Imperial College London

Lecture 2

Amplification and Single-rail Op-amp

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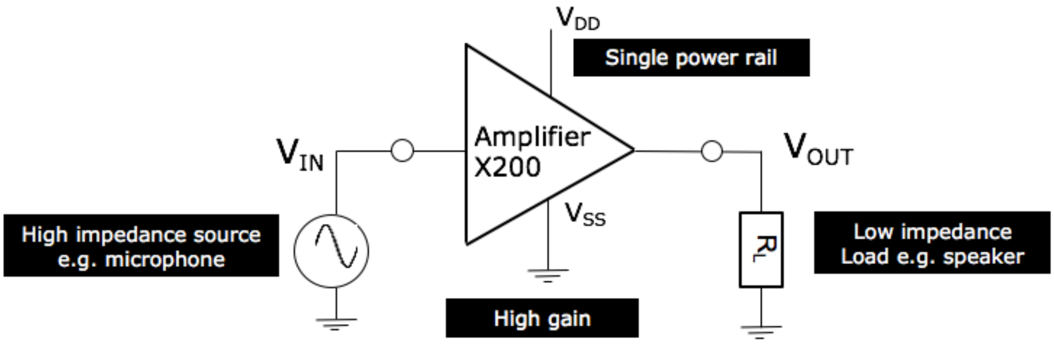
In this 2nd lecture, I will revisit the use of op-amps as voltage amplifiers. Unlike last year, we will focus on using actual devices instead of theory and simulations. This lecture is tightly linked to the practical work you will be doing for Lab 1.

You will also need to download and read the datasheet for the following devices to understand and appreciate the limitations and features of the following device:

1. MCP6002 – Low power dual operational amplifier
2. AP430i – 2.5V voltage reference
3. LM386 – Audio amplifier

What you will learn in Lectures 2 and 3?

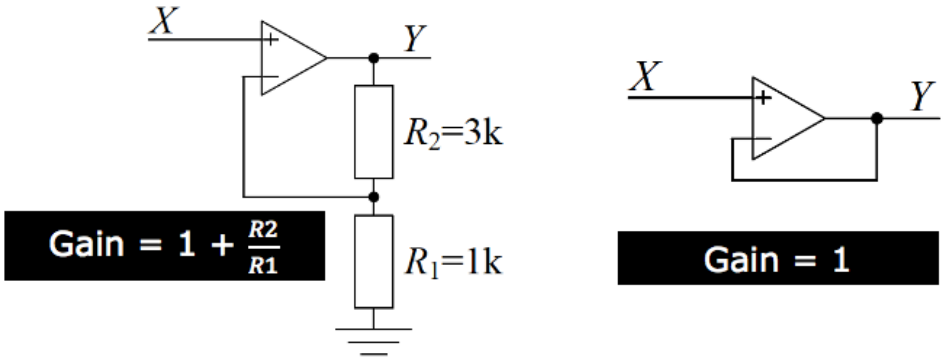


- Small input signal
- High gain amplification
- Working with single power supply rail
- Low impedance load (next Lecture)

In this lecture, you will learn how to design a high gain amplifier that overcomes the following four challenges:

1. **Low source voltage** - The source signal may be very small, of the order of millivolts.
2. **High source impedance** - The source impedance may be high, say, could be 10's of kW. Examples like this are plentiful: temperature transducer, microphone, light sensor, hall-effect sensor etc..
3. **Low load impedance** - Such amplifier may provide high voltage gain (e.g. 100's). It may require to drive relatively low impedance load such as an 8 ohm speaker. (This will be dealt with in the next lecture.)
4. **Single supply rail** – Modern electronics are often required to work in standalone, mobile applications where only a single power rail is available. Therefore this amplifier would need to achieve 1) to 3) above using only a single power supply (e.g. +5V).

Non-inverting Amplifier & Voltage Follower



- Year 1 circuits module, part 1, lecture 9, slides 11 and 12
- Non-inverting amplifier using op-amp, Gain x4
- Special case: R2 = 0, R1 = ∞, Gain = 1
  - Voltage follower or unity gain buffer

You have already learned about non-inverting amplifier using op-amp last year (lecture 9 in circuits, slide 11).

The gain of the amplifier is +4. If you make R2 = 0 and R1 is open-circuit, the gain is exactly 1. This is a special case of the non-inverting amplifier.

An amplifier with a gain of 1 is not amplifying at all. What it does is to isolate the signal source at X from the output load at Y. In this way, loading the output with a low impedance resistor (say) will not change Y.

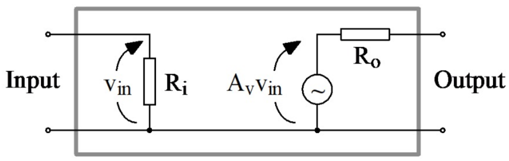
Using a non-inverting amplifier with reasonable gain therefore solves the problems of high source impedance, low output load impedance and amplification of the small input signal.

However, we must now examine whether this is true when we use a real-life operation amplifier such as the MCP6002.

Here is the datasheet for MCPP6001/2/4 op-amp:

https://ww1.microchip.com/downloads/en/DeviceDoc/MCP6001-1R-1U-2-4-1-MHz-Low-Power-Op-Amp-DS20001733L.pdf

MCP6001/2/4 as a near ideal op-amp



- Ideal op-amp
  - $R_i \rightarrow \infty$
  - $A_v \rightarrow \infty$
  - $R_o \rightarrow 0$

✓ Z_{in} of MCP6001 is very large

Common Mode Input Impedance	Z_{CM}	10^{13}‖6	Ω‖pF
Differential Input Impedance	Z_{DIFF}	10^{13}‖3	Ω‖pF

✓ Input current is negligible

Input Bias Current:	I_B	±1.0	pA	
Industrial Temperature	I_B	19	pA	T_A = +85°C
Extended Temperature	I_B	1100	pA	T_A = +125°C

✓ Gain is near infinite (true at low frequency)

DC Open-Loop Gain (Large Signal)	A_{OL}	112 >1 x10^5	dB

✓ Output impedance is low (specified as I_{SC})

Output Short Circuit Current	I_{SC}	±6	mA	V_{DD} = 1.8V
		±23	mA	V_{DD} = 5.5V

Now let us examine how close is the MCP6001/2/4 op-amp to the ideal model that you learned last year.

The input impedance is very high because it has a MOSFET input stage. The gate of the MOSFET has extremely high impedance that is close to open-circuit.

This also means that the input bias current is extremely small. However, this leads to a potential problem. If you leave any input open circuit the voltage at the input could be anything! There is nothing to determine (or bias) such input node to the gate of a MOSFET.

The gain of this op-amp at DC or very low frequency is extremely high – over 100,000! However, this does not apply to higher frequency as we will see later. The very high gain of the amplifier allows us to use this in a feedback configuration, and trade-off the excess gain for better performances (such as input impedance and output impedance). You will learn more of this in the feedback control module next term.

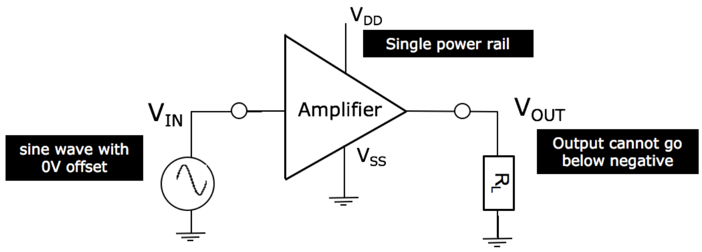
The output impedance is specified in the form of maximum short-circuit current. Negative feedback will drive the output voltage independent of the load until the maximum output current is reached. As seen here, for 5.5V supply, maximum output current is around 23mA. This implies that the output resistance is around 5.5V/0.023A ≈ 157Ω when running at 5.5V and around 300Ω when running at 1.8V .

Problem with single supply rail

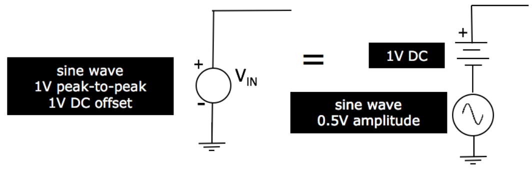
- Output swing limited to rail voltages

Maximum Output Voltage Swing	V_{OL}, V_{OH}	V_{SS} + 25 V_{DD} – 25	mV

- Input cannot be a sinewave with 0V DC offset



- Need to add DC offset to input



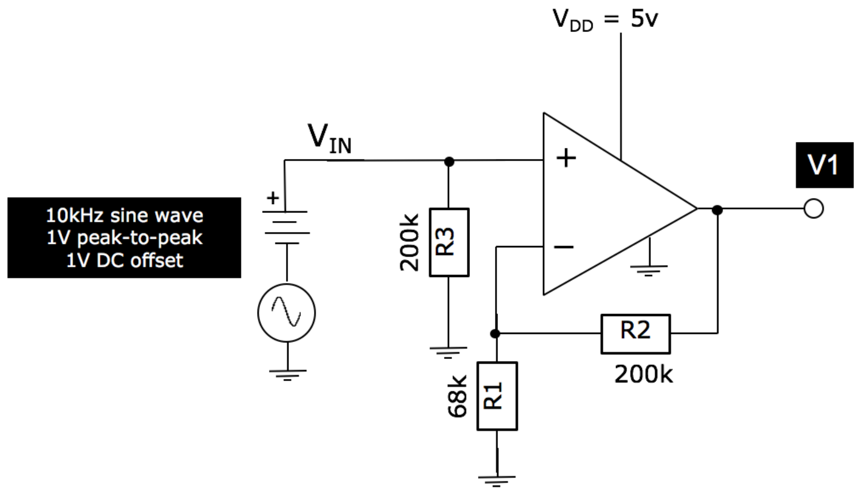
Because we only use only single power supply rail with our op-amp, the output is limited to VDD and GND (VSS). (Note: VDD and VSS are so named because VDD usually supply the drain terminal and VSS the source terminal of the MOSFET transistor inside the op-amp.) For MCP6001, the output swing is within 25mV of the rail voltages.

If we apply a sinewave with 0V offset, the output will be clipped at GND voltage.

In the lab experiment, you will be asked to add a DC offset to the signal source. For example 1V peak-to-peak (or 0.5V amplitude) sine wave with an offset of 1V. If this is a voltage follower (i.e. unity gain amplifier), this will work perfectly.

X4 amplifier fail

- Amplifier Gain = +4, output swing = 2V to 6V – not possible



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However, if we configure the op-amp to give a gain of, say, 4, the circuit will not work.

The gain of this amplifier is x4 because Gain = 1 + R2/R1 which is approximately x4.

The x4 gain applies both to the DC offset and to the sine signal component. Therefore the 1V p-p sine wave becomes 4V p-p, and the 1V DC offset becomes 4V DC offset. T

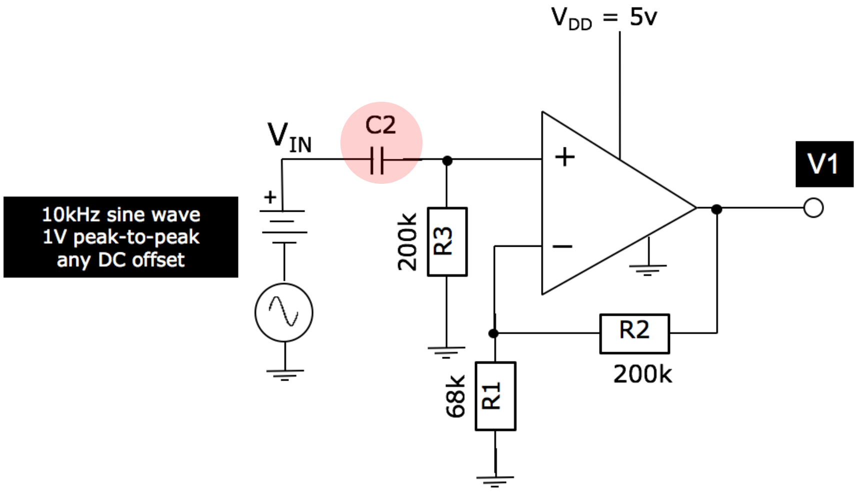
his means that the amplifier is required to give an output swing between 2V and 6V, which is above VDD – not possible.

The output V1 will therefore be clipped at 5V.

Note further that R3 is added to provide a path for input current to the op-amp if the source voltage is open-circuit (i.e. disconnected).

Attempt 1 – AC coupling signal

- AC couple input signal – block DC offset to amplifier
- Does not work for single supply op-amp

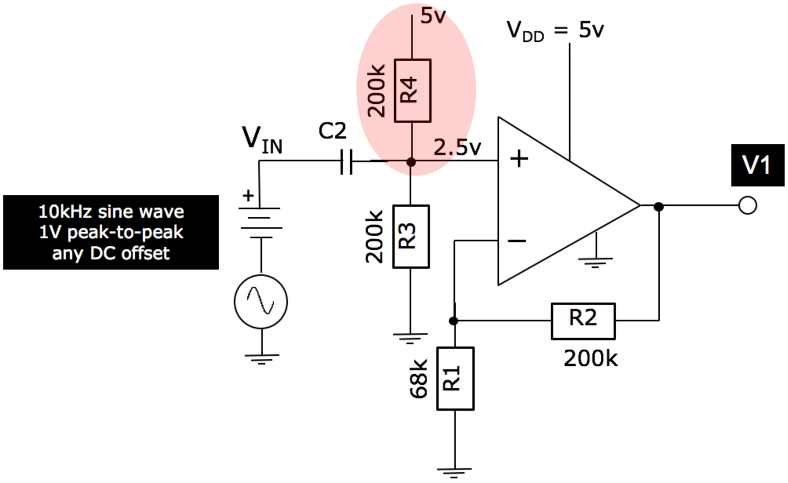


To avoid amplifying the DC offset of any input signal (unless you intend to), one way is to add a capacitor C2 in series with the input as shown in the circuit here.

C2 will block the DC component and only allow the sine component to pass through. Unfortunately this does not work because the input sine signal goes negative again. If we had use dual power supply with ±5V, this AC coupled input circuit would have worked. This is therefore a problem introduced mainly because we insist on using a single rail power supply.

Attempt 2 – Add bias to V+ input

- Bias input V+ to half of power supply rail voltage
  - Maximize input voltage swing
  - Still not working – bias voltage is now the unwanted DC offset!



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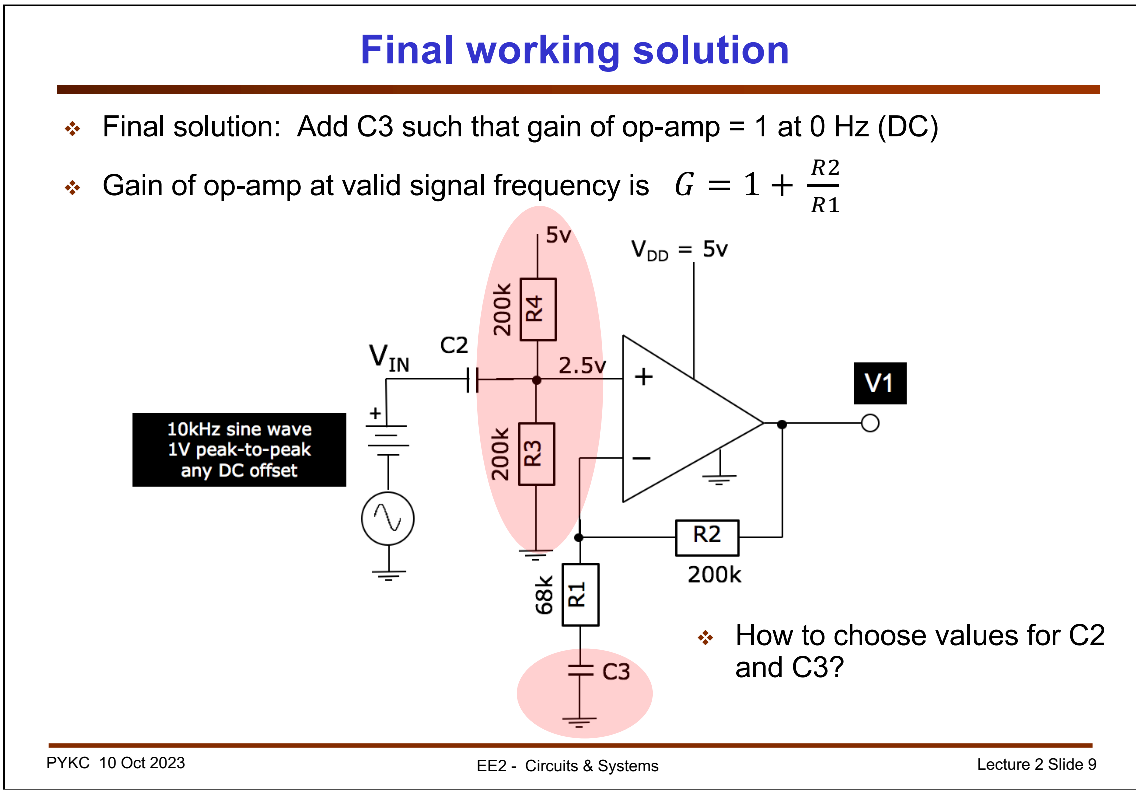
One could try to solve the problem by biasing the V+ input of the op-amp to 2.5V using R3 and R4 as a bias network. Then V+ will always sit on a DC of 2.5V, which is not a bad idea because we now allow a maximum voltage swing to the input.

Unfortunately this does not work because the amplifier will again amplifier both the sine signal and the DC bias voltage.

We therefore need an amplifier that provides a x4 gain to the sine wave, but only a x1 gain to the DC bias.



The solution is simply to add C3 in the feedback network of the op-amp.

At DC, C3 present itself as open-circuit. The gain of the amplifier in general form in terms of impedance (not just resistance) is:

$$G = 1 + \frac{Z2}{Z1}$$

where Z2 = R2, Z1 = 68000 + $1/j\omega C_3$.

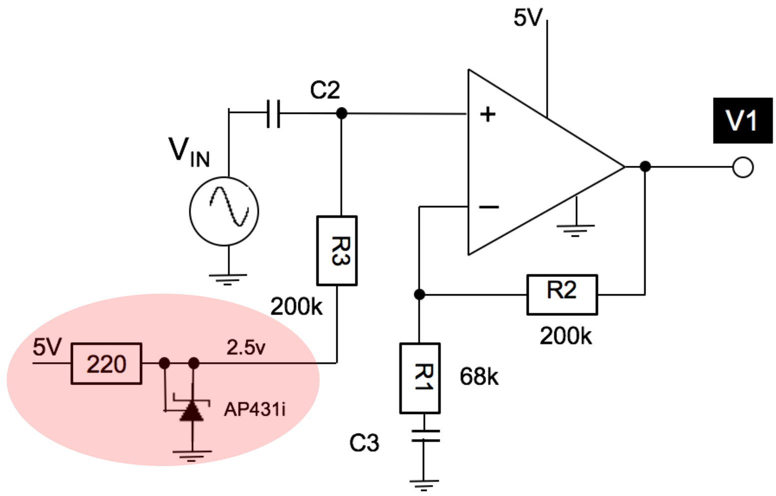
Therefore a DC, Z1 is infinite and this is a voltage follower (unity gain amplifier) to the DC bias voltage.

For sine wave signal at other frequencies, if C3 is chosen such that $|1/j\omega C_3|$ << 68000, then the amplifier has gain close to x4.

The input network is a voltage divider between R3 || R4 or 100k and C2. Therefore C2 must be chosen to such that $|1/j\omega C_2|$ << 100k for the lowest signal frequency.

Better Bias Circuit

- Generate bias voltage using a voltage reference circuit, e.g. AP431i
- Bias voltage NOT susceptible to noise on 5V supply



So far, we used R3 and R4 to provide a voltage divider for the 5V supply to derive the input bias voltage of 2.5V. This is not a very good idea because any noise from the 5V supply would feed directly (with a gain of 0.5) to the input of the amplifier. This power supply noise will be amplified to the output as if it were a valid input signal.

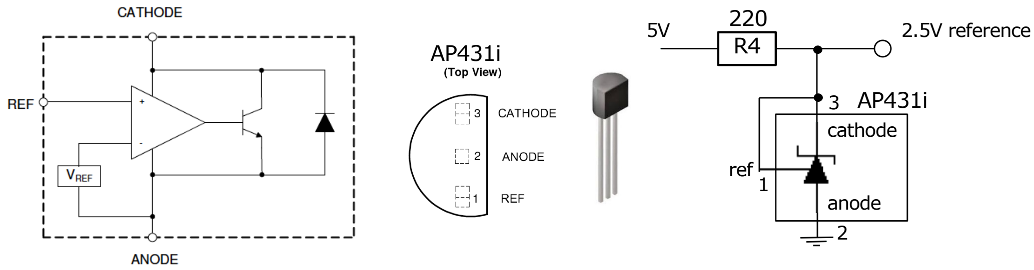
A better design would be to use a proper voltage reference circuit to derive the 2.5V DC bias. A good bias voltage source should have three desirable properties:

1. It has an accurate voltage source value;
2. It has a low source resistance, so that the DC voltage remains the same even if the current drawn from the source changes;
3. It is insensitive to noise on the 5V supply rail.

The voltage reference, the AP431i, which you will be using in the Lab is one such device. (Download datasheet here.)

http://www.farnell.com/datasheets/608809.pdf

AP431i voltage reference in detail



		Min	Max	
I_{KA}	Cathode Current	0.1	100	mA

			Min	Typical	Max	
V_{REF} 1%	Reference Voltage	$V_{KA} = V_{REF}$, I_{KA} = 1mA	2.475	2.500	2.525	V

			Typical	Max	
Z_{KA}	Dynamic Impedance	$V_{KA} = V_{REF}$, I_{KA} = 1 to 100mA, f ≤ 1.0kHz	0.1	0.3	Ω

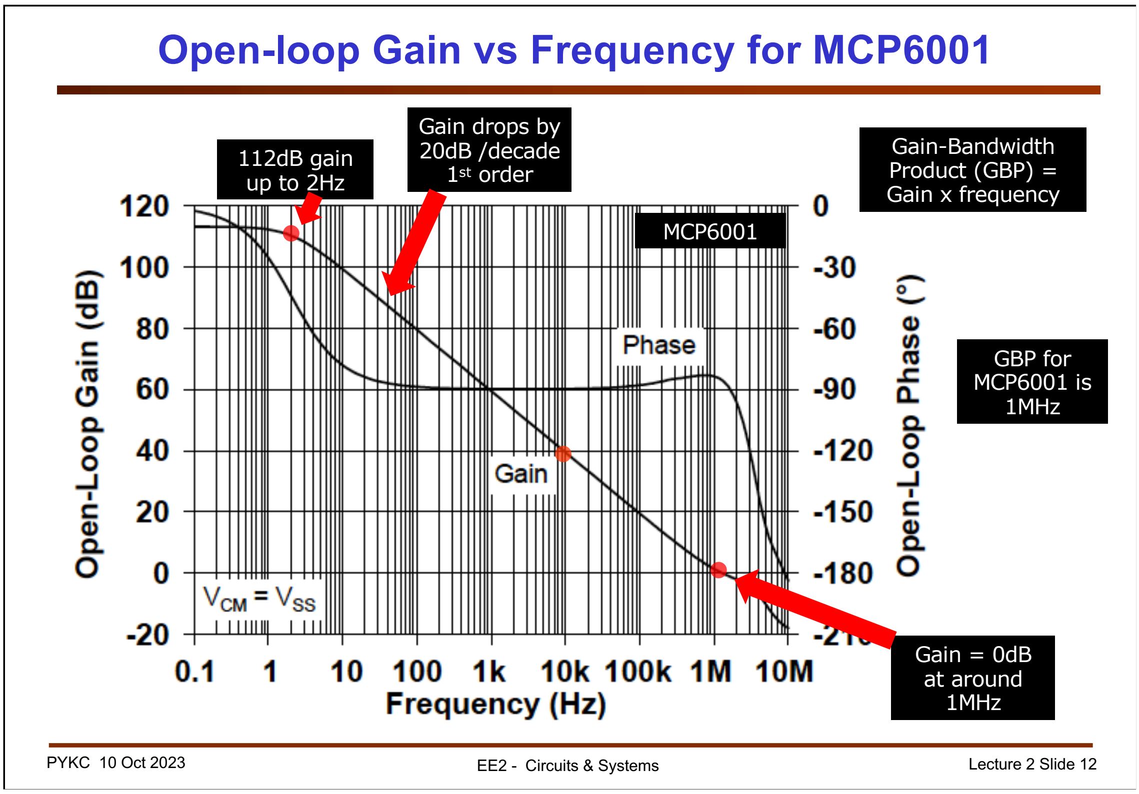
The AP431i actually uses an op-amp internally, with a voltage reference diode as shown here. The output NPN transistor provides high current capability. The diode offers protection if user revise the supply voltage by accident.

This device emulate the behaviour of a tradition voltage reference known as a "Zener diode" (which is isn't really a Zener diode – but much better).

To produce the 2.5V reference, you must connect this device as shown here. Since the op-amp has high gain, it ensures that the voltage at the REF input and the intern 2.5V diode reference are exactly the same no matter what current through the cathode is. (This current is I_{KA}.)

Download the datasheet for this voltage reference. The three most important charaacteristics are:

1. The cathode current – it works between the range of 0.1mA and 100mA. That means even if your circuit draws lots of current (say 10mA), as long as there is 0.1mA left to supply to this voltage reference, the circuit will work.
2. VREF accuracy – this voltage reference has a ±1% accuracy with a nominal voltage of 2.5V.
3. Dynamic resistance – this acts like a constant voltage source of 2.5V±1% with a source resistance of 0.3Ω max!



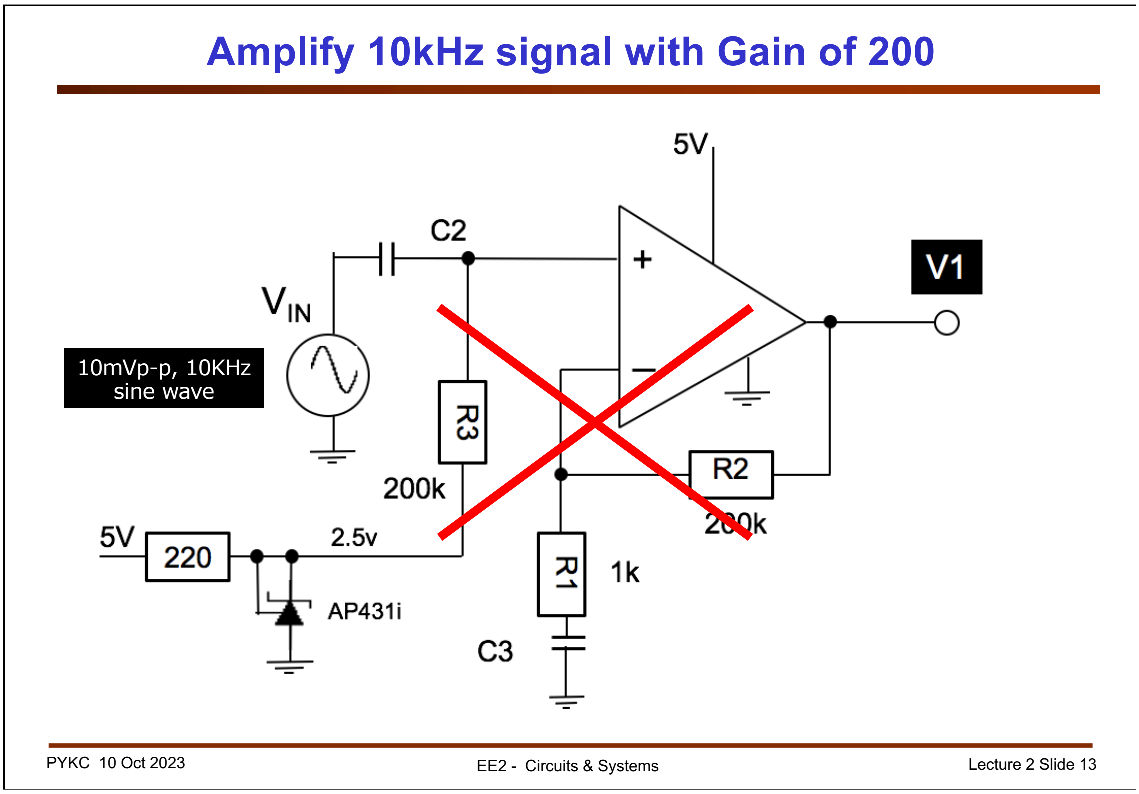
Although the open-loop gain of the MCP6001 at DC (or 0Hz) is very high (at over 100,000), this gain drops off very quickly as the signal frequency is beyond 2Hz. Beyond 2Hz, the gain falls off at a rate of -20dB/decade (i.e. drops by a factor 10 as signal frequency goes up by a factor of 10).

As we reach around 1MHz, the open-loop gain is only 1. That means at this frequency, the op-amp, without feedback, will not behave like an amplifier any more.

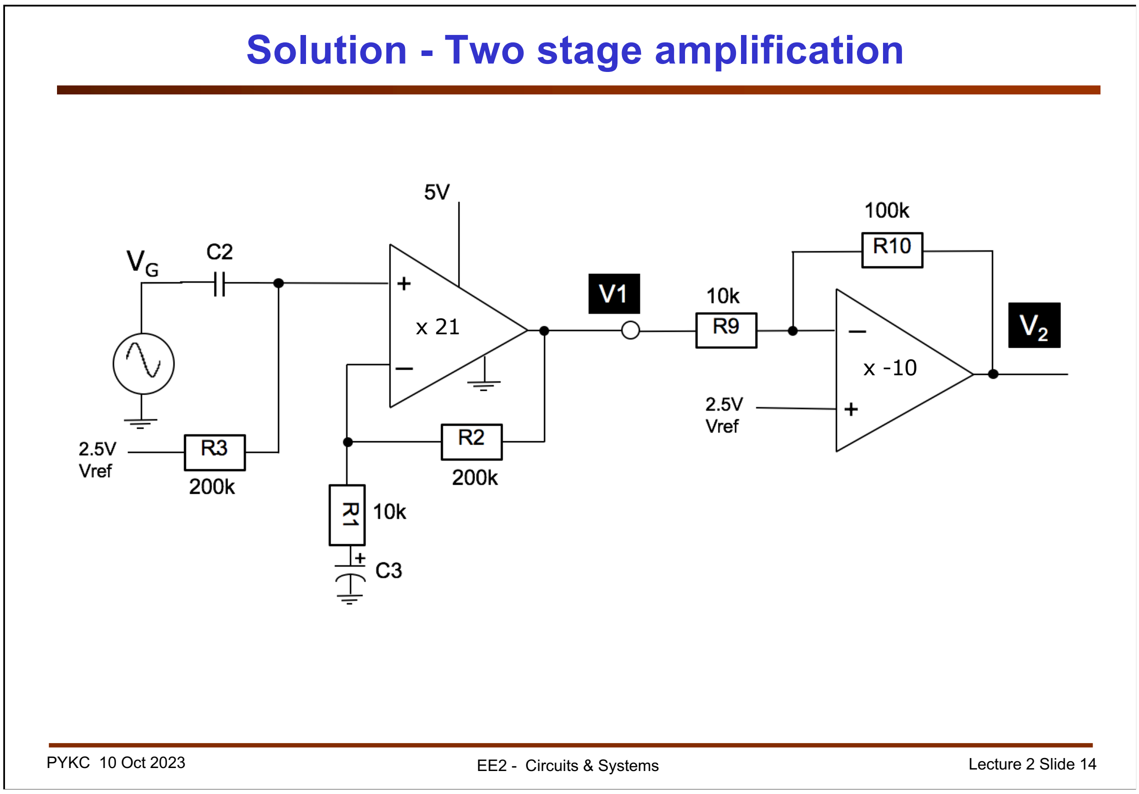
The frequency at which the gain drops to 1 is known as the Gain-Bandwith Product (GBP). Notice that beween 2Hz and 1MHz, the open-loop gain and the signal frequency, when multiplied together, is a constant = 10^6.

In other words, given the maximum frequency of your signal that you need to amplify, the GBP tells you how much gain you can obtain from this op-amp. For example, If your maximum signal frequency is 10kHz, you will not be ablet o design an amplifier that gives a gain of at most 40dB (x100), actually will be somewhat lower than x100. You will be exploring this in Lab 1.

There are op-amps designed to have much higher GBP than this is one. However, the higher the GBP, the more likely the op-amp will oscillate (i.e. go unstable). For these op-amp to work, one would need to design the PCB carefully to avoid unexpected feedback path for signals.



Given the GBP limitation of the MCP6001, the circuit shown here will not work if your signal is 10kHz. Here the gain is expected to be x201. This is beyond the capability of this op-amp. We need a different solution.

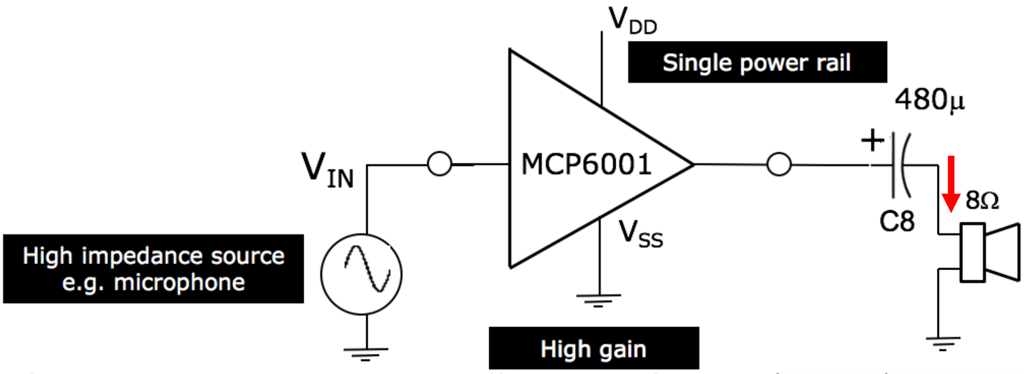


Here is one that you will be asked to try in Lab 1.

Instead of using a single op-amp, you can design TWO amplifier and connect them in cascade as shown here. The first op-amp has a gain of x21, and the second stage has a gain of 10 (but it is inverting, therefore the gain is -10). This gives an overall gain of x210.

This is actually a non-optimum design. I will leave you to consider the reason why we could have done better as a discussion point.

Problem with driving low impedance load



Output Short Circuit Current	I_{SC}	±6 ±23	mA mA	V_{DD} = 1.8V V_{DD} = 5.5V

- Needs AC coupling due to output bias voltage of 2.5V
- Maximum current is over 600mA!
- MCP6001 cannot drive 8Ω speaker

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Our final goal is to design a circuit to drive a low impedance load such as an 8Ω speaker.

Note that we need to drive the speaker through an AC decoupling (or DC blocking) series capacitor C8. Otherwise the cone of the speaker will have a constant bias and the speaker may not work well. In some case, a large DC voltage may even damage the speaker.

The specification of the MCP6001 shows that at most this op-amp can deliver around ±20mA. The demand of the speaker at maximum voltage swing is much higher at over 600mA. Therefore this op-amp CANNOT drive the speaker.

We need a different solution, which is the topic for the next Lecture.