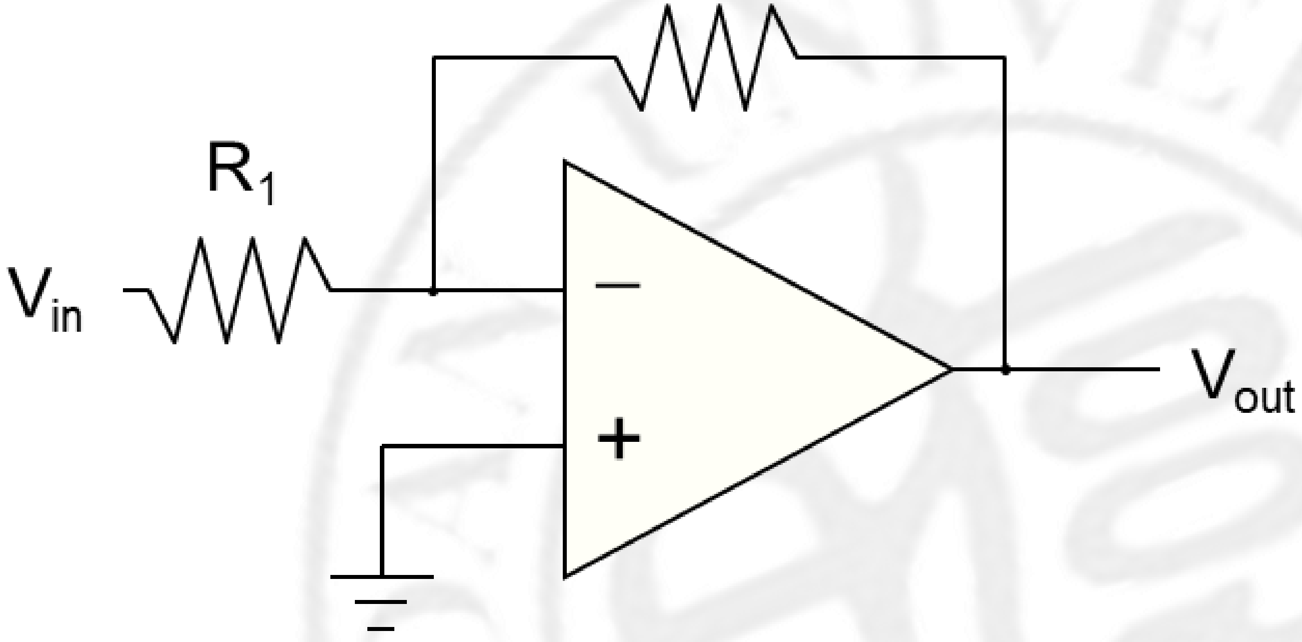
→虚短

→虚断



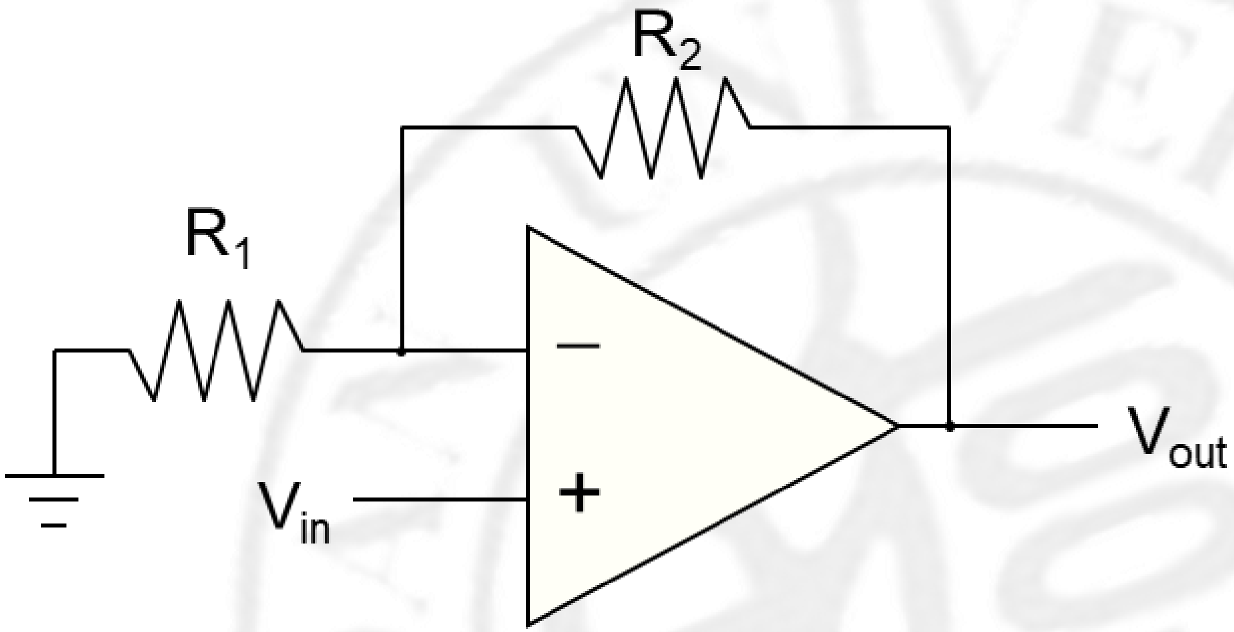
反向放大器

- Current through R_1 is $I_f = V_{in}/R_1$
- the current through R_1 must go through R_2
- Voltage drop across R_2 is then $I_f R_2 = V_{in} \times (R_2/R_1)$
- $V_{out} = 0 - V_{in} \times (R_2/R_1) = -V_{in} \times (R_2/R_1)$
- Amplify V_{in} by factor $-R_2/R_1$
  - negative sign → "inverting"



非反向放大器

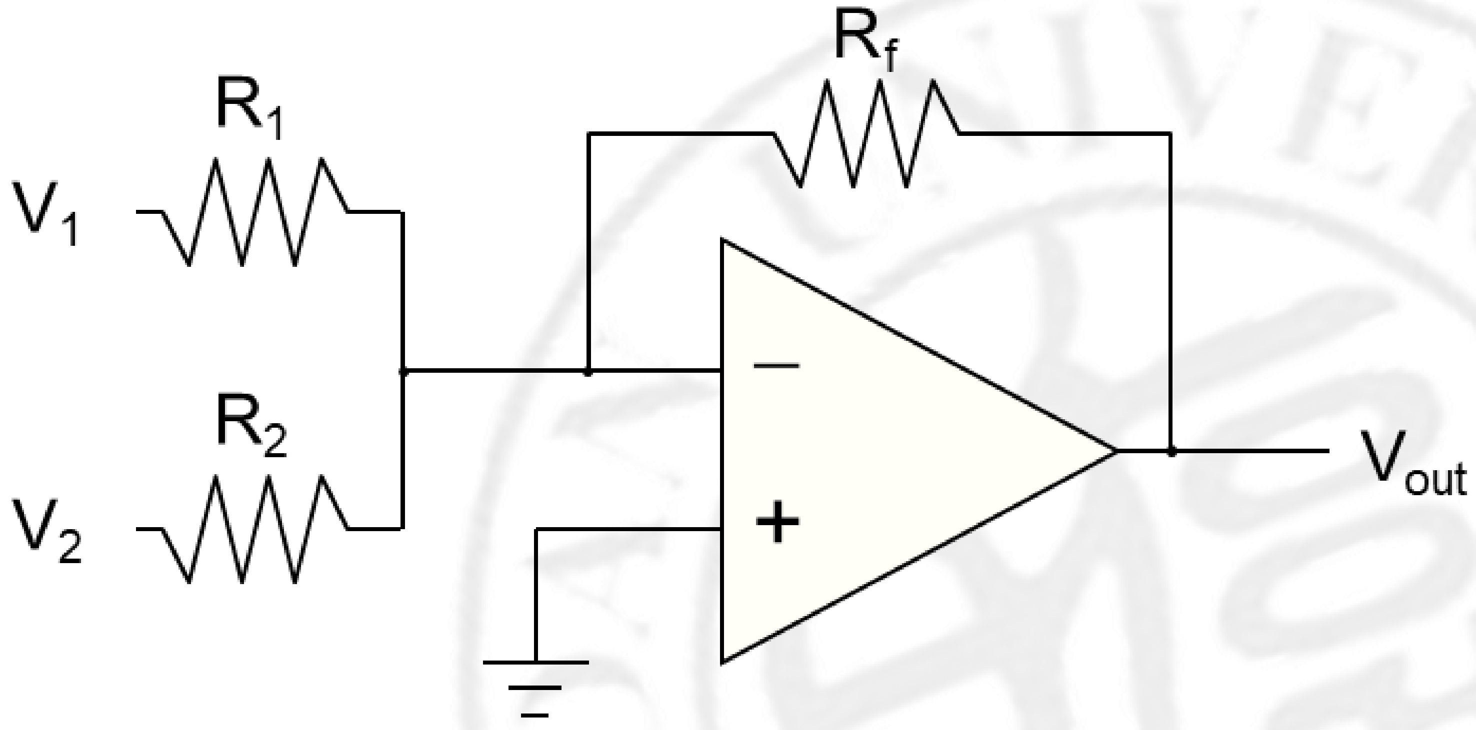
- Current through R_1 is $I_f = V_{in}/R_1$ (to left, into ground)
- Voltage drop across R_2 is $I_f R_2 = V_{in}\times(R_2/R_1)$
- $V_{out} = V_{in} + V_{in}\times(R_2/R_1)$
  $= V_{in}\times(1 + R_2/R_1)$
- The gain is $(1 + R_2/R_1)$, and is positive (non-inverting)



模拟加权加法器

- inverting input still held at virtual ground
- I_1 and I_2 are added together to run through R_f
- Get the (inverted) sum: $V_{out} = -R_f \times (V_1/R_1 + V_2/R_2)$

- 加权系数由电阻的比例决定

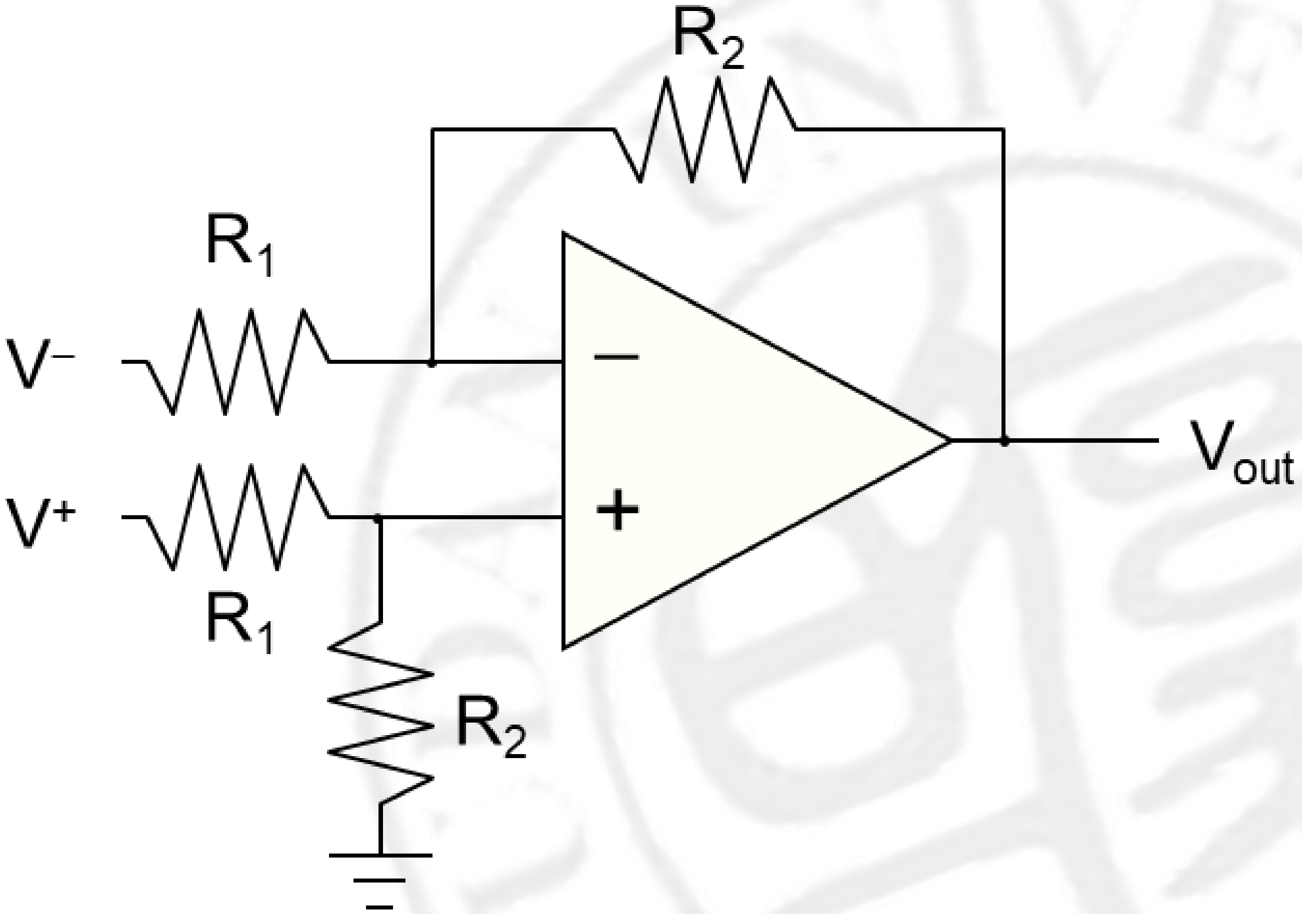


模拟加权减法器

- 运放正端输入

  $V_{\text{node}} = V^{+}R_2/(R_1 + R_2)$

- 运放负端输入
- $I_f = (V^{-} - V_{\text{node}})/R_1$
- $V_{\text{out}} = (R_2/R_1)(V^{+} - V^{-})$

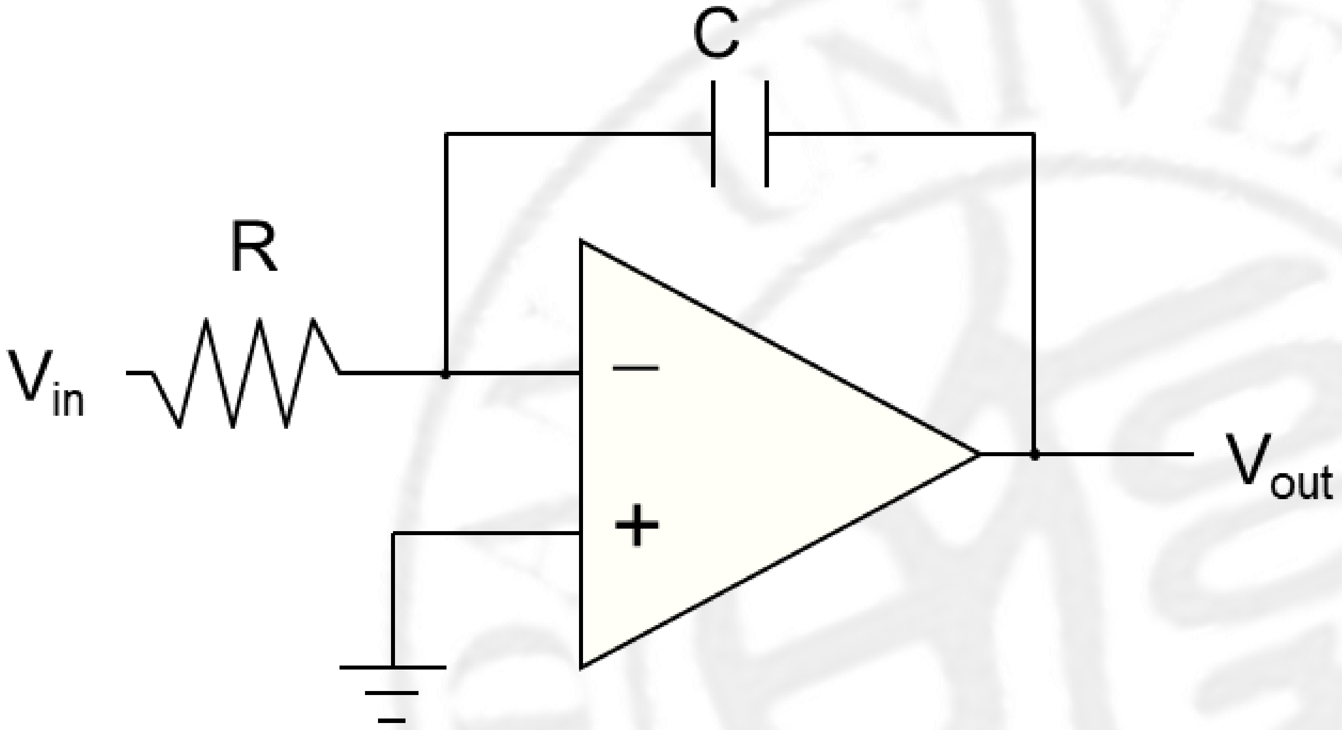


积分器（低通滤波器）

- $I_f = V_{in}/R$
- $C \cdot dV_{cap}/dt = V_{in}/R$

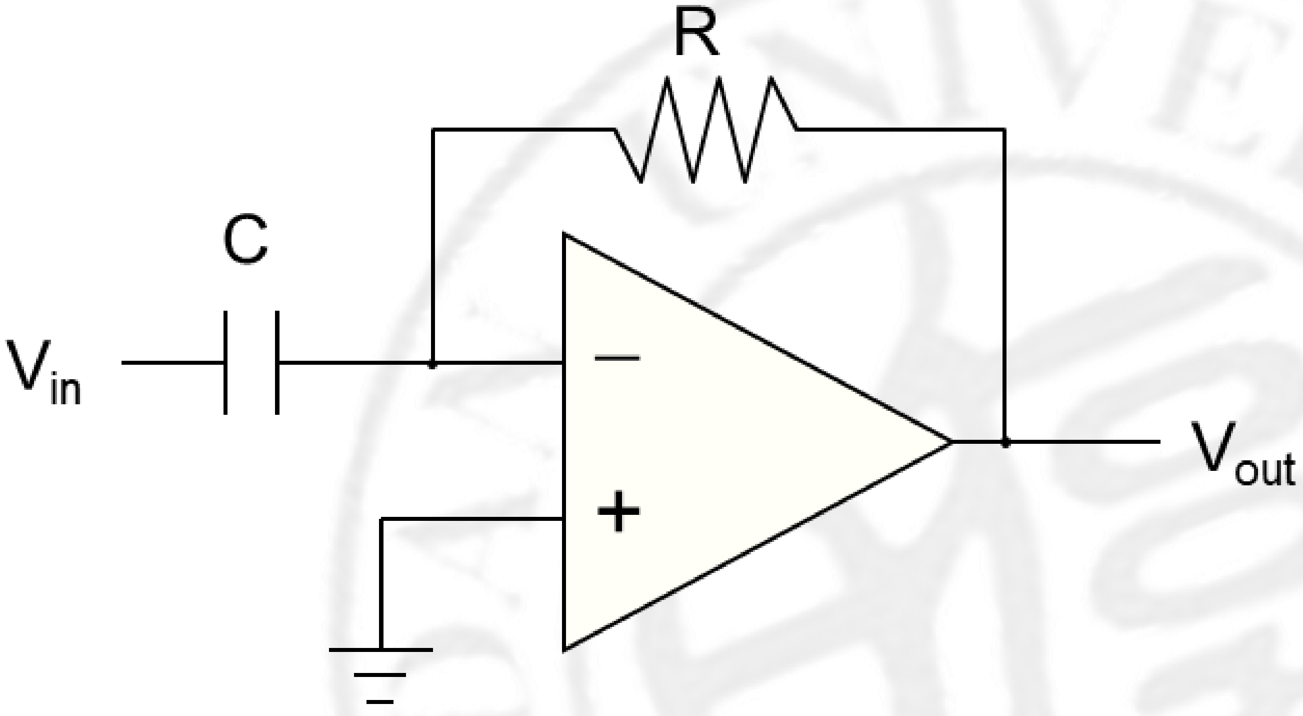
$$V_{\text{out}} = -\frac{1}{RC}\int V_{in}dt$$

- 将电容的等效阻值1/sC代入反向放大器

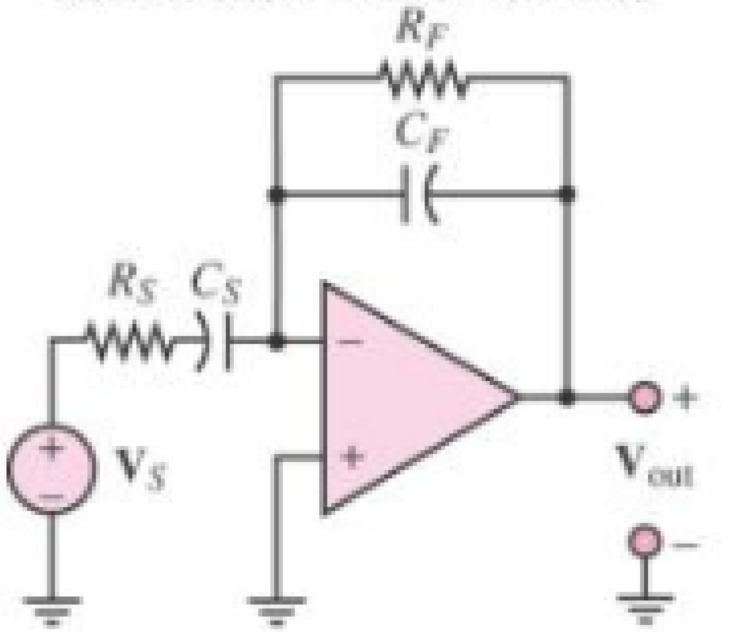


微分器（高通滤波器）

- $Q = CV$
- $I_{cap} = dQ/dt = C \cdot dV/dt$
- $V_{out} = -I_{cap}R = -RC \cdot dV/dt$
- 将电容的等效阻值1/sC
  代入反向放大器



带通滤波器



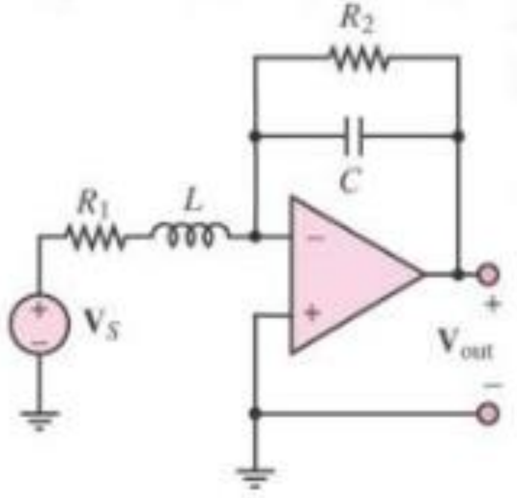
$$\frac{V_{out}}{V_S}(j\omega) = -\frac{Z_F}{Z_S}$$

$$Z_S = R_S + 1/j\omega C_S$$
$$= (1 + j\omega C_S R_S)/j\omega C_S$$

$$Z_F = R_F \parallel C_F$$
$$= \frac{R_F}{1 + j\omega C_F R_F}$$

$$\frac{V_{out}}{V_S}(j\omega) = -\frac{j\omega C_s R_F}{(1 + j\omega C_S R_S)(1 + j\omega C_F R_F)}$$

二阶低通滤波器



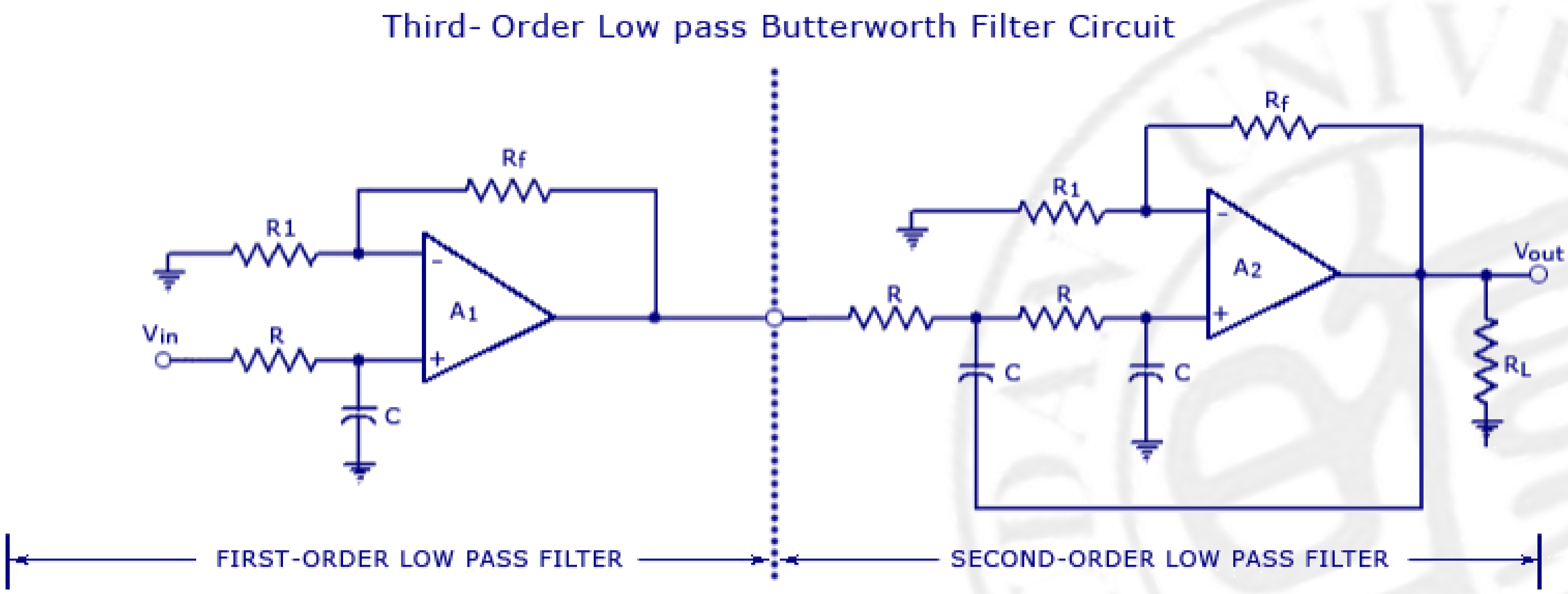
R_1, R_2, C and L are specially chosen so that:
$\omega_0 = 1/(CR_2) = R_1/L$.

$$H_v(j\omega=)\frac{V_{out}}{V_S}(j\omega)=-\frac{R_2}{R_1(1+j\omega/\omega_0)^2}$$

Above ω_0, H_v is reduced by a factor of **100** for a ten fold increase in ω (40dB drop per decade)

First-order filter: H_v is reduced by a factor of **10** for a ten fold increase in ω (20dB drop per decade)

高阶低通滤波器


Third- Order Low pass Butterworth Filter Circuit
Rf
R1
A1
Vin
R
C
Rf
R1
A2
Vout
R
R
C
C
RL
FIRST-ORDER LOW PASS FILTER
SECOND-ORDER LOW PASS FILTER

Pulse Width Modulator / 比较器

- Output changes when
  - V_{in} ~= V_{pot}
- Potentiometer used to vary duty cycle