Introduction to Biomedical Engineering

Section 1: Basic electronics

Lecture 1.2: Amplifiers

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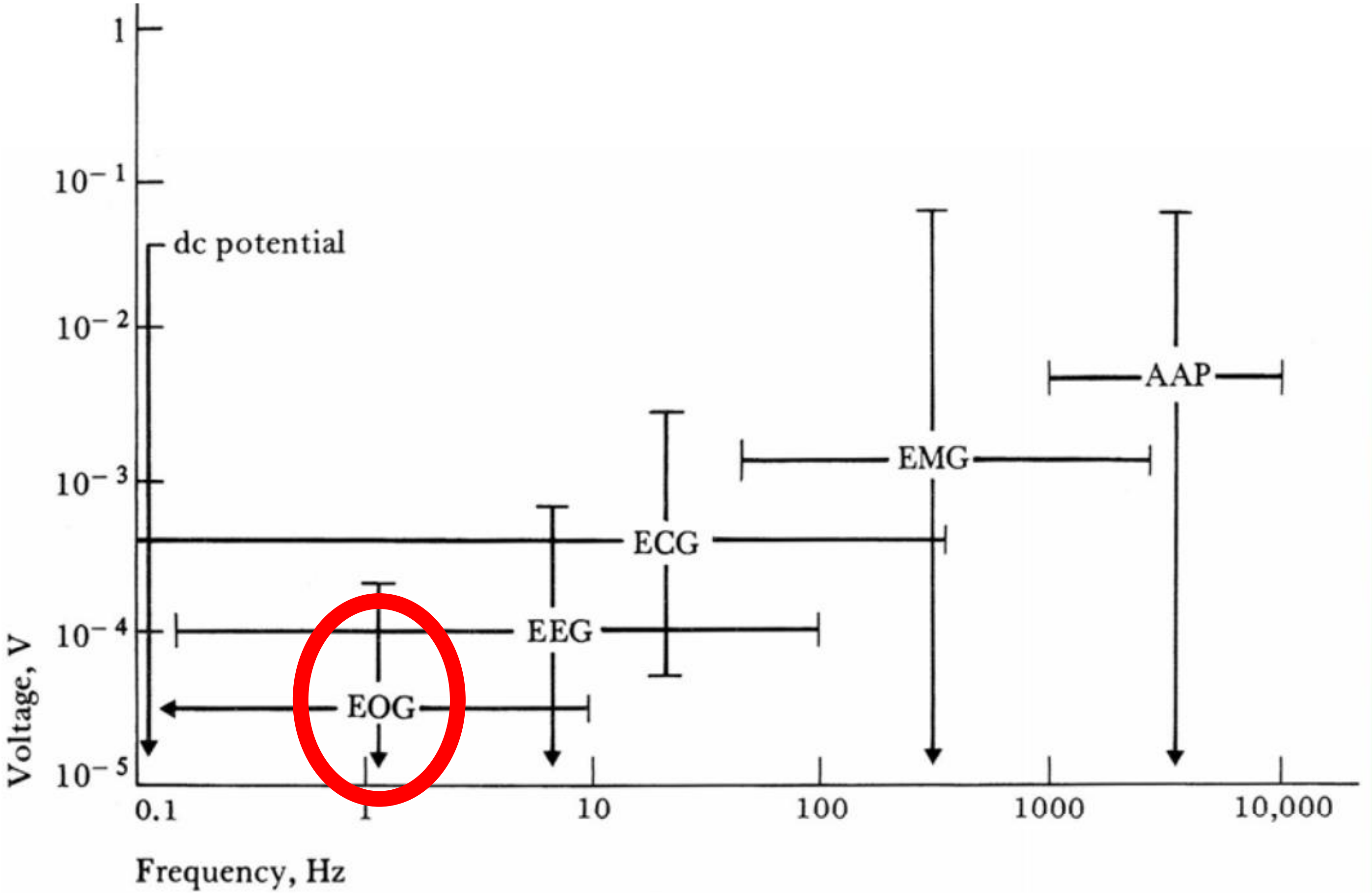
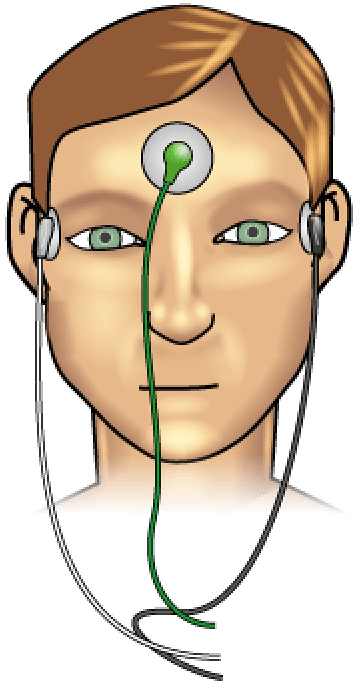
Why do we need to amplify signals?

Biophysical signals are very small
- mV if you are lucky!

EOG – **E**lectro**o**culo**g**raphy
Measures eye movements





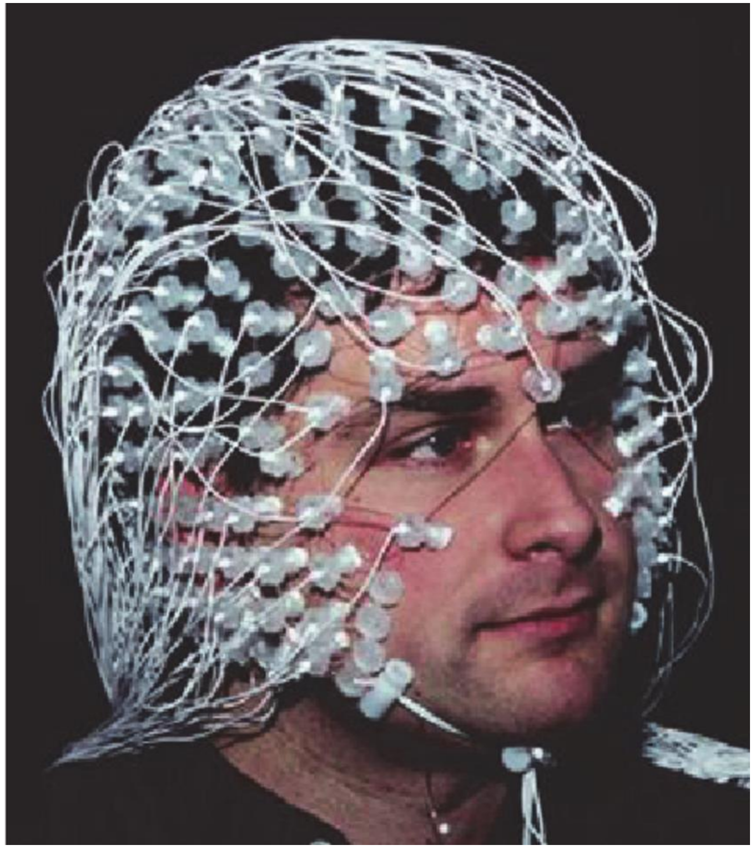
3-5 electrodes
on the face

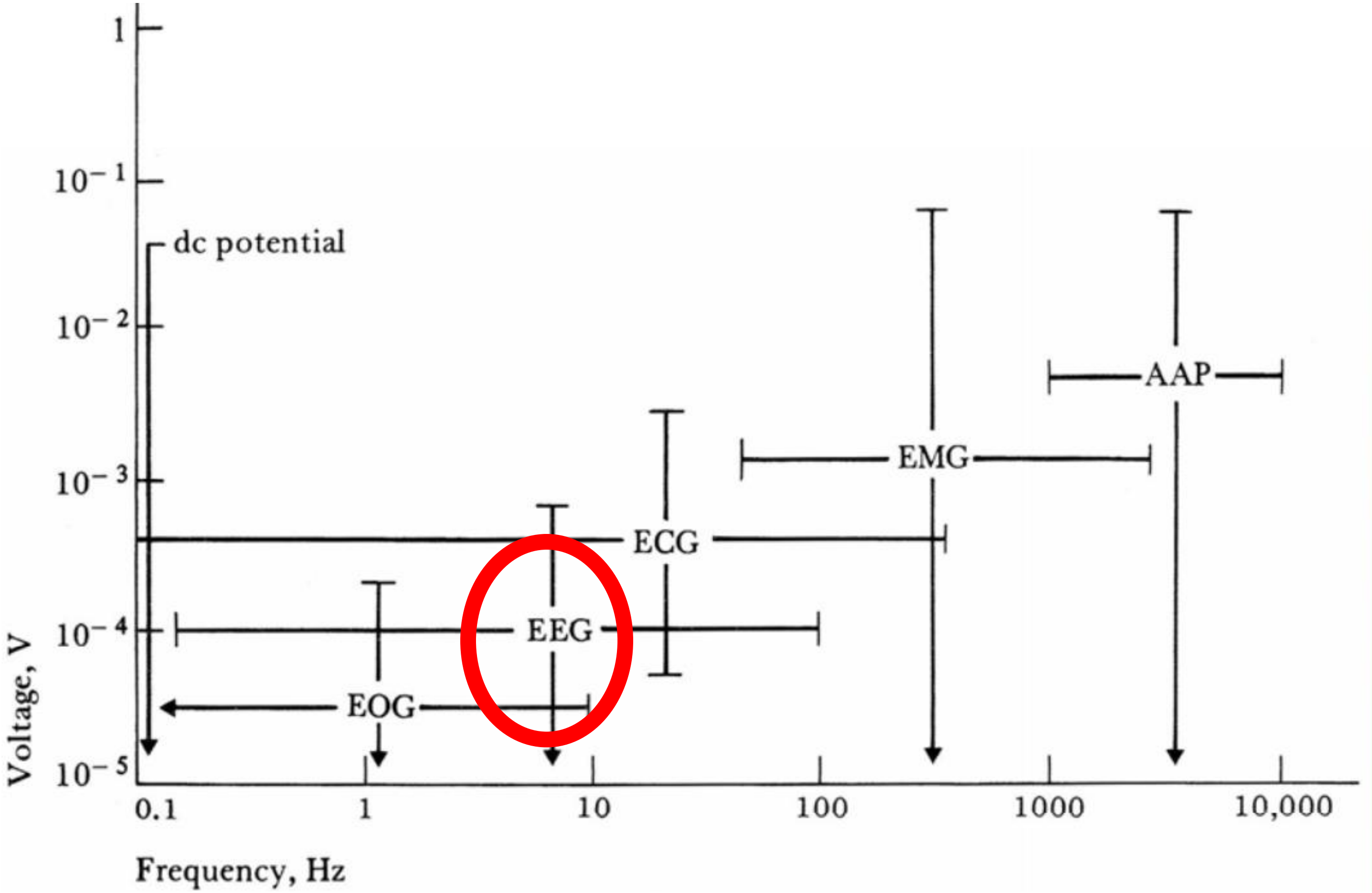
Eye movements
saccades

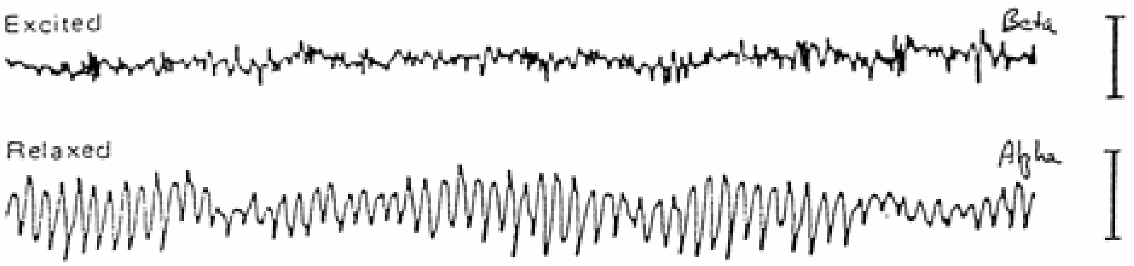
As with the photodiode:
Fast sensors probably
have small signals

Why do we need to amplify signals?

EEG – **E**lectroen**c**ephalo**g**raphy
Electrical activity of the brain

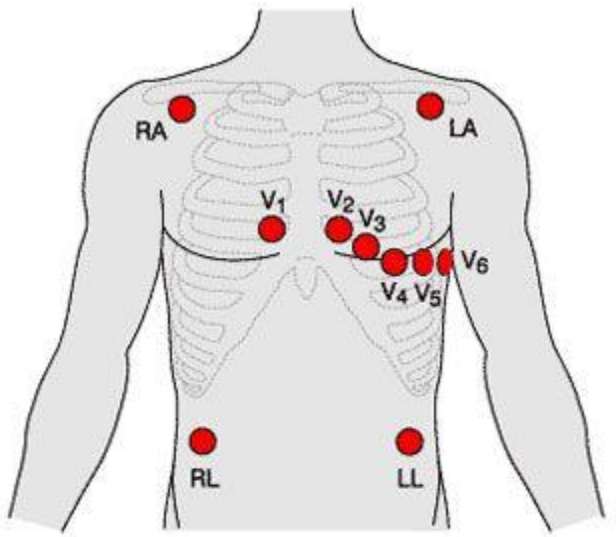


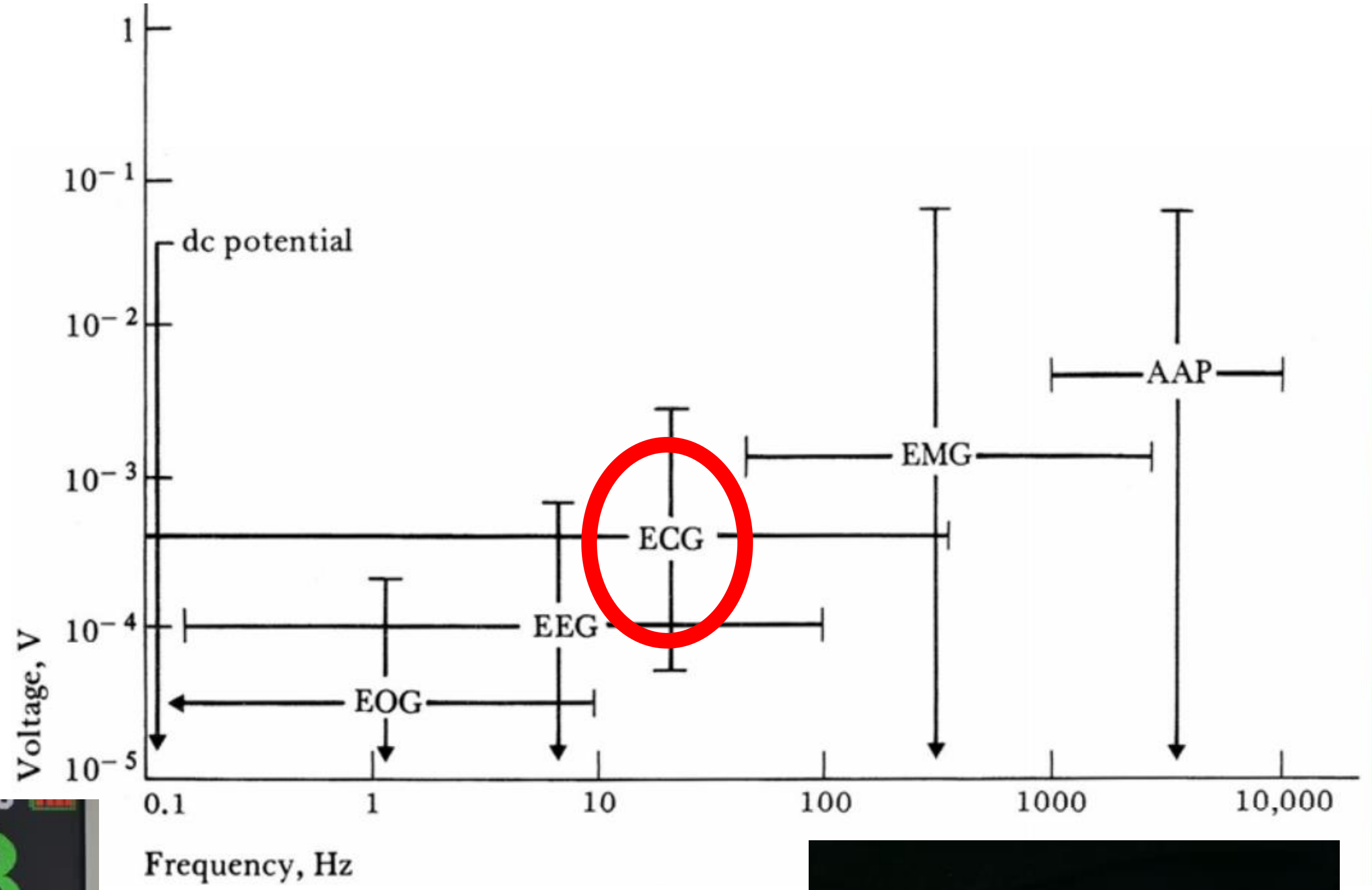




Why do we need to amplify signals?

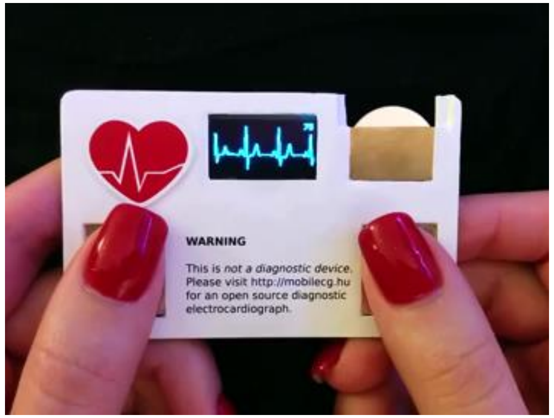
ECG/EKG – **E**lectro**c**ardio**g**raphy
Electrical activity of the heart





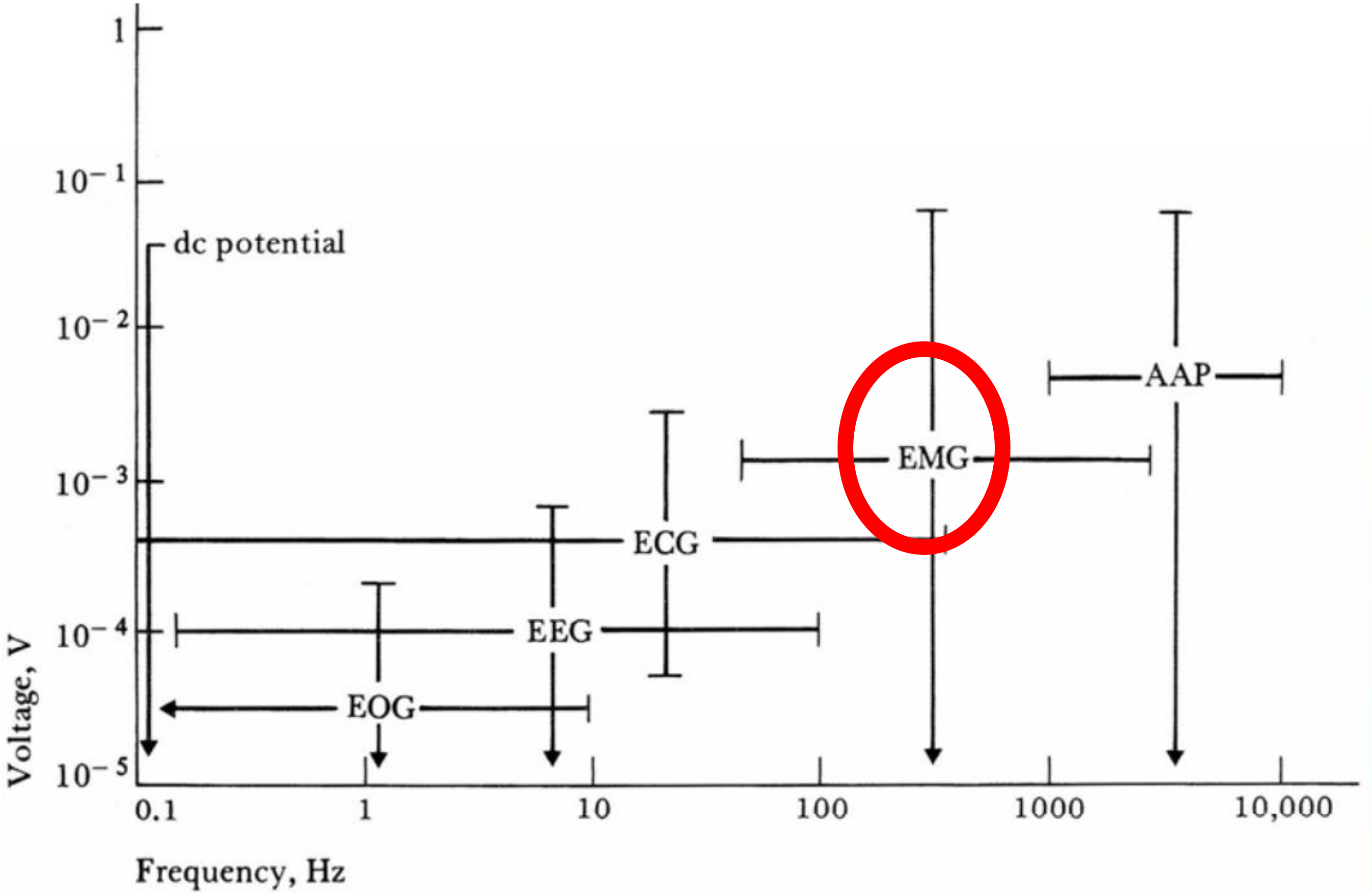
Patient monitors,
pacemakers

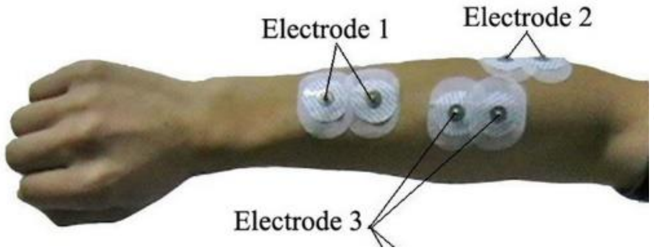
Business cards!

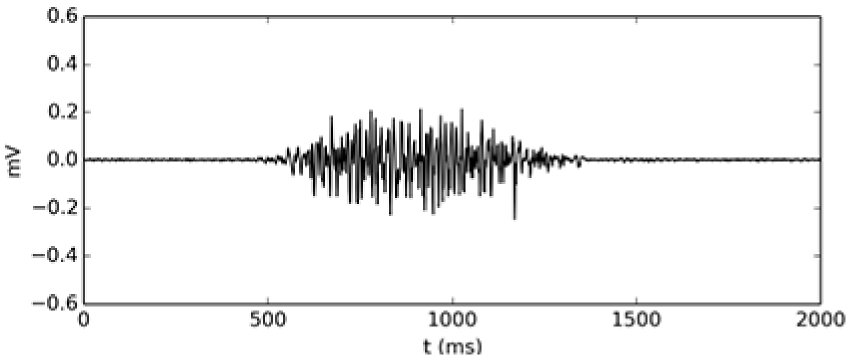


Why do we need to amplify signals?

EMG – **E**lectro**m**yo**g**raphy
Electrical activity of skeletal muscles





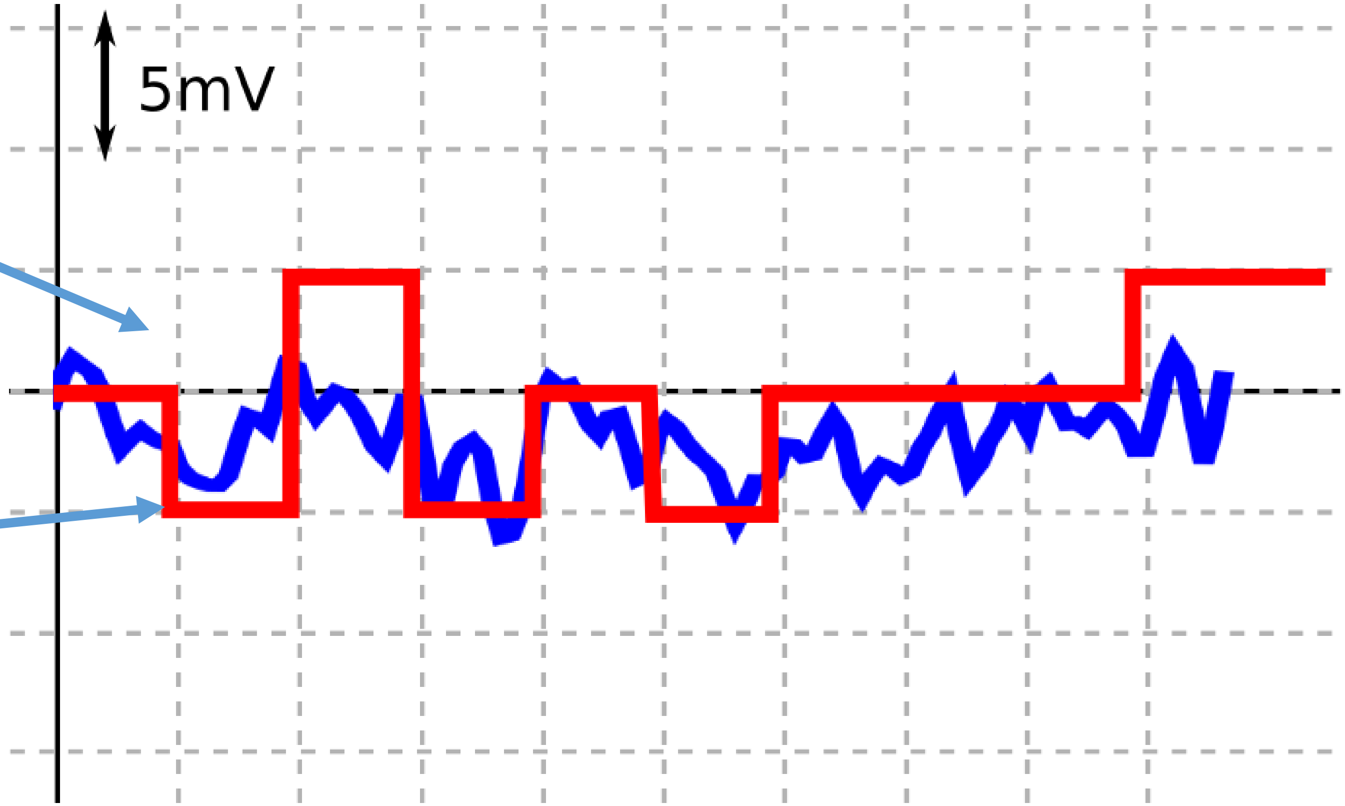


Forms basis of many bionic prosthesis

Why do we need to amplify signals?

Range of ADC is typically order of Volts.
So we may not even be able to see anything!

Signal in



ADC out

Arduino has 10 bit ADC with 5V range
Each ADC value is $5/(2^{10}) = \sim 4.8$ mV

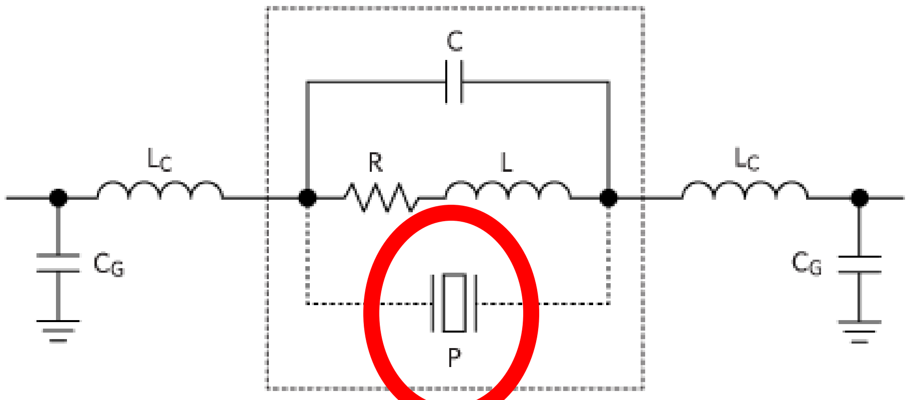
However
Amplification not only about making signals larger
Op Amps can improve or “condition” signal before digitisation

Components in the real world - Parasitics

Pure passive components *do not exist*.
Wires have inductance and resistance, capacitive coupling between wires.

Mostly a problem at higher frequencies and amplitudes, but many biomedical applications still need to take these into account (at least the EEs do!)

A resistor!



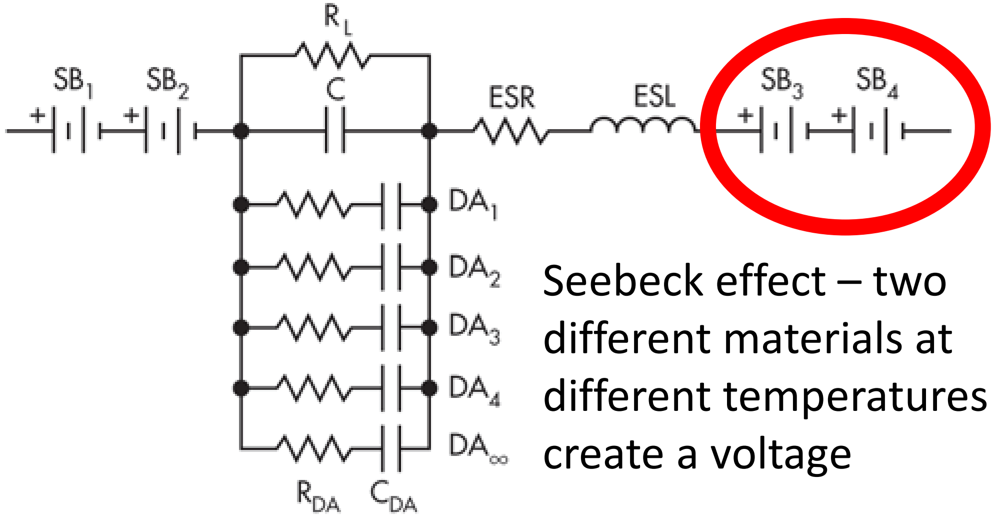
Piezo-element i.e. if you bend it the resistance changes!

Photo # NH 96931 Commo. Hopper hands out "nanoseconds"

Grace hopper handing out "nanoseconds" ~ 30cm

Physics limits how fast a signal can travel in a wire, and thus bandwidth

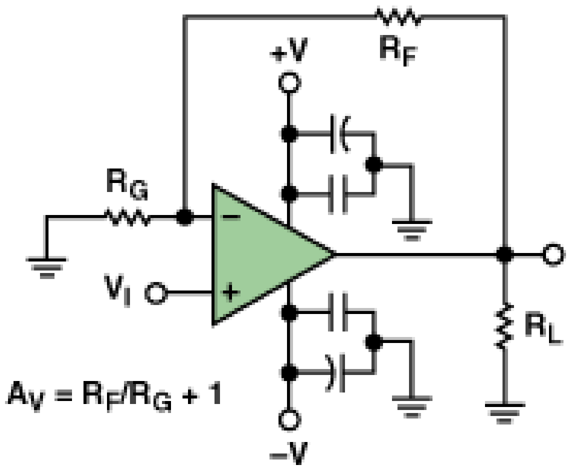
A capacitor!



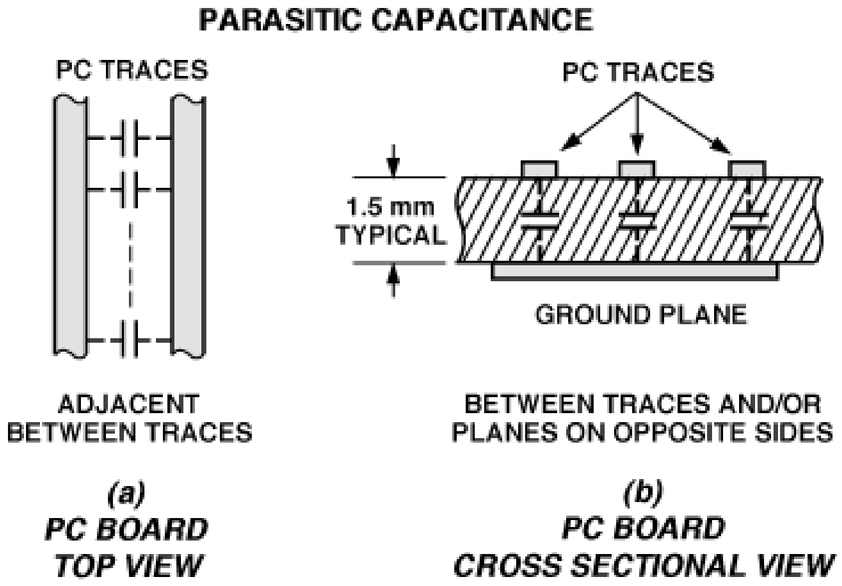
Seebeck effect – two different materials at different temperatures create a voltage

Components in the real world - Parasitics

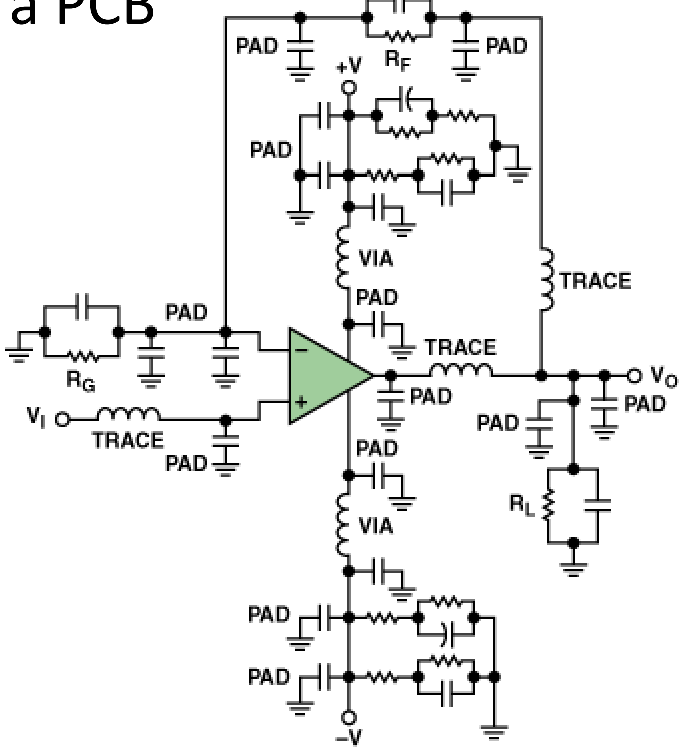
Things get even more complicated when considering the circuits on a PCB



Circuit as designed



PCB parasitics



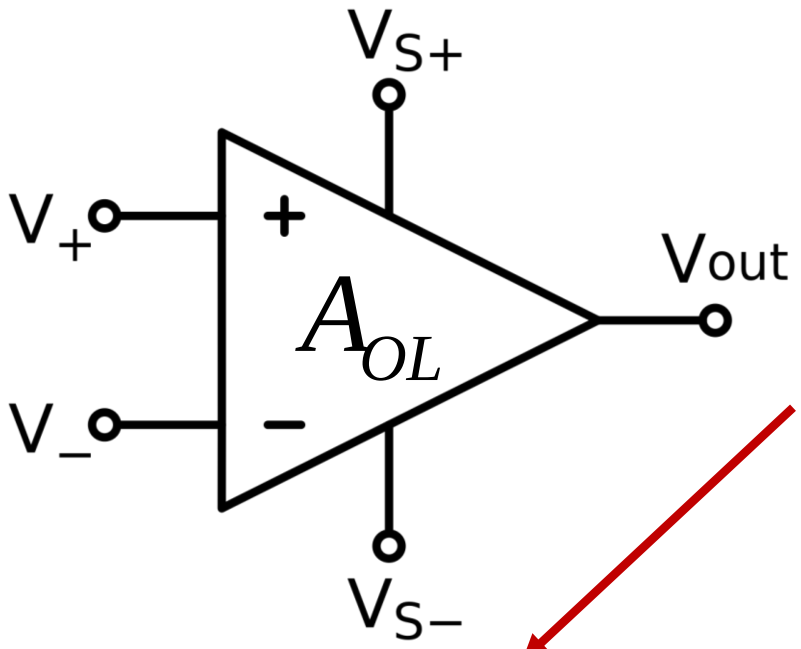
When you take these into account!

You may get ~90% (*totally made up*) of expected performance without considering these which is fine for many applications. Unfortunately we don't have this luxury in most biomedical applications!

Even small changes to components can have unexpected effects, and are extremely difficult to debug.
-This is why analogue circuit designers have a job!

Operational Amplifiers – Ideal Characteristics

Consider an ideal Op-Amp, which amplifies the difference between the two input pins

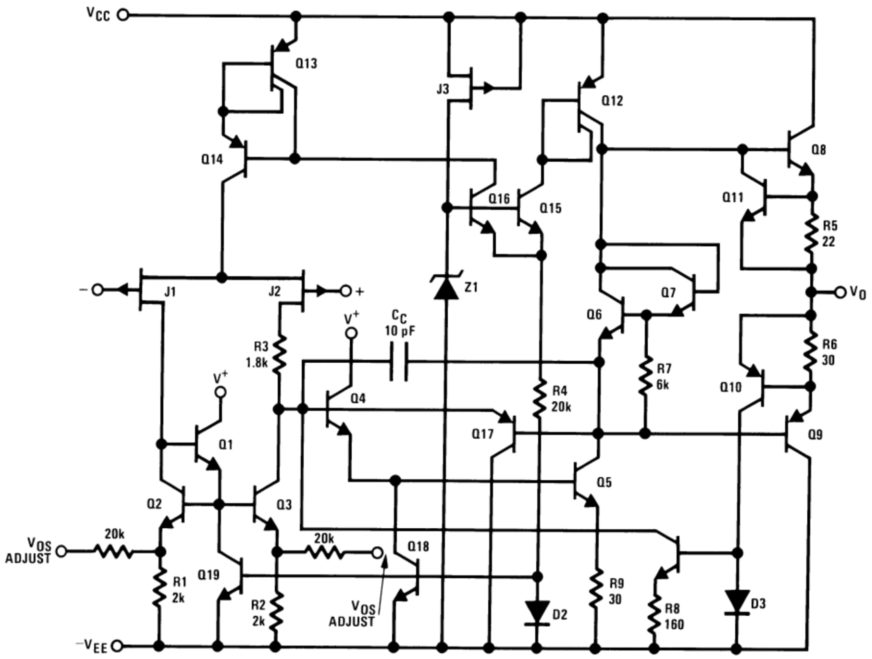


i.e. Ideal behaviour is *linear*

$$V_{OUT} = \left(V_{+} - V_{-}\right) A_{OL}$$

For this to be true, it would imply the op amp acts *instantaneously*, can produce *infinite* voltage and have *zero* effect on the input signals!

In reality op amps have limitations arising from internal parasitics



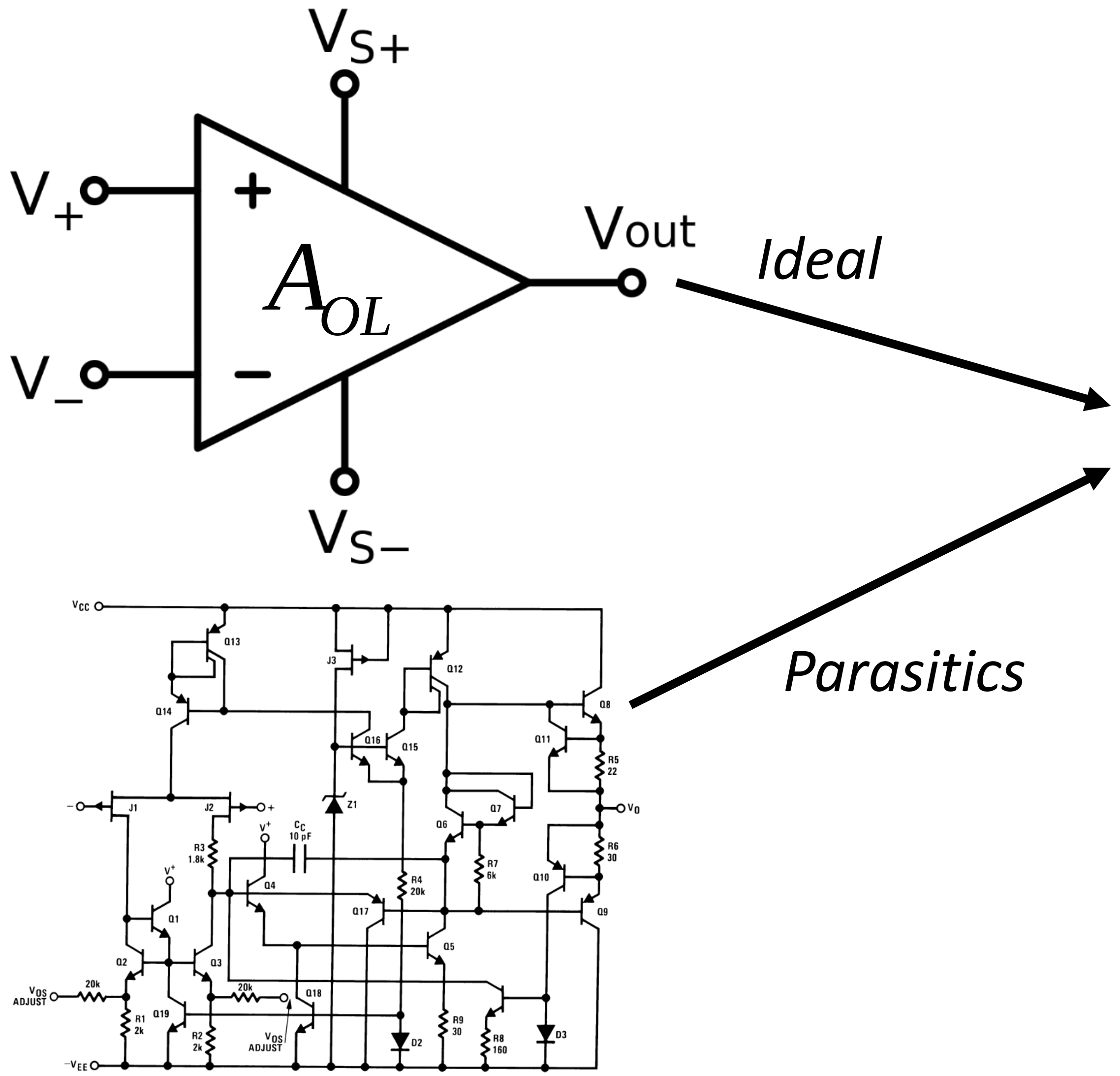
LF411 – old(ish) but common Op-amp

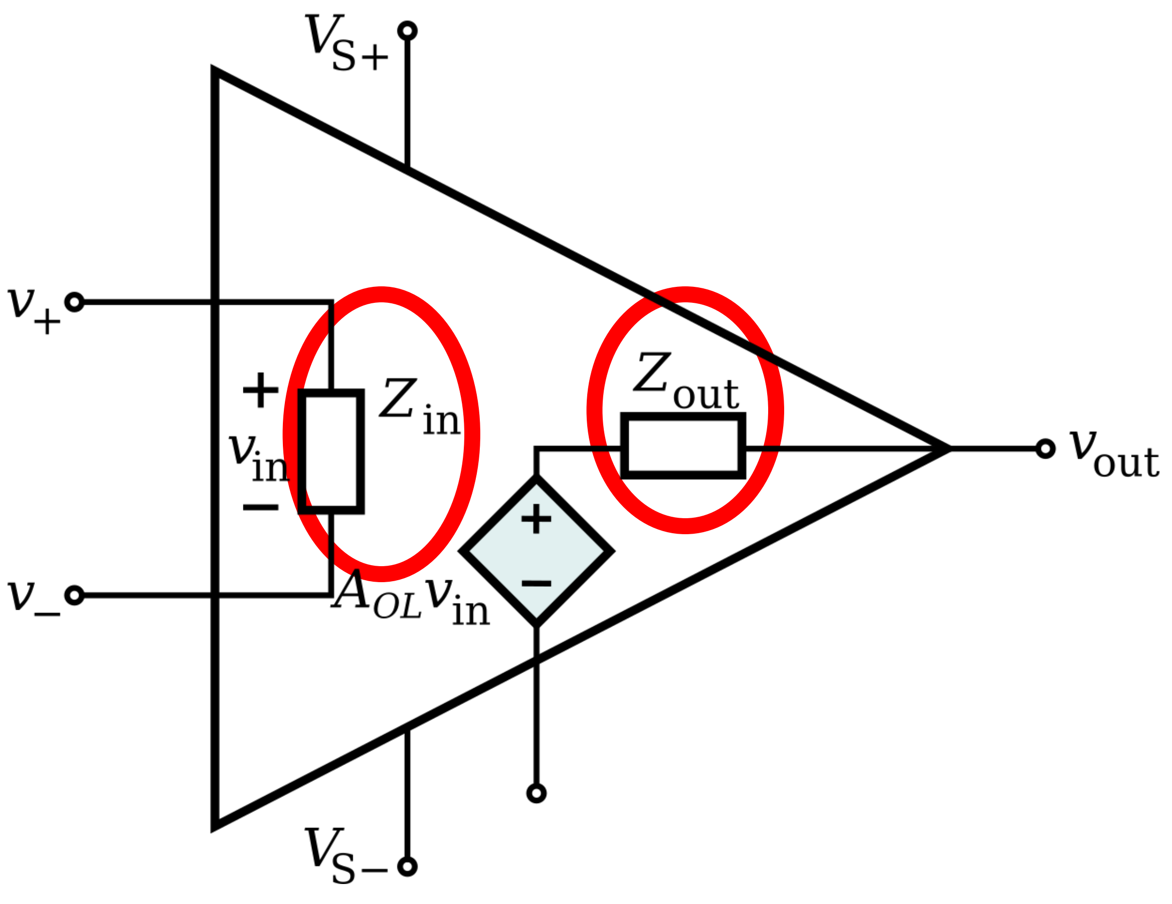
Components are not ideal either

Operational Amplifiers – Ideal Characteristics

All these non-idealities are simplified as “lumped” parameters.

More useful to describe ideal Op-Amp properties in relation to these parameters



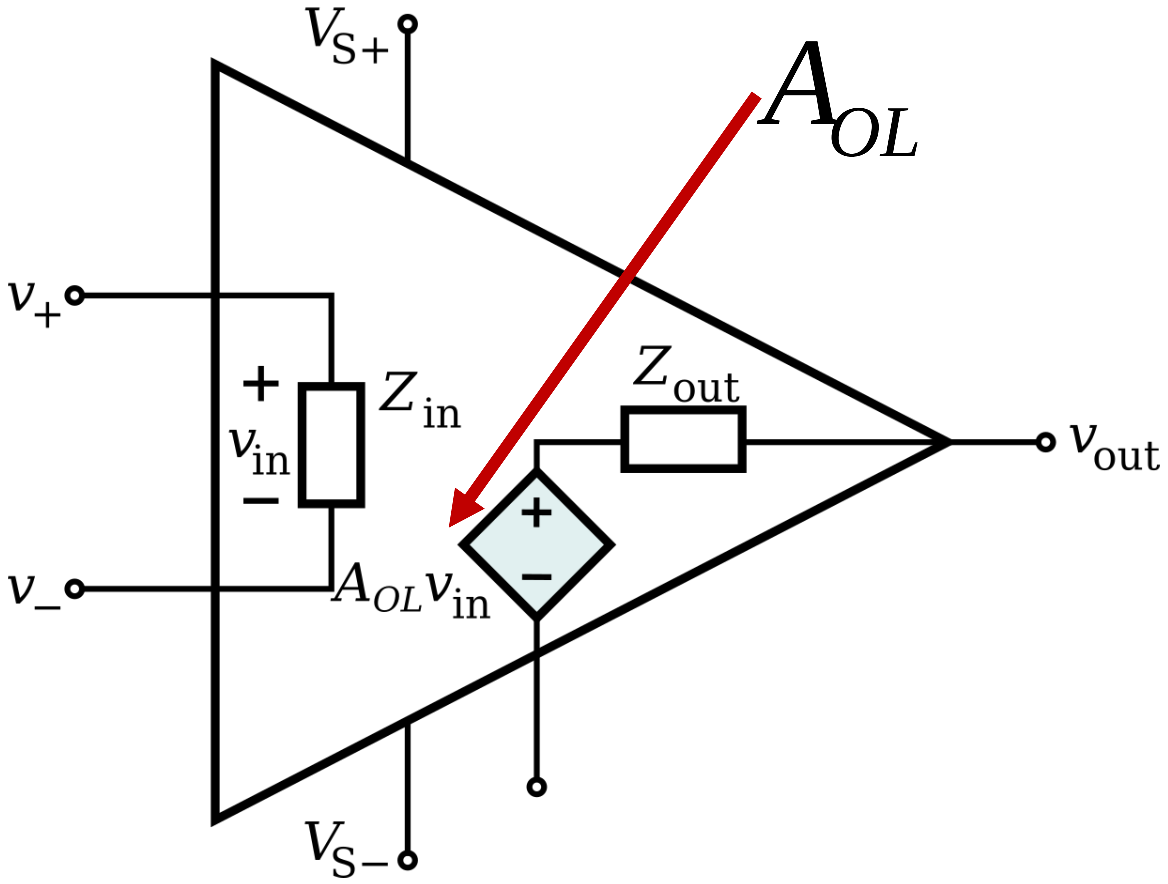


Lumped parameters Zin and Zout

Ideal Op Amp – 1. Infinite Open Loop Gain

$$A_{OL} = \infty$$

- Its an amplifier, so more gain the better.
- Also means the properties of the *closed loop* circuits are dependent *entirely* on the external components (we need this later)

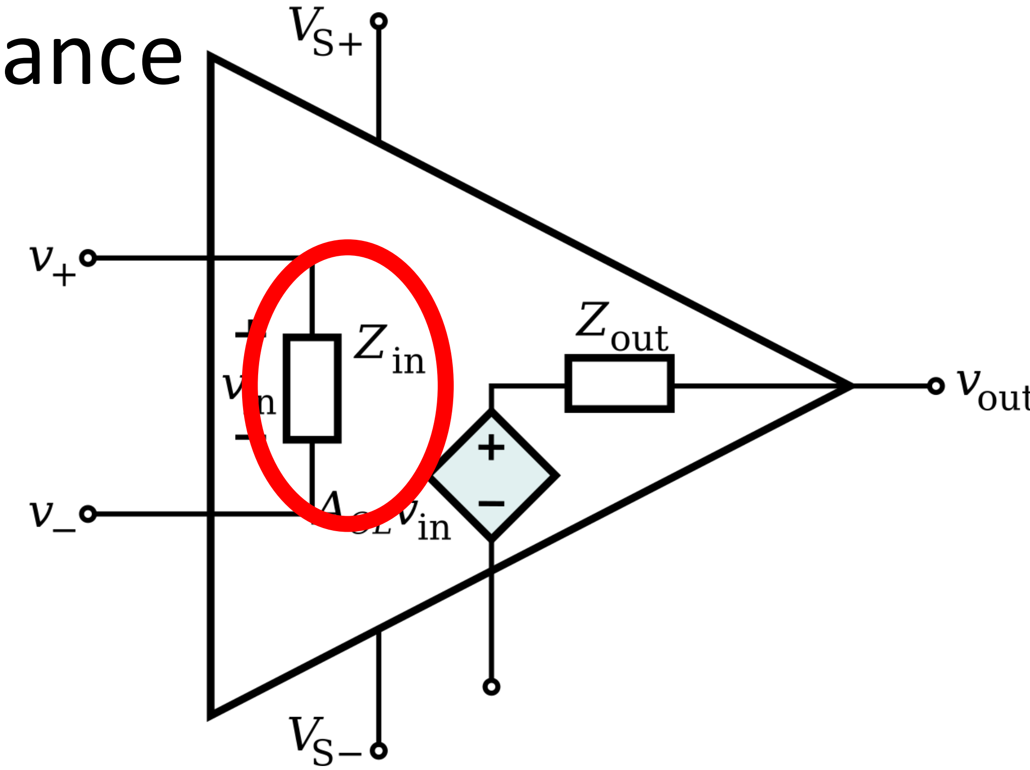


Reality:

A_{OL} typically 20,00 – 200,000. Close enough for most applications

Ideal Op Amp – 2. Infinite Input Impedance

$$Z_{IN} = \infty$$

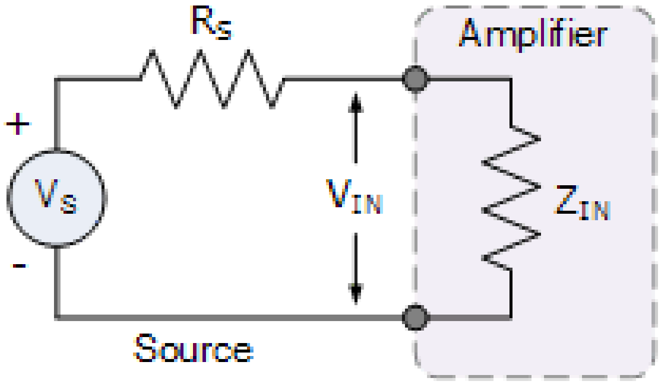


This means that ***no current flows into input terminals.*** In other words, the Op-Amp has no effect on the input signal.

Reality:

Z_{IN} can be anywhere from 10 MΩ up to TΩ (according to datasheet!)

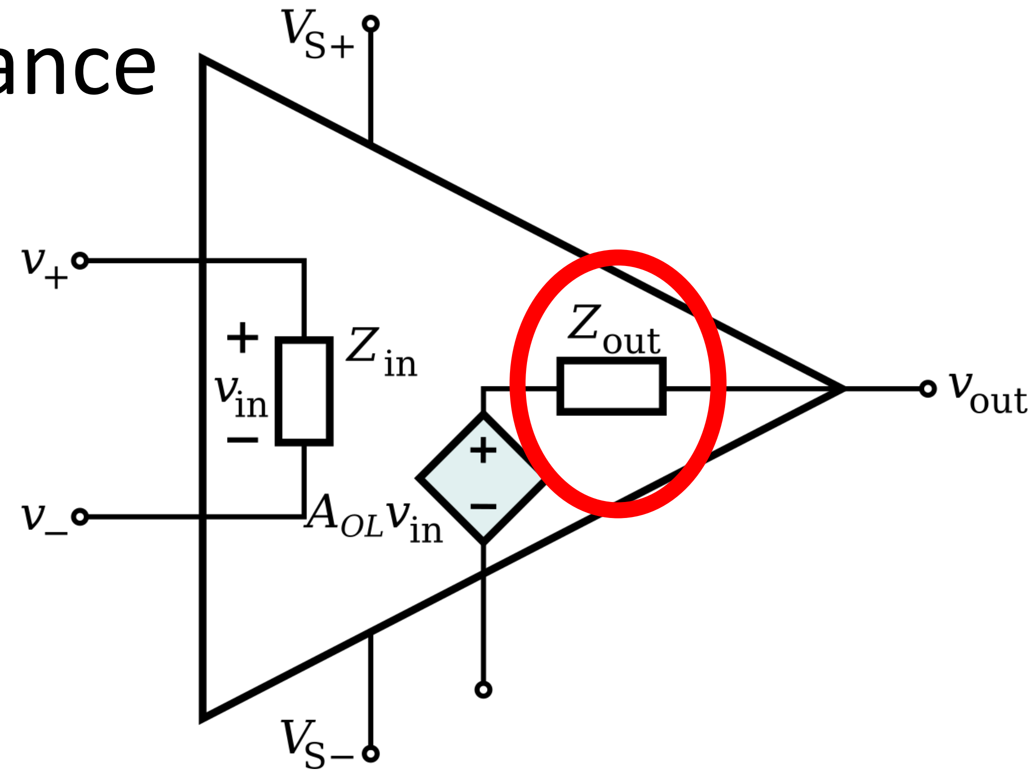
A signal has an associated voltage and current (given by V_S.R_S) This source "sees" the input impedance Z_{IN}, so we get a voltage divider at input



$$V_{IN} = V_s\left(\frac{Z_{IN}}{R_S + Z_{IN}}\right)$$

So (usually small) fraction of signal is lost!

Ideal Op Amp – 3. Zero Output Impedance



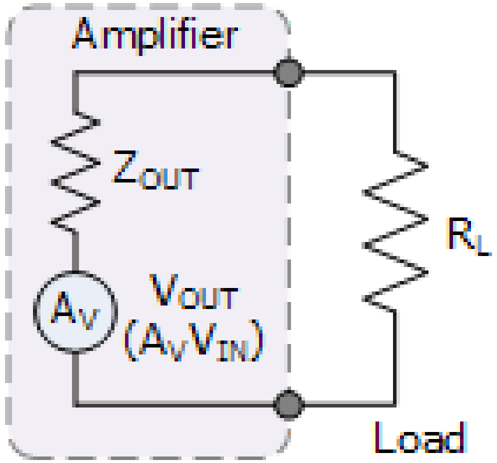
$$Z_{OUT} = 0$$

This means source can supply ***as much current as necessary.*** In other words, the Op-Amp output is not effected by external components.

Reality:

Z_{OUT} can be anywhere from 1 Ω up to ~kΩ (according to datasheet!)

There is another voltage divider at output, with Z_{OUT} and load (where you want your signal to go)



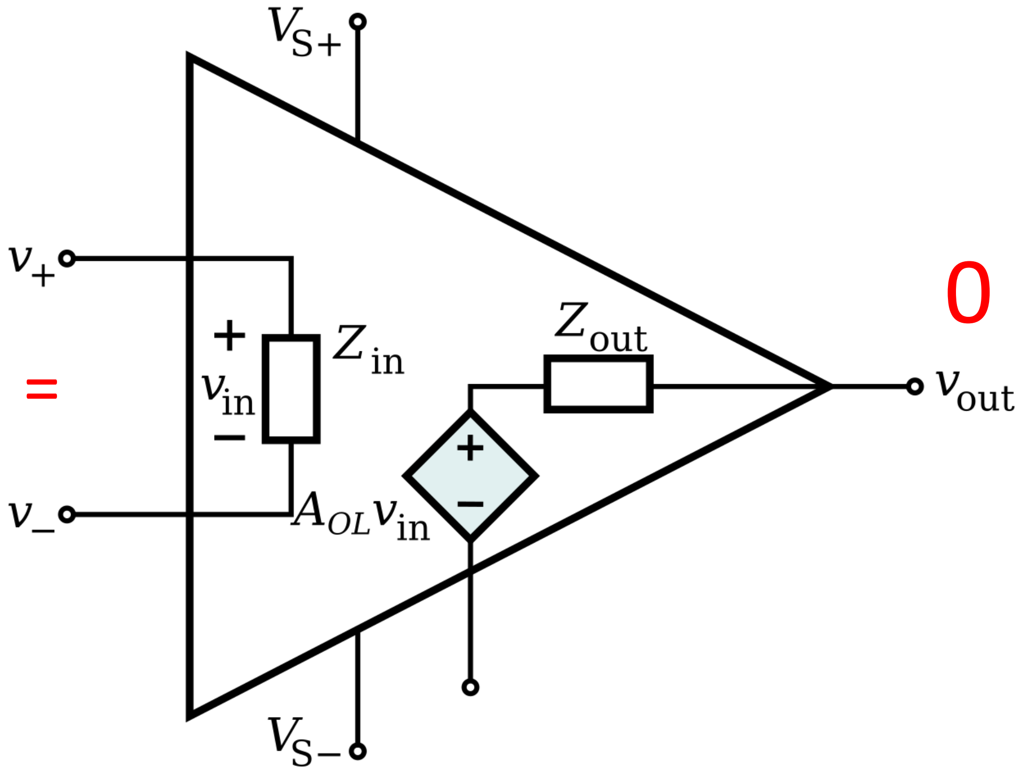
$$V_L = V_{OUT}\left(\frac{R_L}{Z_{OUT} + R_L}\right)$$

So another (usually small) fraction of signal is lost!

Ideal Op Amp – 4. No offset

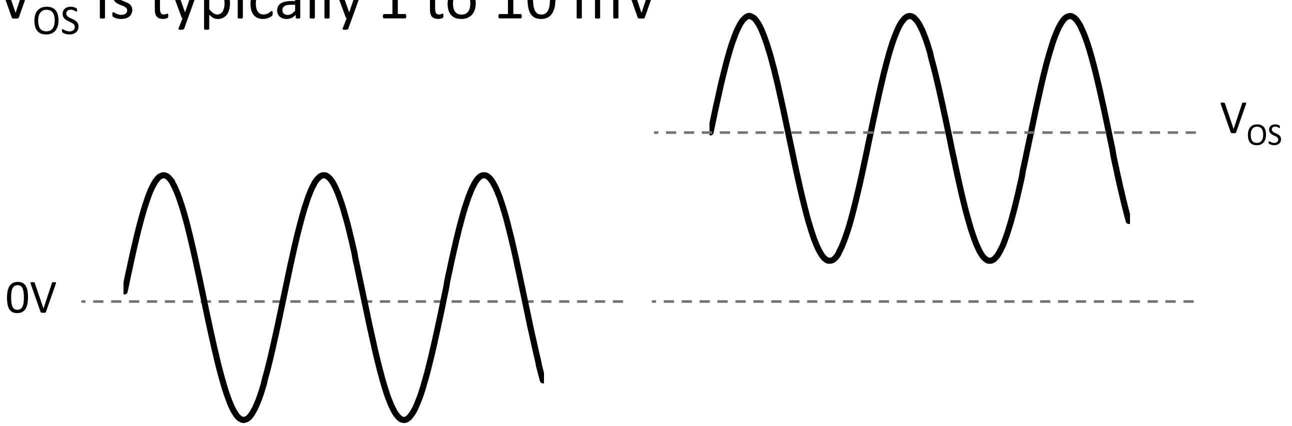
$$V_{OUT} = 0 \text{ when } V_{-} = V_{+}$$

The input voltage required to get zero output voltage. i.e. there is no output when there is no input



Reality:

V_{OS} is typically 1 to 10 mV



Pure AC input

Output is AC with DC offset

Specialised ICs (£££), or compensation circuits (offset nulling etc.) or filtering needed

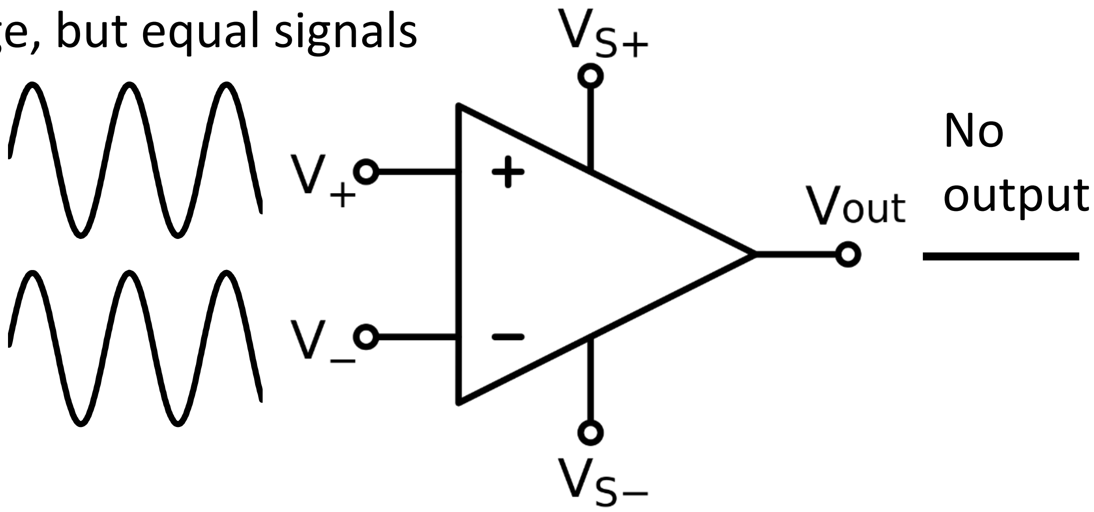
Ideal Op Amp – 5. Infinite CMRR

$$CMRR = \infty = \left(\frac{A_d}{A_{cm}} \right)$$

Diff. Gain
———
Common mode Gain
(should be 0)

Related to V_{OS}, explicitly states error from "common mode" signals, and given across frequency.
In other words same signal at inputs gives no output

Large, but equal signals



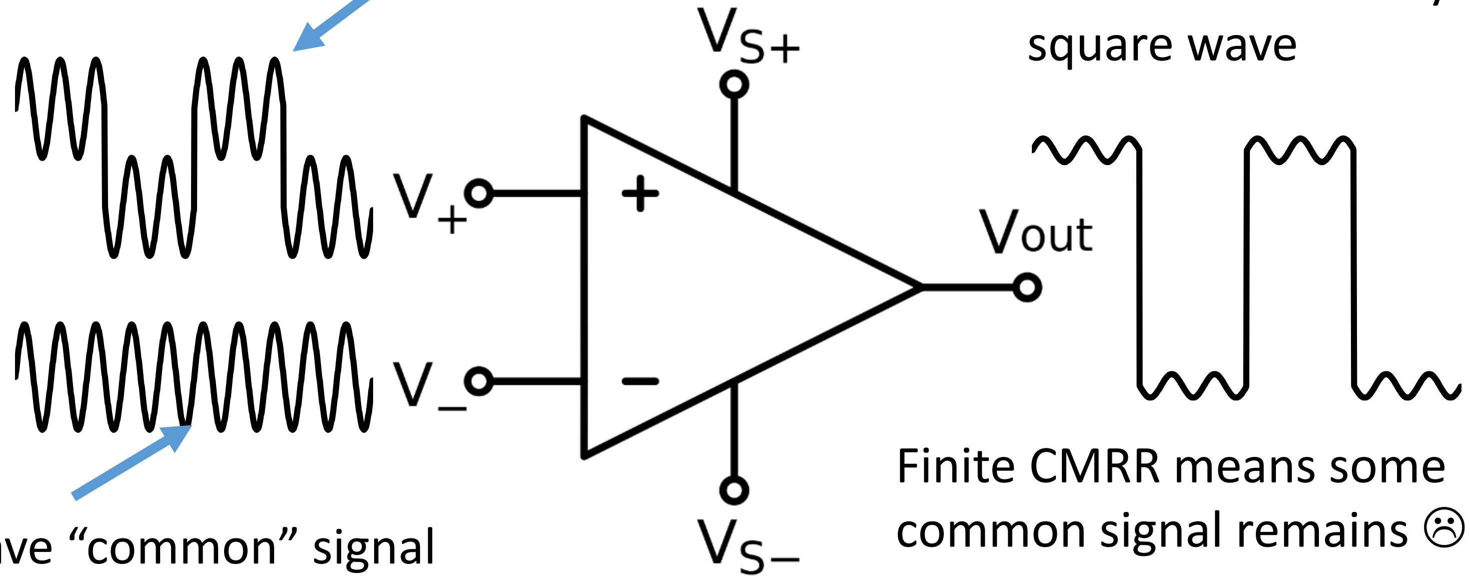
No output

Reality:

CMRR approximately 80-100 dB (at DC) i.e. some fraction of common mode signals remain and contaminate desired signal

Square wave + common signal

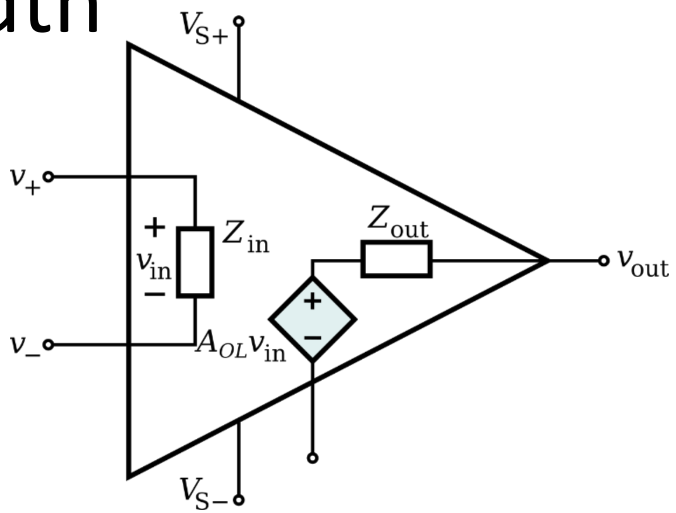
Ideal would be only square wave



Sine wave "common" signal

Finite CMRR means some common signal remains ☹

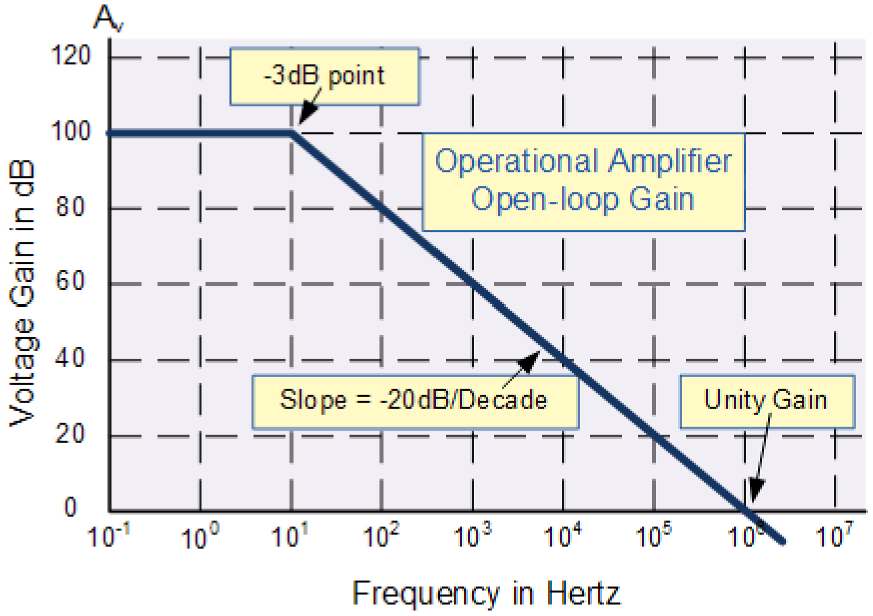
Ideal Op Amp – 6. Infinite Slew Rate or Bandwidth



Frequency domain: Op-amp can amplify any frequency signal. **Bandwidth** from DC to ∞

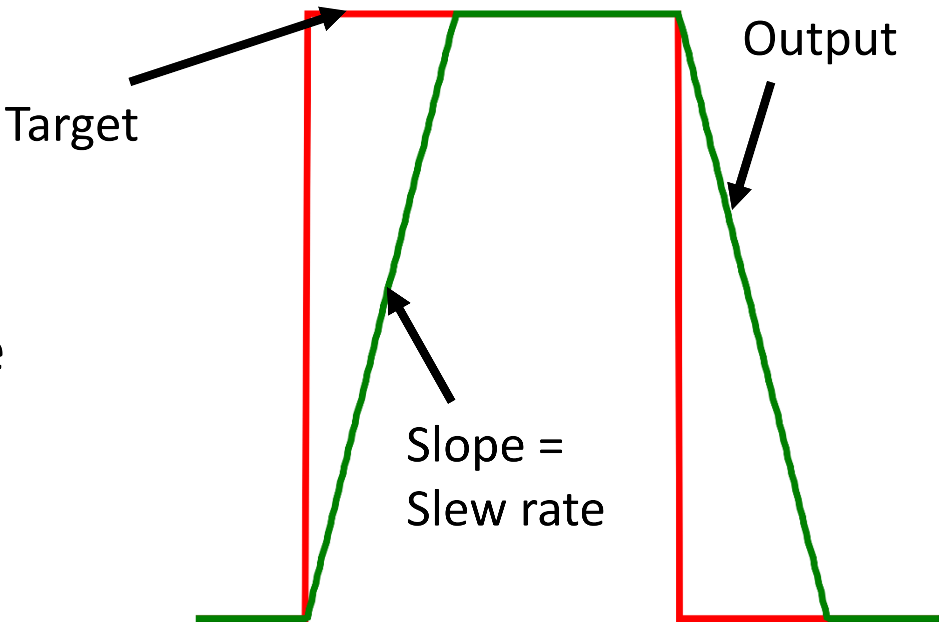
Time domain: No delay between input and output. **Slew rate** (rate of change of voltage) is ∞

Reality:



Gain decreases with frequency

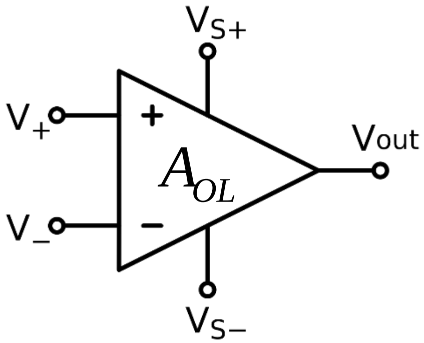
Or related in the time domain

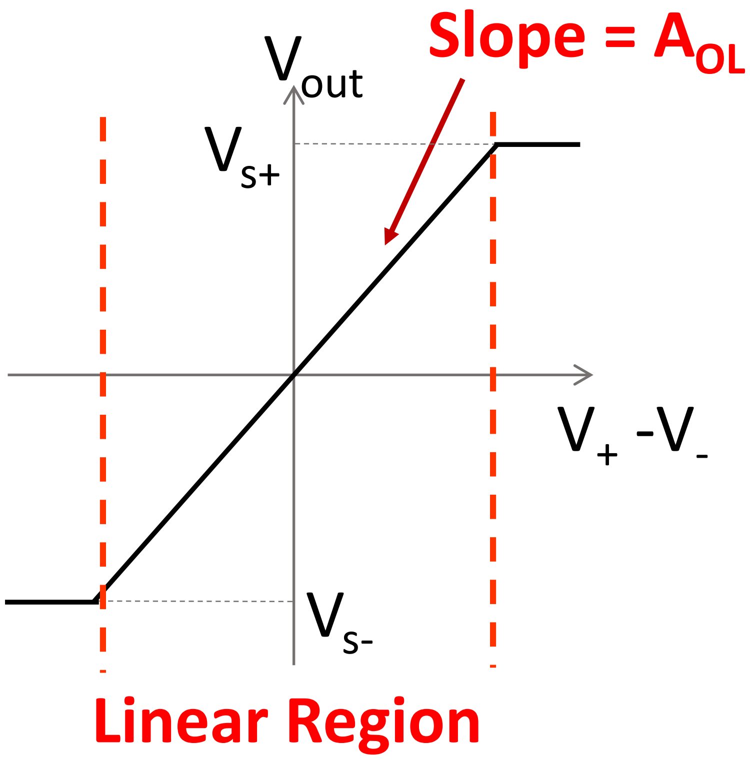


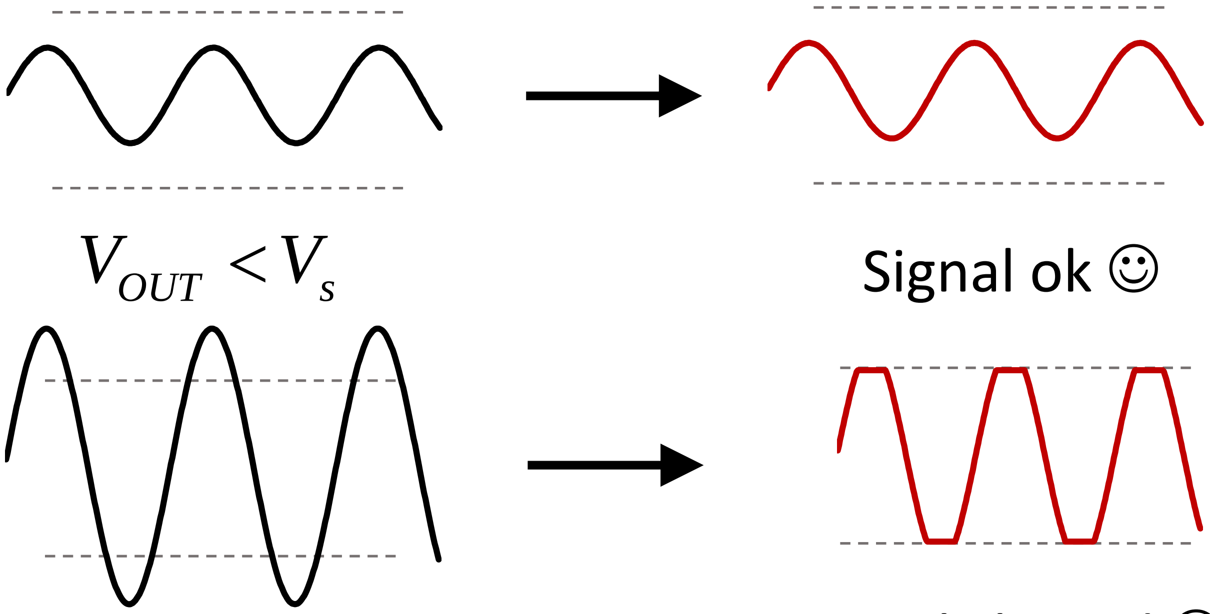
Delay in reaching target voltage
Linearised for simplicity

Op Amp – Saturation

There is a *linear region* where output is between supply voltages ±Vs







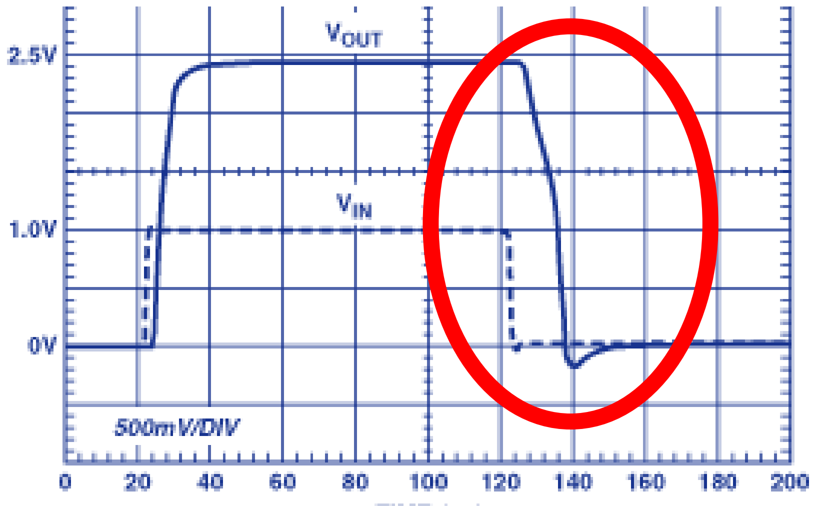
$V_{OUT} < V_s$

Signal ok ☺

$V_{OUT} > V_s$

Saturation

Signal clipped ☹



Want to avoid saturation!

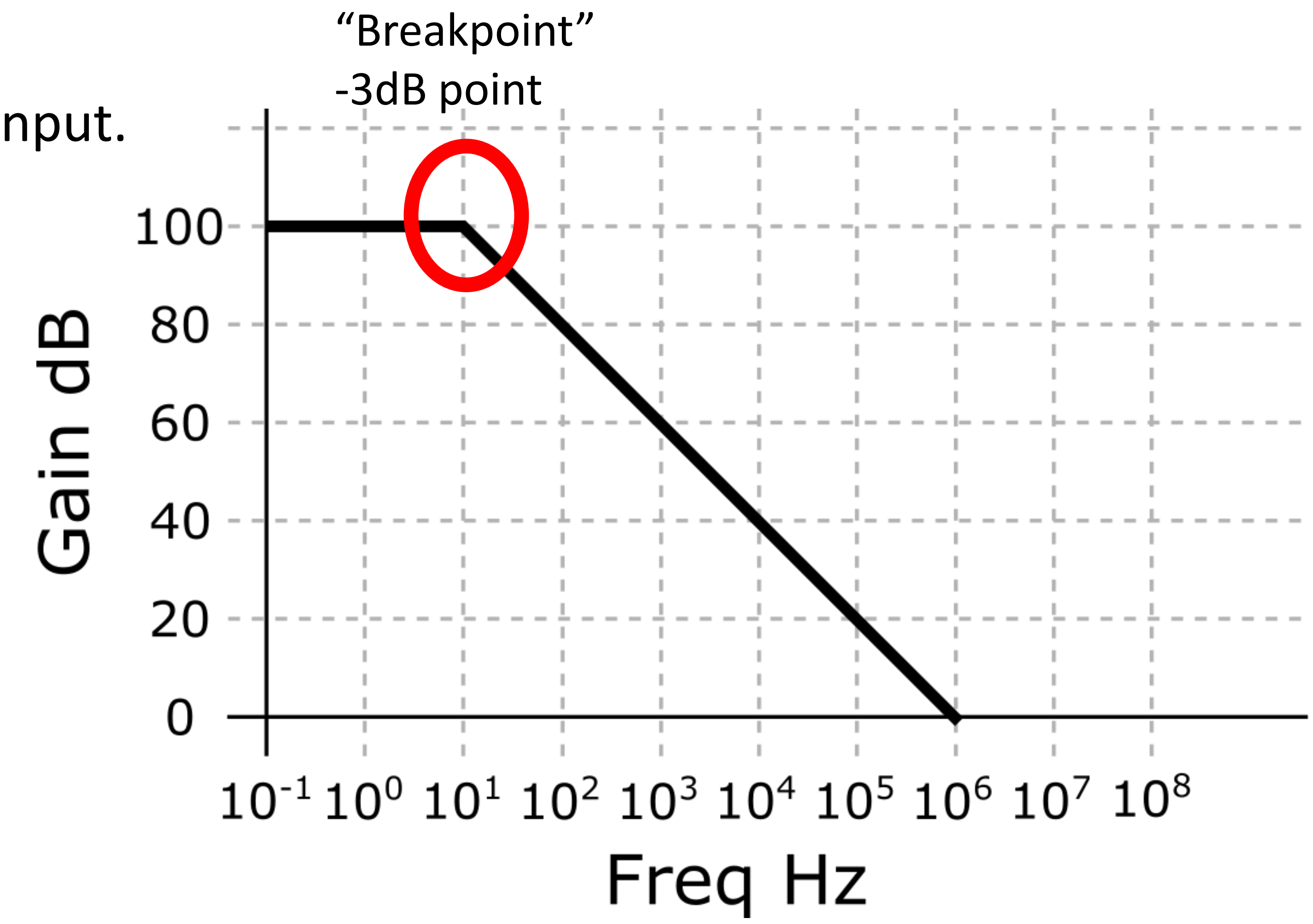
It not only clips the signal, but op amp takes time to recover from it

Open Loop Gain across frequency

Aim of amplification is to linearly scale input.
We do not want to *distort the signal*.

Gain from DC to -3dB point is approximately flat

Beyond that gain decreases *linearly* equal to -20 dB/Decade

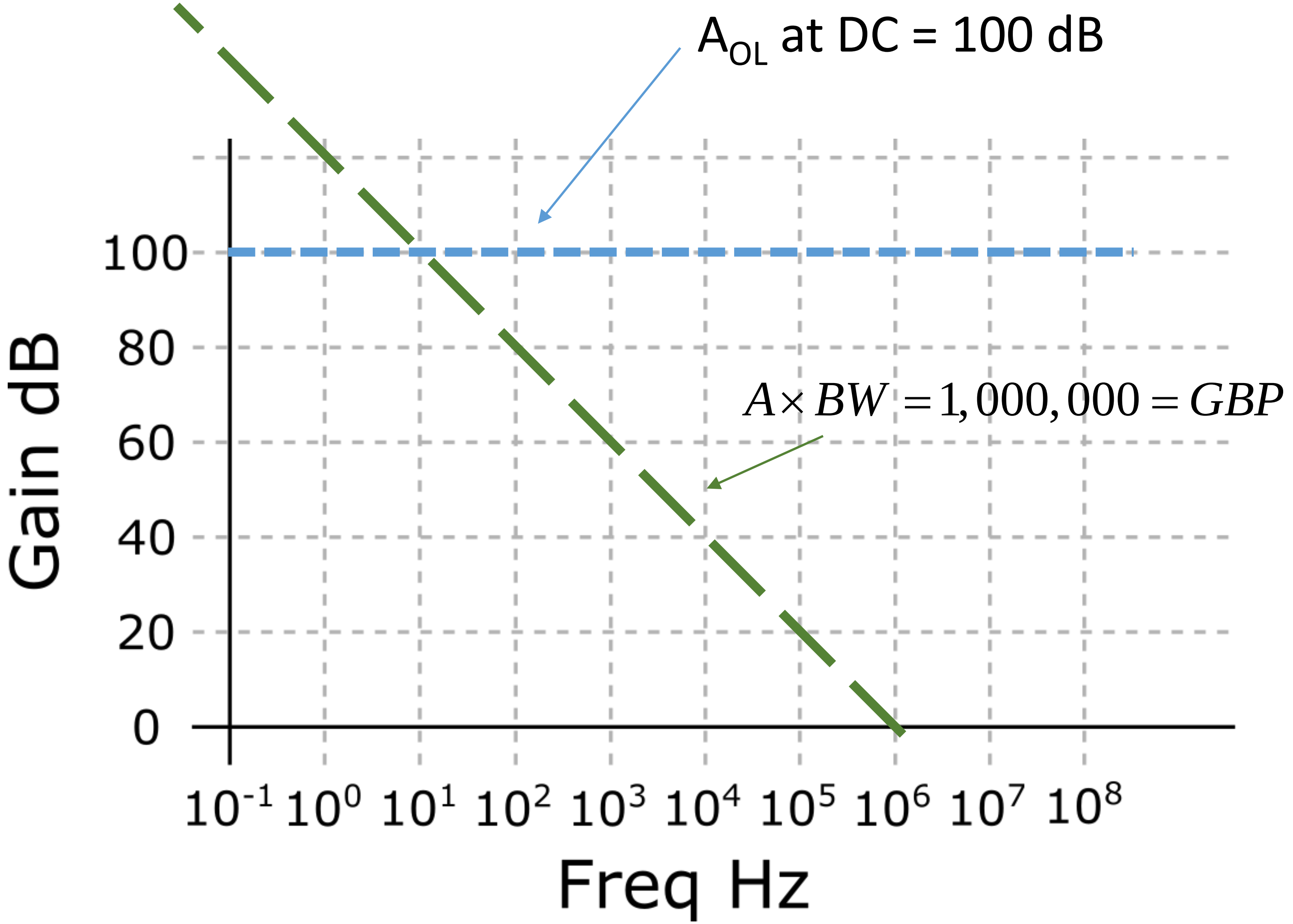


Gain bandwidth product - GBP

Two approximate the Open Loop Gain A_{OL} across frequency we need two pieces of information:

- A_{OL} at DC: This is the *maximum* open loop gain, and the one specified in the datasheets (if it is specified at all!)

- Gain Bandwidth Product: The constant product which describes the decrease in gain as bandwidth increases



In this example, A_{OL} is 100 dB and GBP is 1 MHz

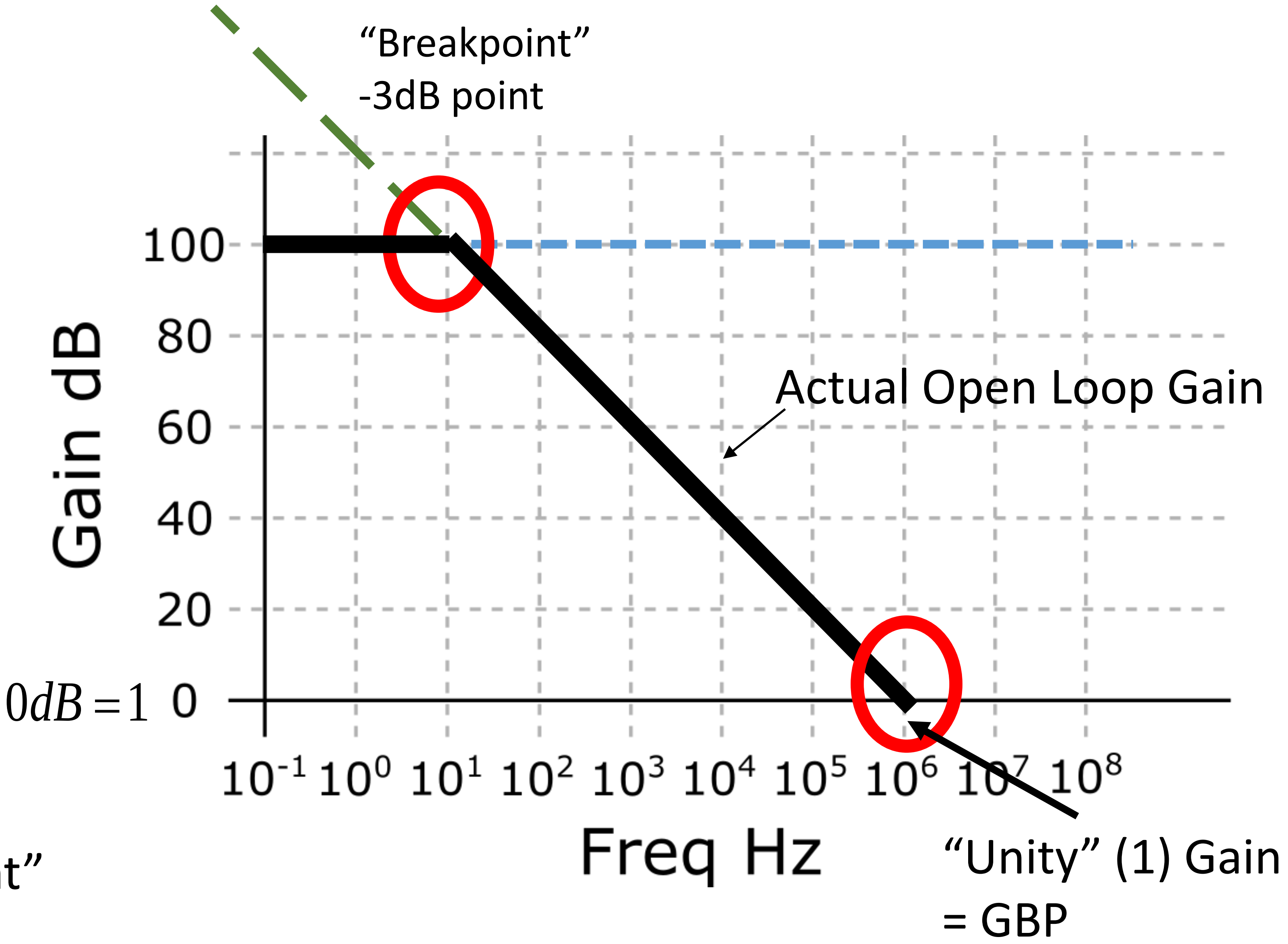
Gain bandwidth product - GBP

The point at which these two lines intersect is called:

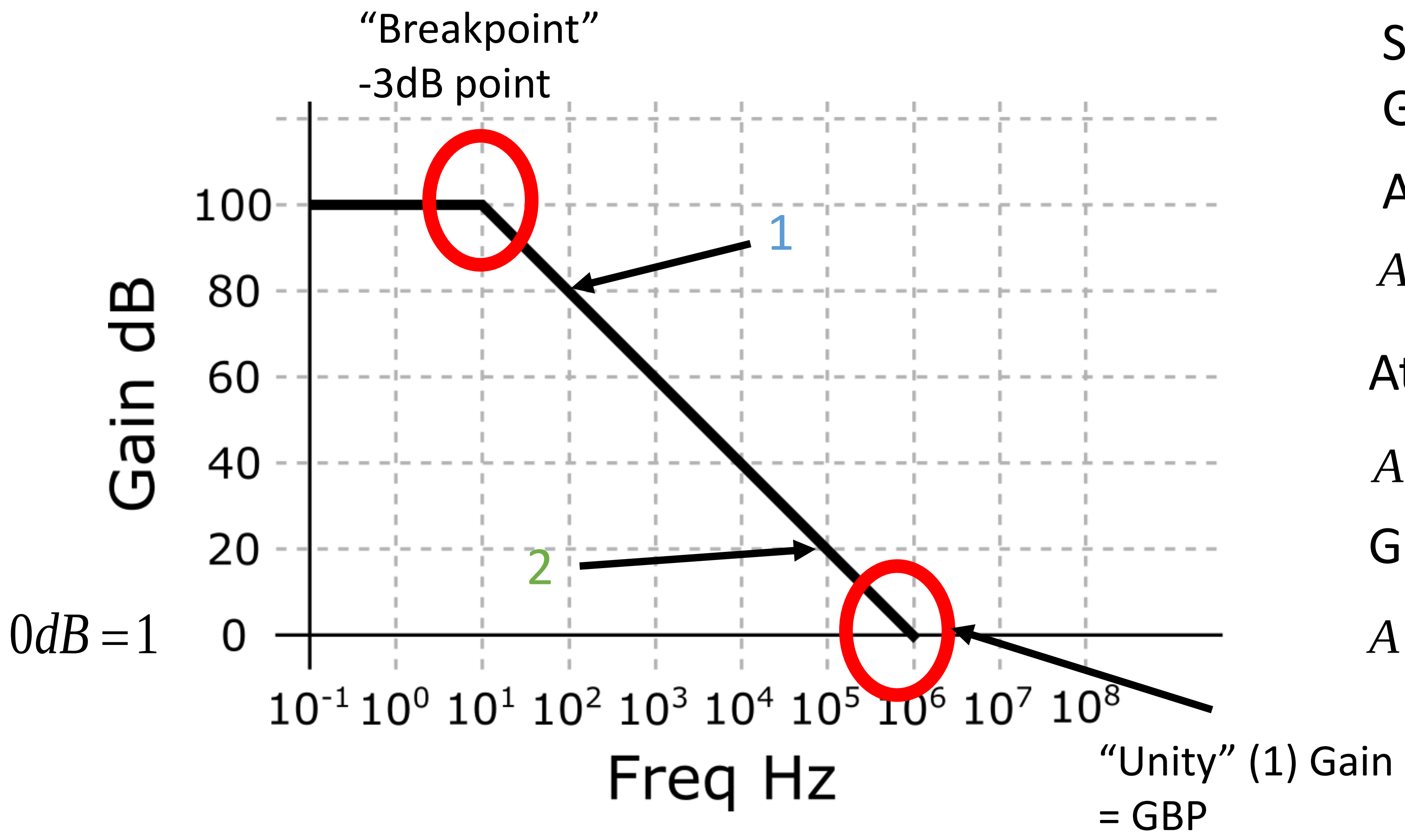
- The “breakpoint”
- The -3dB point
- The 3dB point

After this point, the Op-Amp cannot maintain the same gain, and it starts to roll-off based on the GBP

The point where it reaches 0dB or 1 gain, is known as the “unity gain point”



Gain bandwidth product - GBP



Slope of this linear region is:

GBP = Gain x Bandwidth = A x BW

At point 1 A=80dB = 10k

$$A \times BW = 10,000 \times 100 = 1,000,000$$

At point 2 A=20dB = 10 =GBP

$$A \times BW = 10 \times 100,000 = 1,000,000$$

GBP also defines unity gain point

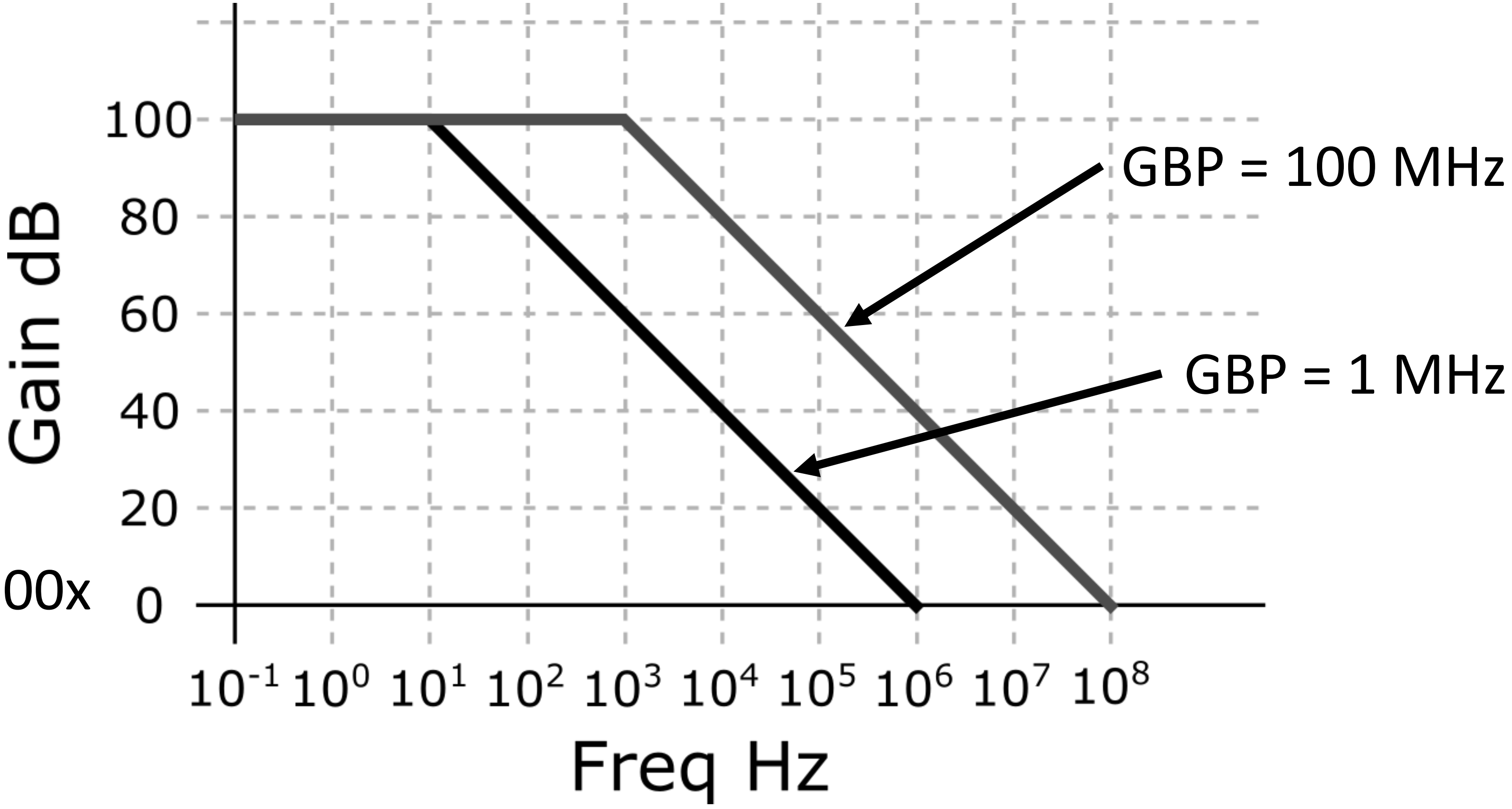
$$A \times BW = 1 \times 1,000,000 = 1,000,000$$

Gain bandwidth product - GBP

Gain bandwidth product common specification of Op-amps.

Still -20 dB/Decade decrease after breakpoint, even for different GBP

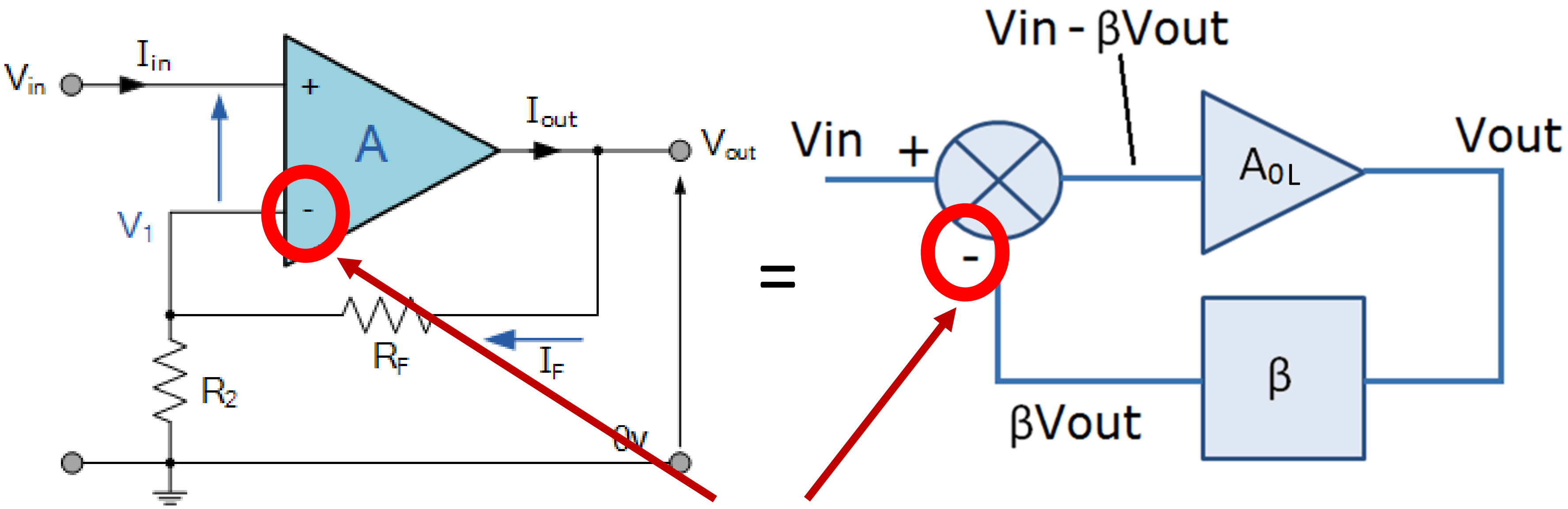
Unlikely to be able to increase GBP 100x (as in figure), without compromising other specs!



GBP also determines the maximum possible gain of a *closed loop* Op-amp circuit at a given frequency. As we shall see!

Op Amp Circuits – Negative Feedback

If A_{OL} is huge, then immediately saturating with any input is not that useful! We want V not KV! So instead we feedback only a fraction of the output signal to the input.



$$V_{OUT} = A_{OL}\left(V_{in} - \beta V_{OUT}\right)$$

$$\frac{V_{OUT}}{V_{in}} = \frac{A_{OL}}{\left(1+\beta A_{OL}\right)} = A_{CL}$$

Ideally $A_{OL} = \infty$

$$A_{CL} = \frac{V_{OUT}}{V_{in}} = \frac{1}{\beta}$$

$$\beta = \frac{R_2}{R_2 + R_F}$$

Must to go *non-inverting* or *negative* terminal to subtract

Ideal Op-amp properties mean closed loop gain determined *entirely* by external components. Thus predictable and configurable

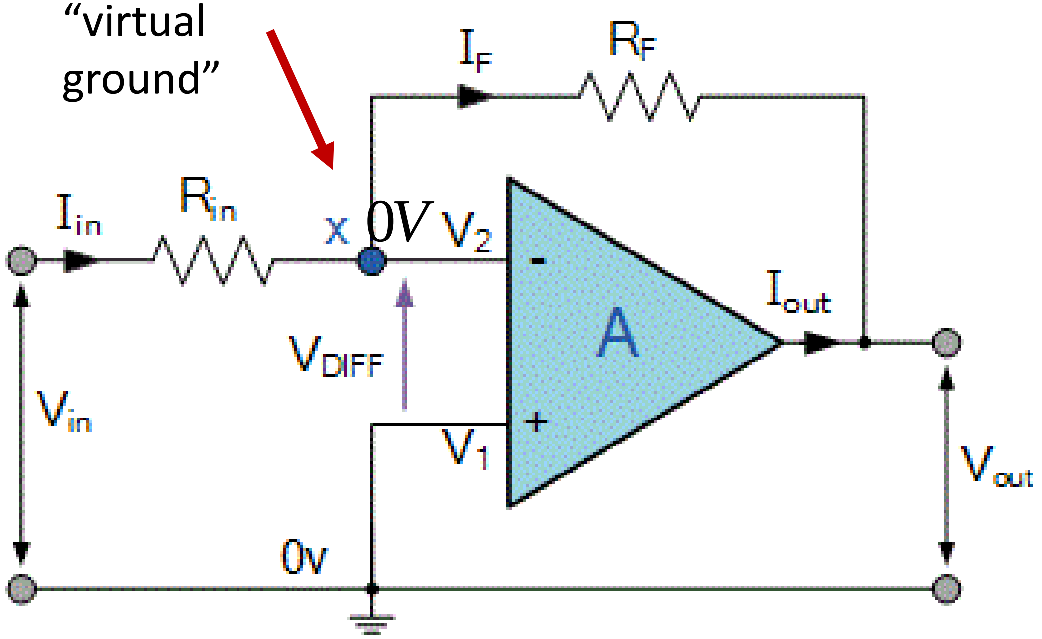
Op Amp Circuits – Negative Feedback

RULE #1 Negative feedback also keeps both inputs at the same voltage or output will do whatever it can to make the difference input voltages zero

RULE #2 Inputs draw no current

Understanding the *function* of the circuits more important than knowing equations for each voltage/current, but they all follow from these "golden rules" and Kirchoffs laws

Point x is a "virtual ground"



$V_1 = V_2 = 0V$ RULE #1 $\qquad I_{in} = -I_f$ RULE #2

From voltage drop across R_{in}: From voltage drop across R_f:

$$I_{in} = \frac{V_{in}}{R_{in}} \qquad I_f = -\frac{V_{out}}{R_f}$$

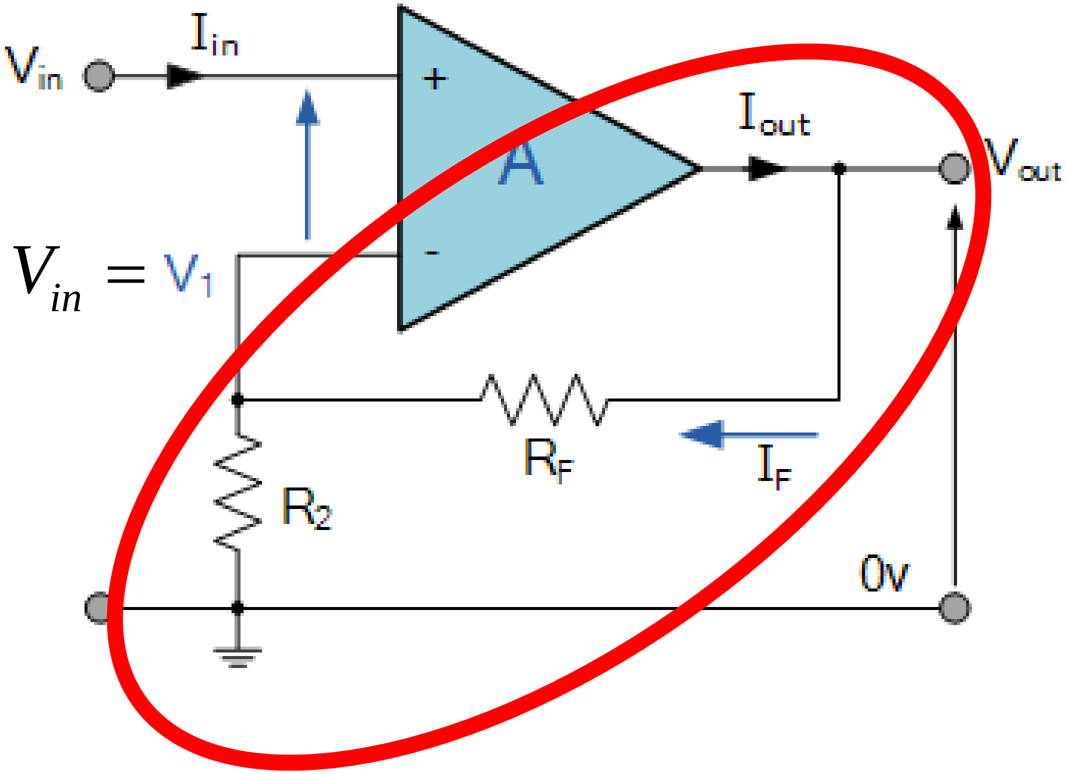
Remember sign conventions!

$$\frac{V_{in}}{R_{in}} = -\frac{V_{out}}{R_f} \rightarrow V_{out} = -\frac{R_f}{R_{in}} V_{in}$$

Input signal connected to **inverting** terminal – **inverting** amplifier

Op Amp Circuits – Non-inverting Amplifier

Input signal connected to **non-inverting** terminal – **non-inverting** amplifier



RULE #1 Voltage at input terminals are the same $V_1 = V_{in}$

RULE #2 No current flows into Op-amp, so feedback section simplifies to voltage divider $V_1 = \frac{R_2}{R_2 + R_F} V_{out}$

Combining:

$$V_{in} = \frac{R_2}{R_2 + R_F} V_{out}$$

So: $$V_{out} = \frac{R_2 + R_F}{R_2} V_{in}$$

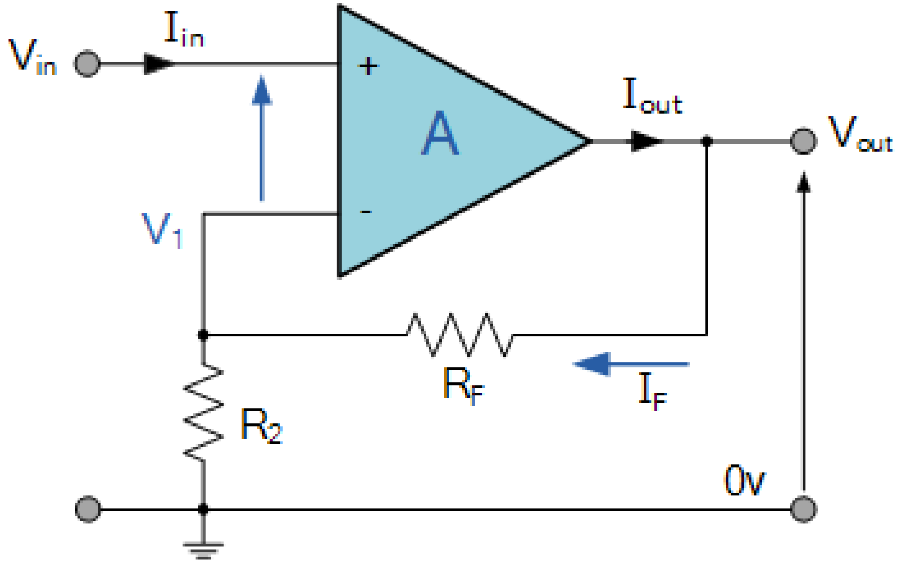
$$V_{out} = \left(1 + \frac{R_F}{R_2}\right) V_{in}$$

Or as a gain $$\frac{V_{out}}{V_{in}} = \left(1 + \frac{R_F}{R_2}\right) = A_{CL}$$

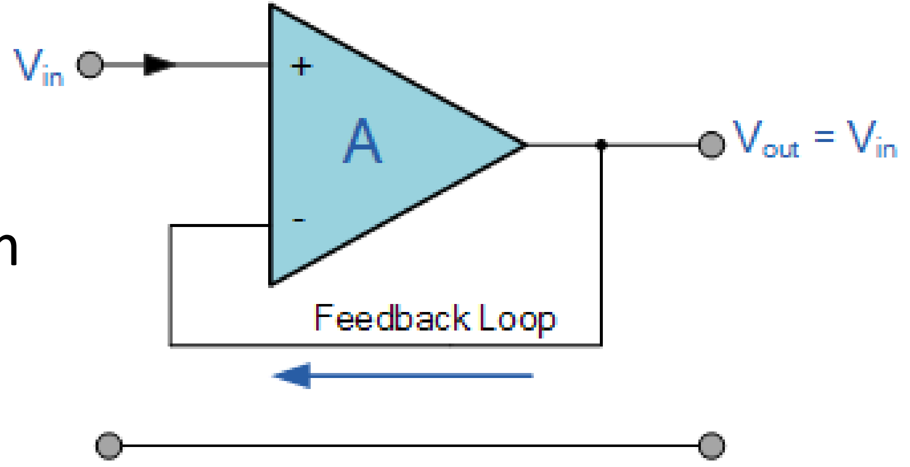
Op Amp Circuits – Buffer Amplifier

Special case of non-inverting amp $R_F = 0 \quad R_2 = \infty$

$$V_{out} = \left(1 + \frac{R_F}{R_2}\right) V_{in} \rightarrow V_{out} = V_{in}$$



Or directly from
RULE #1

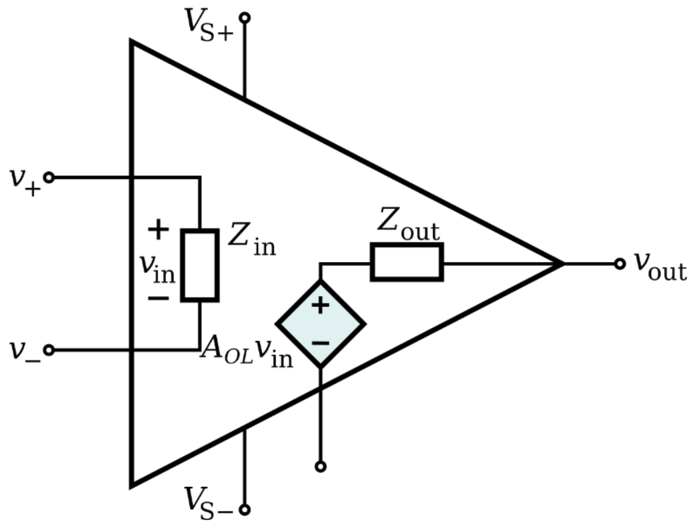


Unity gain? What's the point?

Remember ideal Op-amp has infinite input impedance. So there is no connection between +ve and –ve terminals, we can consider V_{in} and V_{out} as entirely separate signals.

We may have long cabling, filters, ADCs etc, which could all alter the signal – known as "loading". Buffer amp separates the input signal from any circuitry after the Op-amp.

ECG electrodes



Cables/ Filters/ ADC

Zout is 0. So much more current too!

Gain across frequency

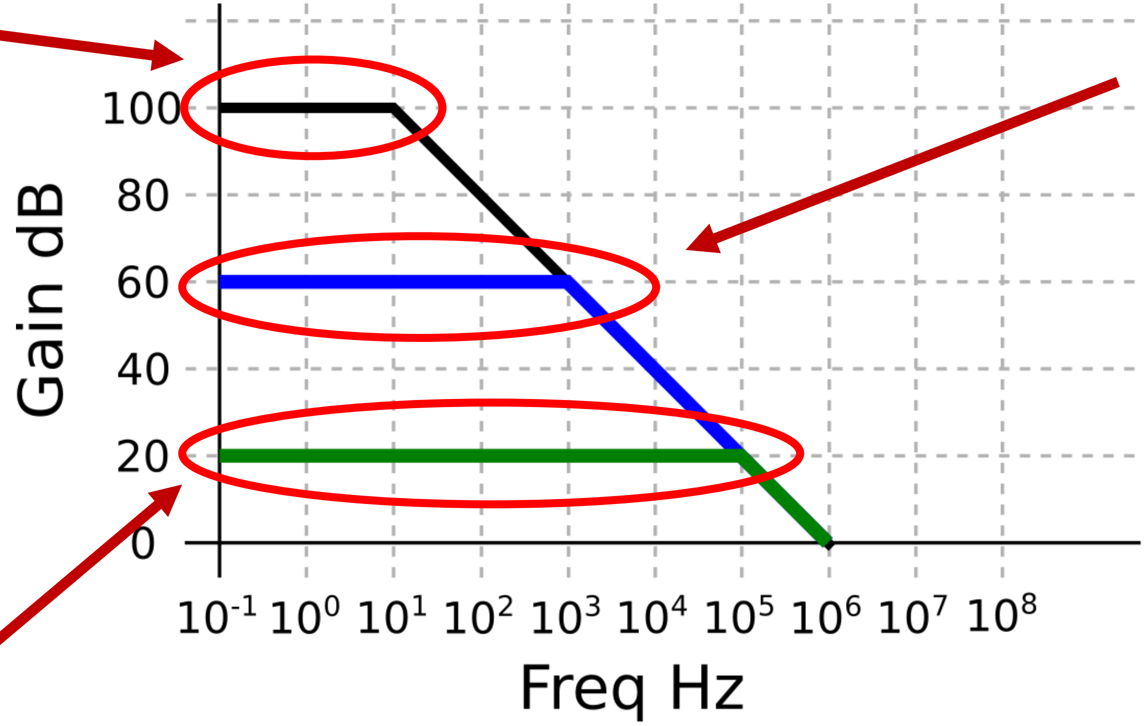
Aim of amplification is to linearly scale input. We do not want to *distort the signal*.
We want flat frequency response across our signal range. But this was only the case for a very narrow range.
Luckily, using negative feedback not only reduces the gain, but also widens the bandwidth.

No feedback

$$A_{OL} = 100dB$$
$$= 1,000,000$$
$$f_c = 1Hz$$

Closed loop – high gain

$$A_{CL} = 60dB$$
$$= 1,000$$
$$f_c = 1000Hz$$



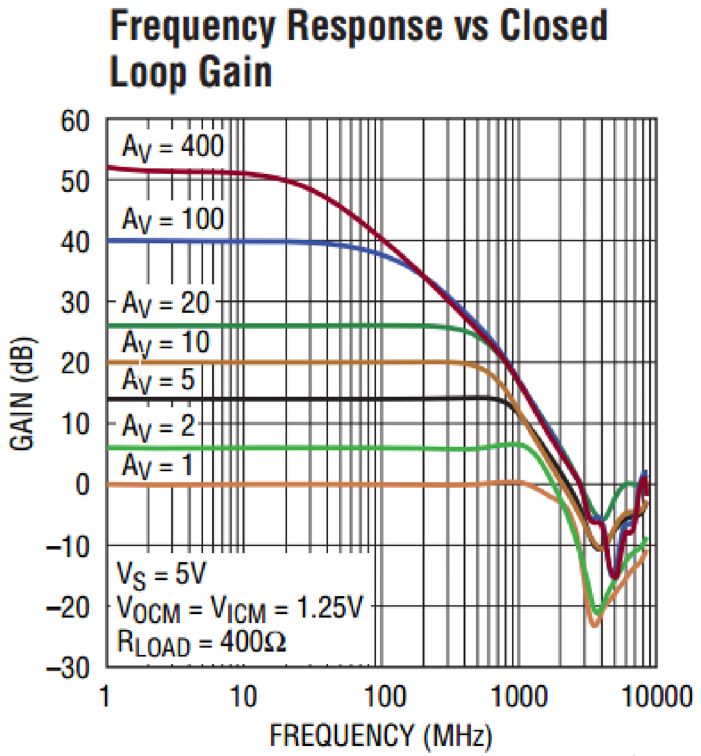
Closed loop – low gain

$$A_{CL} = 20dB$$
$$= 10$$
$$f_c = 100,000Hz$$

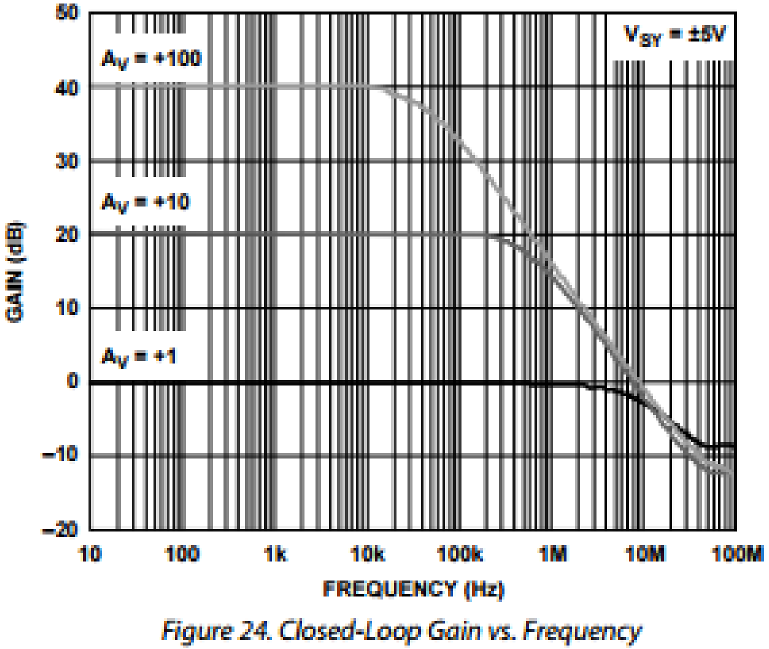
In every case: $A_{CL} \times f_c = GBP$

Gain across frequency

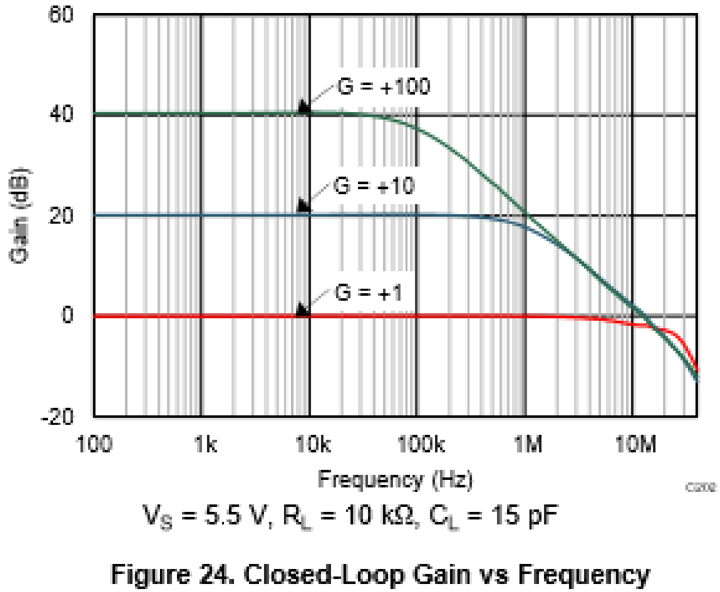
Comparing the true *closed-loop* gain across frequency demonstrate the utility of this approximation.
Larger errors close to fc, so usually set higher than required based on specific Op-amp



LTC6409 GBP=10 GHz



ADA4062 GBP=1.4 MHz



OPA2325 GBP=10 MHz

The take-home here is that there is a direct *trade-off* between bandwidth and gain. Understanding the application (i.e. what signals you have and what you need to do them) allows you to optimise.
In other words, when someone asks what the frequency range of the signal is, they aren't just being difficult!

Thank you for your attention!

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