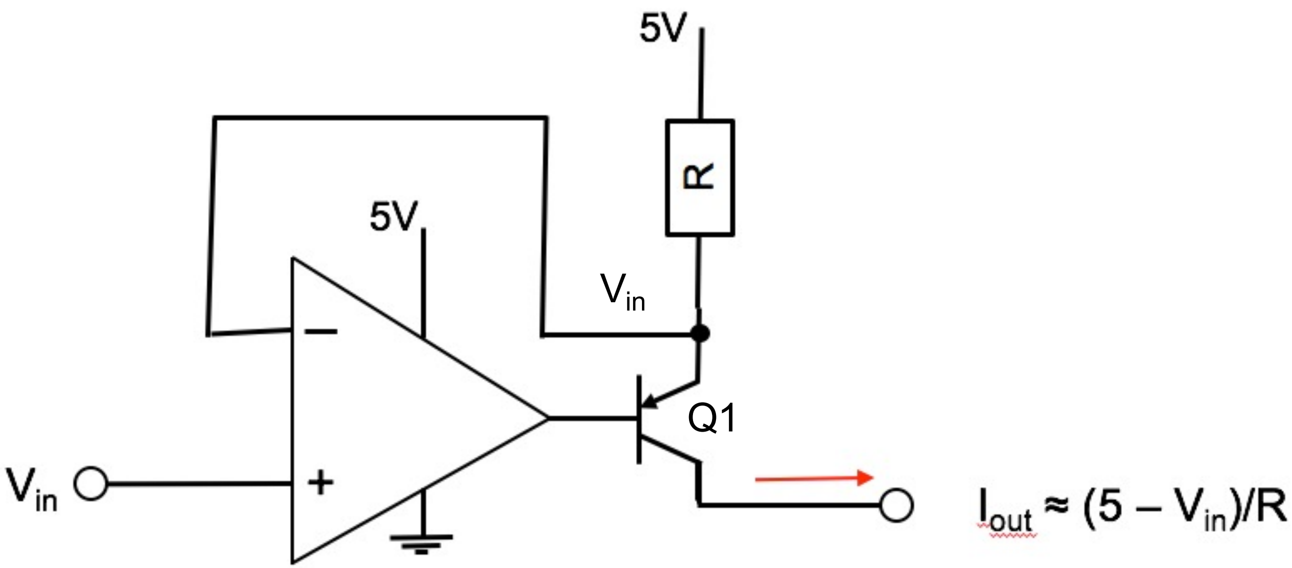
Lecture 4

Applications of Operational Amplifiers

Prof Peter YK Cheung
Imperial College London

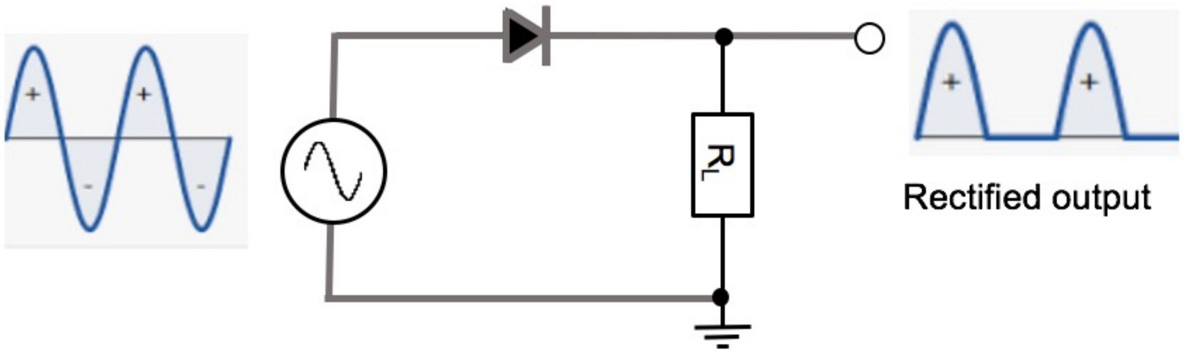
URL: www.ee.ic.ac.uk/pcheung/teaching/EE2_CAS/
E-mail: p.cheung@imperial.ac.uk

Voltage to current converter

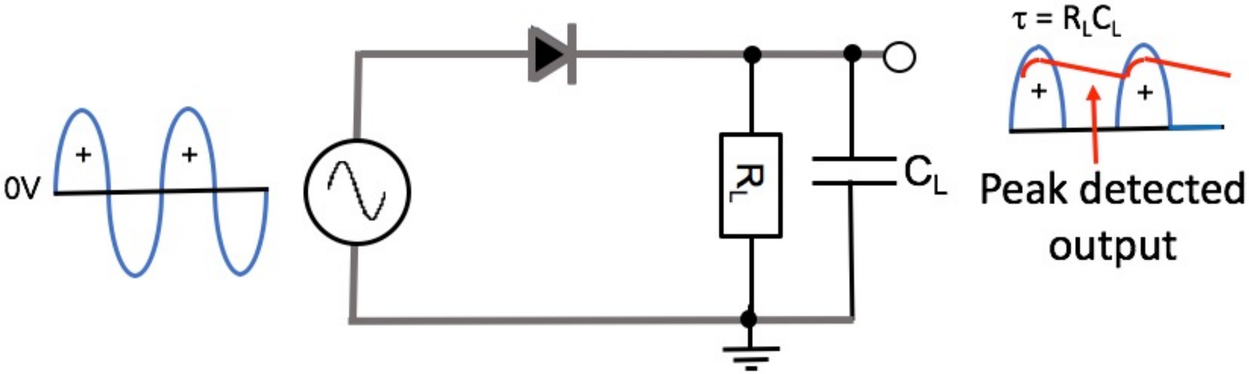


- PNP transistor Q1 must be in linear region
- Op-amp forces V- = Vin
- R (with 5V) determines the current as $I_R = (5 - V_{in})/R$
- Assume no current flows into input of op-amp
- $I_C = I_E - I_B$, assume current gain $\beta >> 1$, $I_C \approx I_E \approx I_R$
- Can use FET or MOSFET in place of BJT

Half-wave rectifier & Peak detector

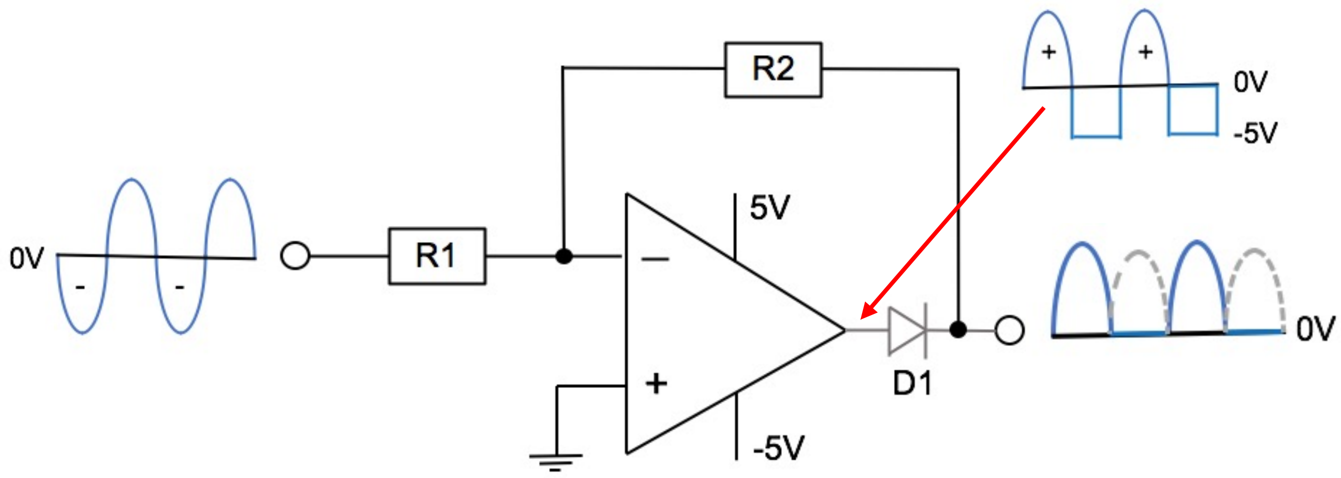


- Diode and resistor – simple half-wave rectifier
- Commonly used in power electronics or and multimeters

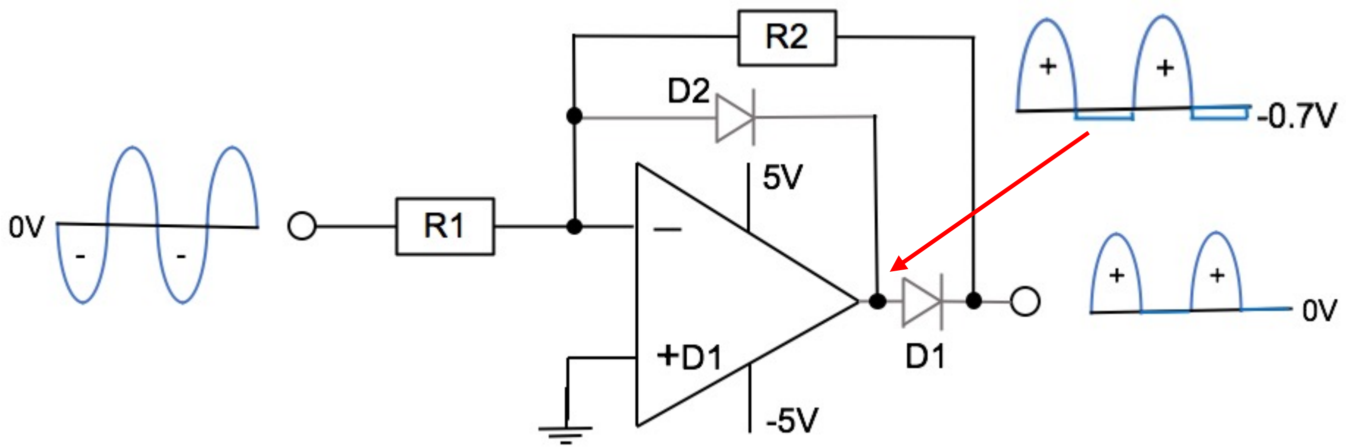


- C_L charges to V_{in} peak – V_D
- Diode prevents C_L discharging when V_{in} drops
- R_L discharges capacitor with time constant R_LC_L
- CL charges again on the positive cycle

Rectifier with op-amp buffering

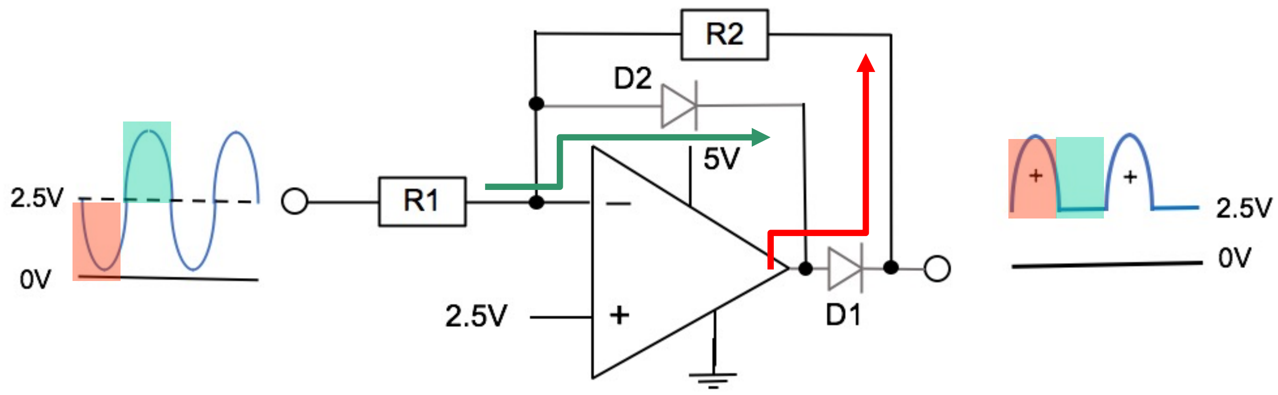


- Assume R1 = R2
- Negative cycles result in an inverting amplifier with gain = -1
- Op-amp drives output with low impedance
- Positive cycles, op-amp isolated from output
- Poor full-wave rectification



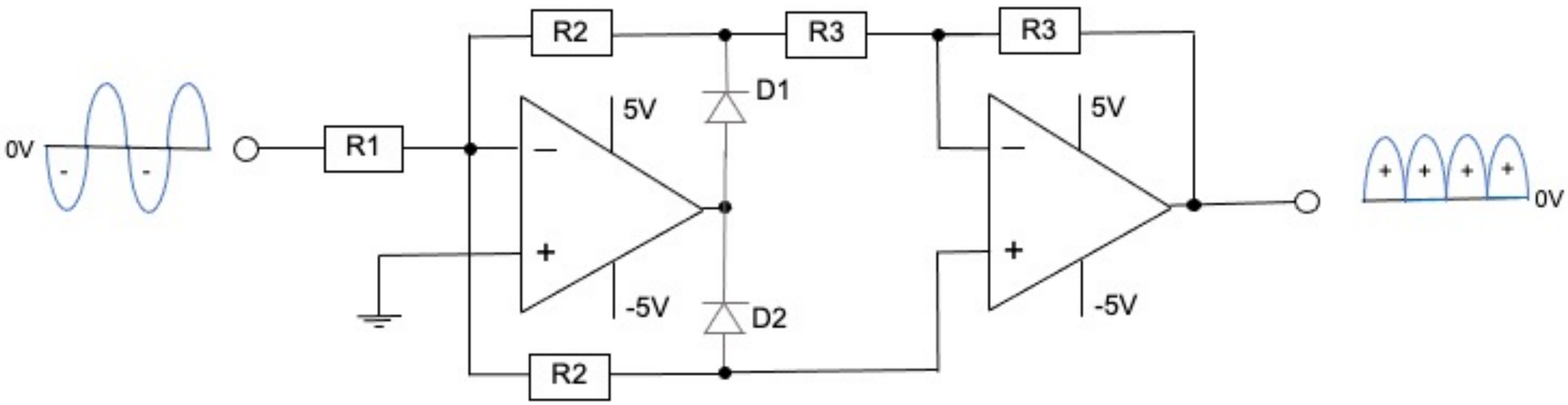
- D1 provides feedback path for negative input cycles
- D2 provides feedback path for positive input cycles
- Op-amp operating throughout entire cycle

Single power supply "rectifier"



- Single power supply rectifier is implemented by shifting the reference voltage to ½ V_{DD}

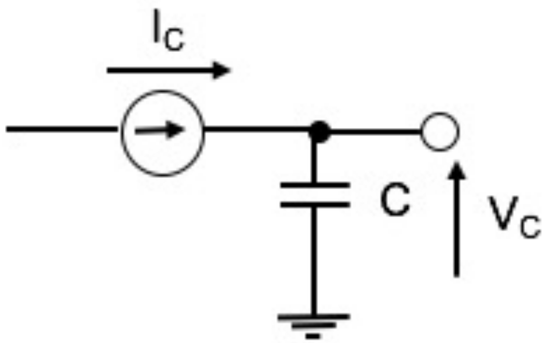
Full-wave rectifier

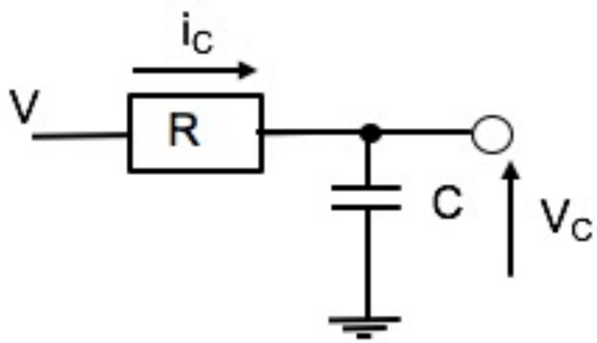


- Precision full-wave rectifier with two op-amps
- Op-amp 1 provides two separate half of the rectified signals
- Op-amp 2 sums two half cycles together

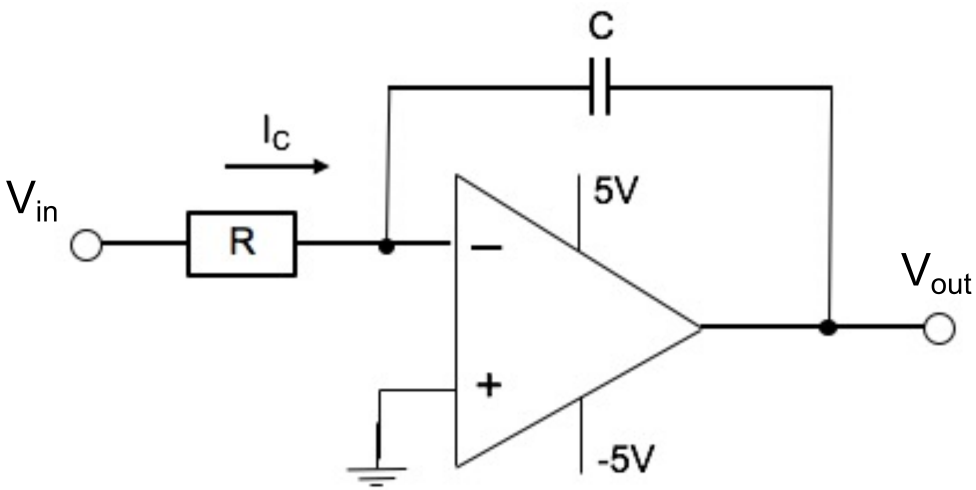
Integrator

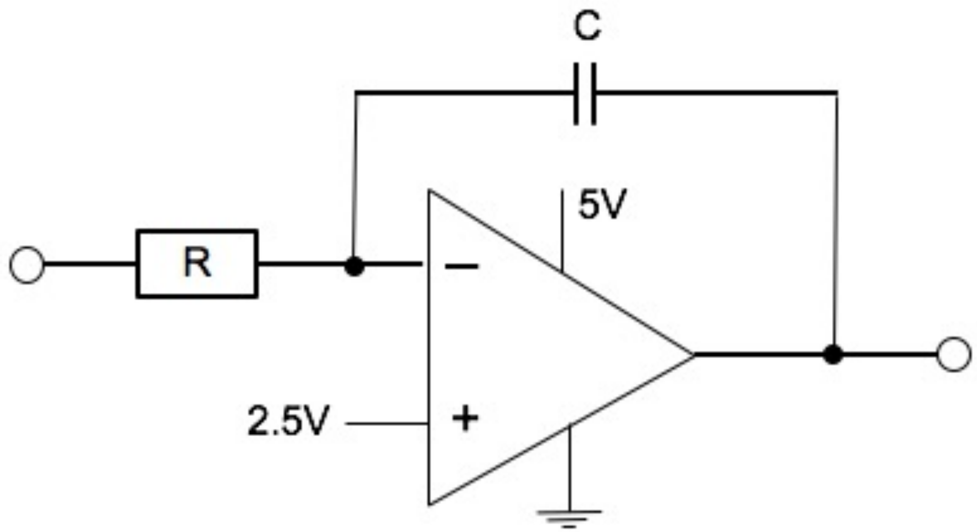
- $i_C = C\frac{dV_C}{dt} \Rightarrow V_C = \frac{1}{C}\int i_C dt + V_C(0)$





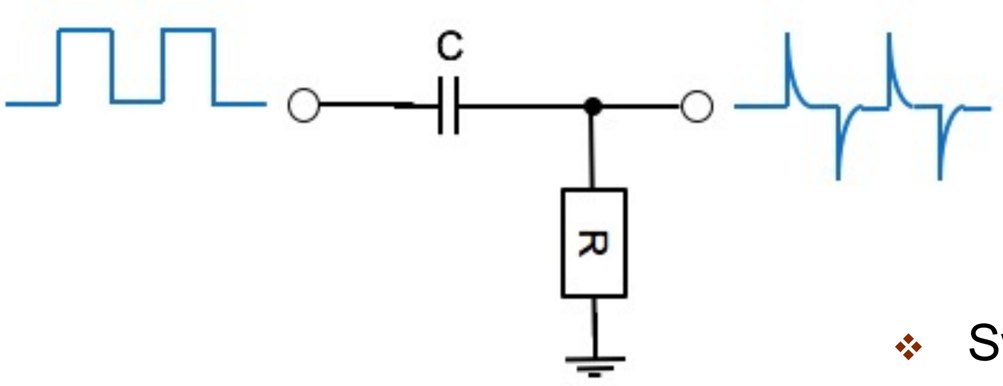
- I_C changes with V_C
- V_C is an exponential rise function (not perfect integral)
- Constant I_C, $V_C = \frac{i_C}{C}t + V_C(0)$



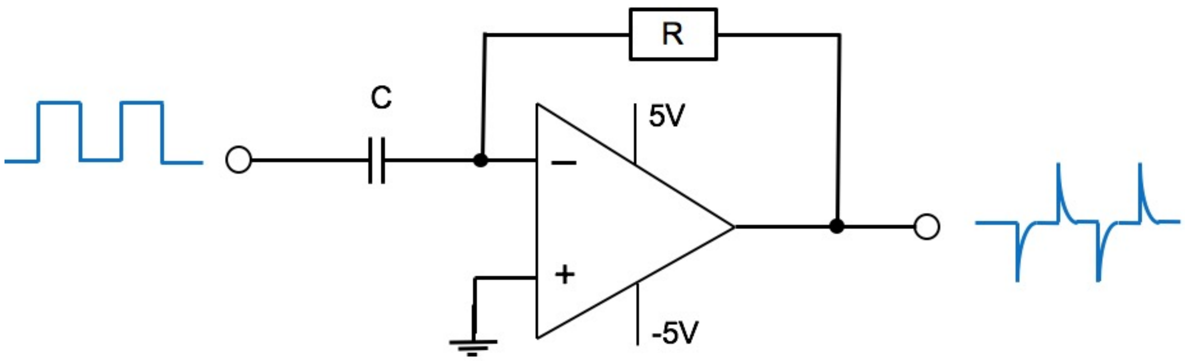


- $v_{out} = -\frac{V_{in}}{RC}t + V_C(0)$
- Single supply operation

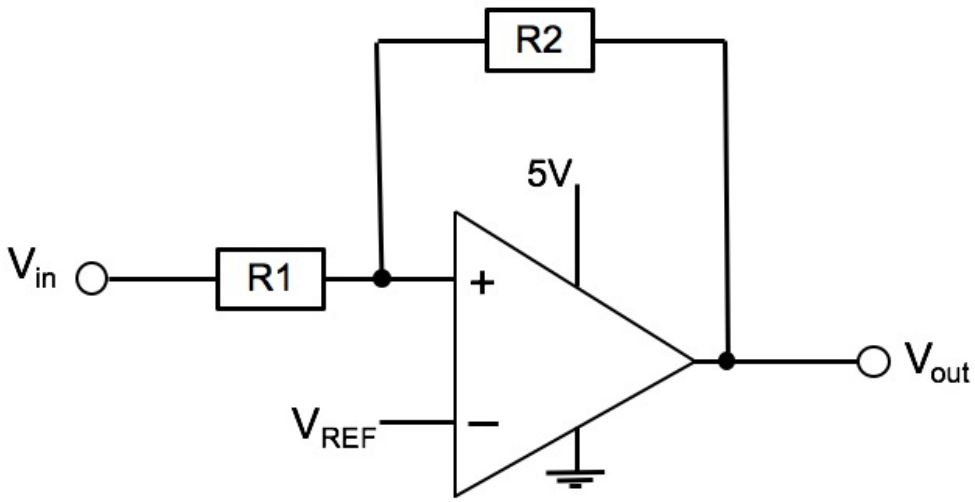
Differentiator

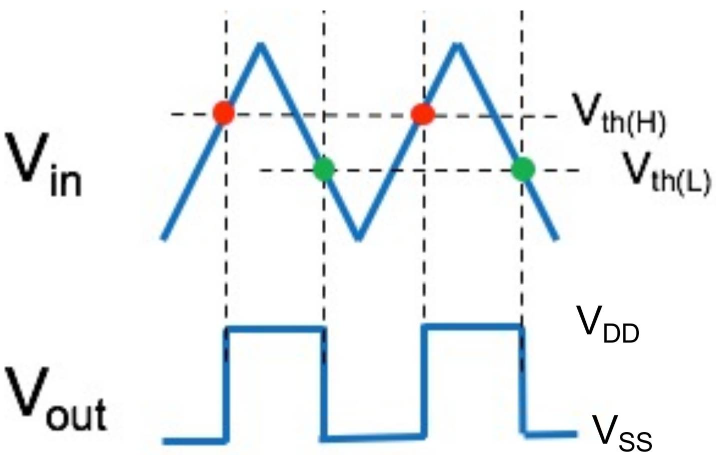


- Swap R and C
- Implement a differentiator
- Not used often because circuit tends to produce noisy output



Comparator with hysteresis





- V_{out} swings between V_{DD} and V_{SS}
- V_{out} changes state when V+ reaches V_{REF}
- Apply KCL at V+:

$$\frac{V_{REF}-V_{in}}{R1} = \frac{V_{out}-V_{REF}}{R2}$$

$$\Rightarrow V_{in} = V_{REF}\left(1+\frac{R1}{R2}\right) - V_{out}\left(\frac{R1}{R2}\right)$$

- If R1 = 0 or R2 = ∞, $V_{th} = V_{REF}$

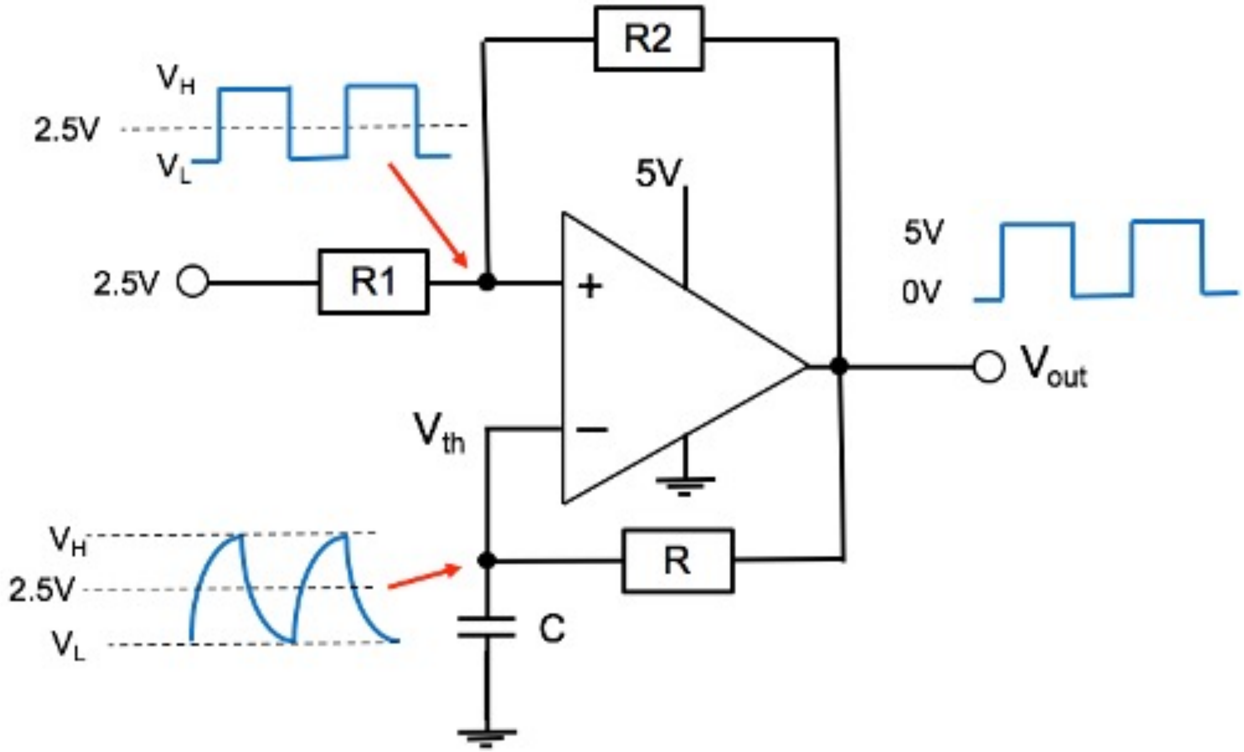
- R1 > 0, R2 ≠ ∞

$$V_{th(H)} = V_{REF}\left(1+\frac{R1}{R2}\right) - V_{SS}\left(\frac{R1}{R2}\right)$$

$$V_{th(L)} = V_{REF}\left(1+\frac{R1}{R2}\right) - V_{DD}\left(\frac{R1}{R2}\right)$$

- Hysteresis = $V_{th(H)} - V_{th(L)}$

Simple Oscillator



- Combine comparator with hysteresis and RC network = oscillator
- Voltage at V+ change instantly with V_{out}:

$$V_H = 2.5\left(1 + \frac{R1}{R1+R2}\right)$$

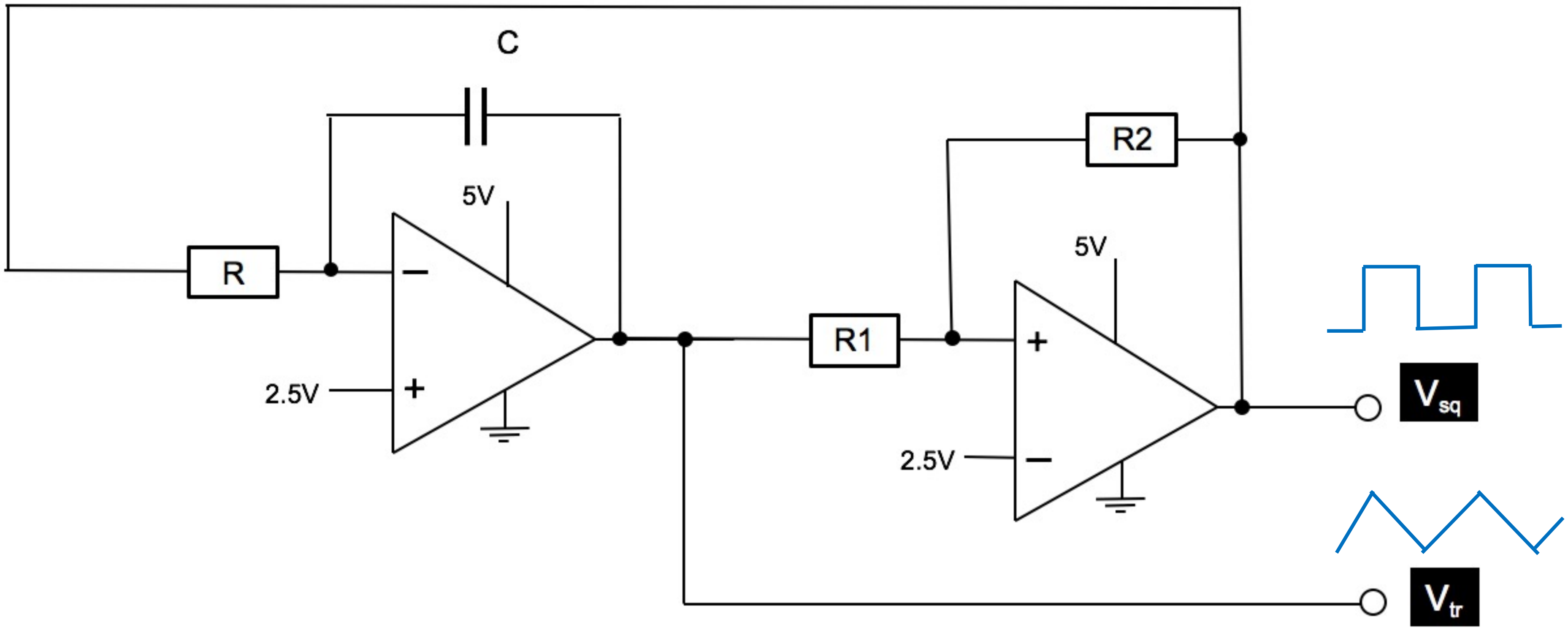
$$V_L = 2.5\left(\frac{R2}{R1+R2}\right)$$

- V- = V_{th} rises and falls exponentially with a time constant of RC between V_H and V_L
- This is determined by the equation:

$$V_{th} = V_f + (V_i - V_f)e^{-\frac{t}{\tau}}$$

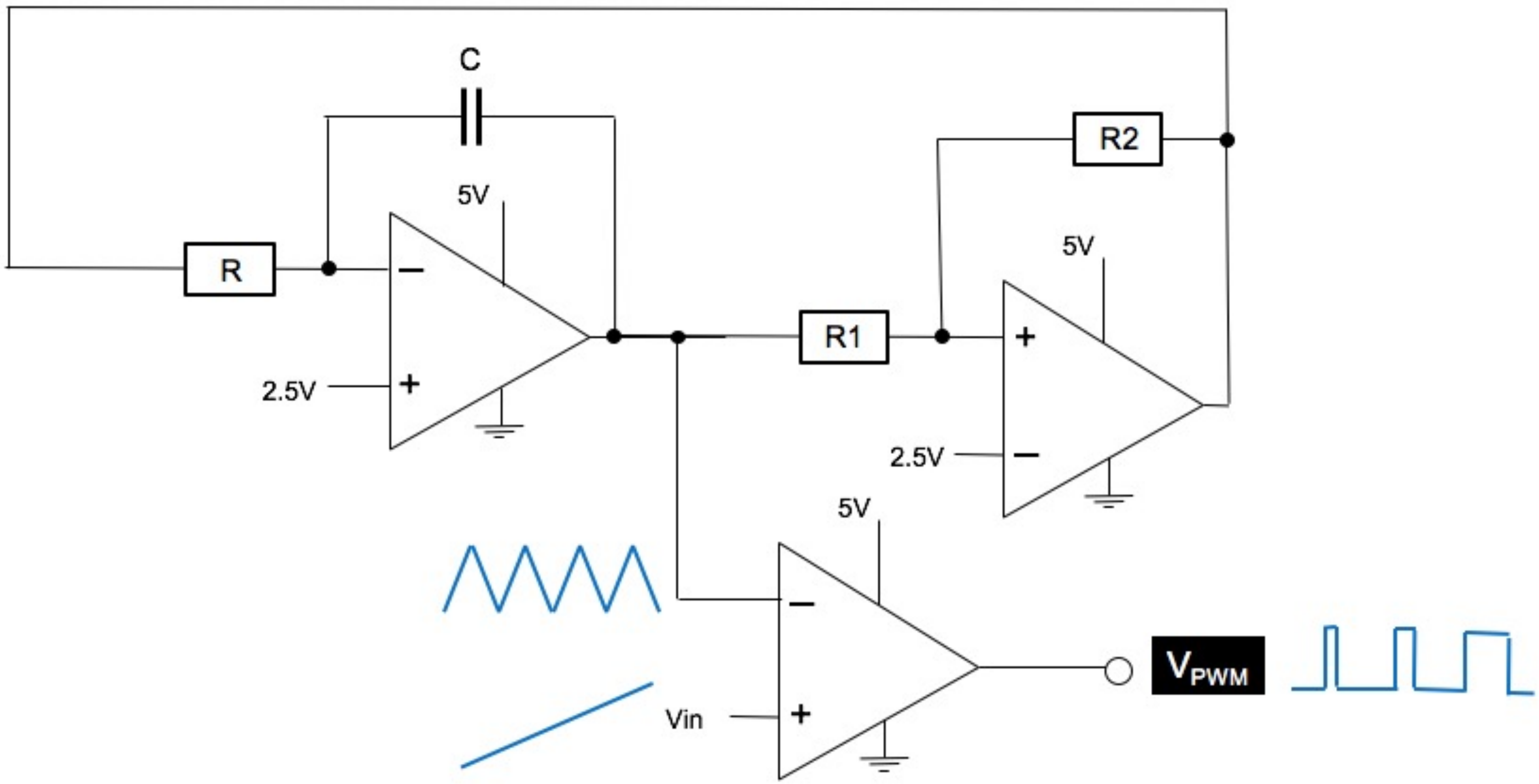
V_i = initial value, V_f = final value, τ = time constant RC

Triangular and Square wave generator



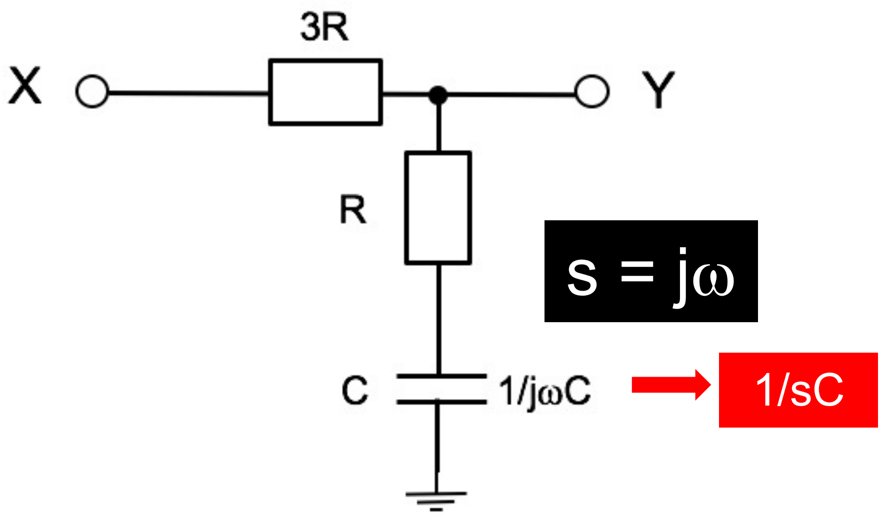
- Better oscillator circuit using integrator + comparator with hysteresis
- Integrator output produces a triangular signal
- Comparator (with hysteresis) produces a square signal
- Feedback circuit ensures oscillation is maintained

Pulse-width Modulator



- Comparing triangular signal with V_{in} -> pulse-width modulated output
- Frequency of triangular signal >> V_{in} frequency
- Output pulse width proportional to value of V_{in}
- Recover V_{in} by lowpass filtering V_{PWM}

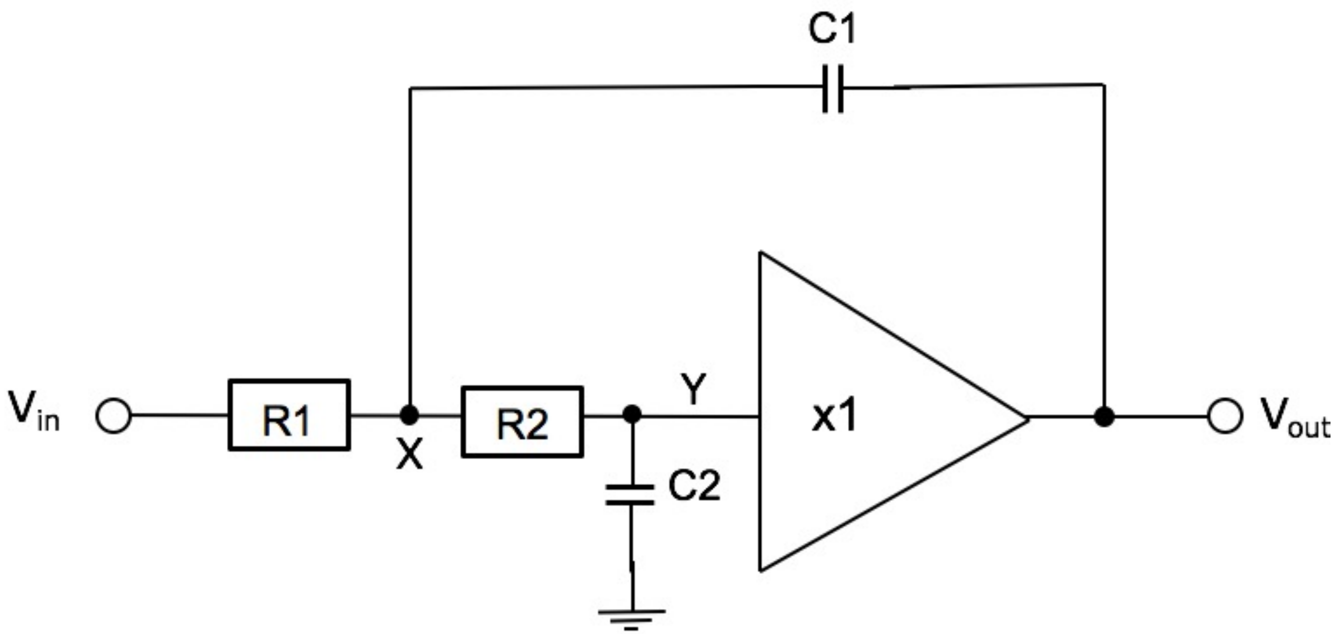
Transfer Function of 1st order LP Filter



- More general if use **complex frequency s** to represent the quantity jω
- Covered in Signals and Systems module this term, and Control module next term
- Express impedance of capacitor as 1/sC instead of 1/jωC
- Capture both steady state (ac) and transient behaviour

- Year 1 ADC Part 1 Lecture 11, slide 3
- Transfer function defined as: $H(s) = \frac{Y(s)}{X(s)} = \frac{R+1/sC}{4R+1/sC} = \frac{1+sRC}{1+4sRC}$
- Frequency response is calculated as $H(s)|_{s=j\omega} = \frac{Y(j\omega)}{X(j\omega)} = \frac{1+j\omega RC}{1+4j\omega RC}$
- Easier to perform algebra manipulation than using jω
- Provides better intuitions on system behaviour

Sallen-Key 2nd order lowpass filter (1)



- Y = V_{out} apply KCL at node X, and obtain transfer function in s as:

$$H(s) = \frac{V_{out}(s)}{V_{in}(s)} = \frac{1}{R1C1R2C2} \times \left[\frac{1}{s^2 + s\left(\frac{1}{R2C1} + \frac{1}{R1C1}\right) + \frac{1}{R1C1R2C2}} \right]$$

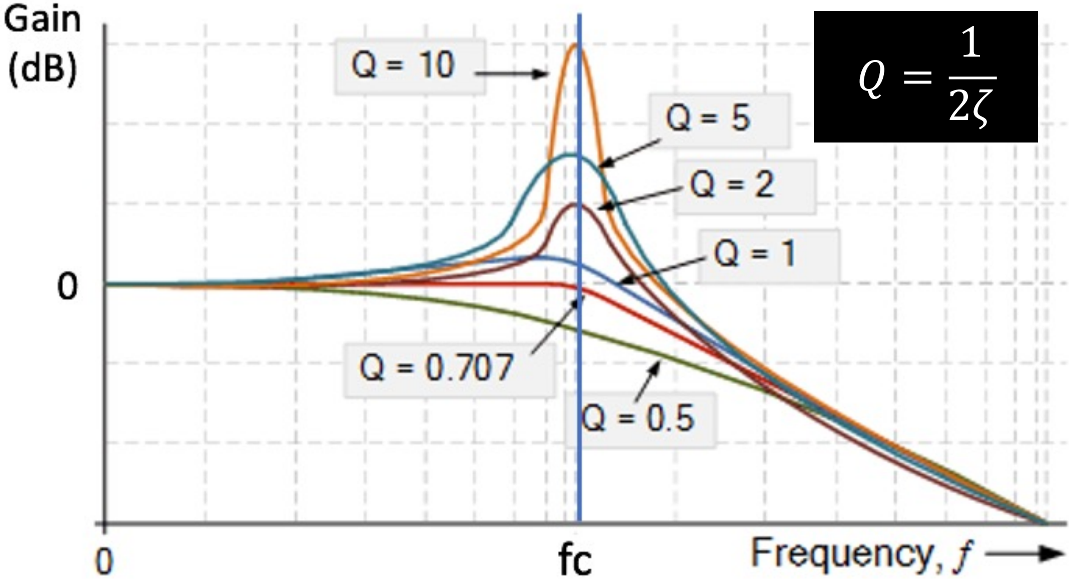
Sallen-Key 2nd order lowpass filter (2)

$$H(s) = \frac{V_{out}(s)}{V_{in}(s)} = \frac{1}{R1C1R2C2} \times \left[\frac{1}{s^2 + s\left(\frac{1}{R2C1} + \frac{1}{R1C1}\right) + \frac{1}{R1C1R2C2}} \right]$$

- Cut-off frequency fc is:

$$H(s) = (2\pi f_c)^2 \times \left[\frac{1}{s^2 + 2\zeta(2\pi f_c)\, s + (2\pi f_c)^2} \right]$$

$$H(s) = G_0 \times \left[\frac{1}{s^2 + a_1 s + a_0} \right]$$



$$Q = \frac{1}{2\zeta}$$

- a_0 determines the **cut-off frequency** of filter
- a_1 determines the **resonance behaviour** of filter
- G_0/a_0 is the **gain of the filter at dc**
- **Butterworth filter**: $2\zeta = 1.414$, $Q = \frac{1}{2\zeta} = 0.707$
- **Maximally flat** gain in passband
- Monotonically decreasing gain in stop band