電子電路入門導論

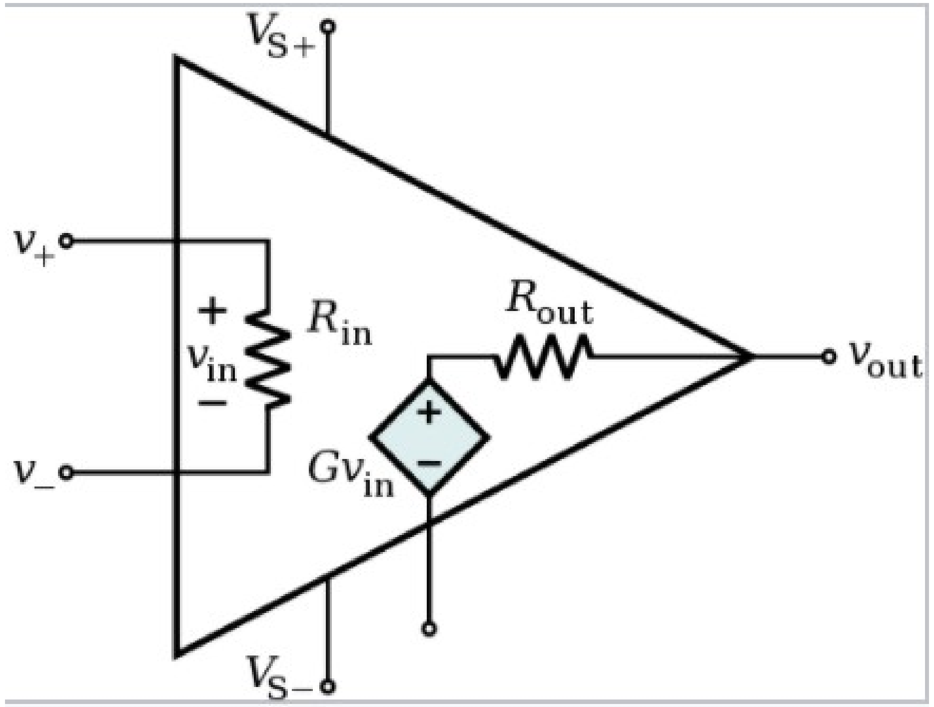
運算放大器 - OP Amp

成功大學資訊工程系

蘇文鈺

此資料圖片取自網路

運算放大器的簡易等效模擬模型



An equivalent circuit of an operational amplifier that models some resistive non-ideal parameters.

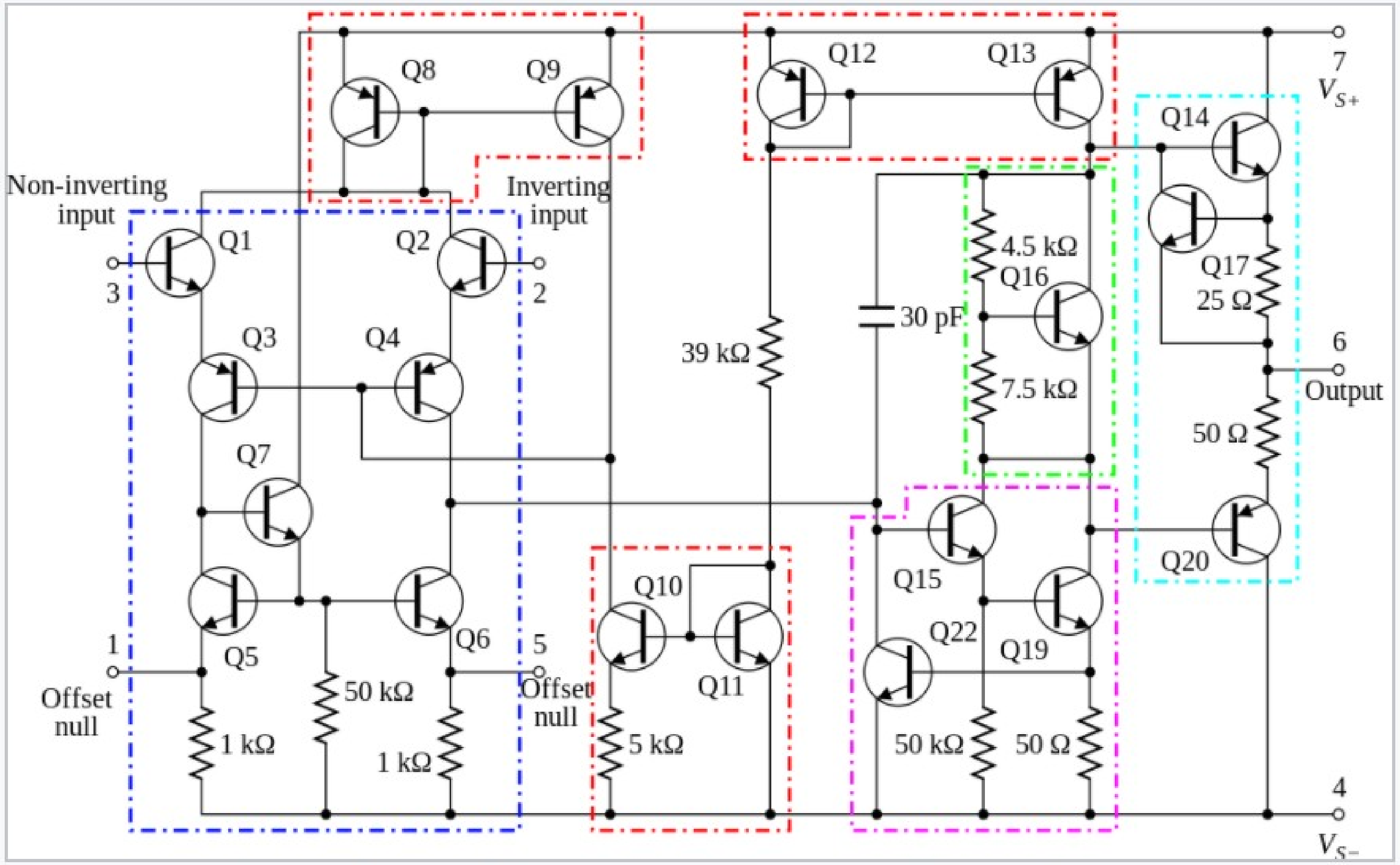
理想的運算放大器

- Infinite open-loop gain , G = v_{out} / v_{in}
- Infinite input impedance R_{in}, that is zero input current
- Zero input offset voltage
- Infinite output voltage range
- Infinite bandwidth with zero phase shift and infinite slew rate
- Zero output impedance R_{out}
- Zero noise
- Infinite common-mode rejection ratio (CMRR)
- Infinite power supply rejection ratio.

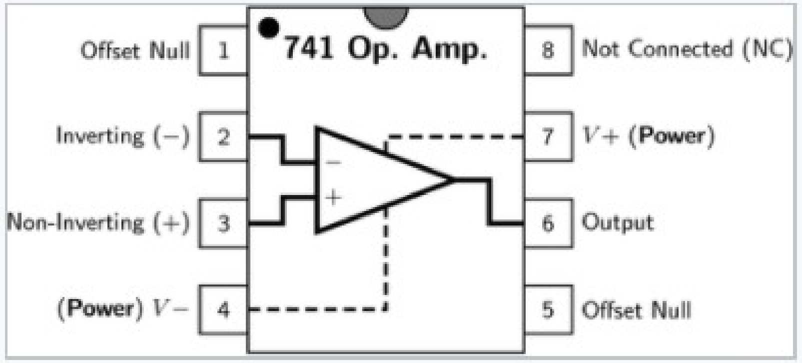
名詞解釋

- Offset voltage: 偏離 0 Volt 或是 Vcc/2 的電壓。
- Bandwidth: 頻寬，元件可以處理的頻率範圍。
- Phase shift: 相位的位移，以三角函數來解釋，就是函數內的角度差異。
- Slew rate: 訊號電壓上升可以達到的最大速度
- CMRR: 消除共模雜訊干擾的能力
- PSRR: 消除電源雜訊干擾的能力

741 運算放大器

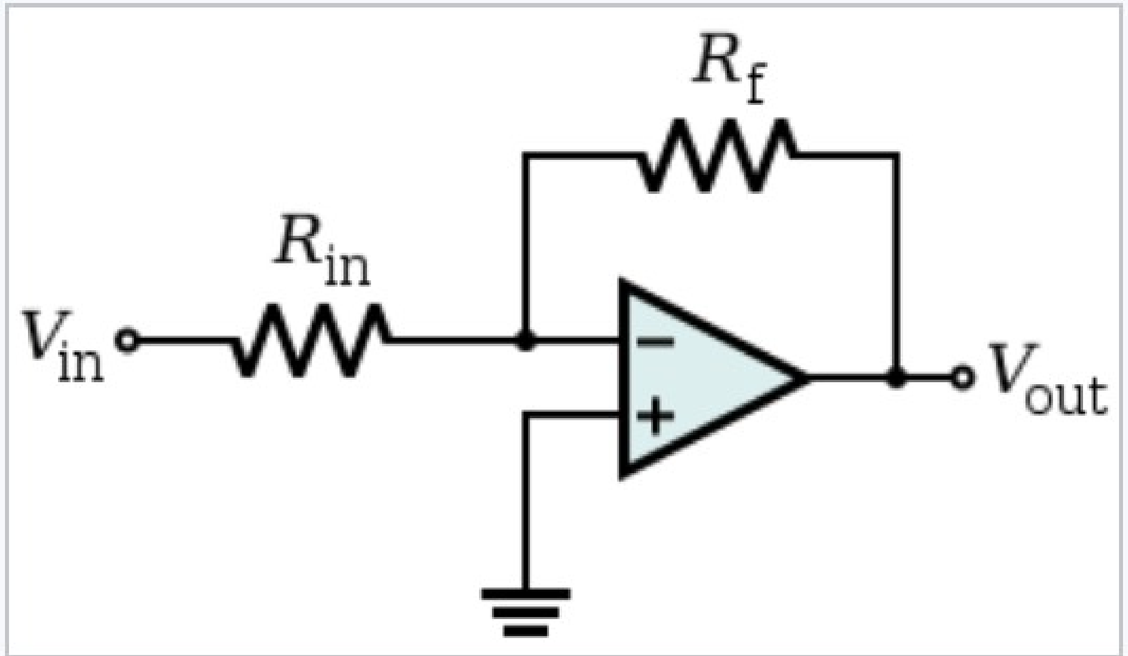


A component-level diagram of the common 741 op amp. Dotted lines outline: current mirrors; differential amplifier; class A gain stage; voltage level shifter; output stage.



DIP pinout for 741-type operational amplifier

Linear Amplifier – Inverting Amplifier

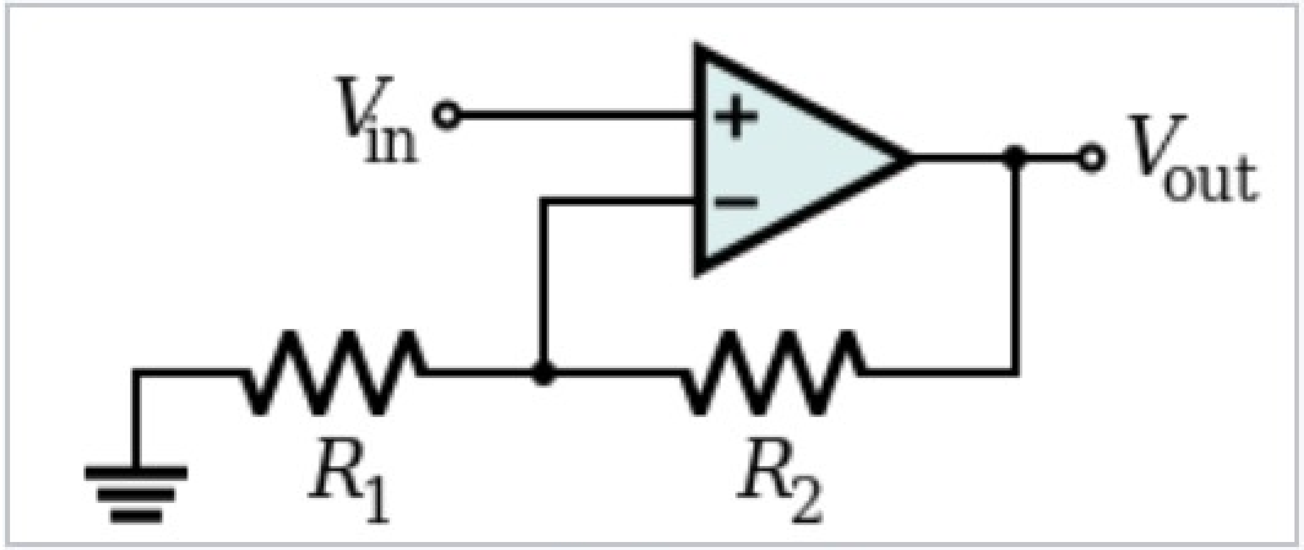


An op amp connected in the inverting amplifier configuration

$$V_{out} \approx -V_{in} \frac{R_f}{R_{in}}.$$

How?

Linear Amplifier – Non-inverting Amplifier

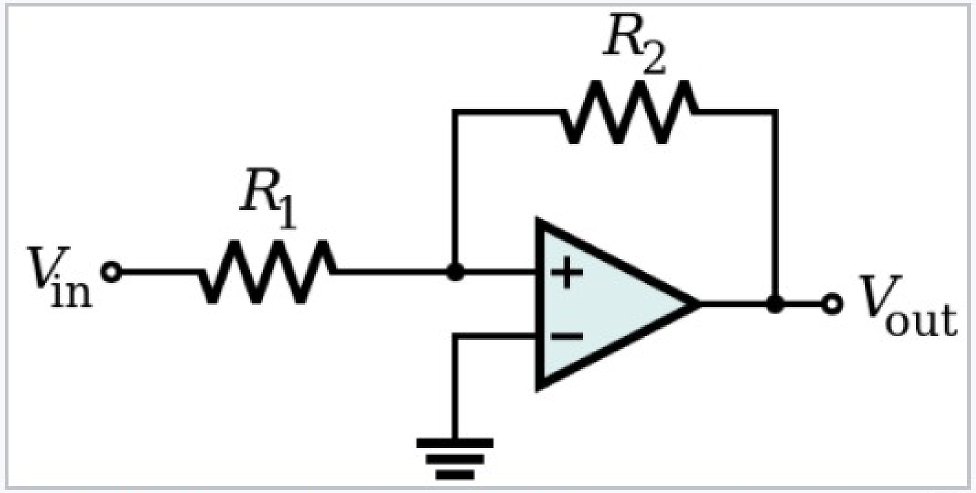


An op amp connected in the non-inverting amplifier configuration

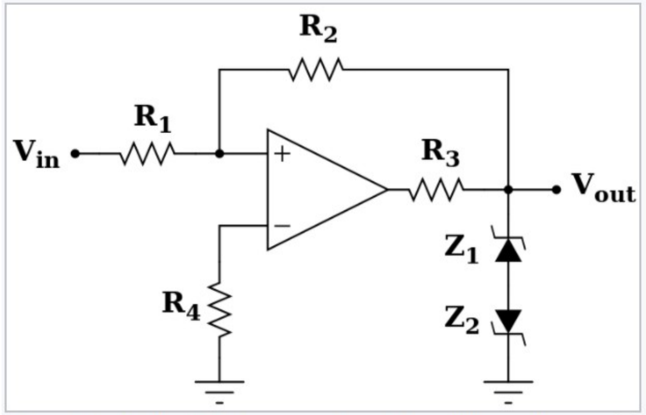
$$V_{out} \approx \frac{V_{in}}{\beta} = \frac{V_{in}}{\frac{R_1}{R_1+R_2}} = V_{in}\left(1+\frac{R_2}{R_1}\right).$$

How?

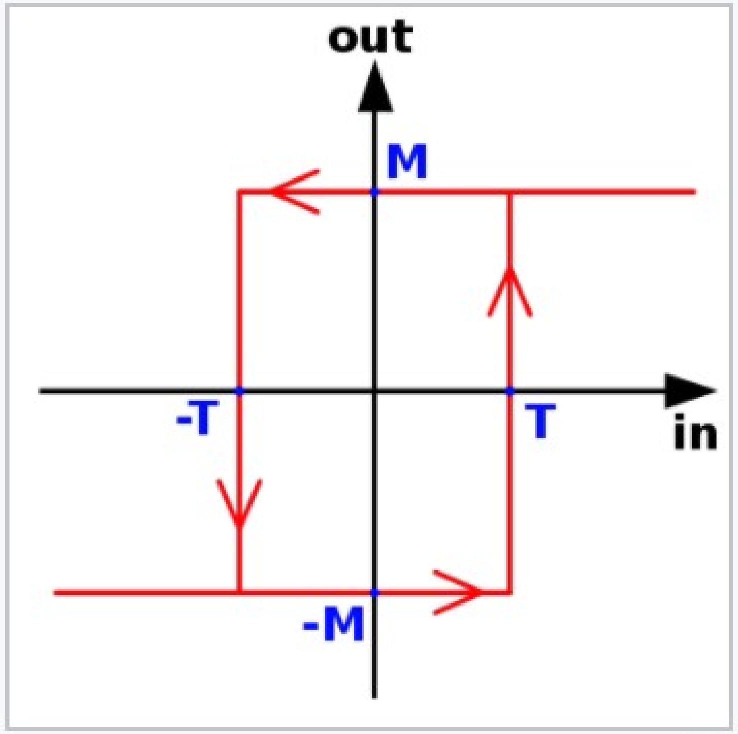
Comparator/Schmitt trigger (Positive feedback)



Schmitt trigger implemented by a non-inverting comparator



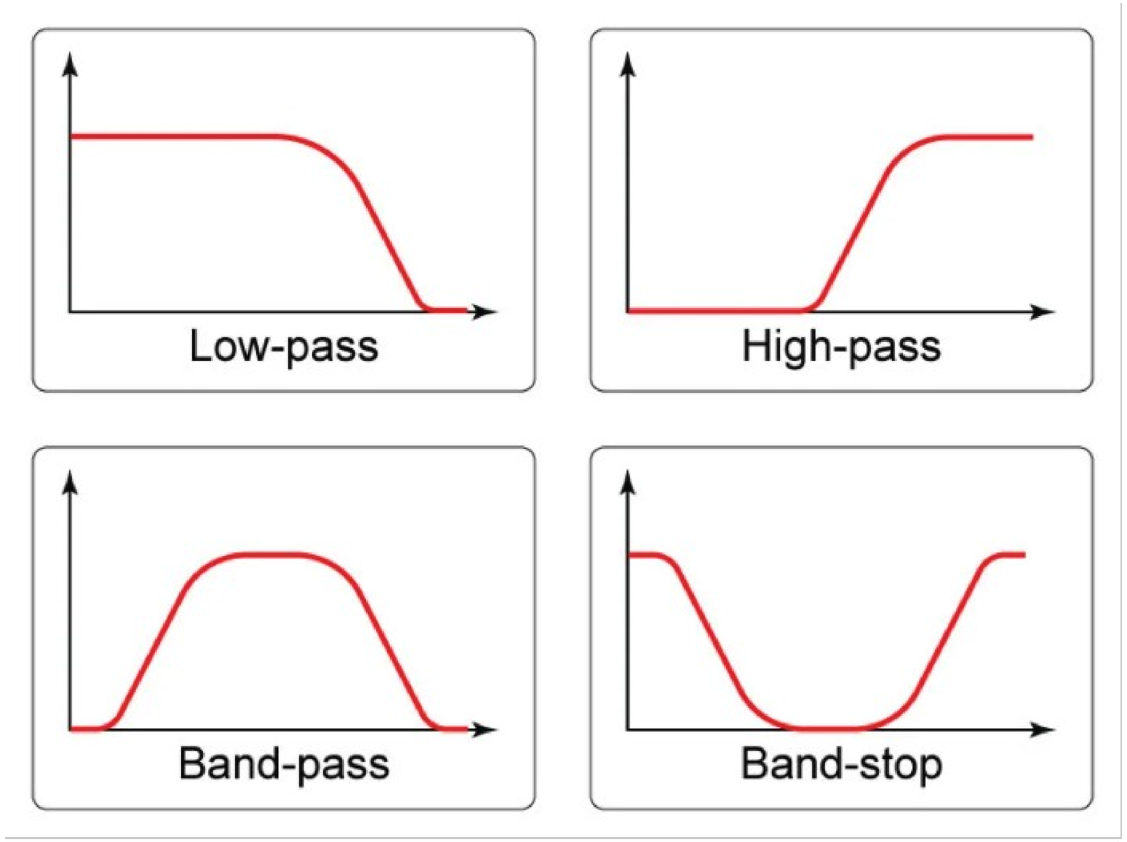
A practical Schmitt trigger configuration with precise thresholds



Typical transfer function of a non-inverting Schmitt trigger like the circuit above.

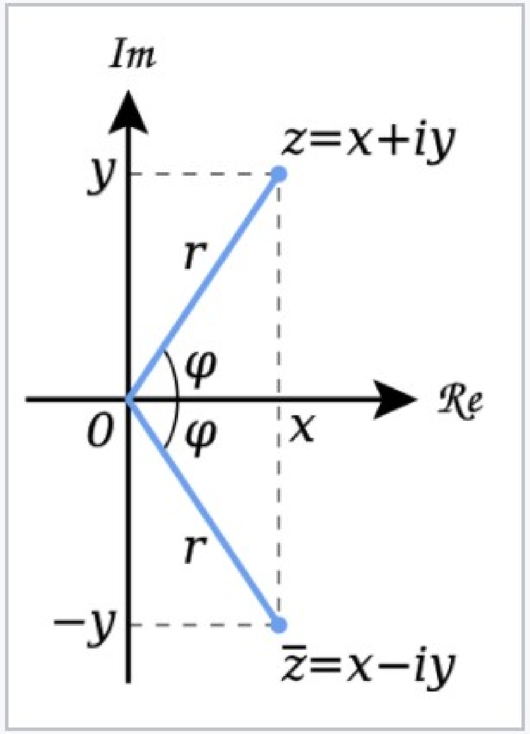
主動濾波器（filter）

- 濾除不需要的頻段的訊號
  - Low Pass
  - High pass
  - Band pass
  - Notch
  - https://www.allaboutcircuits.com/technical-articles/low-pass-filter-tutorial-basics-passive-RC-filter/



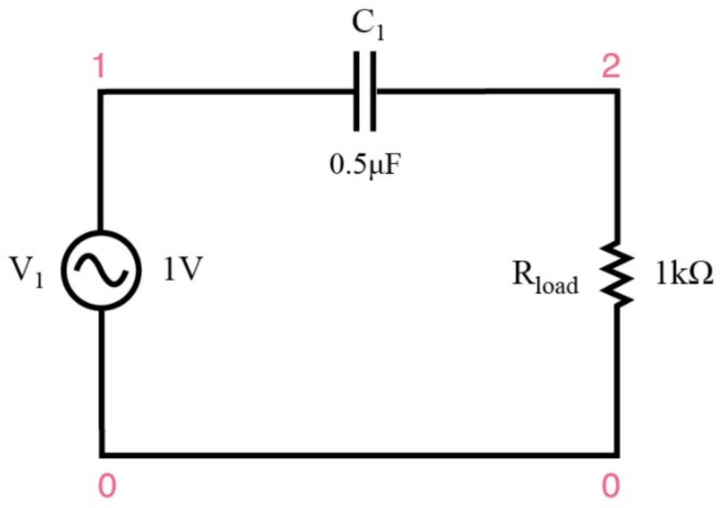
Complex Number (複數) and Impedance (阻抗)

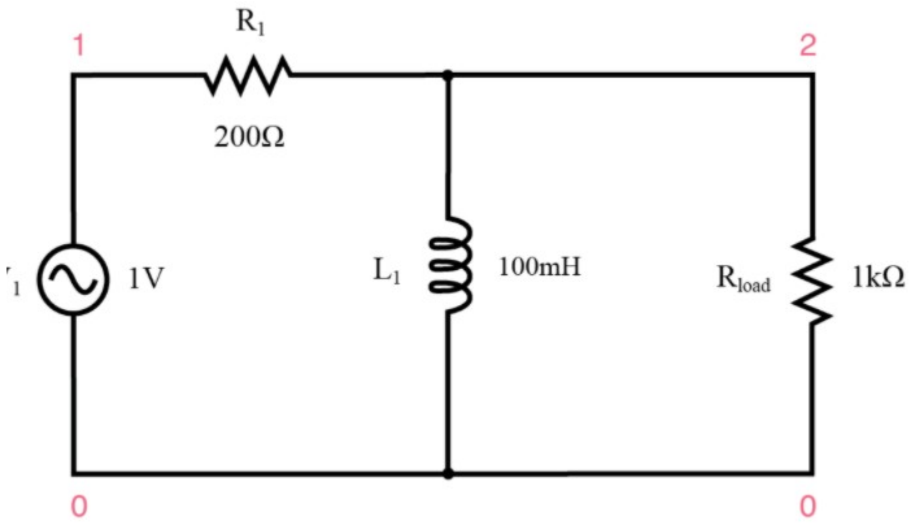
- https://en.wikipedia.org/wiki/Complex_number
- 電容的阻抗＝
  - C 為電容值
- 電感的阻抗＝
  - L 為電感值



An illustration of the complex plane. The real part of a complex number $z = x + iy$ is x, and its imaginary part is y.

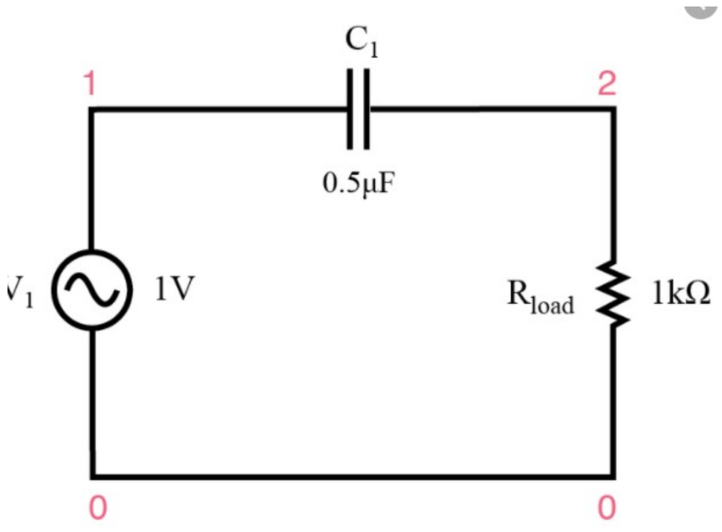
計算濾波器的頻率響應

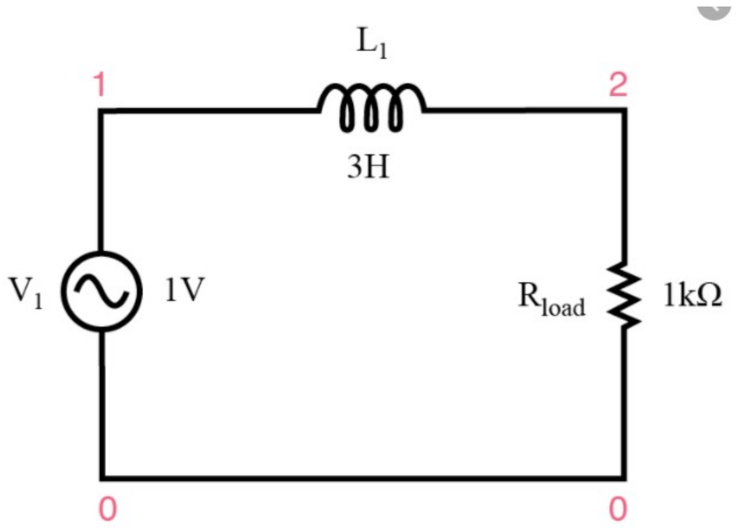




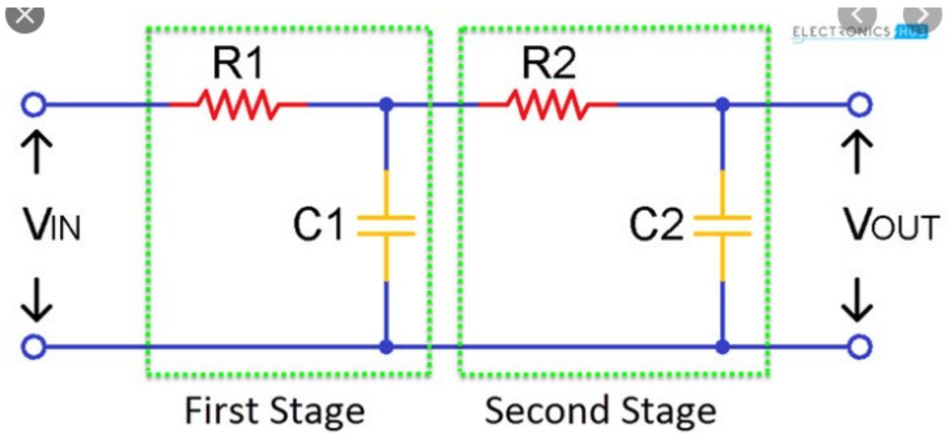
讓我們來發揮複數（Complex Number）的用處，
但是把他的基本原理與由來留給工程數學吧！

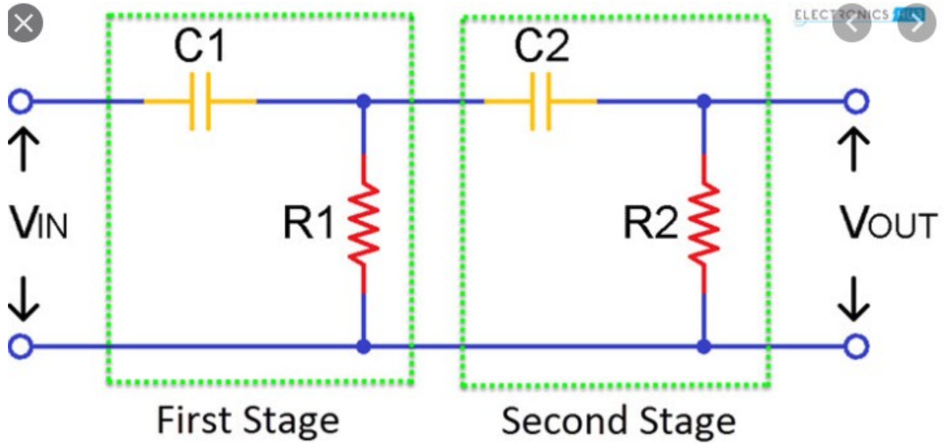
换一下位置如何？





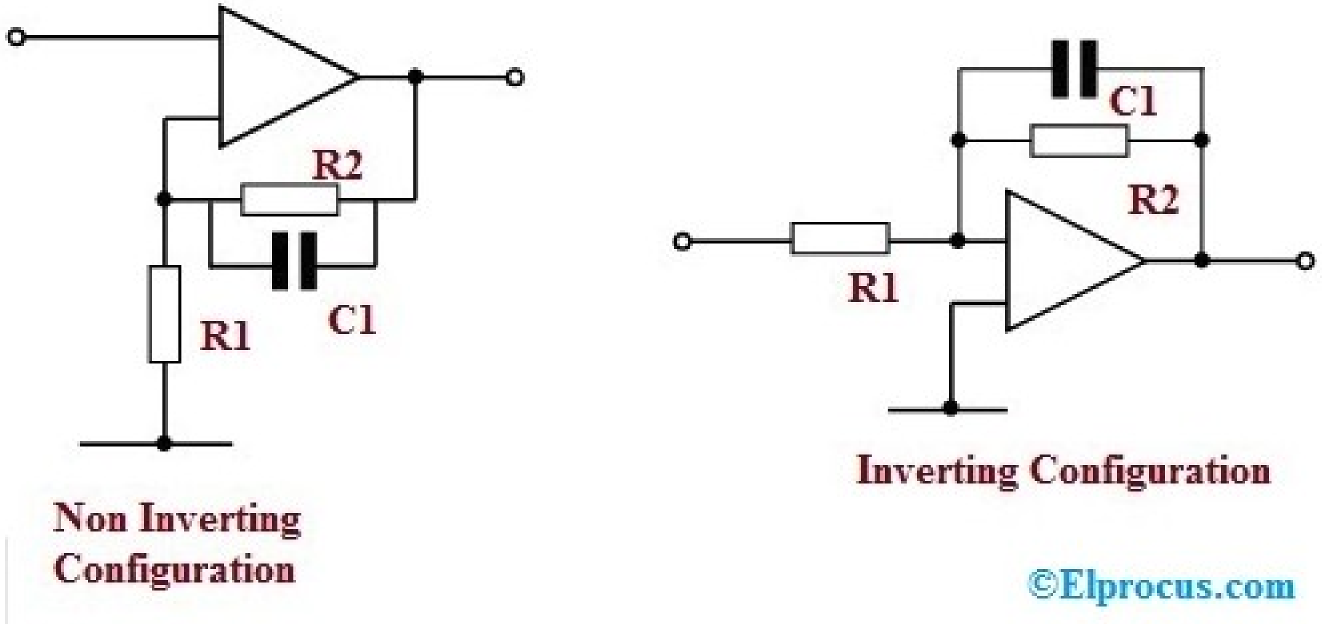
2nd order LPF/HPF





主動式的一階低通濾波器

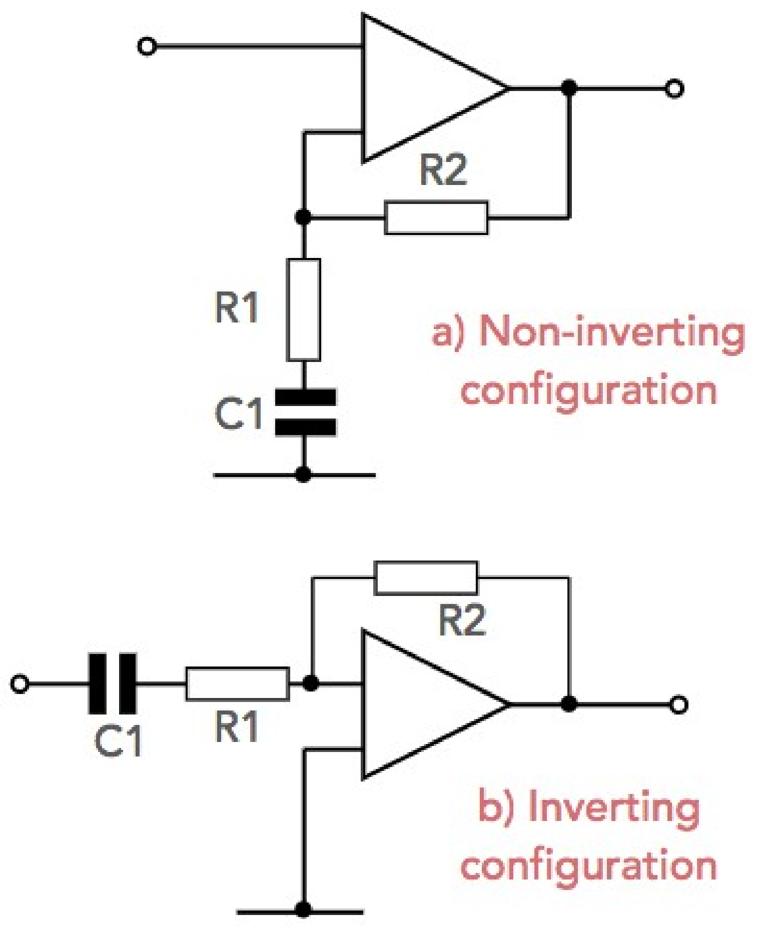
- https://www.elprocus.com/what-is-low-pass-filter-lpf-using-op-amp-applications/



只要都換成阻抗，其計算與 P.6 計算增益的方式沒有兩樣！

主動式的一階高通濾波器

- https://www.electronics-notes.com/articles/analogue_circuits/operational-amplifier-op-amp/high-pass-active-filter.php



Single pole high pass op amp filters

Butterworth filter

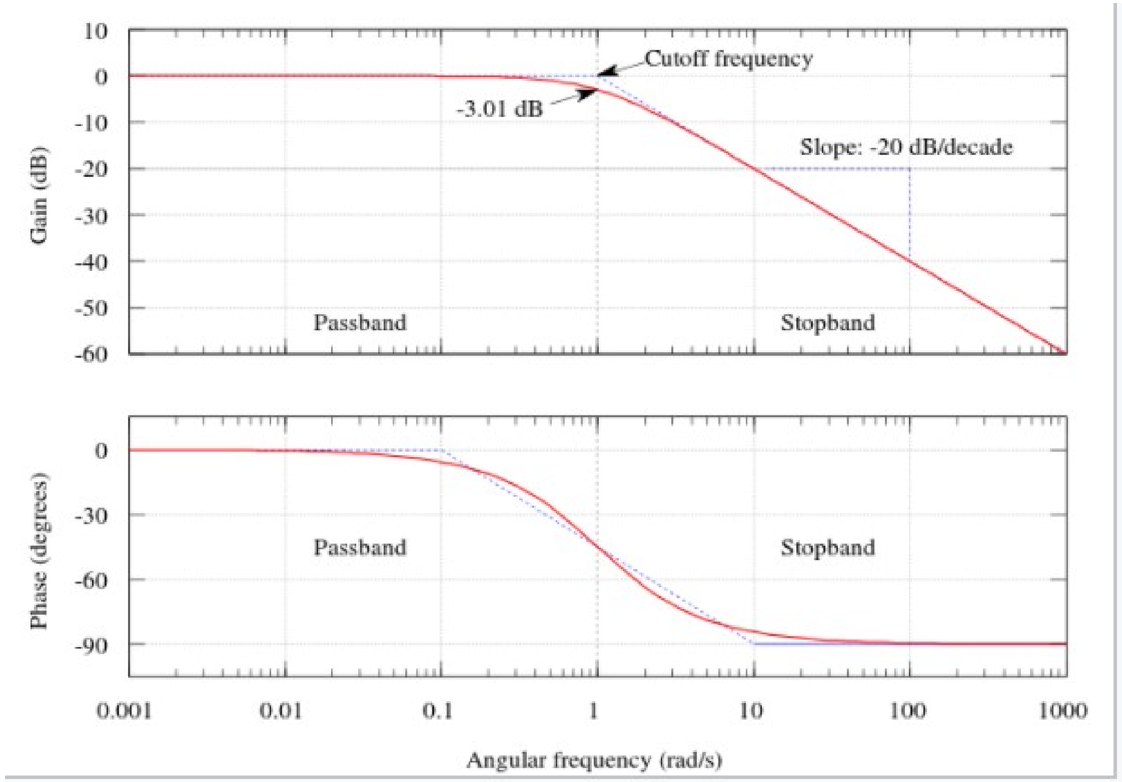
- Butterworth stated that:“An ideal electrical filter should not only completely reject the unwanted frequencies but should also have uniform sensitivity for the wanted frequencies”. 雖然這個是不可能的。
  - https://en.wikipedia.org/wiki/Butterworth_filter
- 因為計算公式的不同，filter 的特性也不一樣，Butterworth 只是其中一種，它比較常用的原因是“**maximally flat magnitude**”或是“**equal ripple**”。
- 公式：

$$G(\omega) = \frac{1}{\sqrt{1+\omega^{2n}}}$$

$$G^2(\omega) = |H(j\omega)|^2 = \frac{{G_0}^2}{1+\left(\frac{j\omega}{j\omega_c}\right)^{2n}}$$

什麼是頻率響應（frequency response）？

- 礙於先備知識，我們這裡只講 Magnitude response。
- 什麼是 **first-order**?
- 什麼是 **db**?
- 什麼是 **octave** 與 **decade**?



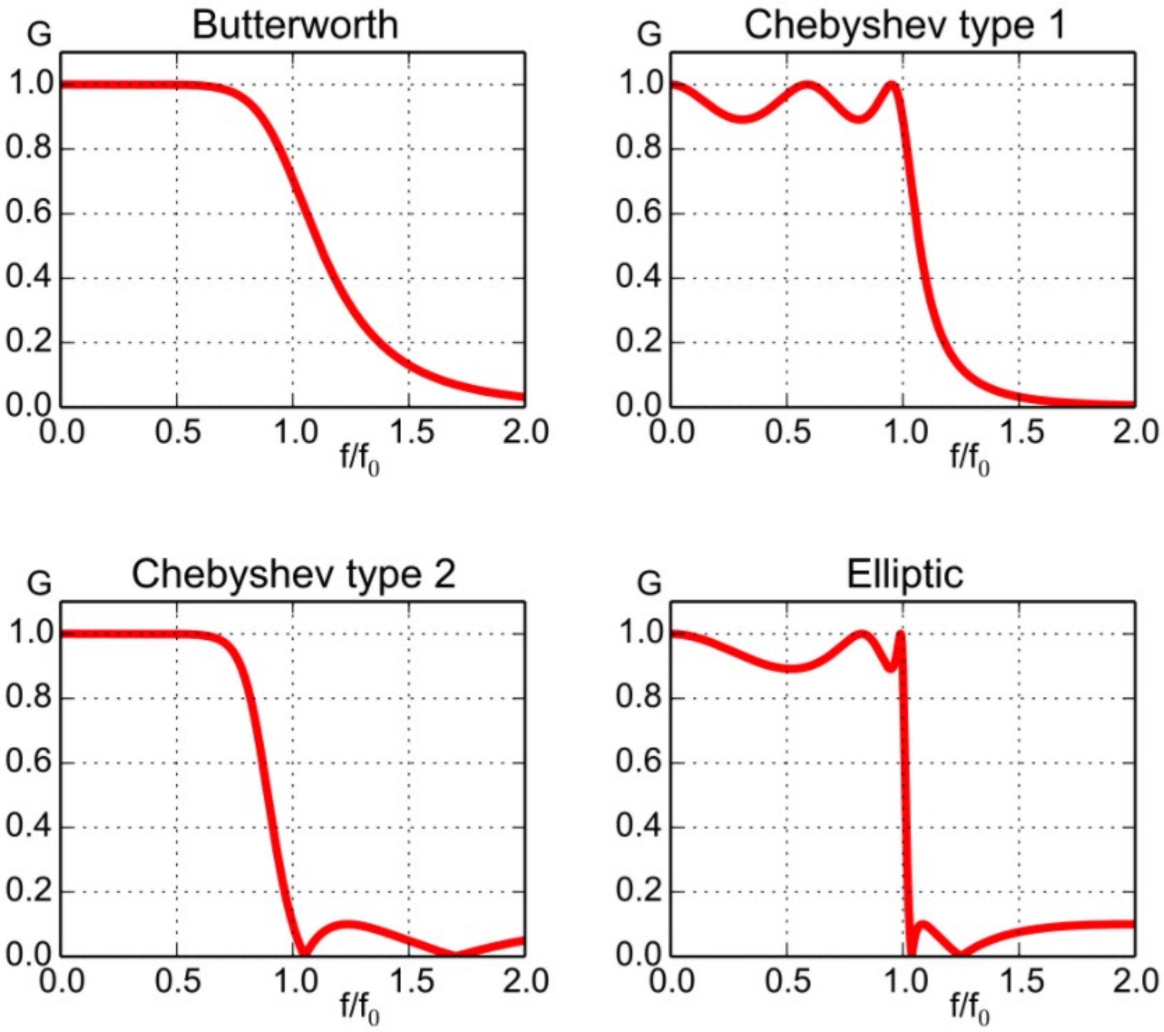
The Bode plot of a first-order Butterworth low-pass filter

如果你把 *jw* 換成 s

n	Factors of Polynomial $B_n(s)$
1	$(s+1)$
2	$(s^2+1.4142s+1)$
3	$(s+1)(s^2+s+1)$
4	$(s^2+0.7654s+1)(s^2+1.8478s+1)$
5	$(s+1)(s^2+0.6180s+1)(s^2+1.6180s+1)$
6	$(s^2+0.5176s+1)(s^2+1.4142s+1)(s^2+1.9319s+1)$
7	$(s+1)(s^2+0.4450s+1)(s^2+1.2470s+1)(s^2+1.8019s+1)$
8	$(s^2+0.3902s+1)(s^2+1.1111s+1)(s^2+1.6629s+1)(s^2+1.9616s+1)$
9	$(s+1)(s^2+0.3473s+1)(s^2+s+1)(s^2+1.5321s+1)(s^2+1.879s+1)$
10	$(s^2+0.3129s+1)(s^2+0.9080s+1)(s^2+1.4142s+1)(s^2+1.7820s+1)(s^2+1.9754s+1)$

因為還沒上過工程數學，請大家先以此為事實！

其他類型的濾波器特性



Butterworth
Chebyshev type 1
Chebyshev type 2
Elliptic
G
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.5
1.0
1.5
2.0
f/f0

實現 Butterworth 濾波器的架構之一

- Sallen-Key 架構

$$\frac{v_{\text{out}}}{v_{\text{in}}} = \frac{Z_3 Z_4}{Z_1 Z_2 + Z_3(Z_1 + Z_2) + Z_3 Z_4}$$

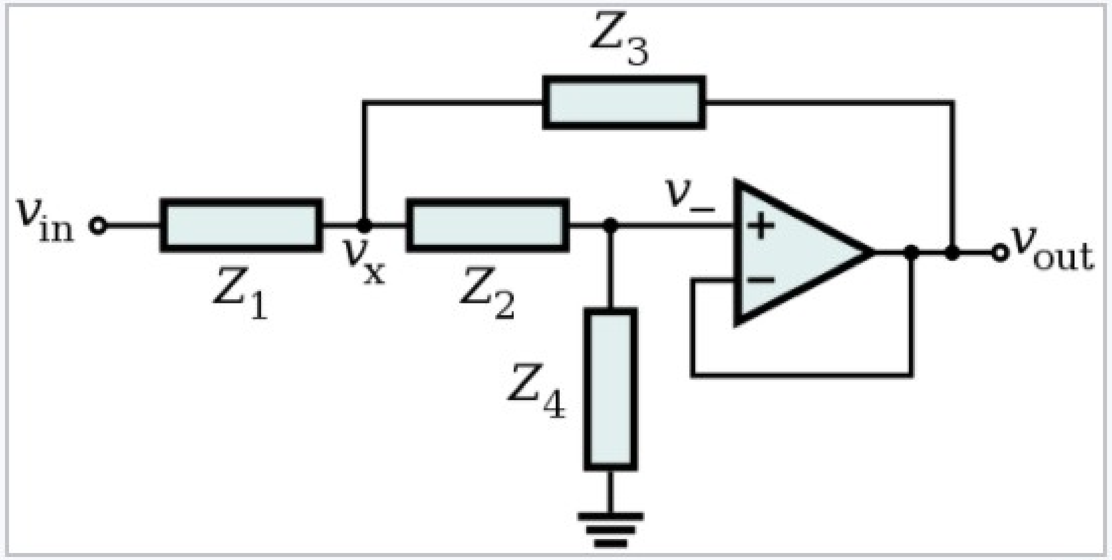


Figure 1: The generic Sallen–Key filter topology

https://www.electronics-tutorials.ws/filter/sallen-key-filter.html

Sallen-Key 低通濾波器

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

$$\omega_0 = 2\pi f_0 = \frac{1}{\sqrt{R_1 R_2 C_1 C_2}}$$

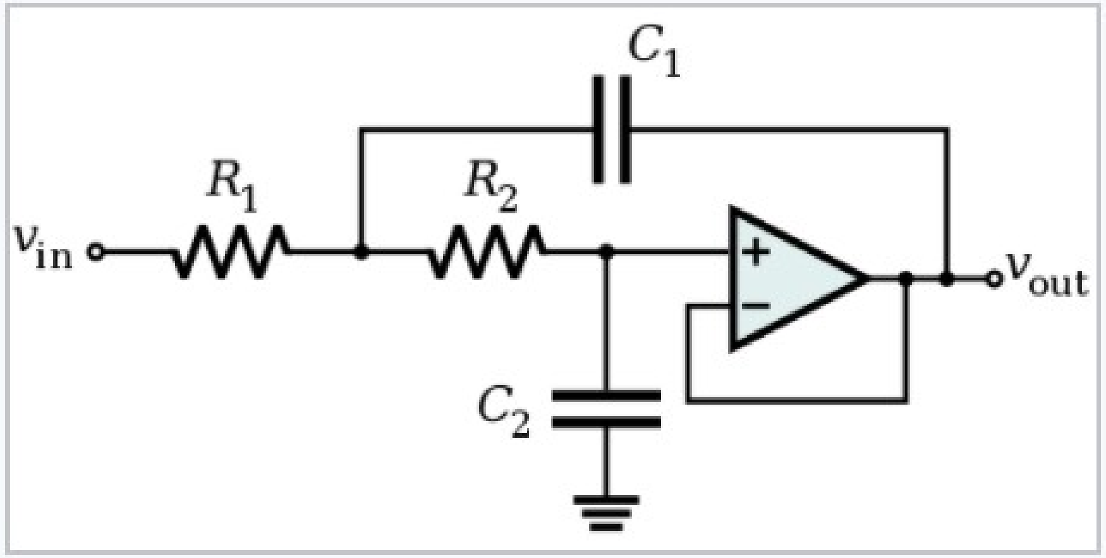


Figure 2: A unity–gain low–pass filter implemented with a Sallen–Key topology

$$2\alpha = 2\zeta\omega_0 = \frac{\omega_0}{Q} = \frac{1}{C_1}\left(\frac{1}{R_1} + \frac{1}{R_2}\right) = \frac{1}{C_1}\left(\frac{R_1 + R_2}{R_1 R_2}\right)$$

highpass 濾波器與 lowpass 濾波器的不同只不過把元件的位置調換，而 bandpass 與 bandstop 則是可以把一個 highpass 與一個 lowpass 串接起來

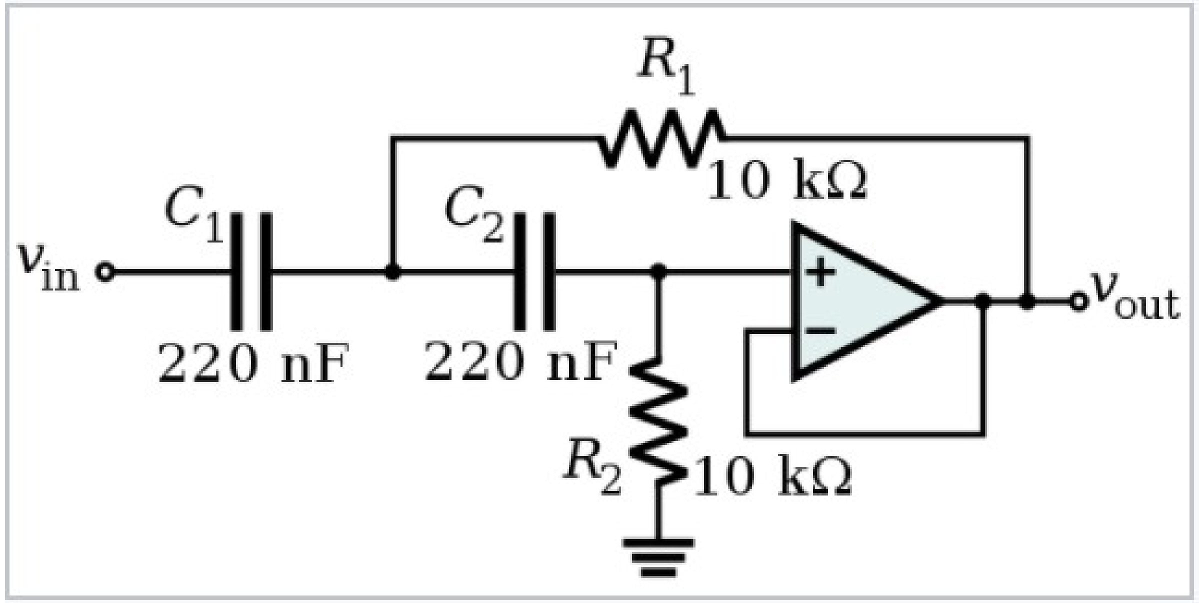


Figure 4: A specific Sallen–Key high-pass filter with f_c = 72 Hz and Q = 0.5

https://www.electronics-tutorials.ws/filter/band-stop-filter.html

Quiz(下週)

- 正反向線性放大器的增益的計算
- lowpass 濾波器的參數計算

實做 (下下周)

- 請備妥材料
  - Op 741 若干顆
  - 可變電阻與電容若干個
    - 以你認為適當的數值為準
  - 麵包板一片
    - 請買有附導線者
  - 鱷魚夾連接線兩包
  - 杜邦連接線 (公的)
- 驗收
  - 線性放大器
  - 高通濾波器
    - X frequency = 10~15KHz

測驗（下下週）

- 基於 Quiz 更為深入的計算問題，包含其他種類的濾波器

補充資料

- https://www.electronics-tutorials.ws/opamp/opamp_1.html
  - 這個已經包含課堂會用到的了。此篇下面有其他連結，部分會需要看。請看 1~9 即可。
- https://www.ti.com/lit/an/sboa093a/sboa093a.pdf
  - 說明很清楚，公式很多，但是我真的建議聽我上原理就好，不要套公式，雖然套公式在考試的時候很好用。看前四章就可以。
  - 54 頁之後很多範例可以用
- https://www.electronics-tutorials.ws/filter/sallen-key-filter.html
  - 2^{nd} order 的濾波器，其實通常都夠用了。也有公式考試時可以套。
- 影片：
  - https://www.youtube.com/watch?v=lJDjWZqhpVc&list=RDCMUC4a-Gbdw7vOaccHmFo40b9g&start_radio=1&t=5
  - https://www.youtube.com/watch?v=Nnp42W67R0Y
  - https://www.youtube.com/watch?v=kYChLRKpMA0