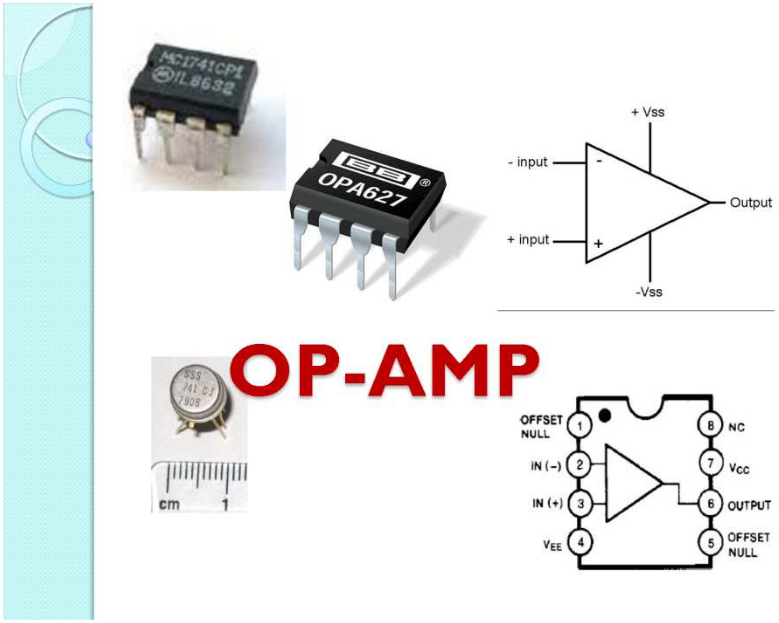
ENGG1000

Electrical Stream 2018

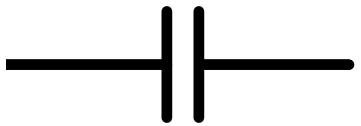
Week 5 – Op-Amps and Filters

Never Stand Still | Faculty of Engineering | School of Electrical Engineering and Telecommunications

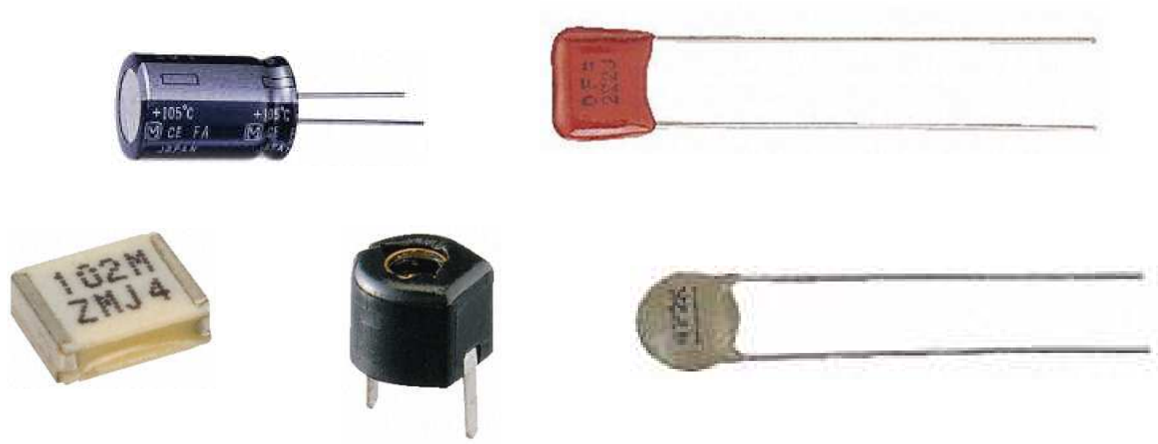


The Capacitor

- Two conducting plates close to each other
  - Separated by an insulator (dielectric)
  - Stores charge when a voltage is applied
  - Releases charge when voltage taken away

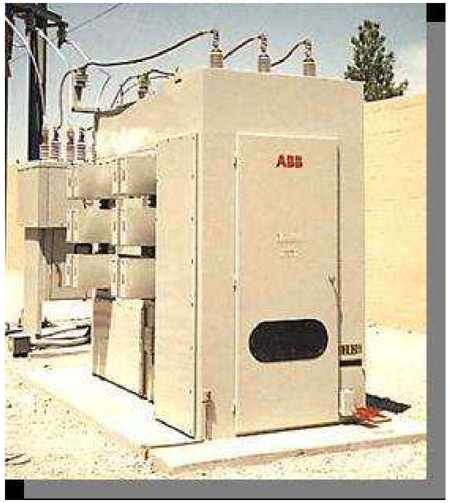


$$q = CV$$



source: http://australia.rs-online.com

The Capacitor



- Capacitance is denoted as C
  - In Farads
  - Typical values: ~1 pF to ~10μF
  - Only certain values available
    - Like resistors

- Values shown on package
- Or use LCR bridge
- Tend to very imprecise
  - 10%-20% typical

The Capacitor

- Since current is the flow of charge, i.e.

$$I = \frac{dq}{dt}$$

  we have the following linear relationship between voltage and current:

$$I(t) = C\frac{dV(t)}{dt}$$

  – *I*(*t*), *V*(*t*) : capacitor current, voltage as a function of time *t*

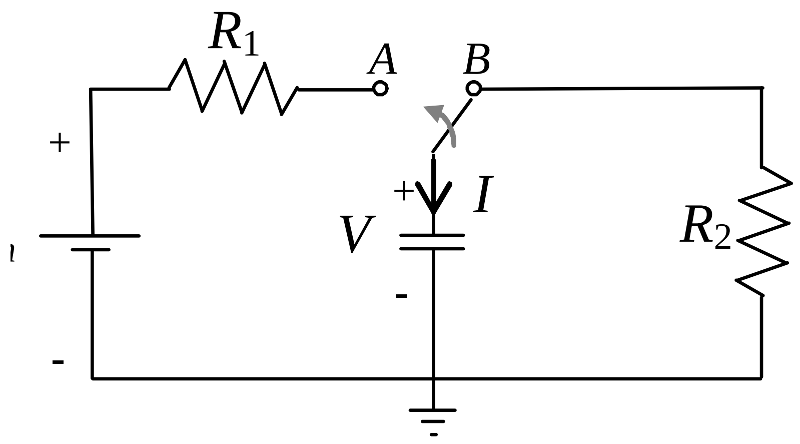
  – Capacitor voltage constant $\Rightarrow$ no current

  – Voltage changing linearly $\Rightarrow$ current constant

First-order Capacitive Circuits

- Example of capacitive behaviour
- Suppose switch $B \to A$ in circuit below
  - Before this, no voltage across capacitor C

    $\therefore V = 0$
  - After switch, capacitor will charge up to V_{in}



First-order Capacitive Circuits

- Voltage around loop:

$$V_{in} = R_1 I(t) + V(t) = R_1 C \frac{dV(t)}{dt} + V(t)$$

  - Differential equation, solution

$$V(t) = V_{in}\left(1 - e^{-\frac{t}{R_1 C}}\right)$$

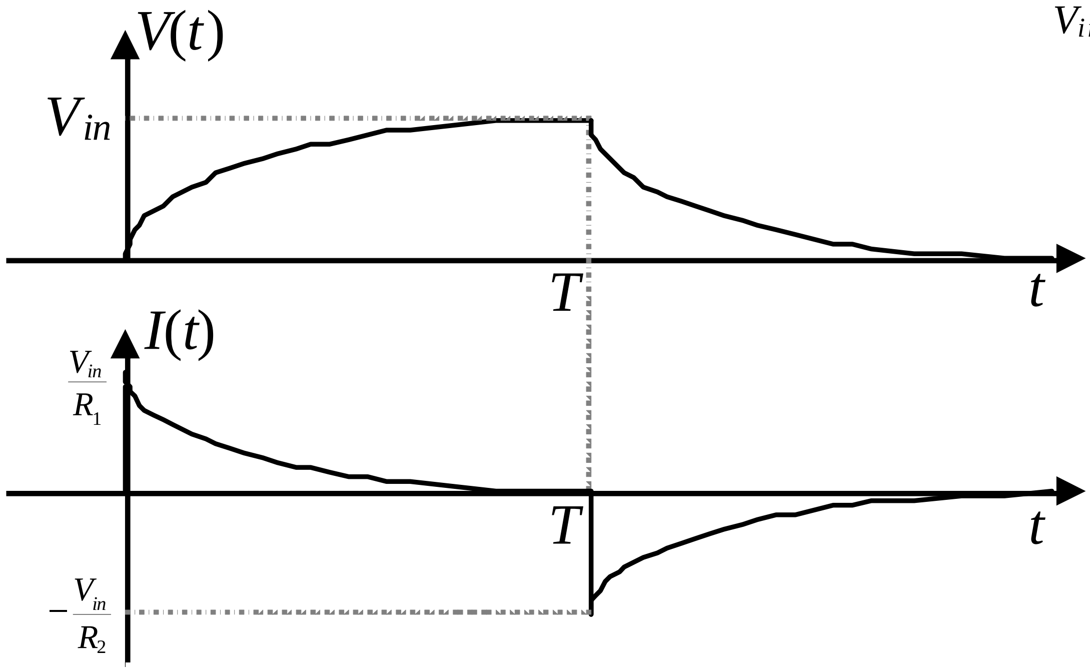
  - $I(t) = C\frac{dV(t)}{dt} \quad \rightarrow \quad I(t) = \frac{V_{in}}{R_1} e^{-\frac{t}{R_1 C}}$
  - So at time of switching (t=0) and after ($t \rightarrow \infty$)

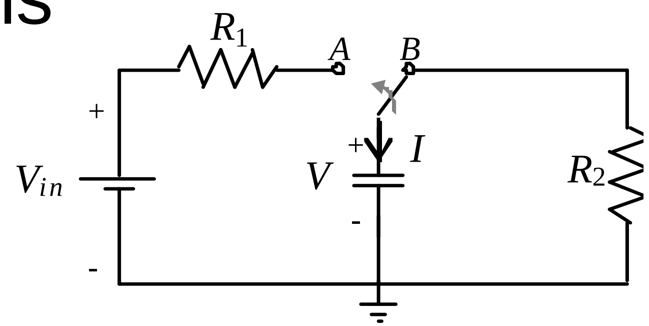
$$t = 0 : V(0) = 0 \qquad t \rightarrow \infty : V(\infty) = V_{in}$$

$$t = 0 : I(0) = \frac{V_{in}}{R_1} \qquad t \rightarrow \infty : I(\infty) = 0$$

First-order Capacitive Circuits

- Voltage and current waveforms





B → A at t = 0

A → B at t = T

First-order Capacitive Circuits

- Capacitor voltage for circuits undergoing a change in voltage from $V_{initial}$ to V_{final} at time t = 0:

$$V(t) = V_{final} - (V_{final} - V_{initial})e^{-\frac{t}{RC}}$$

- R is the charging/discharging resistance
  – Needs to be determined based on the circuit surrounding the capacitor
  – In our example
    - During charging $R = R_1$ $$V(t) = V_{in}\left(1 - e^{-\frac{t}{R_1 C}}\right)$$
    - During discharging $R = R_2$ $$V(t) = V_{in}e^{-\frac{t-T}{R_2 C}}$$

Capacitors: Peak Detector

Diode output follows positive part of waveform only

Increasing V_{in}:

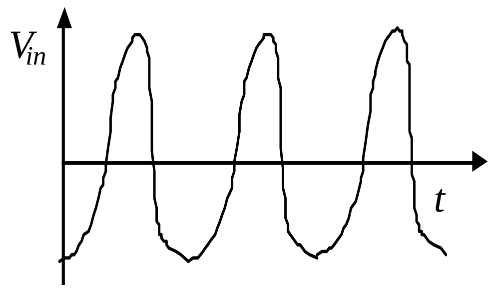
– *C* charges rapidly through diode

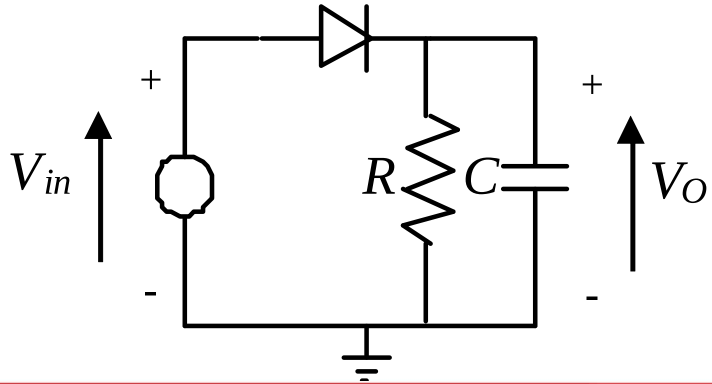
Increasing V_{in}:

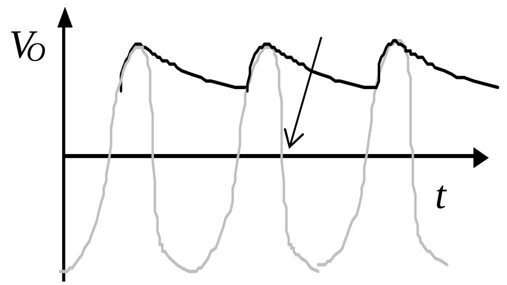
– *C* discharges slowly through *R*

– Choose *R* to control rate of decay

approximately constant if R is large





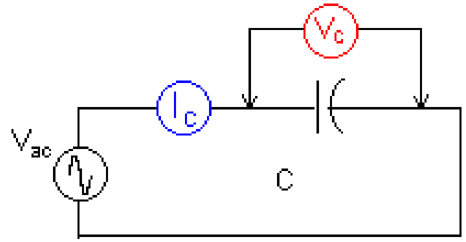


Capacitors: Frequency Behaviour

– Consider a capacitor with a constant frequency sinusoid input

– How are the voltage and current through the capacitor related?

$$V_{ac} = V_c = V_0 \sin(2\pi f t)$$



$$I_C = C\frac{dV_C}{dt} = 2\pi f C V_0 \cos(2\pi f t)$$

– Effective resistance of the capacitor (called the 'impedance')

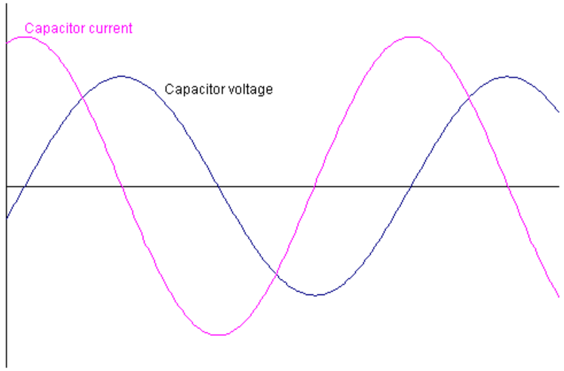
$$X_C = \frac{|V_C|}{|I_C|} = \frac{1}{2\pi f C}$$

– Ratio of voltage amplitude to current amplitude

Capacitors: Frequency Behaviour

– Note that the current and voltage are out of phase

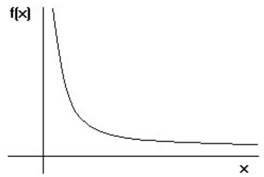
  – One peaks while the other is zero



$$X_C = \frac{|V_C|}{|I_C|} = \frac{1}{2\pi f C}$$

– Impedance as function of frequency

– Note that the capacitor offers a large 'resistance' at low frequencies, but a small resistance at high frequencies



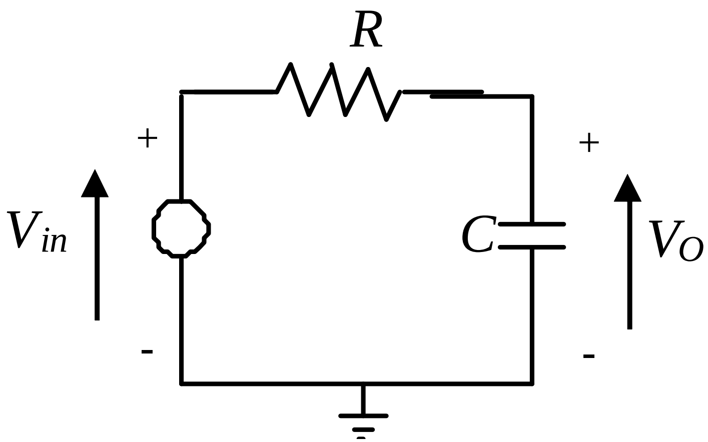
– Forms the basis of 'FILTERS'

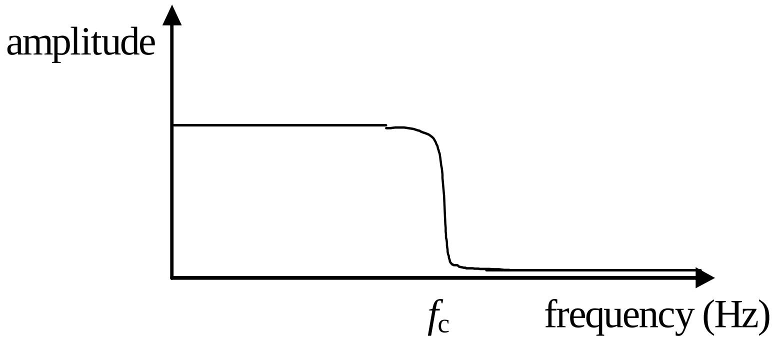
– Circuits to separate frequency

components in an input signal…

Capacitors: Low Pass Filter

Passes low frequencies, blocks high frequencies



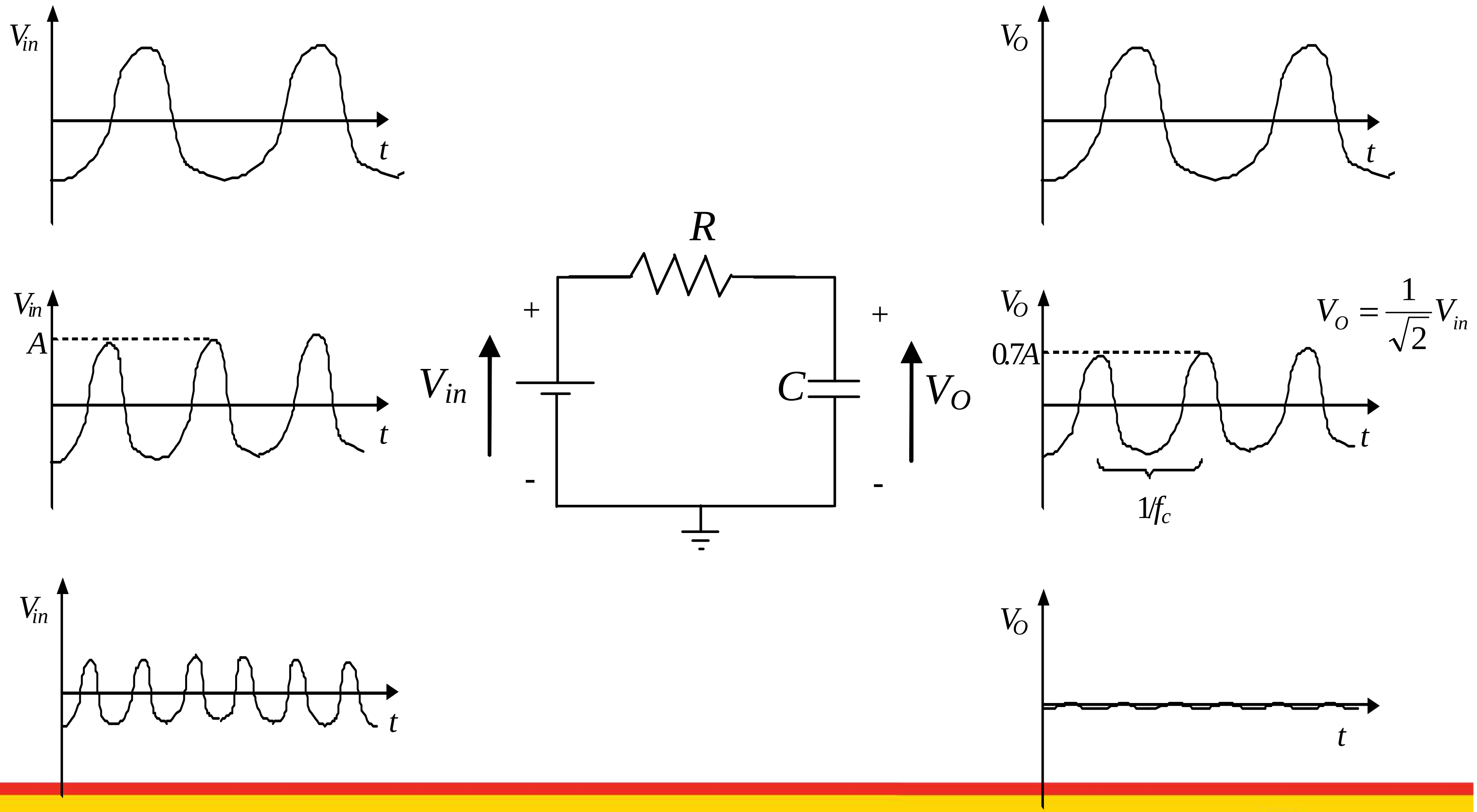


Choose

$$V_O = \frac{1}{\sqrt{1+(2\pi fRC)^2}} V_{in}$$

$$f_c = \frac{1}{2\pi RC}$$

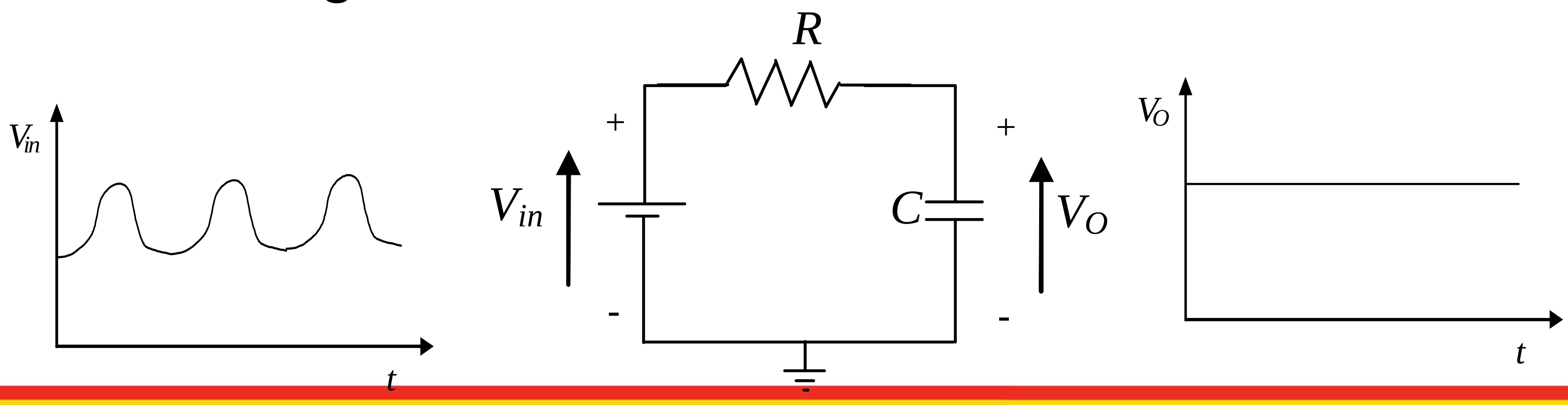
Capacitors: Low Pass Filter



Capacitors: Low Pass Filter

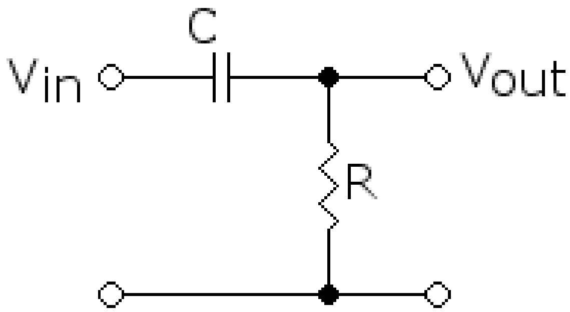
Suppose you have a voltage that is oscillating

- You want just the DC part, or some smooth version of the voltage
- e.g. removing fluorescent light noise from an IR signal



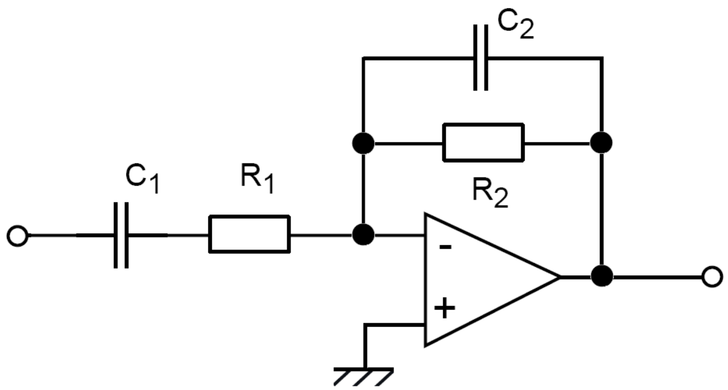
Capacitors: High Pass Filter

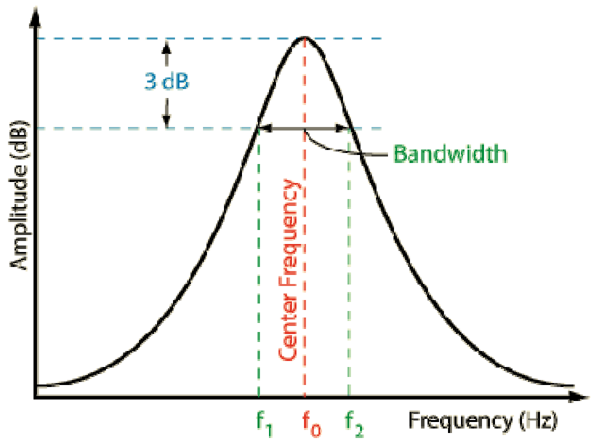
- On the other hand, you could reverse the location of the capacitor and the resistor and you would get a ‘high pass filter’
  - A filter that removes low frequency parts of the signal, but passes the high frequencies



Capacitors: Band Pass Filter

- Cascade a low pass filter with a high pass filter to pass only a range of frequencies
  - Choose the LPF cut-off and HPF cut-off to obtain the desired response

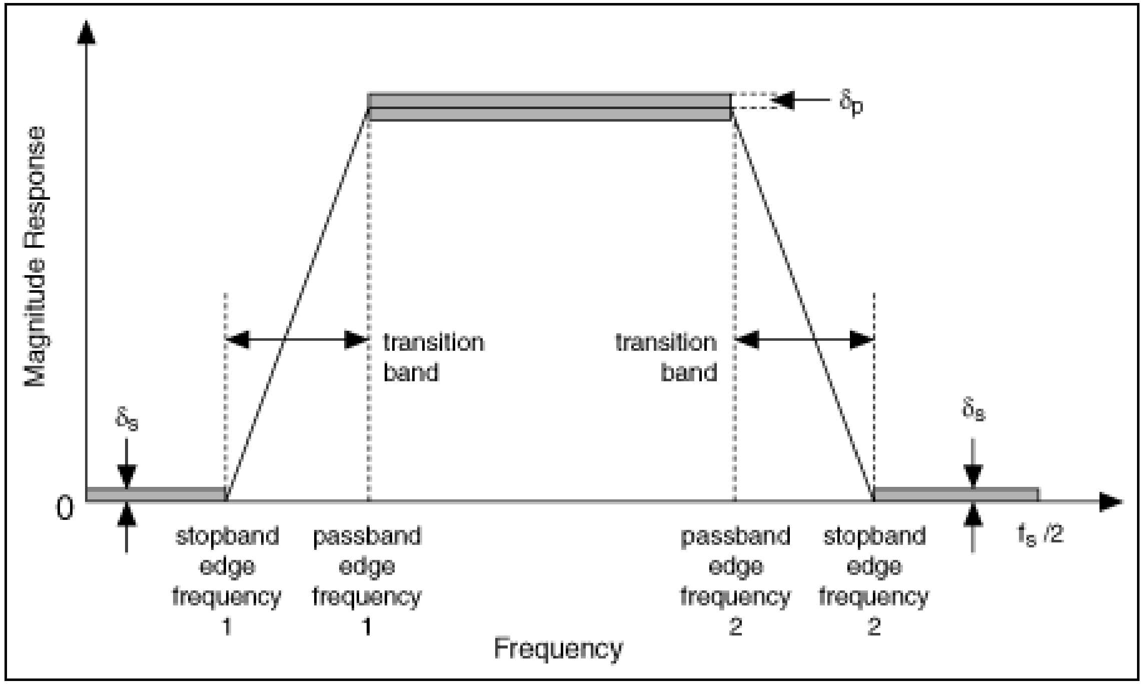




Sources: http://www.changpuak.ch/electronics/Simple_Bandpass.php; http://www.rane.com/note170.html

Filters - Characteristics

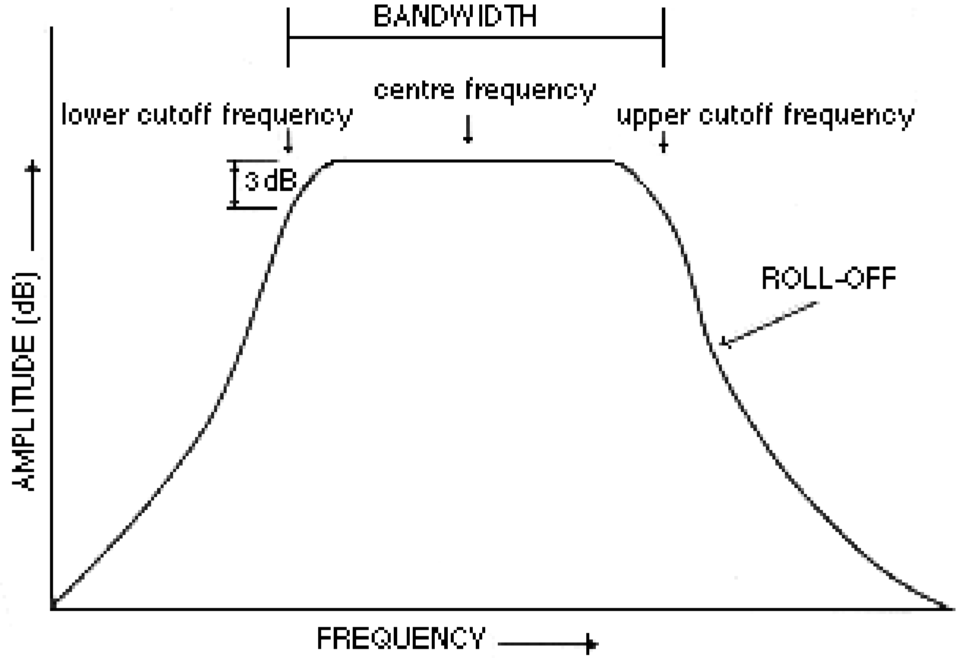
- Examples: Bandpass Filter



Source: http://zone.ni.com/reference/en-XX/help/371988B-01/lvdfdtconcepts/dfd_filter_spec/

Filters - Characteristics

- Examples:



Source: http://www.sfu.ca/sonic-studio/handbook/Filter.html

Filters - Notes

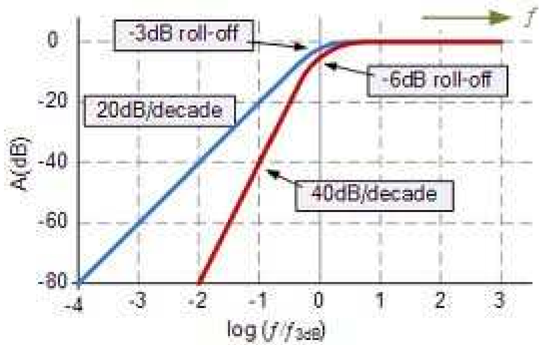
- Be wary of the input and output impedance of your filters
  - Op-amp based circuits are a good choice here
- Cut-off frequency – usually defined as the 3dB point
  - At this point output amplitude drops to $1/\sqrt{2}$ (and power by ½)
  - If you're looking to remove a component, you'll need to cut-off well before this point
- Be wary of variations in component tolerances
  - Actual cut-off frequencies will be different from what you calculate
  - Consider variable resistors to allow 'in the field' tuning

Filters - Notes

- Roll-off issues
  - The rate at which it attenuates out of band signals
  - First order filter rolls off at 20dB/dec
  - Recall: $X_C \propto \frac{1}{|f - f_0|} \rightarrow P_C \propto \frac{1}{|f - f_0|^2}$
  - For every power of 10 increase in frequency, the output power will drop by 1/100 (we say '20dB/dec')
- Faster roll-off – Higher-order filters
  - Second order filter rolls-off at 40dB/dec
  - Here,

$$X_C \propto \frac{1}{|f - f_0|^2} \rightarrow P_C \propto \frac{1}{|f - f_0|^4}$$

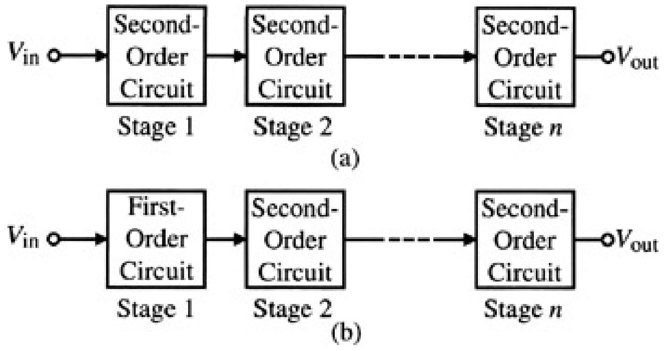
  - Can form a by cascading first order filters together



Source: http://www.electronics-tutorials.ws/blog/second-order-filter.html

Filters - Notes

- Cascaded Filters
  - The attenuation of each stage multiplies



- Can be problematic
  - Leads to many large number of components, wires, stages -> lots of places it can go wrong…
  - Tolerances of components reducing performance
  - Impedance matching between stages (buffers...)
  - Consider ICs (Integrated Circuits)

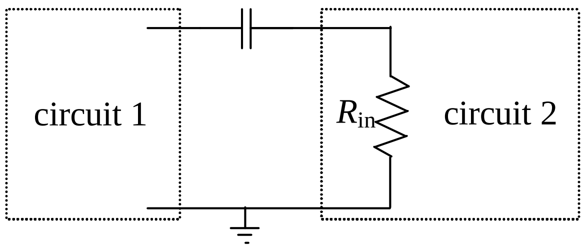
Source: http://www.globalspec.com/reference/56055/203279/9-6-second-order-switched-capacitor-circuits

Capacitors: Other Uses

Lots of other uses

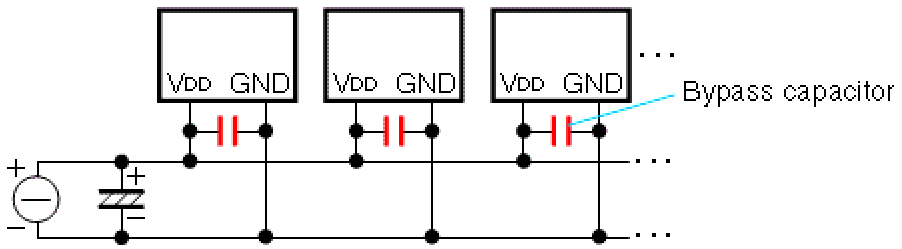
You may come across:

- Coupling capacitor or DC Blocking capacitor
  - Only passes AC signals (DC blocked)
  - Might see in amplifier circuits
  - Together with input impedance of next stage, creates high pass filter



Capacitors: Other Uses

– Bypass or decoupling capacitor
  - Placed across supply rails of an integrated circuit
  - Helps to improve stability of supply voltage (removes fluctuations)
  - Used in voltage regulators
    – Research for yourself!!!



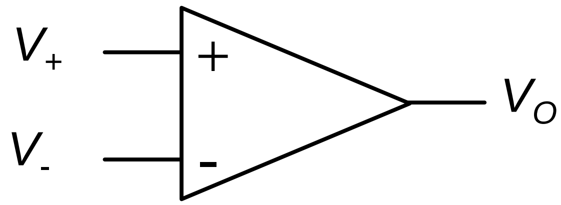
Source: http://www2.renesas.com/faq/en/f_tech.html

The Ideal Amplifier

- Earlier: transistor amplifier
- Amplifiers important
  - $\therefore$ refined over many years
- Characteristics of an ideal amplifier
  - Very large / infinite gain
  - Infinite input resistance
    - Does not load previous circuit stages
  - Negligible output resistance
    - Want output to act as ideal voltage source

The Operational Amplifier

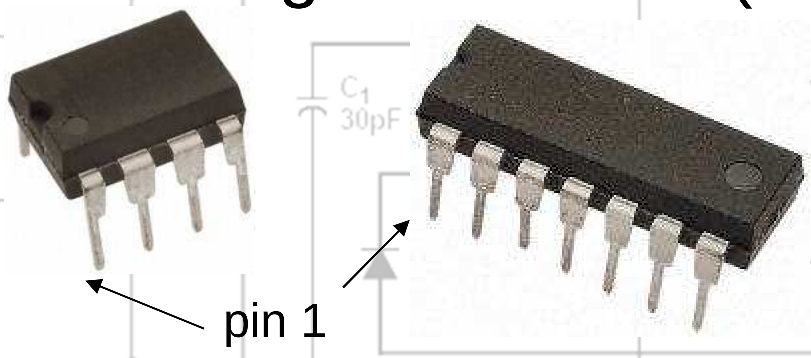
- An approximation to the ideal amplifier



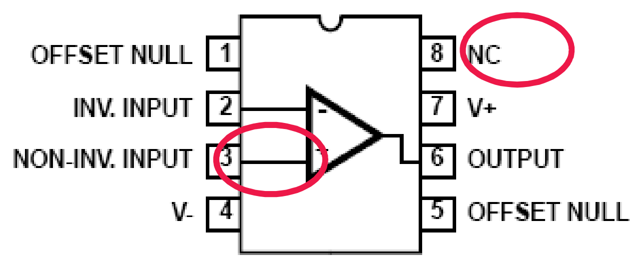
  - Gain $A \geq 10^5$
  - Input resistance $\geq 10M\Omega$
  - Output resistance $< 500\Omega$
- Differential amplifier $V_O = A(V_+ - V_-)$

The Operational Amplifier

- Physical device is an integrated circuit (IC)



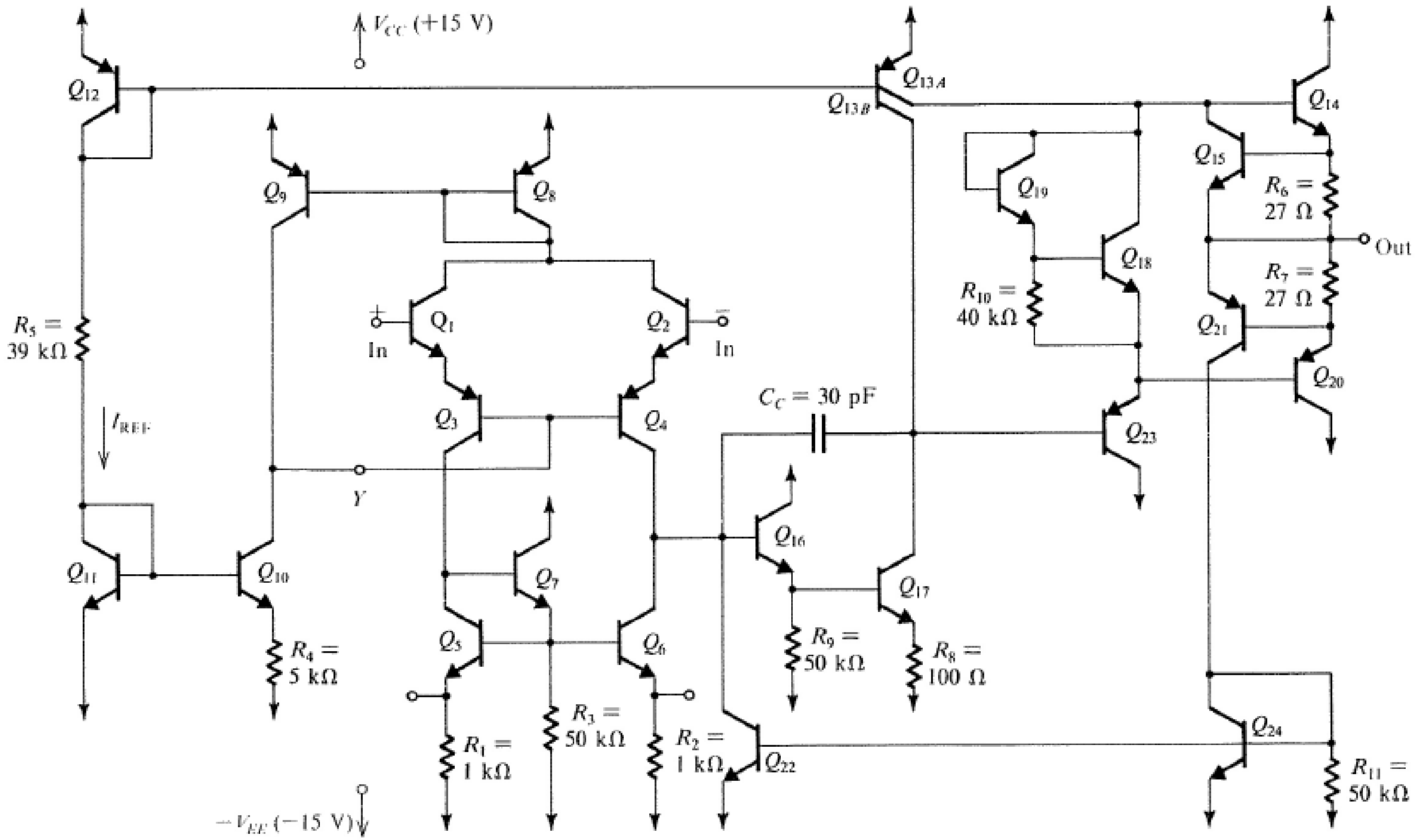
- Has two component terminals we haven't seen
  - power supply



- Pinout, specs etc: see data sheet

sources: http://australia.rs-online.com, http://engg1000.ee.unsw.edu.au/datasheets/Analog-ICs/LM741.pdf

LM741 Circuit



The Operational Amplifier

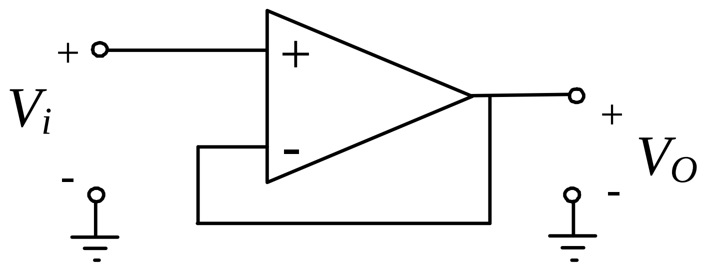
- The op-amp is assumed ideal

$\Rightarrow$ Two rules for analysis:

- Because the input resistance is infinite, *no current enters either input terminal*
- Because the gain $A = \dfrac{V_O}{V_+ - V_-}$ is infinite, if the output voltage is **finite**, then $V_+ - V_- = 0$, i.e. *both input terminals have identical voltage*

Negative Feedback

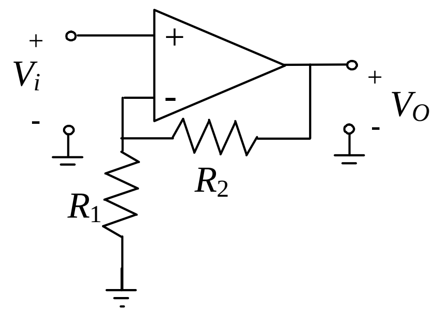
- Path from output to inverting input
  - Provides stable *closed-loop* gain
    - See notes for more detail
- Op-amp buffer



  - $V_- = V_+$, so $V_O = V_- = V_+ = V_i$
  - Gain of 1
  - Output is isolated from input (input resistance is ∞)
  - Input current small (μA or even pA), output large (mA or even 100s of mA)

Negative Feedback Applications

- Non-inverting amplifier



  - No current flows into input terminals, so

$$V_- = \frac{R_1}{R_1 + R_2} V_O$$

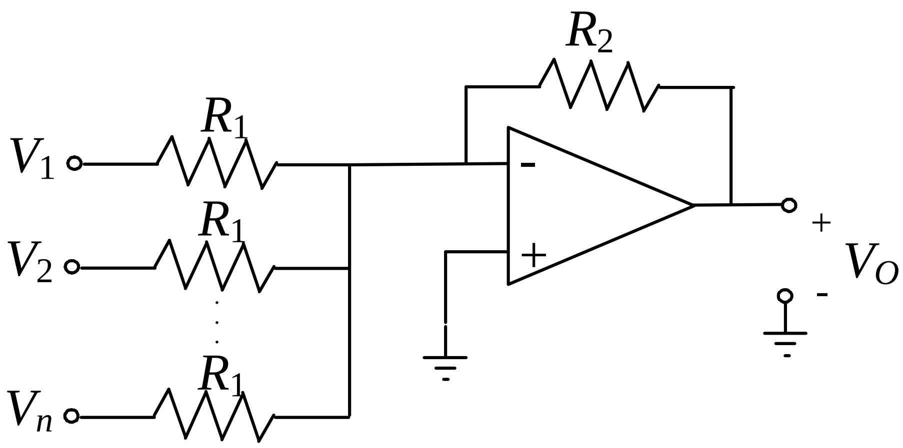
  - So $V_O = \frac{R_1 + R_2}{R_1} V_i$ and closed-loop gain is $1 + \frac{R_2}{R_1}$

  - Choose R_1, R_2 to give desired gain

Negative Feedback Applications

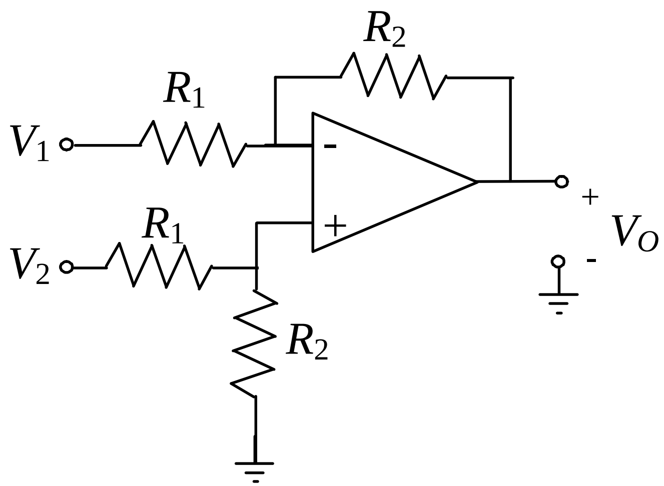
- Adder (inverting)

$$V_O = -\frac{R_2}{R_1}(V_1 + V_2 + \ldots + V_n)$$



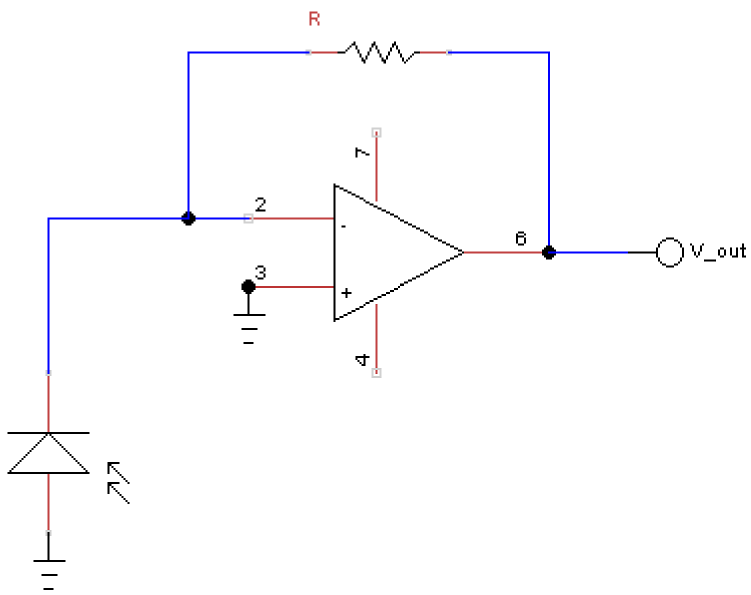
- Subtractor
  - Differential Amp!!!

$$V_O = \frac{R_2}{R_1}(V_2 - V_1)$$



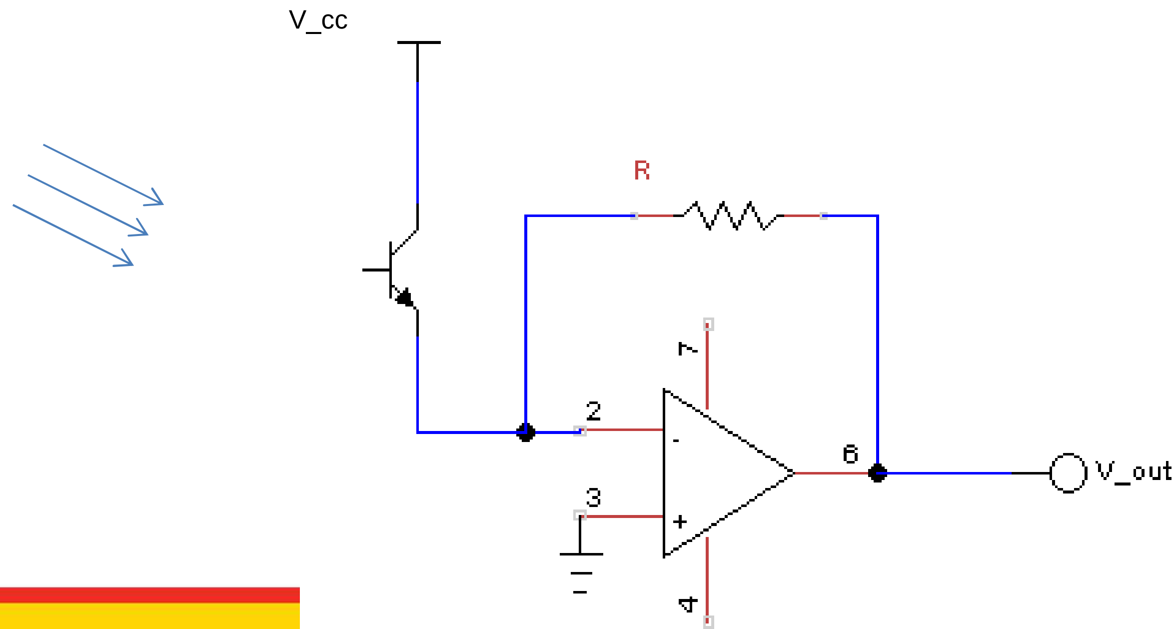
Current to Voltage Converter

- For example, to convert the current received from a photodiode into a voltage signal
- Photodiode operates in reverse-biased mode
- Output voltage: $V_{out} = R \times I$, where *I* is the photocurrent (proportional to the incident light intensity)



Current to Voltage Converter

- An equivalent circuit using a phototransistor
- Note: incident light provides the base current
- In a photodiode, light creates the reverse leakage current

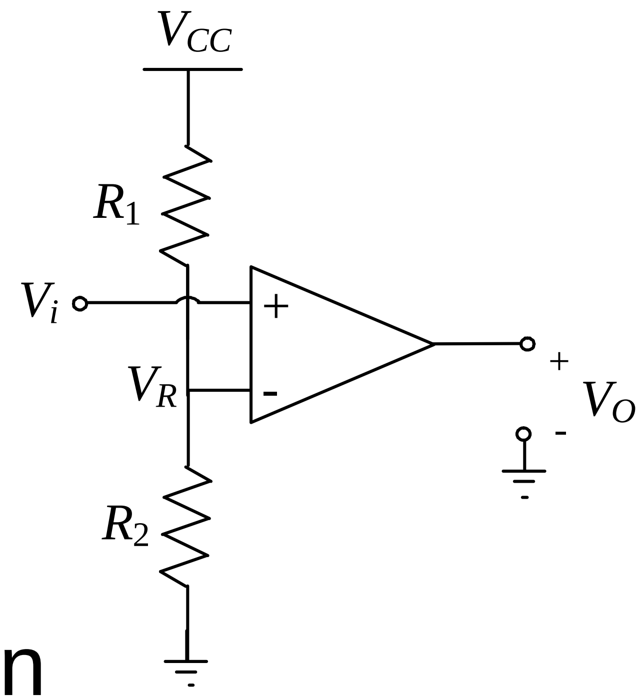


Positive or No Feedback

- Positive feedback
  - Path from output to non-inverting input
    - Causes output to grow exponentially
- No feedback
  - Small difference in inputs $\rightarrow$ very large difference in output
    - $V_O = A(V_+ - V_-)$, $A \sim 10^5$
- In practise, output voltage is limited by supply to $\pm V_{CC}$

Application of No Feedback

- Comparator
  - V_R is constant
    - “reference voltage”
  - $V_i > V_R \Rightarrow V_O = +V_{CC}$
  - $V_i < V_R \Rightarrow V_O = -V_{CC}$



- Good for threshold detection
- Can reverse terminals to get opposite behaviour

Comparators under Noise

- Comparators on noisy signals can result in many misdetections

Source: http://pcbheaven.com/wikipages/The_Schmitt_Trigger/

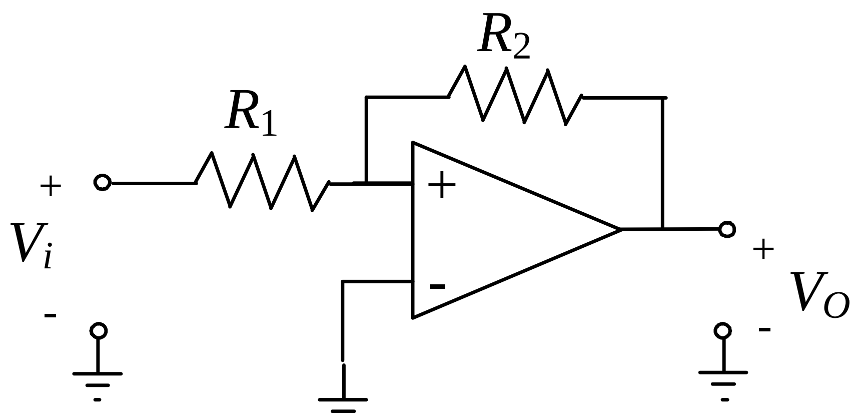
Schmitt Trigger

- Set-up a lower threshold -> only switch back when the signal falls below the lower threshold:

Source: http://pcbheaven.com/wikipages/The_Schmitt_Trigger/

Application of Positive Feedback

- Schmitt trigger
  - Comparator not suitable for threshold detection in noise
  - Schmitt trigger uses hysteresis
    - Choose R_1, R_2 to determine how much hysteresis



Schmitt Trigger

- When input goes above 0V, output goes HIGH
- Voltage at +ve terminal will then be:

$$V_+ = V_{CC} - \frac{R_2}{(R_1 + R_2)}(V_{CC} - V_{in})$$

- The output will not swing low until $V_+ < 0$
- That is, the input must fall to: $V_{in} = -\frac{R_1}{R_2} V_{CC}$

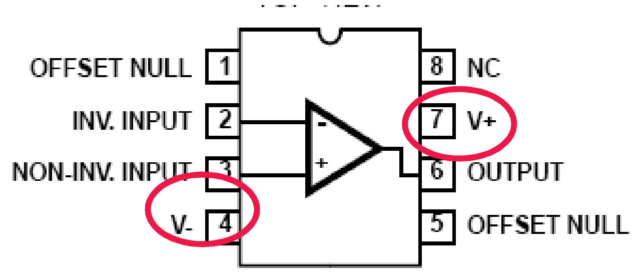
- In Lab 3, you'll use a slightly different circuit…

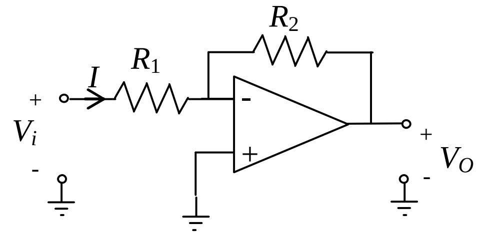
Practical Considerations

- Op-amps are nearly ideal in many respects
- Cannot produce large output current
  - e.g. max 25 mA for LM741 op-amp
    - Check data sheets
  - An op-amp cannot power a loudspeaker, for example
  - Might need to add a transistor amplifier stage to the output of the op-amp circuit

Op-amps: Offset

- Recall:
  - Op-amps have a positive and a negative supply
  - “double-sided” supply





- This means
  - Supplying $-V_{CC}$, ground and $+V_{CC}$ to the circuit
  - Input to circuit has average value of zero
    - Can achieve this using???

Electronics design notes

- Op-amps (negative feedback)
  - Ideal behaviour will only be observed if the inputs and outputs are not saturated
    - i.e. all voltages < +V_{CC} and > -V_{CC}
  - Ensure that feedback is negative
    - Don't mix up inverting and non-inverting inputs
  - Ensure that there is DC feedback in op-amp circuits
    - e.g. don't put a capacitor in series from the output back to the input (i.e. on the feedback path)

Source: Horowitz and Hill, 1989

Electronics design notes

- Op-amps
  - Often the maximum differential input voltage limit is small
    - i.e. the difference between *V*+ and *V*-
    - e.g. 5V
    - Exceed it and larger input currents will flow, op-amp does not behave as expected
  - Keep leads to power supply short
    - Avoid disturbances from power supply affecting output signal (see Scherz for tips)

Source: Horowitz and Hill, 1989, Scherz, 2000

Coming Up

- Lab Openings during Mid-session break
  - Thursday 1-5pm (5th April)
  - Friday 1-4pm (6th April)
  - Lab EEG14
- Week 6 Labs Open (EEG14 & EE214)
  - Monday 2-6pm
  - Thursday 2-6pm
- Circuit Quiz coming up in Week 7
  - Enrolment available on Moodle during Week 6