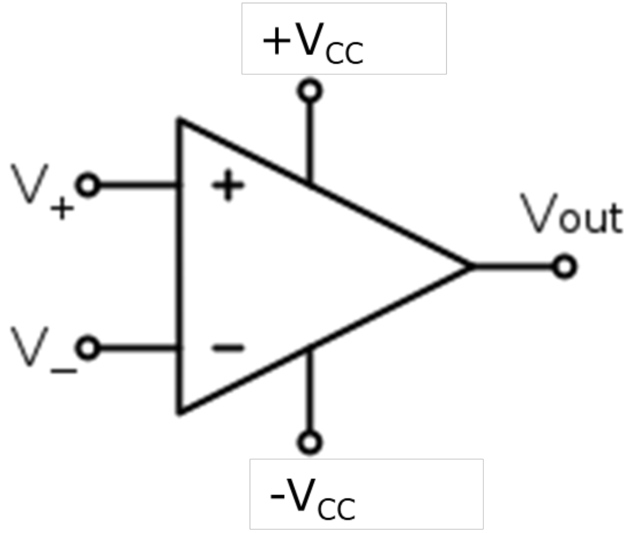
CG1111A:
Engineering Principles & Practice I

Tutorial 4: Reflections & Problem Solutions
(12/13 Oct 2022)

National University of Singapore

Comparator

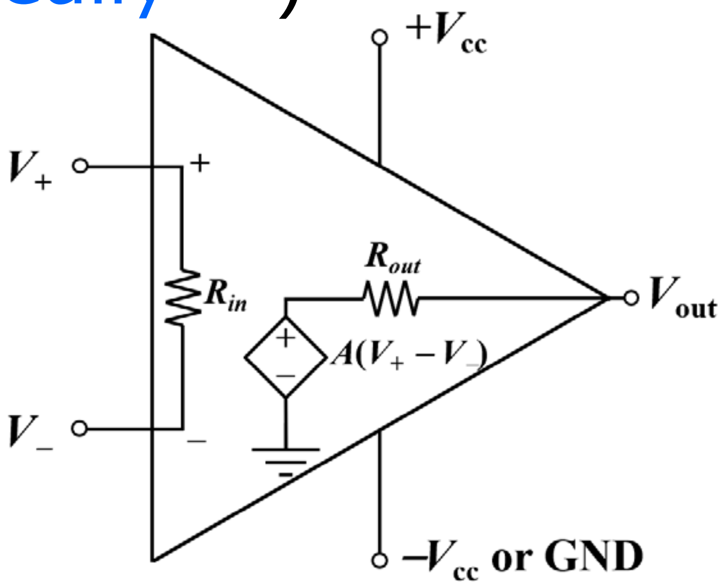


- The comparator is an electronic decision-making circuit that makes use of an op-amp's very high gain in its open-loop state (i.e., there is no feedback resistor)

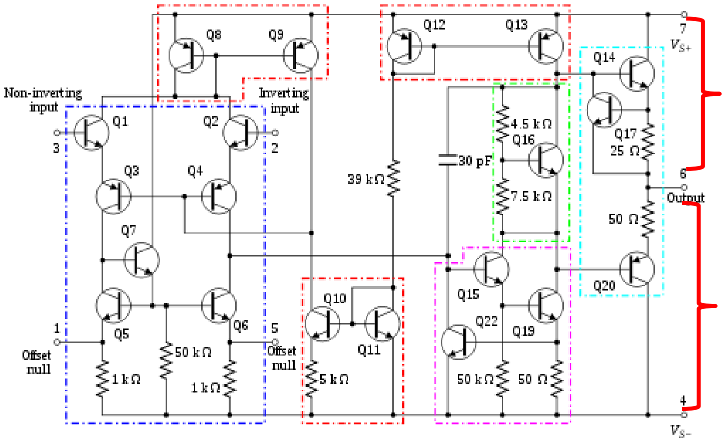
Op-Amp as a Comparator – How It Works

Recall that for op-amp:

- The difference between the two inputs is amplified as '$A(V_+ - V_-)$' at the output
- The open-loop voltage gain ('A') of the op-amp is very high (ideally ∞)
- Even if there is a very small difference between the inputs, the high 'A' will pull the output to "saturation"

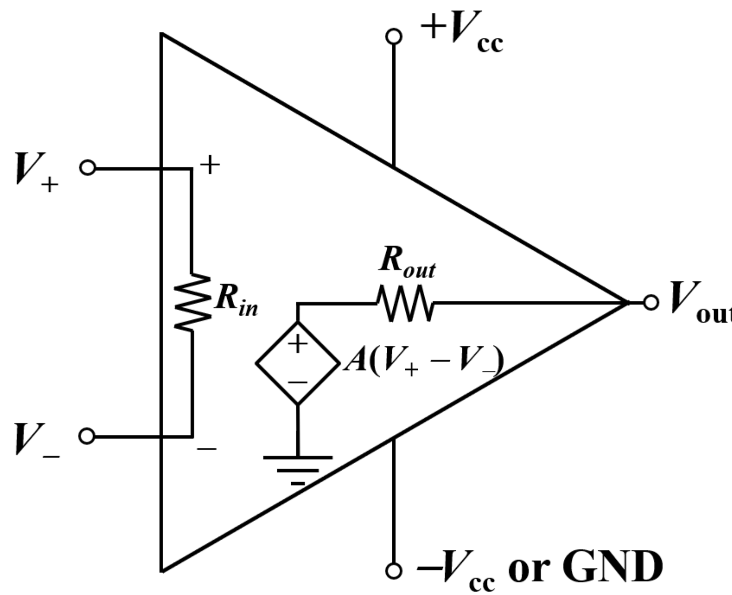


What Are Saturation Voltages?



V_{ovh1} needed for NPN transistor to turn on

V_{ovh2} needed for PNP transistor to turn on



- If **$V_+ > V_-$**:

$$V_{\text{out}} = V_{CC} - V_{\text{ovh1}}$$

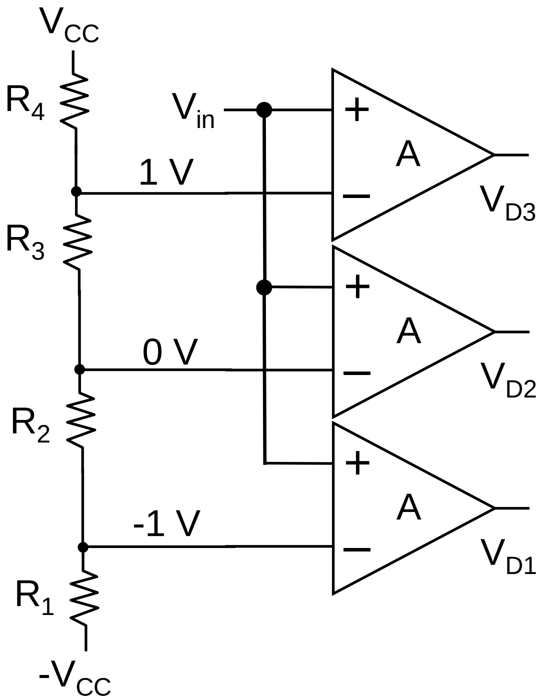
- If **$V_- > V_+$**:

$$V_{\text{out}} = \begin{cases} -V_{CC} + V_{\text{ovh2}} & \text{if dual power supply} \\ V_{\text{ovh2}} & \text{if single power supply} \end{cases}$$

- **V_{ovh1}** & **V_{ovh2}** are the **voltage headrooms** from the supply rails (V_{CC}, $-V_{CC}$, or GND) needed to sustain proper output transistor **turn-on voltage**, and it varies between 0.05 to 1.5 V depending on the output current

Common Application of Comparator

- The comparator is ideal for converting analog signals to digital signals at certain threshold values



V_{in}	V_{D3}	V_{D2}	V_{D1}	ADC
$V_{in} < -1$ V	L	L	L	00
-1 V $< V_{in} <$ 0 V	L	L	H	01
0 V $< V_{in} <$ 1 V	L	H	H	10
$V_{in} >$ 1 V	H	H	H	11

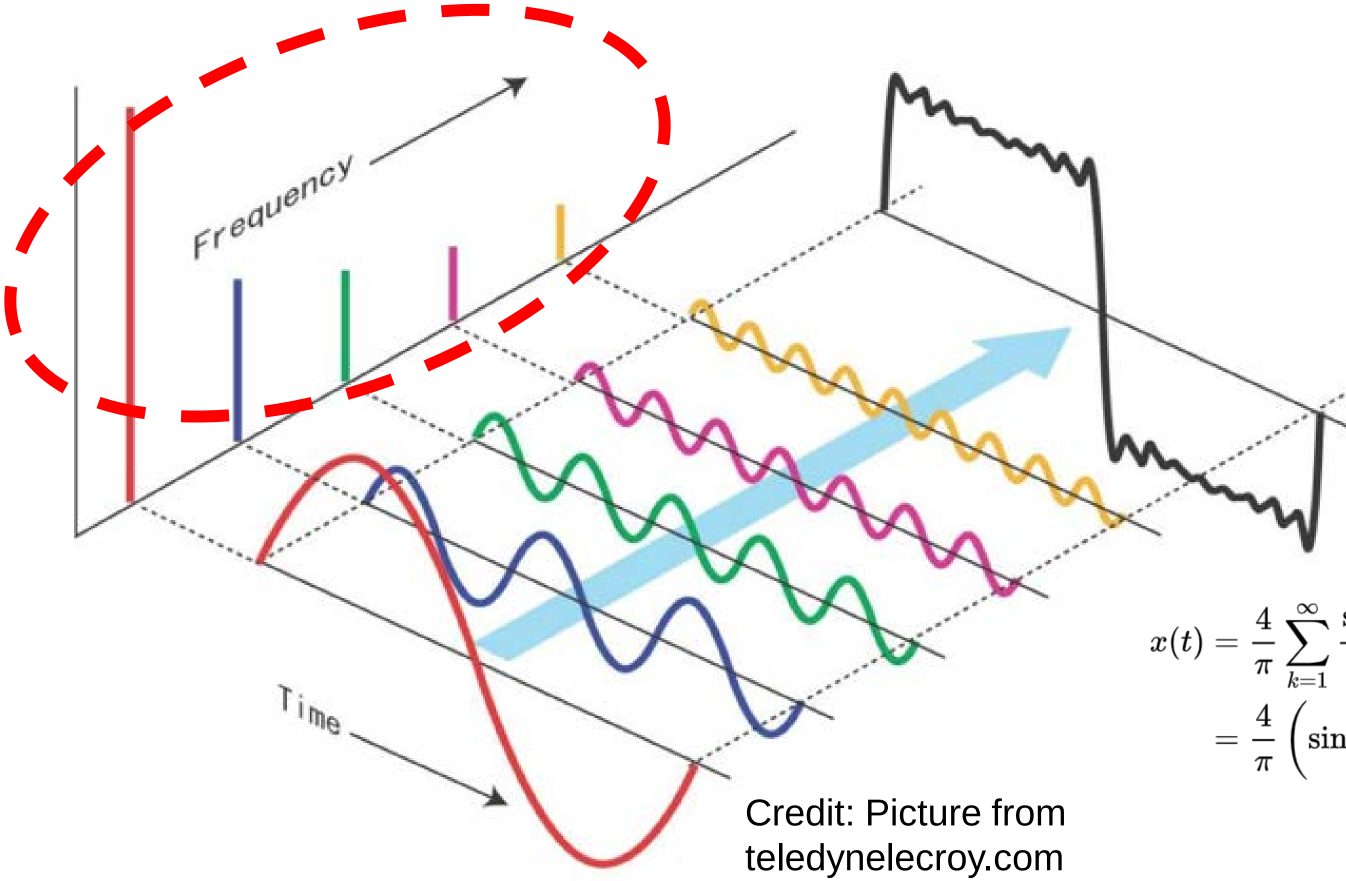
Spectral Analysis

- Any function of time can be described as a sum of sinusoidal waves, each with different amplitudes and frequencies

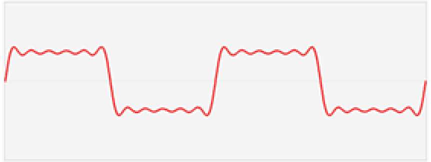
- **Spectral analysis** studies the distribution of a signal's frequency components

- The plot of a signal's frequency components and their corresponding magnitudes is called "**frequency spectrum**"

Spectral Analysis



Credit: Picture from teledynelecroy.com

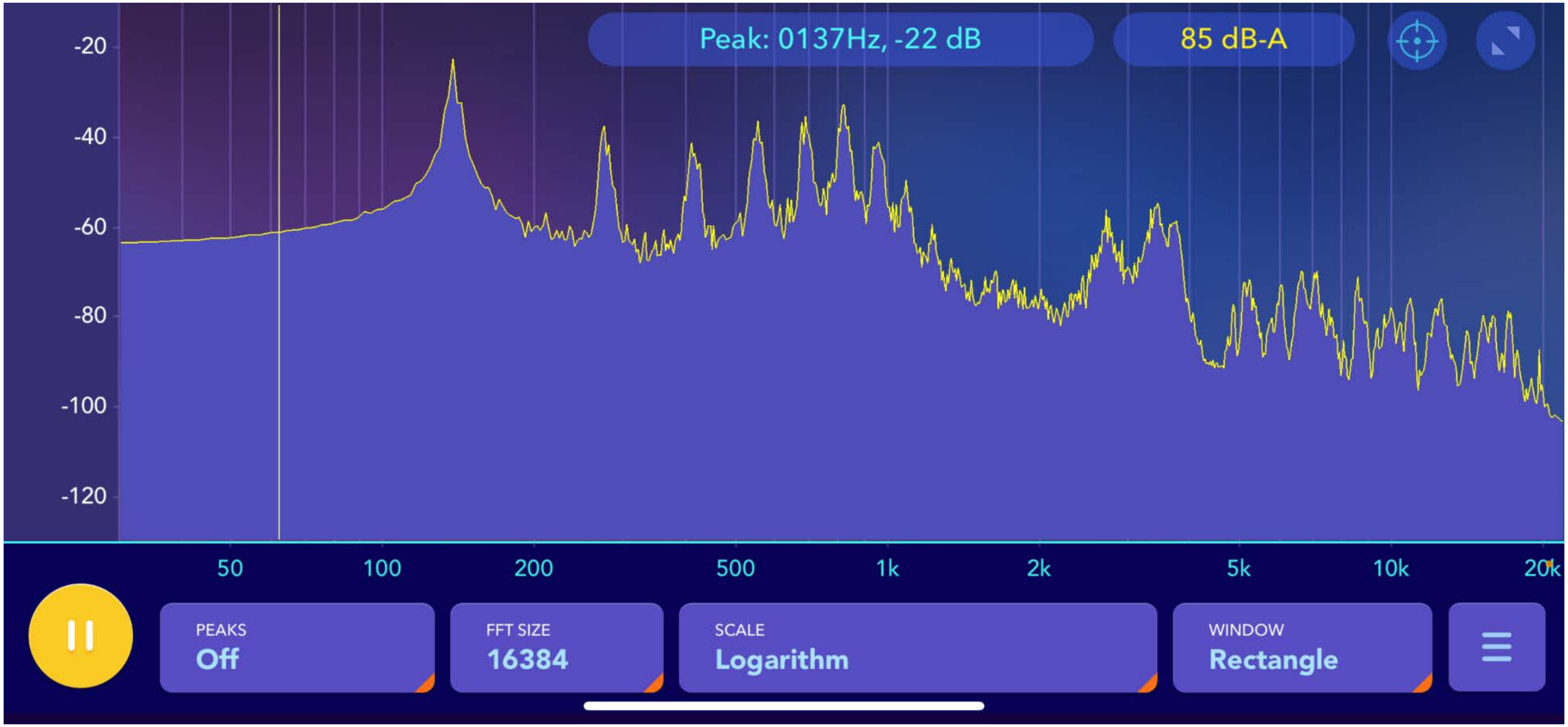


Mathematically, it can be represented using Fourier expansion:

$$x(t) = \frac{4}{\pi}\sum_{k=1}^{\infty}\frac{\sin(2\pi(2k-1)ft)}{2k-1}$$
$$= \frac{4}{\pi}\left(\sin(\omega t) + \frac{1}{3}\sin(3\omega t) + \frac{1}{5}\sin(5\omega t) + \ldots\right)$$

- We are analysing a signal in the **frequency domain**
- A square wave can be decomposed into an **infinite sum** of **sinusoidal** waves

Example of Frequency Spectrum



The frequency spectrum of a particular audio tone

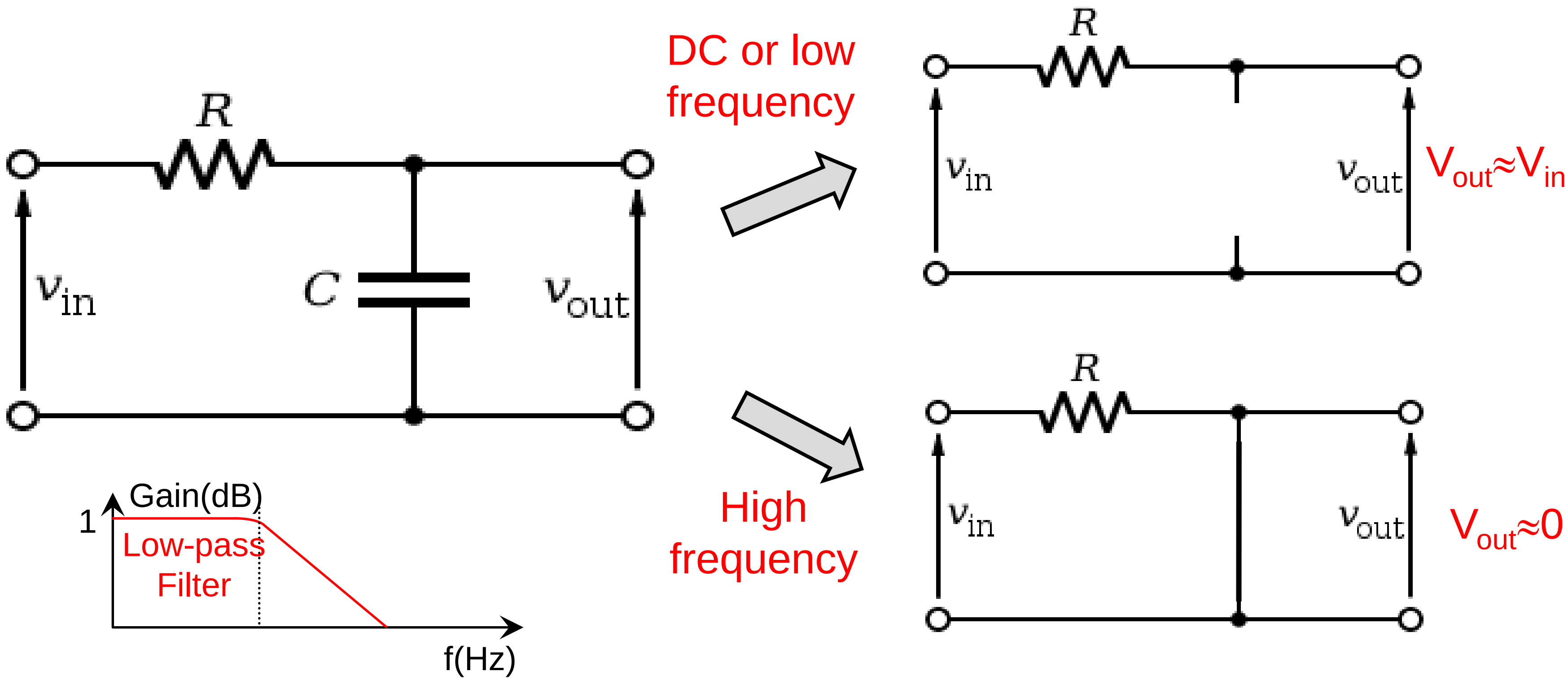
Filter

- A filter is a device or process that removes some unwanted components or features from a signal

- Examples:
  - Removing the noise from measured ECG signal using a filter to help a doctor understand the heart better

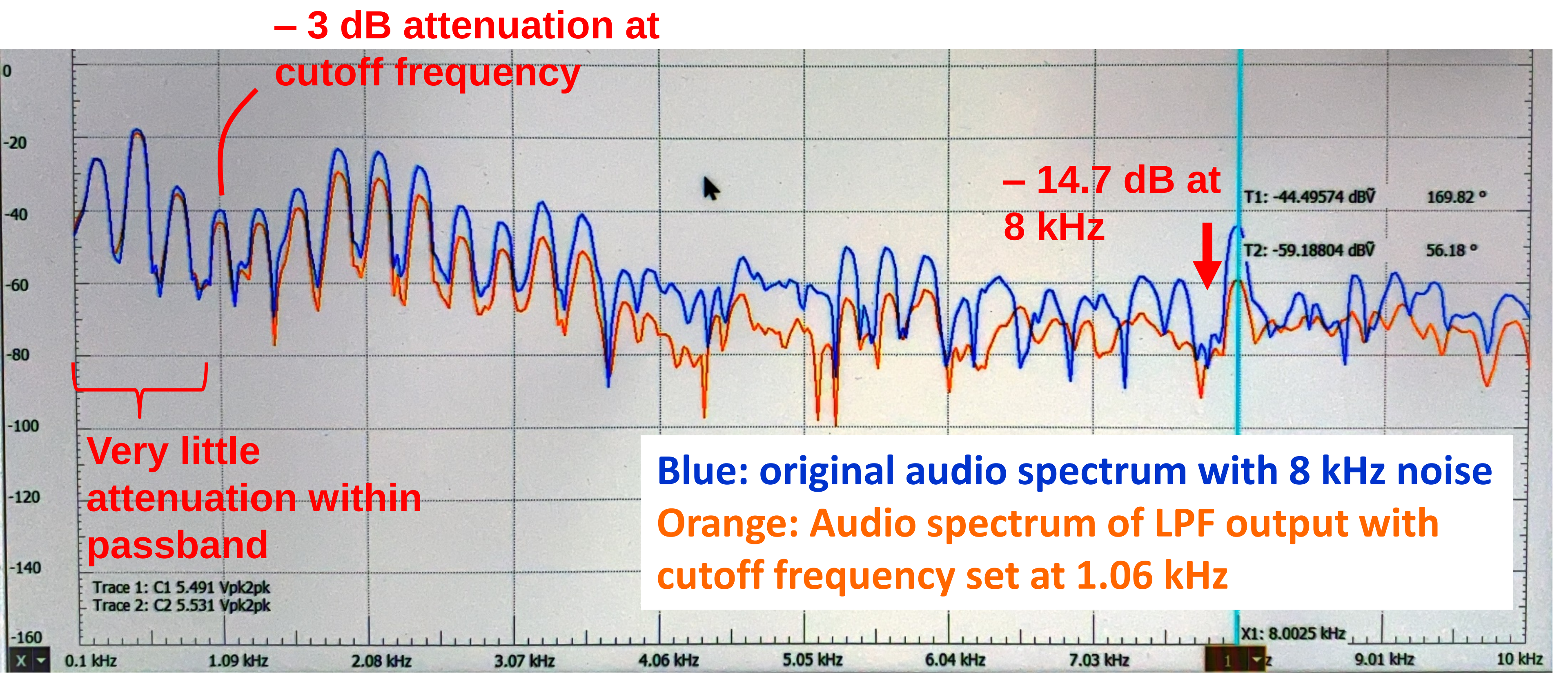
  - Removing some frequencies or frequency bands from an audio signal

Passive Low-Pass Filter



- Capacitor impedance is given as $1/(j\omega C)$
- At low frequency or DC, capacitor behaves like open circuit
- At high frequency, capacitor behaves like short circuit
- Allow low frequency signal to pass through and reject high frequency signal $\Rightarrow$ Low-pass filter

Filters Can Help Suppress (Attenuate) Undesirable Frequencies



Note:
The above spectrum is plotted in linear scale; usual practice is to plot in logarithmic scale if plotted over wide frequency range

Power Gain in decibels (dB)

- The Voltage Amplification (A_v) or Gain of a voltage amplifier/filter is given by:

$$\boxed{A_v = \frac{V_{\text{out}}}{V_{\text{in}}}}$$

- The voltage gain is commonly expressed in terms of the resulting **power** gain in dB:

$$\text{Power Gain (dB)} = 10\log_{10}\left(\frac{P_{\text{out}}}{P_{\text{in}}}\right)\text{dB}$$

(Under certain conditions, to be explained in Q1)

$$= 10\log_{10}\left(\frac{V_{\text{out}}}{V_{\text{in}}}\right)^2\text{dB} = 20\log_{10}\left|\frac{V_{\text{out}}}{V_{\text{in}}}\right|\text{dB}$$

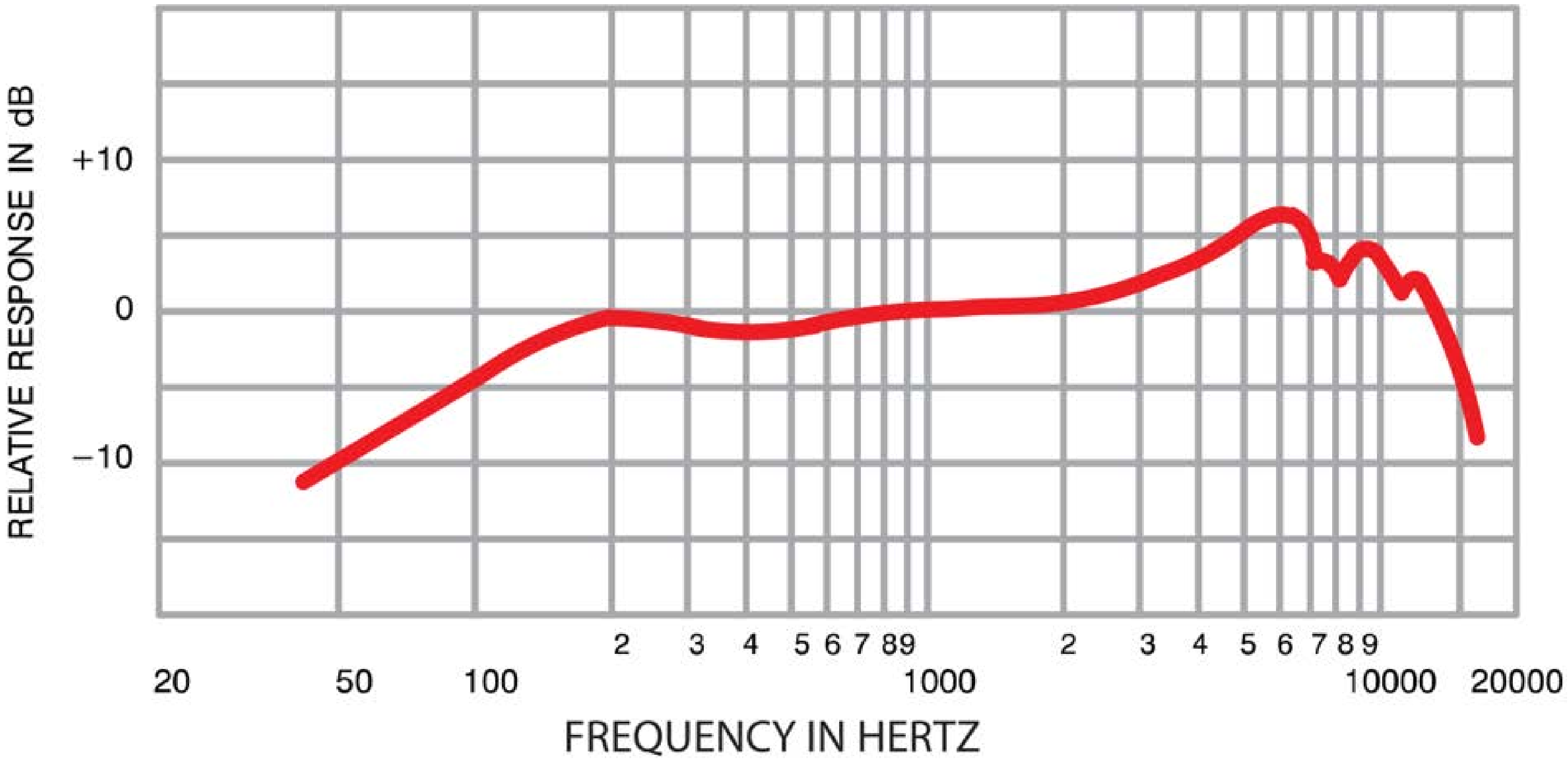
Frequency Response

- It is the quantitative measure of the output spectrum of a system or device in response to a stimulus, and is used to characterize the dynamics of the system
  - –Frequency in logarithmic scale: horizontal x-axis

  - –Power Gain in decibels (dB): vertical y-axis
    To describe a **change in output power** over the **whole frequency range**

$$\boxed{\text{Power Gain in dB }(f) = 20\log_{10}|A_v(f)|}$$

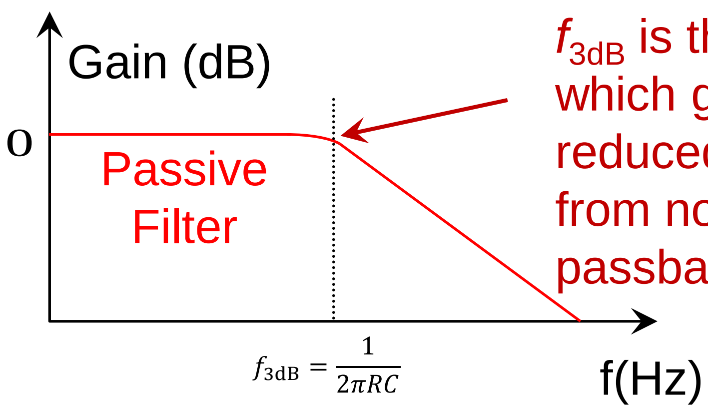
Example of a Microphone's Frequency Response Graph



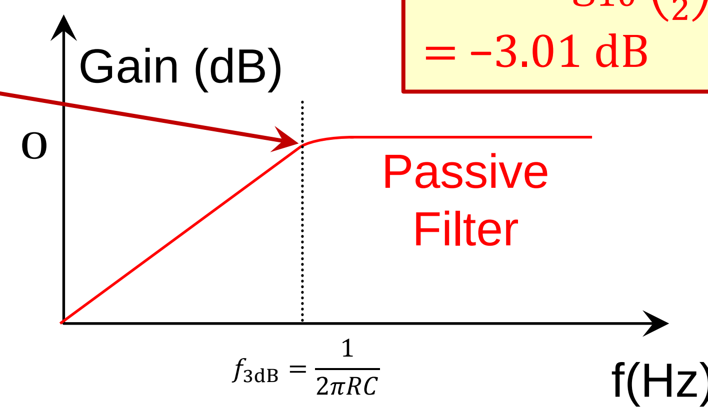
Cut-off Frequency

- In filters, the cut-off frequency characterizes a "boundary" between a passband and a stopband
- It is defined as the frequency at which the **output power** is reduced by **half** compared to the nominal passband value
- In dB scale, this is equivalent to the nominal passband value reduced by about 3 dB

$$10\log_{10}\left(\frac{P_{\mathrm{out}}}{P_{\mathrm{in}}}\right)\,\mathrm{dB} = 10\log_{10}\left(\frac{1}{2}\right)\,\mathrm{dB} = -3.01\ \mathrm{dB}$$

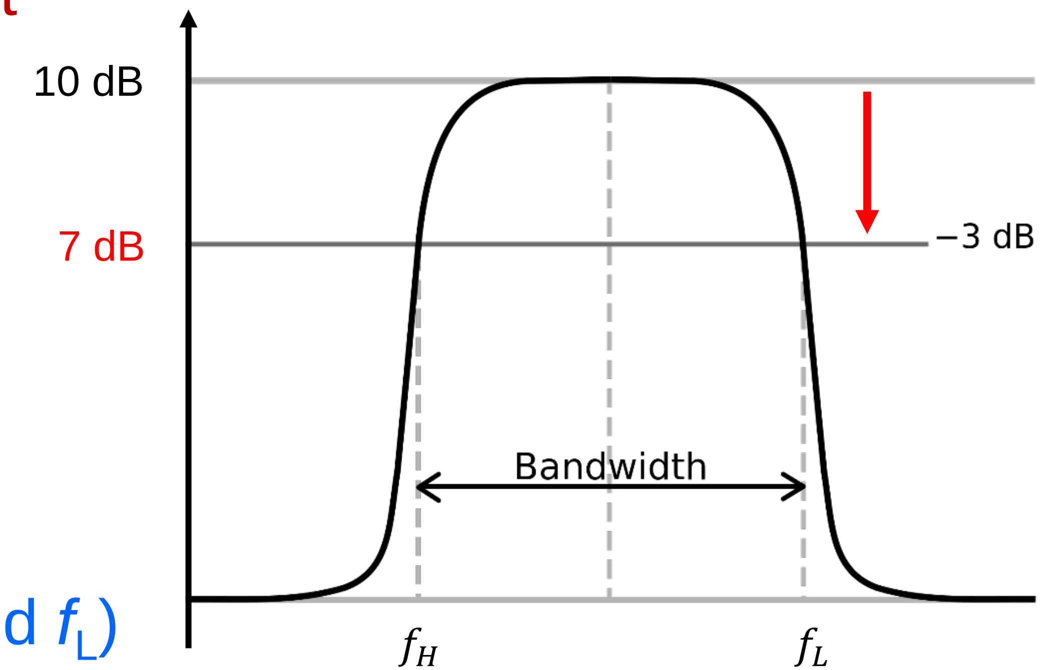


Cutoff frequency $f_{3\mathrm{dB}}$ is the point at which gain is reduced by 3 dB from nominal passband value



Cut-off Frequency: –3 dB Point (i.e., Half-power Point)

- **Graphical** approach:
  - Find the passband gain from the magnitude vs frequency plot
  - Subtract 3 dB from the passband gain and draw a horizontal line on the plot
  - Identify the points where this horizontal line intercepts the plot
  - The frequencies corresponds to these intercepts are the cut-off frequencies (f_H and f_L)



Cut-off Frequency: –3 dB Point (i.e., Half-power Point)

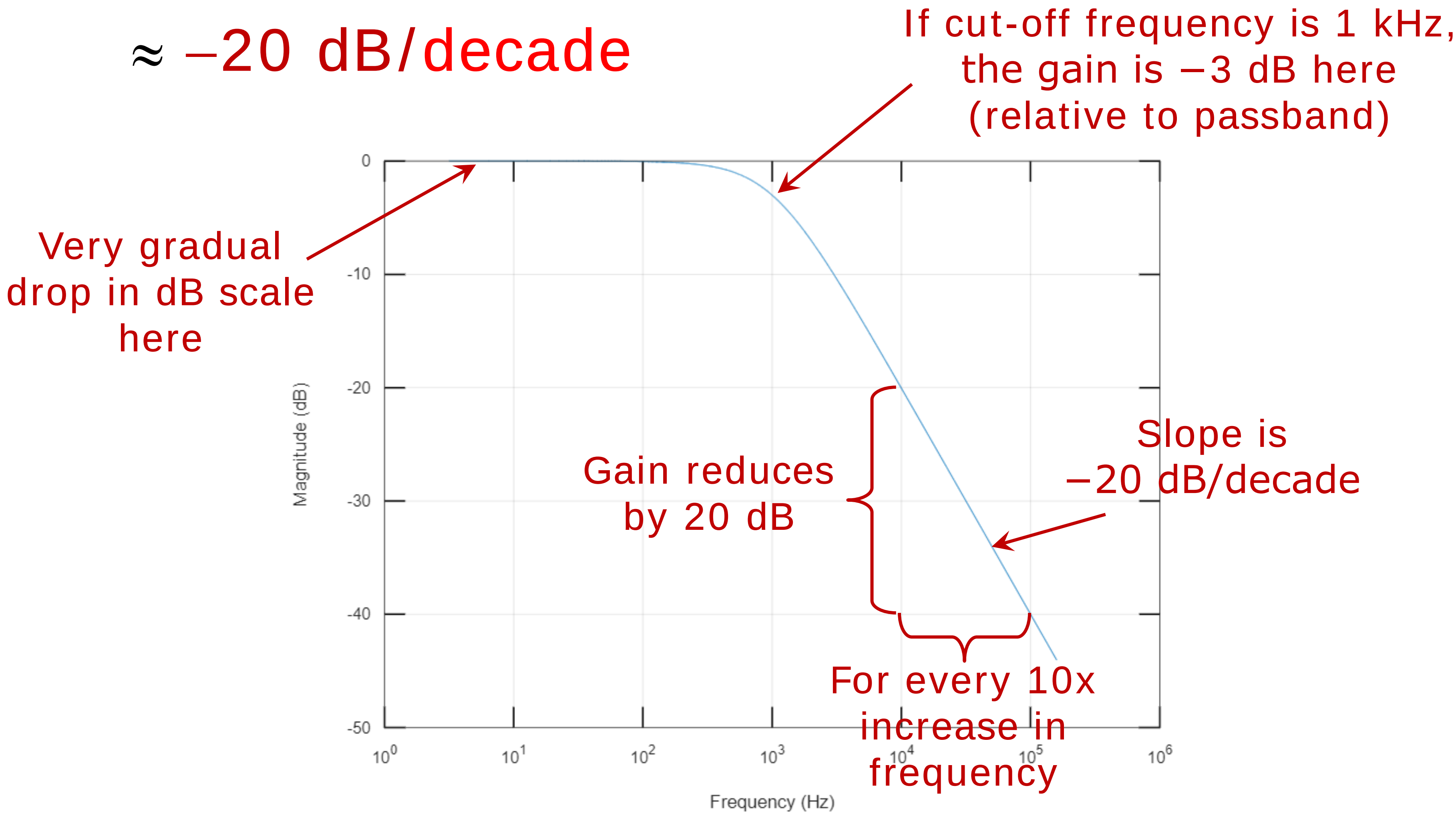
- Quantitative approach (for first-order filters):

$$f_H = \frac{1}{2\pi R_H C_H}, \quad f_L = \frac{1}{2\pi R_L C_L}$$

First-order Low-Pass Filter

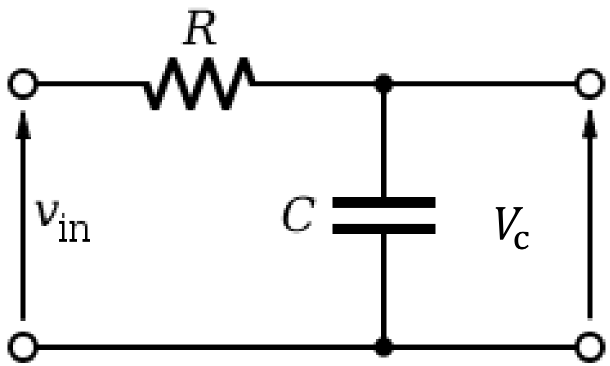
- Slope after cut-off frequency

  ≈ -20 dB/decade



Passive Low-Pass Filter

- Using voltage divider rule to find the voltage gain:



$$\rightarrow V_c = \left[\frac{\frac{1}{j\omega C}}{\frac{1}{j\omega C}+R}\right] V_{in}$$

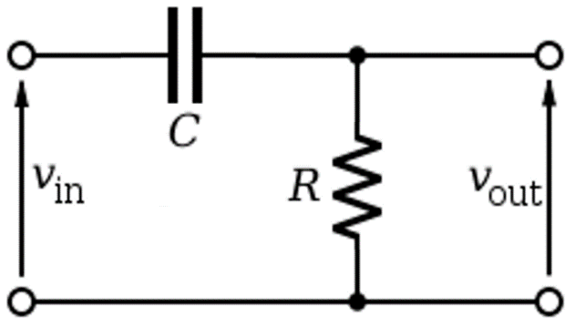
$$\rightarrow \frac{V_c}{V_{in}} = \left[\frac{\frac{1}{j\omega C}}{\frac{1}{j\omega C}+R}\right] = \left[\frac{1}{1+jR\omega C}\right] = \frac{1\angle 0°}{\sqrt{1^2+(R\omega C)^2}\angle\theta°}$$

$$\rightarrow \left|\frac{V_c}{V_{in}}\right| = \left[\frac{1}{\sqrt{1+(R\omega C)^2}}\right]$$

$$\text{Gain in dB} = \underbrace{20\log_{10} 1}_{\substack{\text{Passband gain} \\ (=\ 0\ \text{dB})}} \underbrace{- 20\log_{10}\sqrt{1+(\omega CR)^2}}_{\substack{\text{Change in gain with } \omega \\ (-3\ \text{dB occurs at } f_L = \frac{1}{2\pi RC})}}\ \text{dB}$$

Passive High-Pass Filter

- Using voltage divider rule to find the voltage gain:



$$\rightarrow V_{out} = \left[\frac{R}{R+\frac{1}{j\omega C}}\right] V_{in}$$

$$\rightarrow \frac{V_{out}}{V_{in}} = \left[\frac{R}{R+\frac{1}{j\omega C}}\right] = \left[\frac{1}{1-\frac{j}{\omega CR}}\right] = \frac{1\angle 0^\circ}{\sqrt{1^2+\left(\frac{1}{\omega CR}\right)^2}\angle\theta^\circ}$$

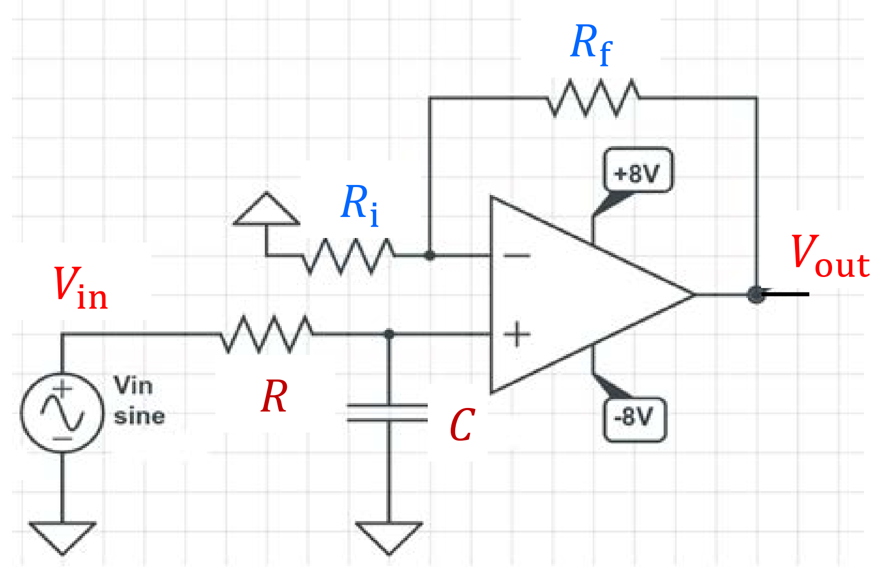
$$\rightarrow \left|\frac{V_{out}}{V_{in}}\right| = \left[\frac{1}{\sqrt{1+\left(\frac{1}{\omega CR}\right)^2}}\right]$$

$$\text{Gain in dB} = \underbrace{20\log_{10}1}_{\substack{\text{Passband gain} \\ (=\ 0\ \text{dB})}} \underbrace{-\ 20\log_{10}\sqrt{1+\left(\frac{1}{\omega CR}\right)^2}}_{\substack{\text{Change in gain with } \omega \\ (-3\ \text{dB occurs at } f_H = \frac{1}{2\pi RC})}}\ \text{dB}$$

The Need for Amplifying Signals

- Voltage output from sensors may be in the order of mV, e.g., microphone signals
- The sensor voltage output would need to be scaled **before A-to-D conversion** for more accurate measurements (e.g., using Arduino Uno)

Active Low-Pass Filter



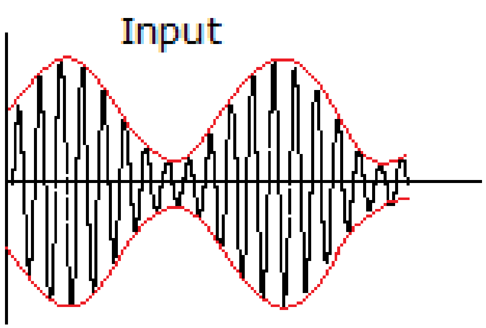
$$\frac{V_{out}}{V_{in}} = \frac{V_{out}}{V_+} \times \frac{V_+}{V_{in}} = \left(1 + \frac{R_f}{R_i}\right) \frac{V_+}{V_{in}}$$

$$\left|\frac{V_{out}}{V_{in}}\right| = \left(1 + \frac{R_f}{R_i}\right) \frac{1}{\sqrt{1 + (R\omega C)^2}}$$

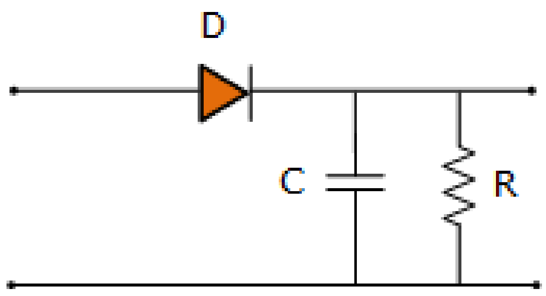
$$\text{Gain in dB} = \underbrace{20 \log_{10}\left(1 + \frac{R_f}{R_i}\right)}_{\substack{\text{Passband gain} \\ (=\ \text{XX dB})}} \underbrace{- 20 \log_{10}\sqrt{1 + (\omega C R)^2}}_{\substack{\text{Change in gain with } \omega \\ (-3 \text{ dB from XX dB occurs at } f_L = \frac{1}{2\pi RC})}} \text{dB}$$

Envelope Detector

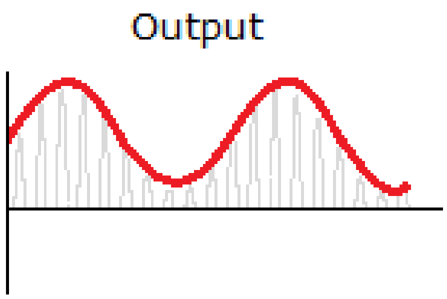
- An envelope detector is an electronic circuit that takes a high-frequency signal as input (**sound**) and provides an output which is the envelope of the original signal
- The capacitor in the circuit stores up charge on the rising edge, and releases it slowly (through the load) when signal falls



(Sound Signal)

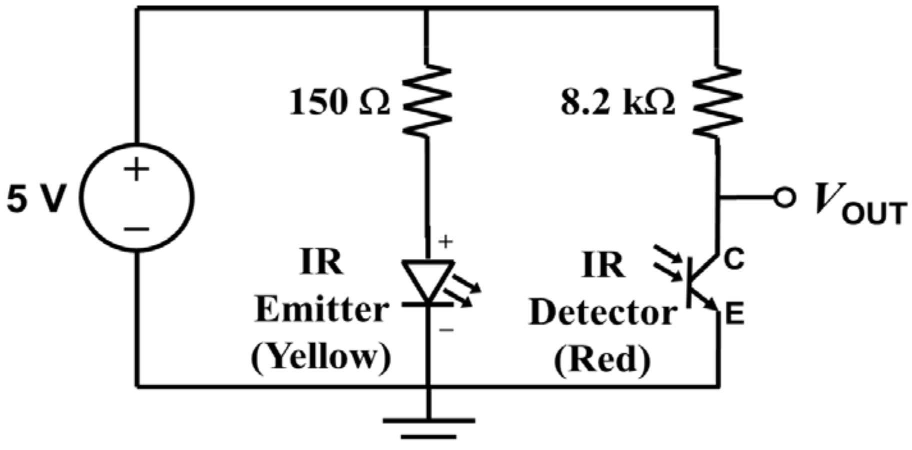


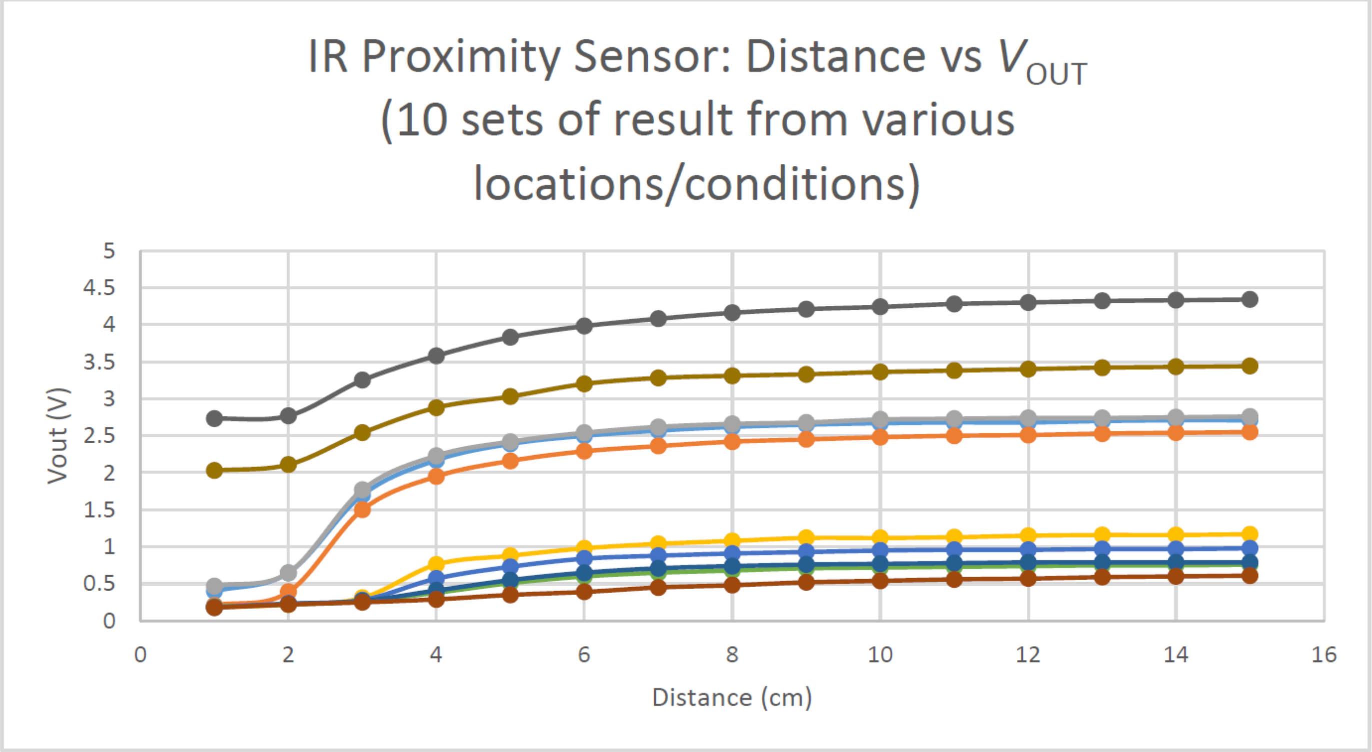
Envelope Detector



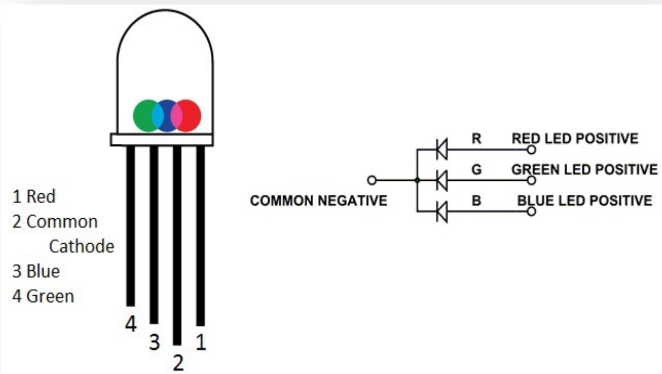
(Envelope of the Input)

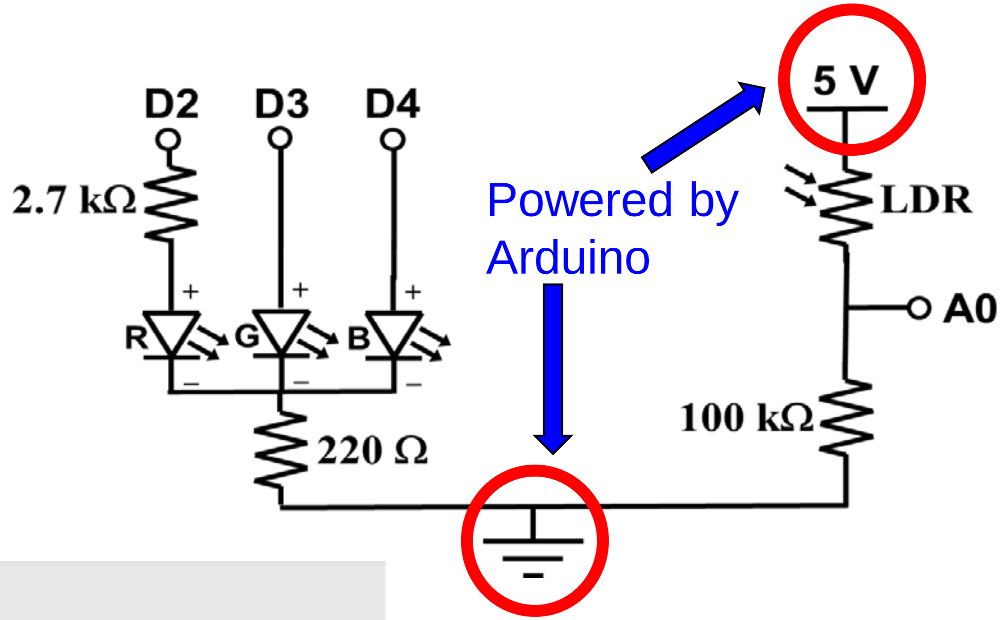
IR Proximity Sensor





LDR Colour Sensor



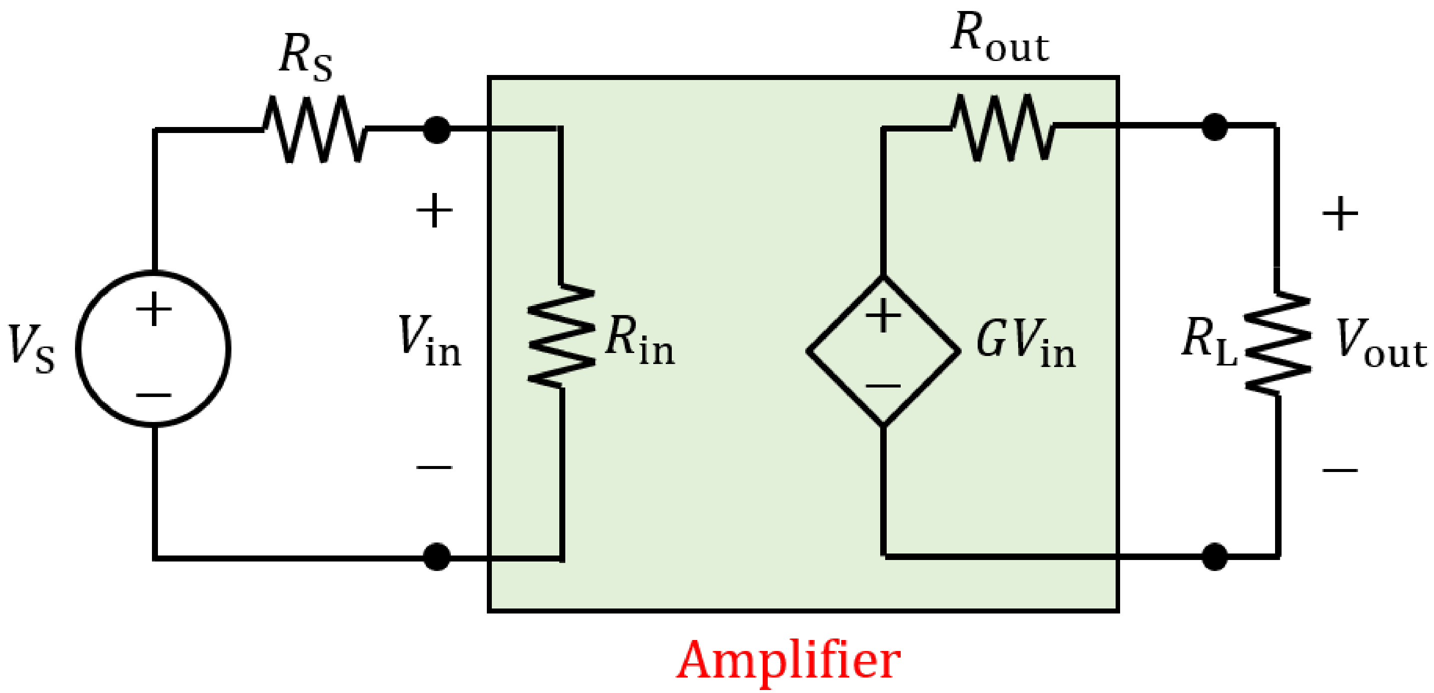


- An RGB colour value is specified with: rgb(red, green, blue)
- Each parameter (red, green, and blue) defines the intensity of the colour as an integer between 0 and 255

Question 1

Show that if $\boldsymbol{R_{in}} = \boldsymbol{R_L}$, then the power gain in dB for an amplifier circuit is given by

$$\boxed{\text{Power gain (dB)} = 20\log_{10}\left|\frac{V_{\text{out}}}{V_{\text{in}}}\right| \text{ dB}}$$



Question 1

- Power at amplifier's input: $P_{\text{in}} = \frac{V_{\text{in}}^2}{R_{\text{in}}}$
- Power delivered to load: $P_{\text{out}} = \frac{V_{\text{out}}^2}{R_{\text{L}}}$
- Power Gain in dB

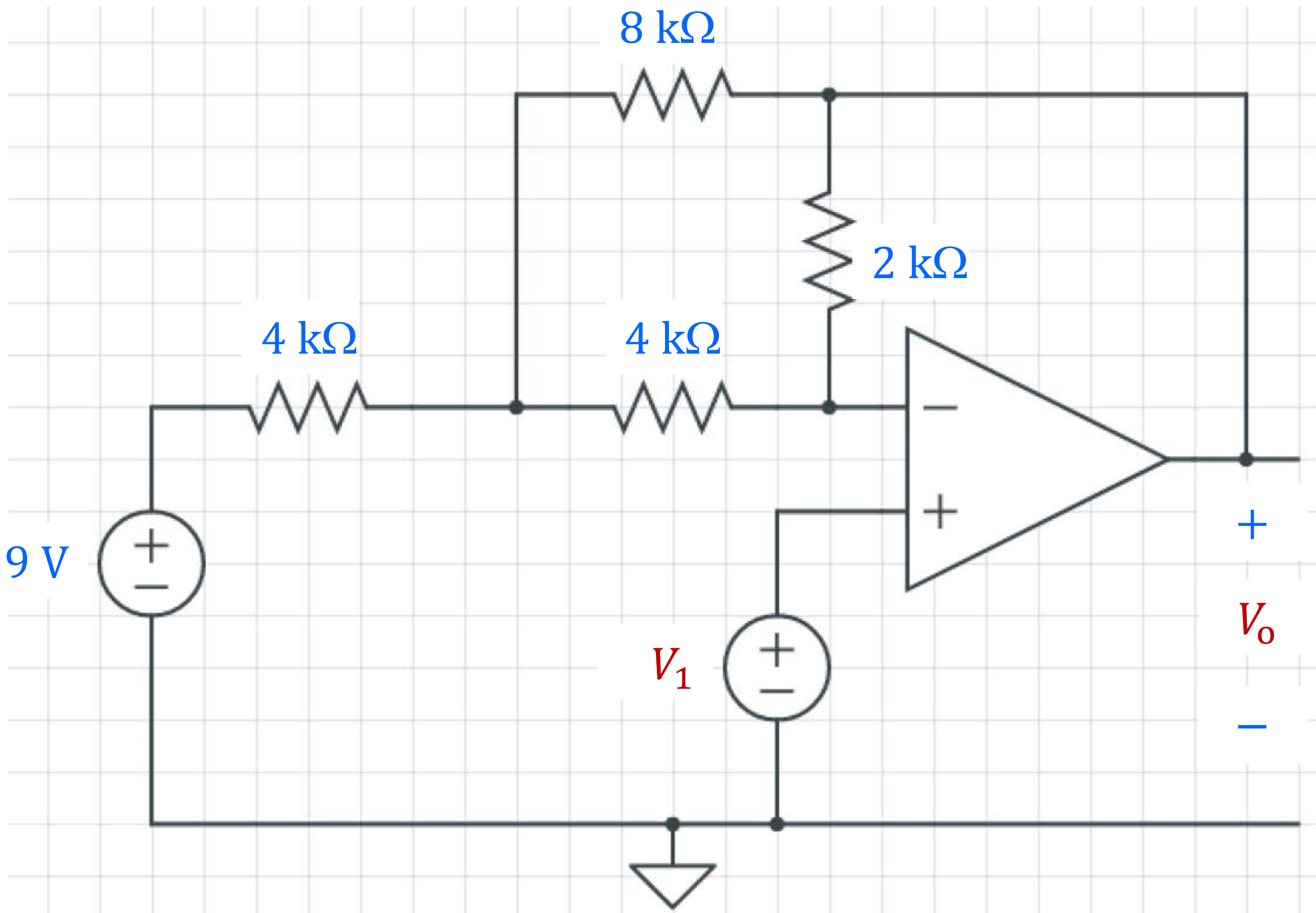
$$= 10 \log_{10}\left(\frac{P_{\text{out}}}{P_{\text{in}}}\right)$$

$$= 10 \log_{10}\left(\frac{V_{\text{out}}}{V_{\text{in}}}\right)^2 + \overbrace{10 \log_{10}\left(\frac{R_{\text{in}}}{R_{\text{L}}}\right)}^{\text{Equals 0 if } R_{\text{in}} = R_{\text{L}}}$$

$$= 20 \log_{10}\left|\frac{V_{\text{out}}}{V_{\text{in}}}\right|$$

Question 2

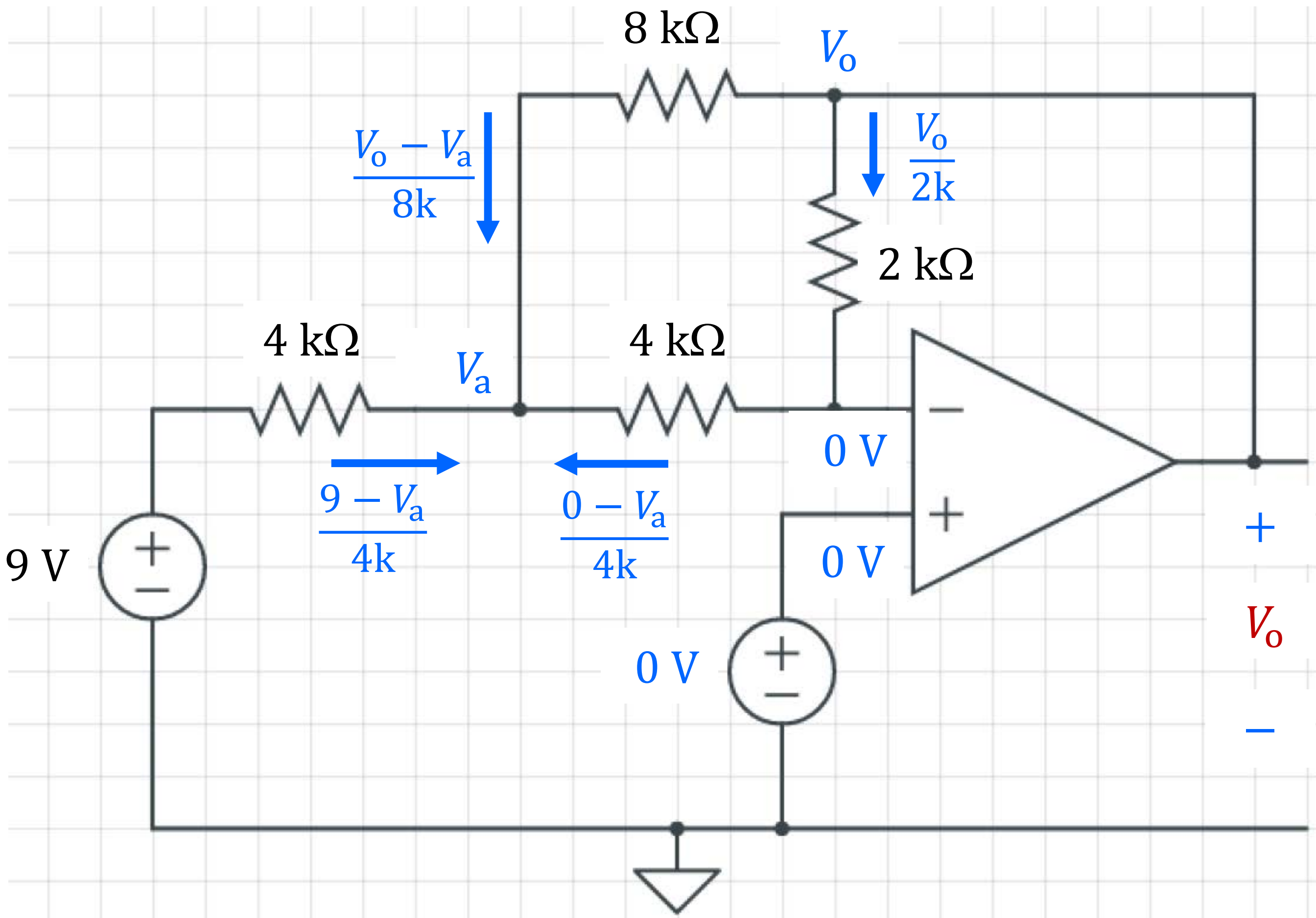
- Calculate V_o in the circuit if $V_1 = 0$



Question 2

$$\frac{9 - V_a}{4k} + \frac{V_o - V_a}{8k} + \frac{0 - V_a}{4k} = 0$$

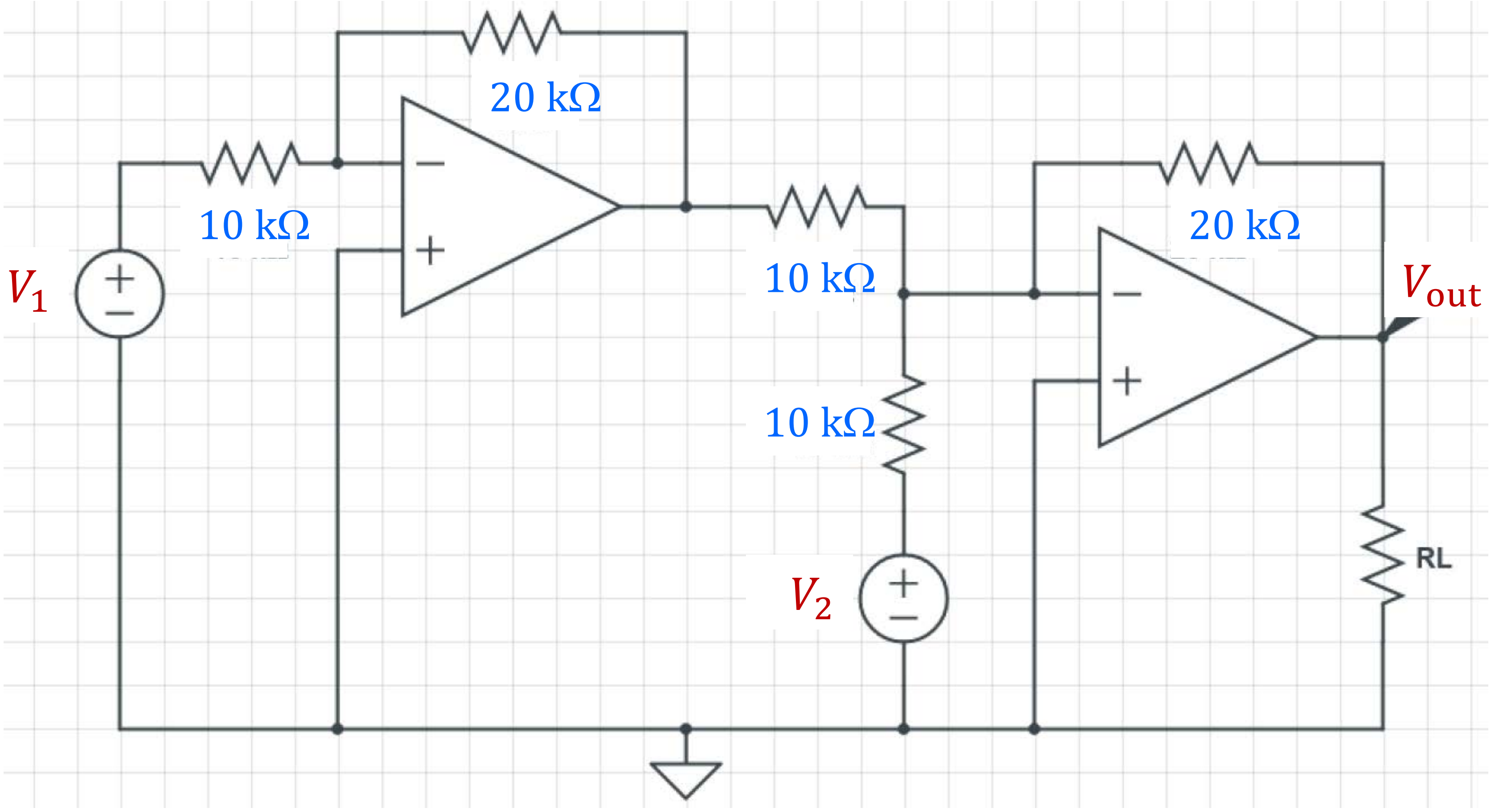
$$\frac{V_o}{2k} + \frac{V_a - 0}{4k} = 0 \rightarrow V_a = -2V_o$$



Solving,
$V_o = -1.64$ V

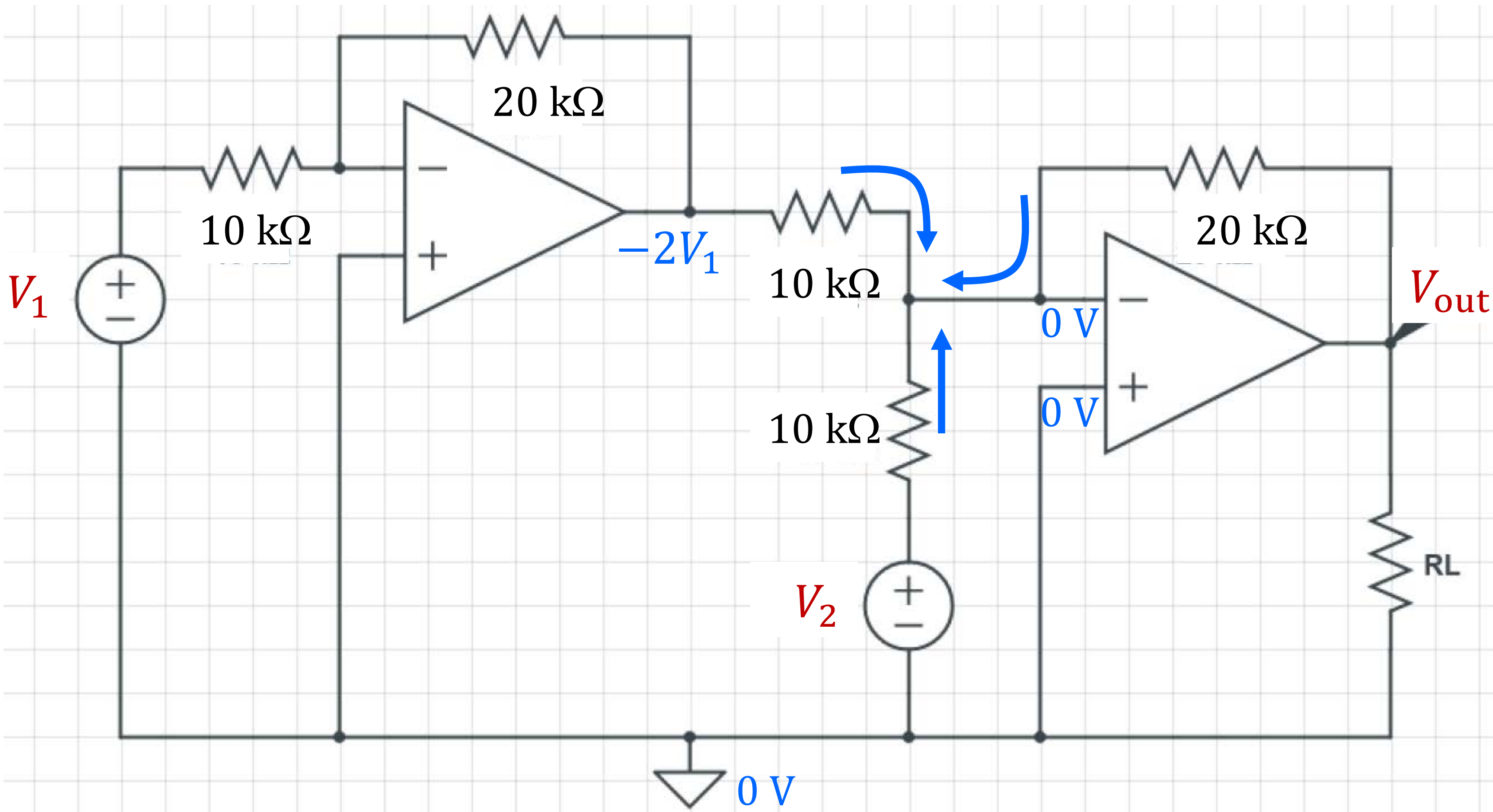
Question 3

- Find an expression for V_{out} (in terms of V_1 and V_2)



Question 3

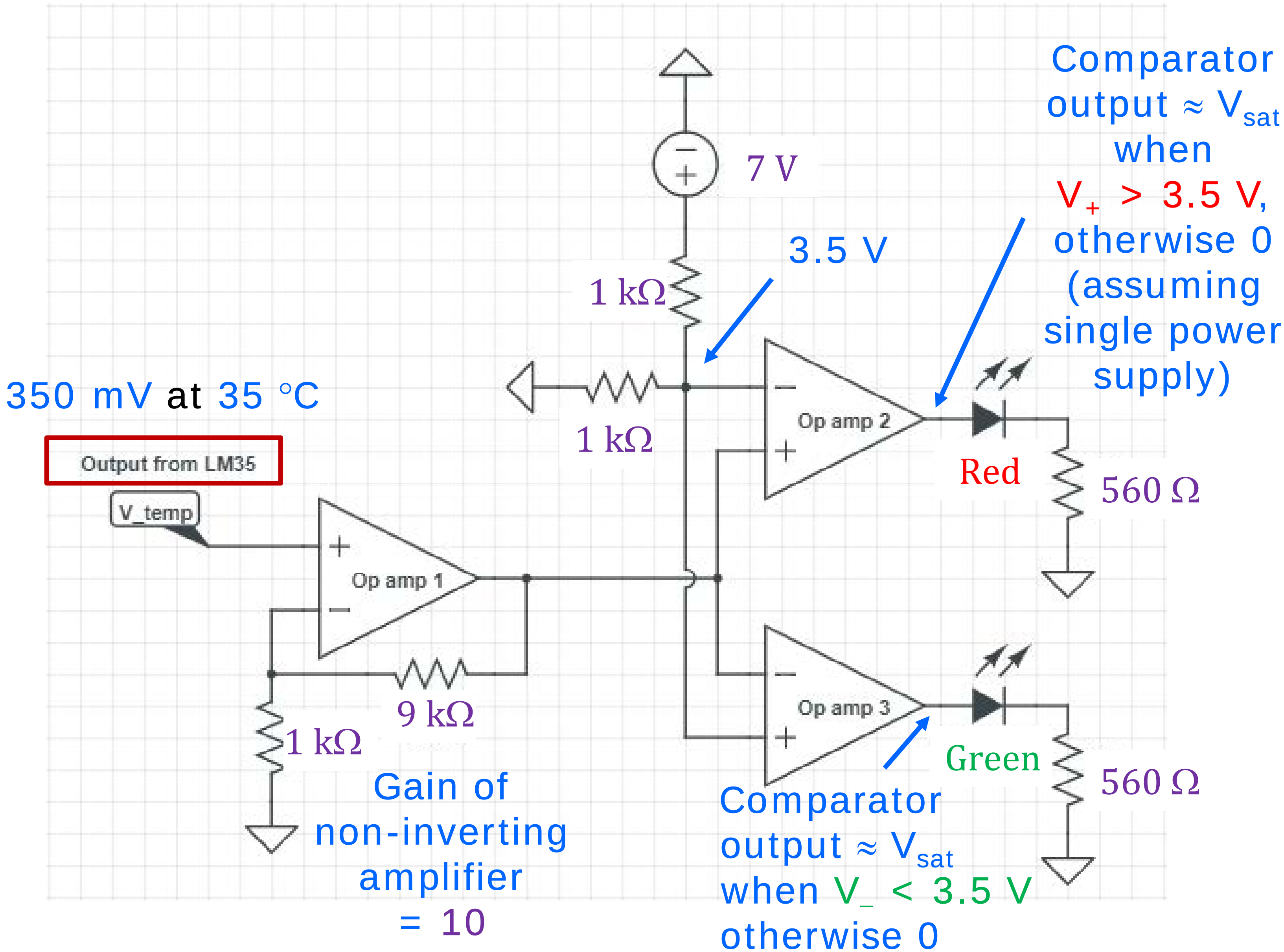
$$\frac{-2V_1 - 0}{10\text{k}} + \frac{V_2 - 0}{10\text{k}} + \frac{V_{\text{out}} - 0}{20\text{k}} = 0 \quad \rightarrow \quad V_{\text{out}} = 4V_1 - 2V_2$$



Question 4

- Design a temperature sensing circuit using LM35 (temperature sensor IC), Op amps, resistors, and LEDs
- LM35 output = 250 mV at 25 °C
- LM35 output varies as 10 mV/°C
- Temperature below 35 °C, GREEN LED on
- Temperature above 35 °C, RED LED on

Question 4


350 mV at 35 °C
Output from LM35
V_temp
Op amp 1
Op amp 2
Op amp 3
7 V
1 kΩ
3.5 V
1 kΩ
9 kΩ
1 kΩ
Red
Green
560 Ω
560 Ω
Comparator output ≈ V_{sat} when $V_+ > 3.5$ V, otherwise 0 (assuming single power supply)
Gain of non-inverting amplifier = 10
Comparator output ≈ V_{sat} when $V_- < 3.5$ V otherwise 0

Question 4

- Op Amp 1 – closed loop gain of 10
- Op Amps 2 & 3 are comparators with reference voltage of 3.5 V
  - Op Amp 2 – non-inverting comparator
  - Op Amp 3 – inverting comparator
- When output of op-amp 1 is more than 3.5 V (i.e., when temperature > 35 °C), Red LED is turned on
- When output of op-amp 1 is less than 3.5 V (i.e., when temperature < 35 °C), Green LED is turned on

Question 5

- Suppose:
  - An audio clip: 100-3000 Hz
  - Corrupted with 10 kHz noise
  - Signal very soft

- Desired outcome:
  - **Active** LPF with passband gain of 6 dB
  - **Suppress** the **10 kHz noise** by 20 dB relative to the passband gain

- What is the cut-off frequency of the low-pass filter?

A Note About –20 dB in Power

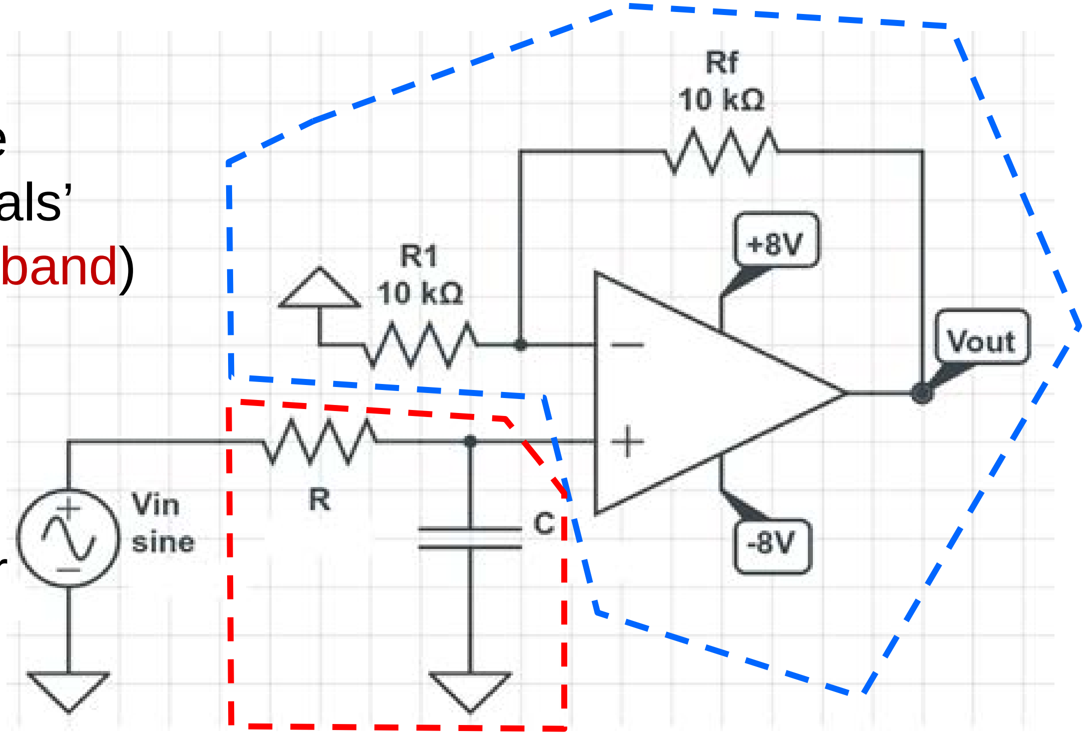
- Suppressing the noise by 20 dB is equivalent to reducing its power to just 1% compared to no filtering
- Also equivalent to reducing its voltage to just 10% compared to no filtering

- $10\ \log_{10}\left(\frac{P_{\text{noise(filtered)}}}{P_{\text{noise(no filter)}}}\right) = 10\ \log_{10}(0.01) = -20\text{ dB}$

- $20\ \log_{10}\left(\frac{V_{\text{noise(filtered)}}}{V_{\text{noise(no filter)}}}\right) = 20\ \log_{10}(0.1) = -20\text{ dB}$

Question 5

Active low-pass filter
(i.e., amplifies **entire** signal while suppressing high frequency signals' power **relative** to signals in passband)



Blue:
Active gain (= 2, i.e., 6 dB) due to non-inverting amplifier

Red:
Passive filter's gain due to RC potential divider (ω-dependent)

$$\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{V_{\text{out}}}{V_+} \times \frac{V_+}{V_{\text{in}}} = \left(1 + \frac{R_f}{R_1}\right)\frac{V_+}{V_{\text{in}}} = 2\left[\frac{\frac{1}{j\omega C}}{\frac{1}{j\omega C} + R}\right] = \frac{2}{1 + j\omega CR}$$

Hence, gain's magnitude w.r.t. ω = $\left|\frac{V_{\text{out}}}{V_{\text{in}}}\right| = \frac{2}{\sqrt{1+(\omega CR)^2}}$

Question 5

$$\text{Gain in dB} = \underbrace{20\log_{10} 2}_{\text{Passband gain}} \underbrace{- 20\log_{10}\sqrt{1+(\omega CR)^2}}_{\text{Change in gain with } \omega} \text{ dB}$$

A gain reduction of 20 dB at f = 10 kHz means:

$$-20\log_{10}\sqrt{1+(\omega CR)^2}\Big|_{f\,=\,10\text{ kHz}} = -20\text{ dB}$$

Hence, $\sqrt{1+(\omega CR)^2} = 10$ when f = 10 kHz

Our low-pass filter needs to have:

$$RC = \frac{\sqrt{10^2-1}}{2\pi\times 10000} = 1.584\times 10^{-4}\text{ s}$$

Choose some *RC* combination that has this value

Question 5

- Cutoff frequency is the frequency at which the gain decreases by 3 dB from passband gain

- A gain reduction of 3 dB at $f = f_c$ means:

$$-20\log_{10}\sqrt{1+(\omega CR)^2}\Big|_{f=f_c} = -3\text{ dB}$$

- Hence, $\sqrt{1+(\omega CR)^2} = 10^{3/20} = \sqrt{2}$ at $f = f_c$

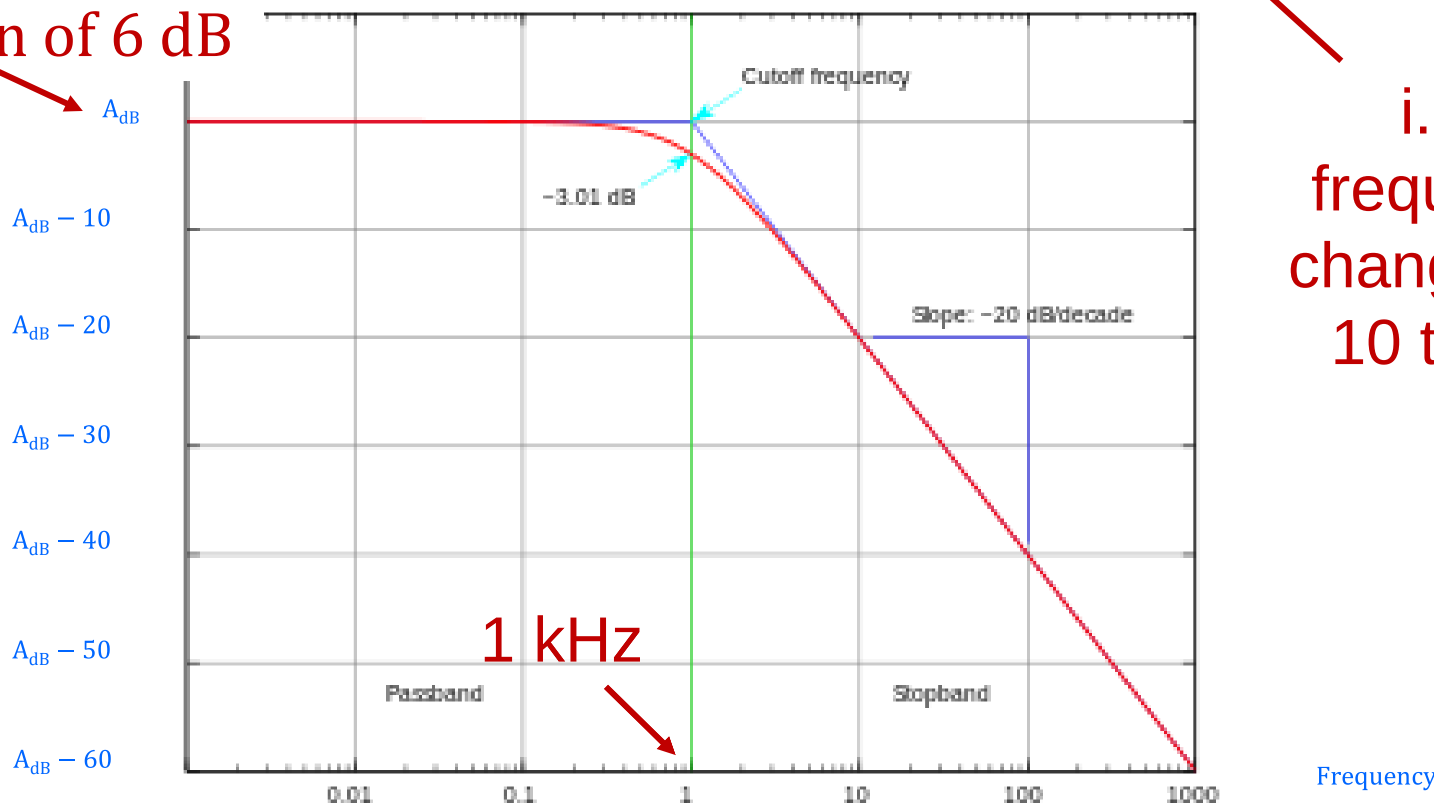
$\omega CR = 1$ at $f = f_c$

Since $\omega = 2\pi f$, we have $\boxed{f_c = \frac{1}{2\pi RC}} = \frac{1}{2\pi \times 1.584 \times 10^{-4}} \approx 1\text{ kHz}$

Graphical Visualization for Q5

- First-order low-pass filter: –20 dB/decade
- Each horizontal box is "1 decade"

DC gain of 6 dB



i.e., frequency changes by 10 times

Why –20 dB/decade?

f	$-20\log_{10}\sqrt{1+(\omega CR)^2}$
f_c	≈ –3 dB
10 x f_c	≈ –20 dB
100 x f_c	≈ –40 dB
1000 x f_c	≈ –60 dB

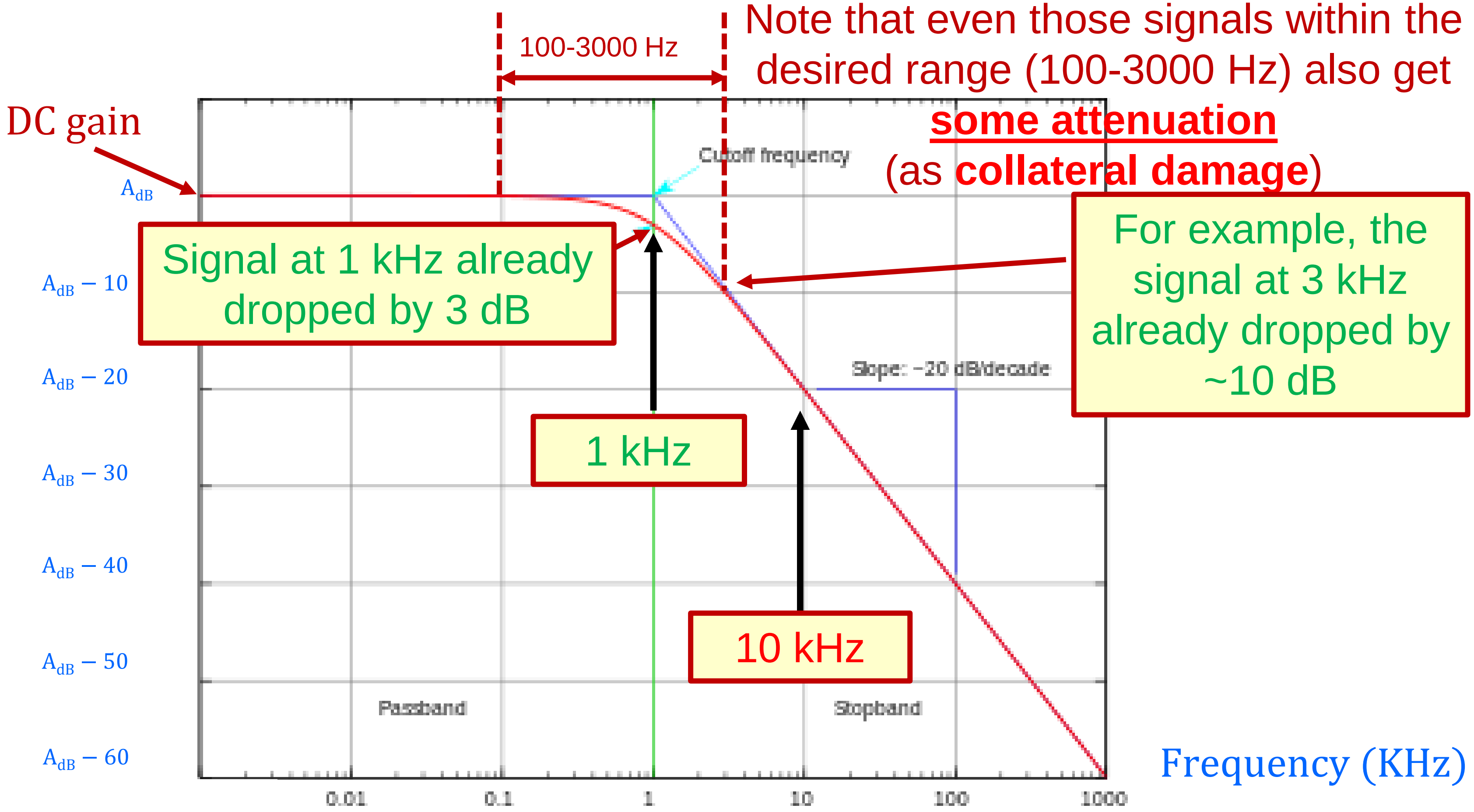
–17

–20

–20

Graphical Visualization for Q5

- If 10 kHz noise has to be reduced by 20 dB, we need to have the cutoff frequency at 1 kHz



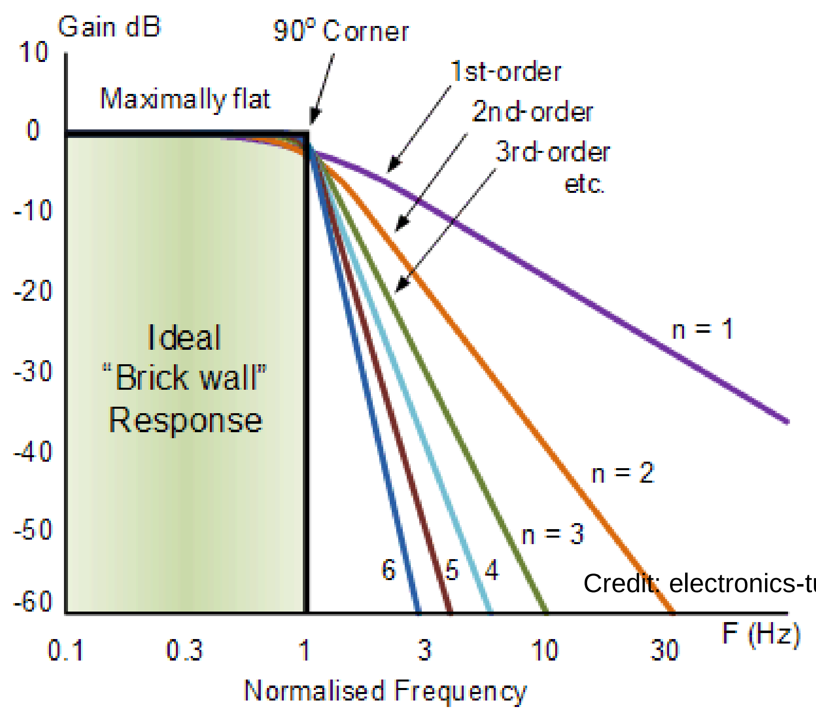
Extra Points to Note for Q5

For your curiosity only:

As can be seen, with a first-order filter, we also lose some audio signals that we desire. How do we improve this?

We can use higher-order filters! This allows us to have sharper attenuation slope, so that our desired passband is not attenuated too much!

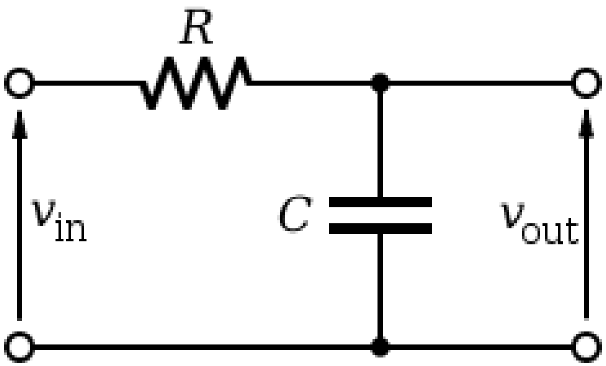
- 2nd order: 40 dB/decade
  - http://www.electronics-tutorials.ws/filter/second-order-filters.html
- 3rd order: 60 dB/decade
  - http://www.circuitstoday.com/higher-order-filters



Credit: electronics-tutorials.ws

Question 6

- Design a passive LPF to suppress 12 kHz noise by at least 15 dB



$$\rightarrow V_{out} = \left[\frac{\frac{1}{j\omega C}}{\frac{1}{j\omega C}+R}\right] V_{in}$$

$$\rightarrow \frac{V_{out}}{V_{in}} = \left[\frac{\frac{1}{j\omega C}}{\frac{1}{j\omega C}+R}\right] = \left[\frac{1}{1+jR\omega C}\right] = \frac{1\angle 0°}{\sqrt{1^2+(R\omega C)^2}\angle\theta°}$$

$$\rightarrow \underbrace{\left|\frac{V_{out}}{V_{in}}\right|}_{\text{Magnitude}} = \left[\frac{1}{\sqrt{1+(R\omega C)^2}}\right] \rightarrow \underbrace{20\log_{10}1}_{\substack{\text{Passband gain}\\(=\ 0\text{ dB})}} - \underbrace{20\log_{10}\sqrt{1+(R\omega C)^2}}_{\substack{\text{Change in gain with }\omega\\(\text{we want }-15\text{ dB at }12\text{ kHz})}}\ \text{dB}$$

Question 6

A gain reduction of 15 dB at f=12 kHz means:

$$-20\log_{10}\sqrt{1+(\omega CR)^2}\Big|_{f\,=\,12\text{ kHz}} = -15\text{ dB}$$

Hence, $\sqrt{1+(\omega CR)^2} = 10^{15/20}$ when f = 12 kHz

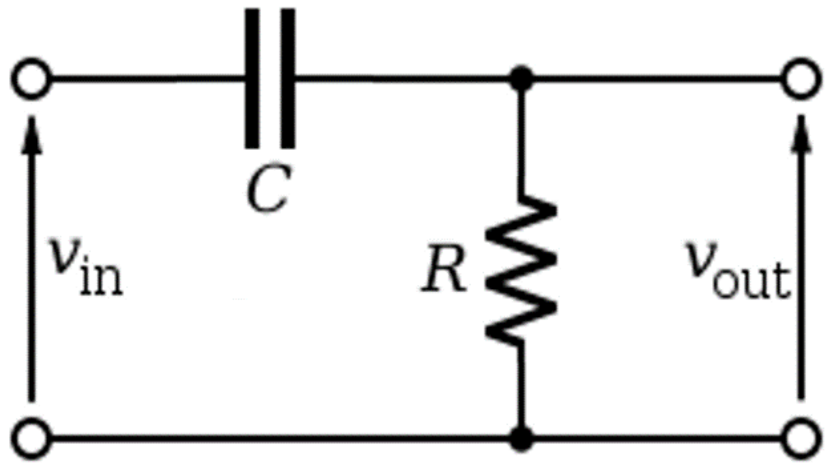
Our low-pass filter needs to have:

$$RC = \frac{\sqrt{10^{(15/20)2}-1}}{2\pi \times 12000} = 73.4\ \mu\text{s}$$

If we choose C = 10 nF, we get R = 7.34 kΩ

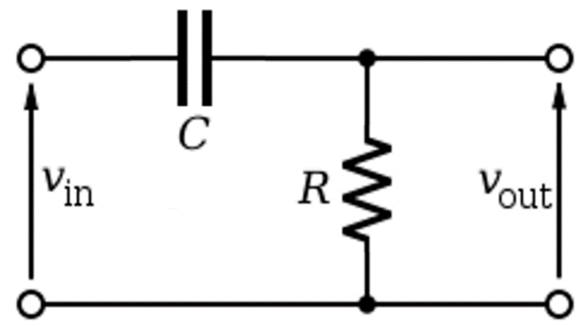
Question 7

For the following passive first-order high-pass filter, show that its cutoff frequency is given by $f_{\mathrm{H}} = \frac{1}{2\pi CR}$



Question 7

- Using voltage divider rule to find the voltage gain:



$$\rightarrow V_{out} = \left[\frac{R}{R+\frac{1}{j\omega C}}\right] V_{in}$$

$$\rightarrow \frac{V_{out}}{V_{in}} = \left[\frac{R}{R+\frac{1}{j\omega C}}\right] = \left[\frac{1}{1-\frac{j}{\omega CR}}\right] = \frac{1\angle 0°}{\sqrt{1^2+\left(\frac{1}{\omega CR}\right)^2}\angle\theta°}$$

$$\rightarrow \left|\frac{V_{out}}{V_{in}}\right| = \left[\frac{1}{\sqrt{1+\left(\frac{1}{\omega CR}\right)^2}}\right] \rightarrow \underbrace{20\log_{10}1}_{\text{Passband gain (= 0 dB)}} \underbrace{- 20\log_{10}\sqrt{1+\left(\frac{1}{\omega CR}\right)^2}}_{\text{Change in gain with } \omega \text{ (–3 dB occurs at } f_H)} \text{ dB}$$

Magnitude

Passband gain (= 0 dB)

Change in gain with ω (–3 dB occurs at f_H)

Question 7

A gain reduction of 3 dB at $f = f_{\mathrm{H}}$ means:

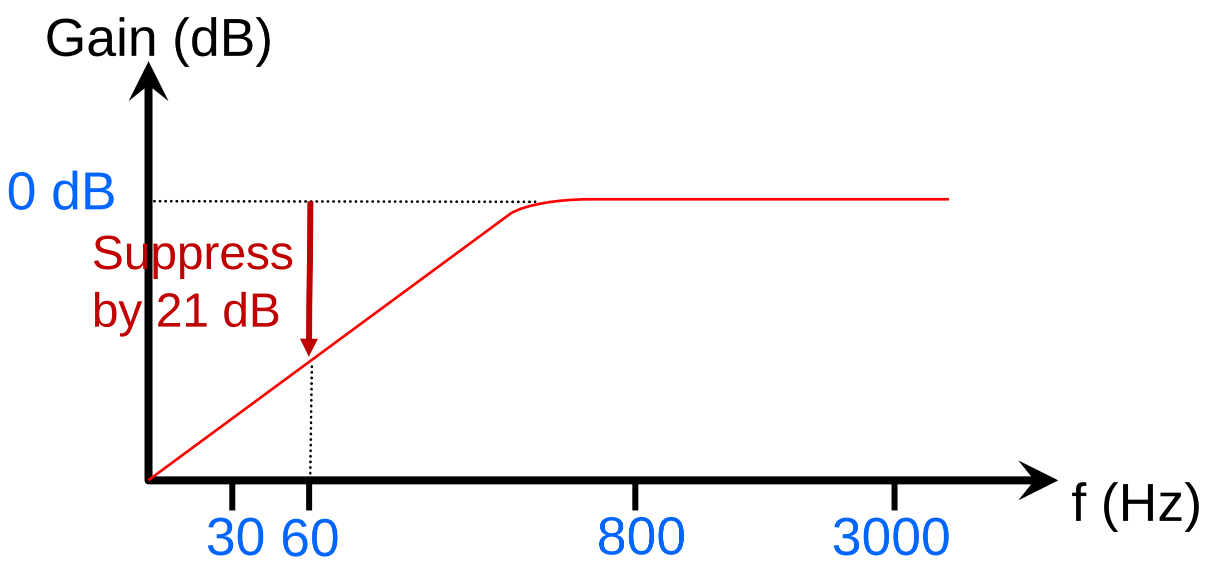
$$-20\log_{10}\sqrt{1+\left(\frac{1}{\omega CR}\right)^2}\,\Bigg|_{f=f_{\mathrm{H}}} = -3\text{ dB}$$

Hence, $\sqrt{1+\left(\frac{1}{\omega CR}\right)^2} = 10^{3/20} = \sqrt{2}$ at $f = f_{\mathrm{H}}$,

which gives $\frac{1}{\omega CR} = \frac{1}{2\pi f_{\mathrm{H}} CR} = 1 \;\rightarrow\; f_H = \frac{1}{2\pi CR}$

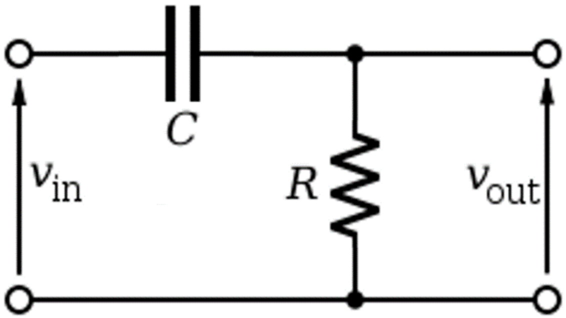
Question 8

- Low frequency humming from the airplane's engine: 30 – 60 Hz
- Electronic dance music: 800 – 3000 Hz
- Design a high-pass filter to suppress the humming by at least 21 dB



Question 8

- We will focus on the passive filter. If need be, a non-inverting amplifier can be cascaded to boost the gain.



$$\left|\frac{V_{\text{out}}}{V_{\text{in}}}\right| = \left[\frac{1}{\sqrt{1+\left(\frac{1}{\omega CR}\right)^2}}\right]$$

$$\rightarrow \underbrace{20\log_{10}1}_{\substack{\text{Passband gain} \\ (=\ 0\ \text{dB})}} \underbrace{- 20\log_{10}\sqrt{1+\left(\frac{1}{\omega CR}\right)^2}}_{\substack{\text{Change in gain with } \omega \\ \text{(we want } -21 \text{ dB at } 60 \text{ Hz)}}}\ \text{dB}$$

Question 8

Hence,

$$-20\log_{10}\sqrt{1+\left(\frac{1}{\omega CR}\right)^2}\Bigg|_{f=60\ \mathrm{Hz}} = -21\ \mathrm{dB}$$

$\sqrt{1+\left(\frac{1}{\omega CR}\right)^2} = 10^{21/20}$ when $f = 60\ \mathrm{Hz}$,

which gives $\frac{1}{\omega CR} = \frac{1}{2\pi(60)CR} = 11.176$

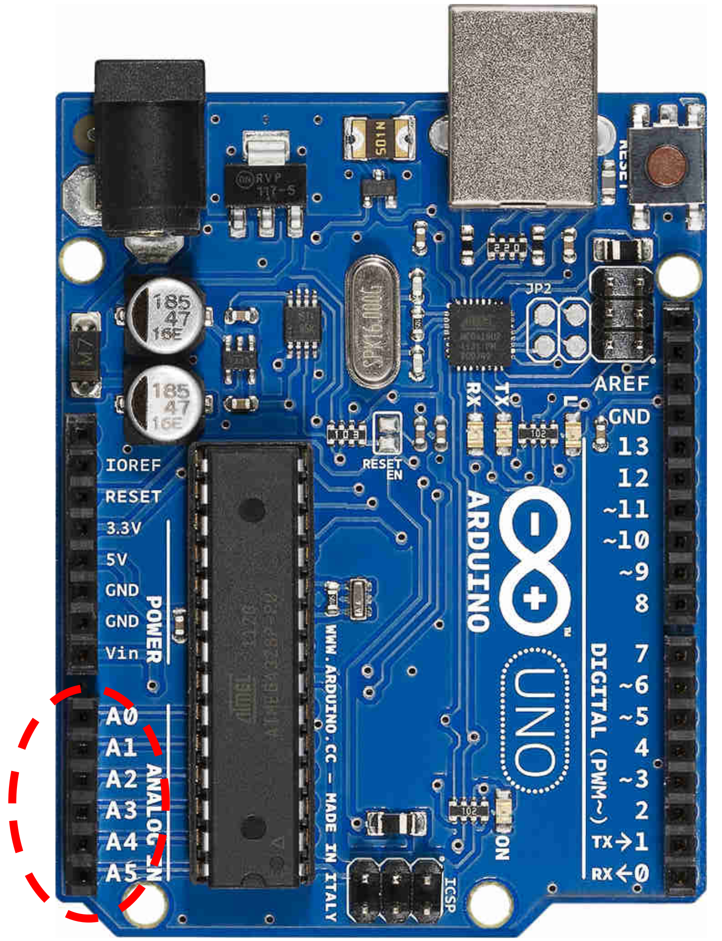
Cutoff frequency of filter = $\frac{1}{2\pi CR} = 670.5\ \mathrm{Hz}$

Question 9

- Pressure sensor: $p = 250\left(\frac{V_{\text{out}}}{V_{\text{cc}}}\right) - 25, \text{where } V_{\text{cc}} = 5\text{ V}$
- Max pressure in setup: 10 PSI
- How to amplify signal before sampling to make good use of Arduino Uno's ADC input range of 0 – 5 V for better accuracy?

ADC input range: 0 – 5 V

ADC Output: 0 – 1023



Question 9

- Since max pressure is 10 PSI, we have

$$10 = 250\left(\frac{V_{\mathrm{out}}}{5}\right) - 25$$

- Solving, we get max $V_{\mathrm{out}} = 0.7\ \mathrm{V}$
- To make good use of the ADC's input range of $0 - 5\ \mathrm{V}$, we need a gain of $\frac{5}{0.7} = 7.14$
- We can pick a non-inverting amplifier with

$$\frac{R_{\mathrm{f}}}{R_{\mathrm{i}}} = 7.14 - 1 = 6.14$$

Question 10

- HIH-4030 humidity sensor IC chip
- V_{out} varies by 30.68 mV/RH% change
- At 0% RH, $V_{\text{out}} = 0.958\,\text{V}$
- Design a humidity sensing circuit using HIH-4030, op-amp, and Arduino Uno

Question 10

- At 100% RH, $V_{\text{out}} = 0.958\,\text{V} + 0.03068 \times 100 = 4.026\,\text{V}$
- We can amplify V_{out} to the range of $0 - 5$ V before sampling it using Arduino Uno, using a non-inverting amplifier with a gain of $\frac{5}{4.026} = 1.242$