ENGG1300
Introduction to Electrical Systems
Week 12
Operational Amplifiers

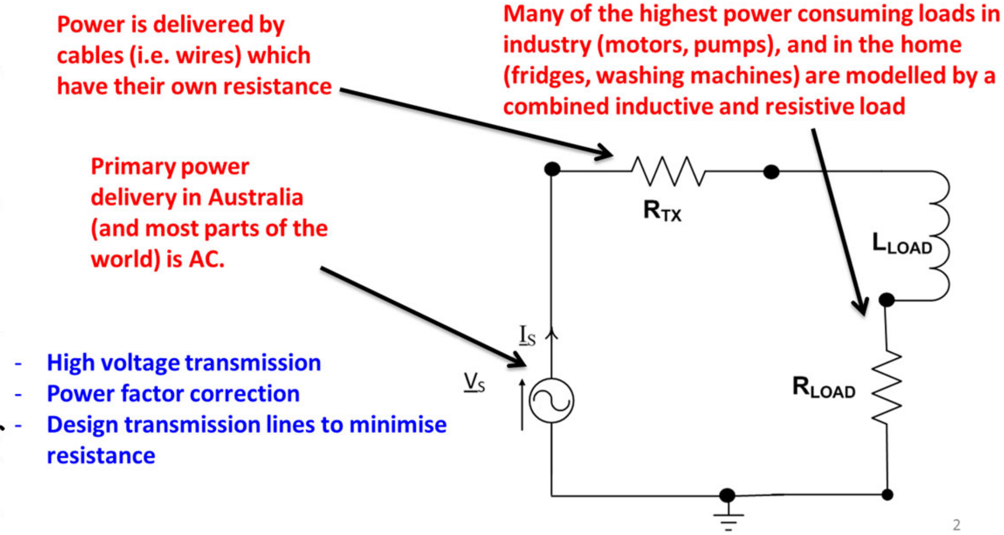
Lecturer:
Dr Philip Terrill

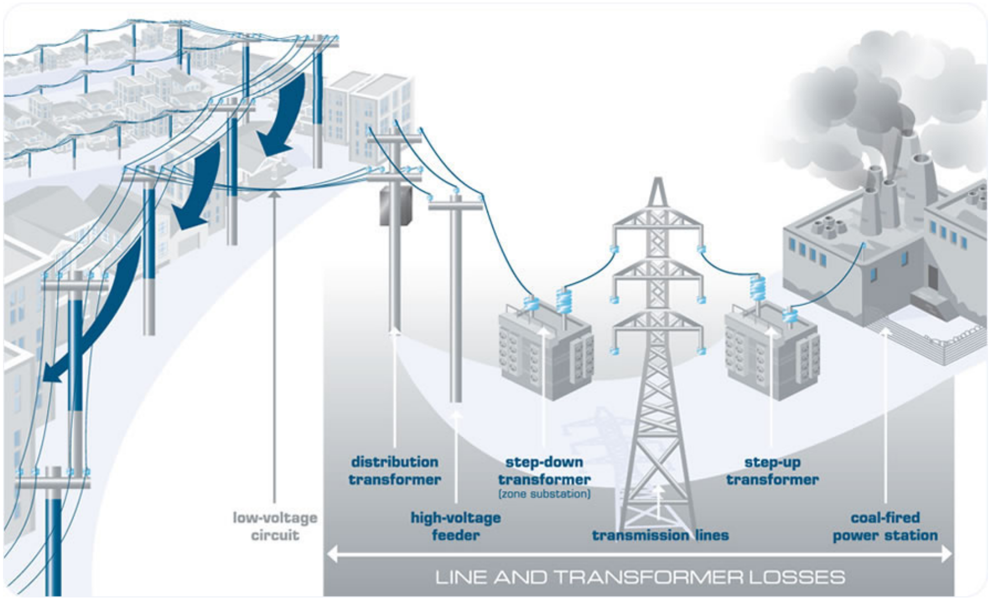
Key Learning Outcomes of Power Systems Module:

- Be able to calculate power factor, and the average power consumed by a reactive load.
- Calculate the necessary value of a power factor correction capacitor for an inductive load.
- Calculate the resistance of a transmission line (based on resistivity, cross-section area and length), and calculate transmission line losses for a given load.
- Calculate currents through, and voltages across primary and secondary windings of transformers
- Calculate the transformer turns ratio to achieve a desired voltage or current, given a supply voltage or current.

Key Learning Outcomes of Power Systems Module:

- Understand how electricity is generated using induction generators
- Appreciate why power is transmitted at high voltages
- Appreciate why power is transmitted as AC
- Appreciate the practical context of power factor correction; be able to calculate the value of a power factor correction capacitor; and explain why this improves efficiency.
- Have an understanding of the power transmission and distribution infrastructure in Queensland, and the organisations involved.
- Describe the technical challenges of integrating renewable sources such as solar and wind power.





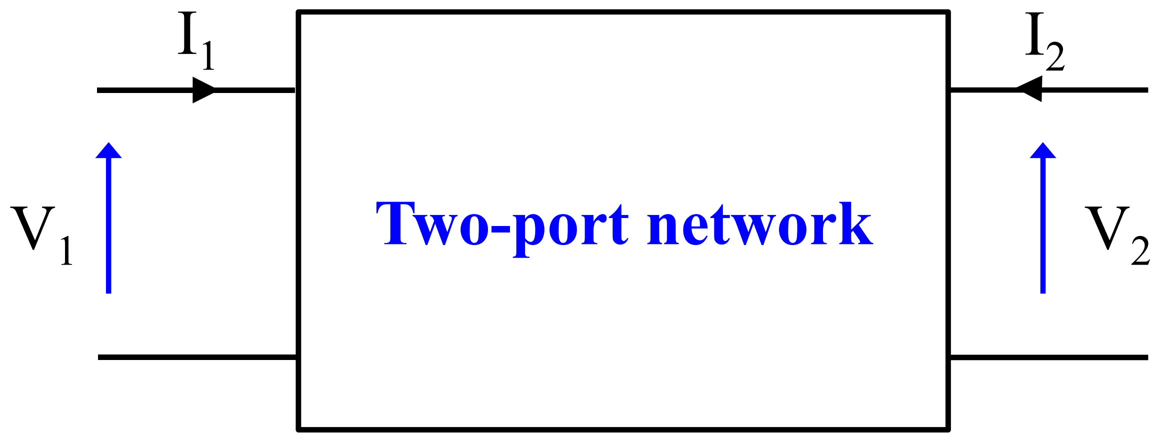
Control Module

- Week 12: Op-Amps (as a negative feedback control device)
- Quiz 10: Due 4pm Monday 17th May, (Week 12).
- Quiz 11 (final one): Due 4pmMonday 24th May, (Week 13)
- Week 13: Feedback and control in practice; Course Revision
  - Open and closed loop control
  - Feedback control systems
  - Proportional, and PID controllers
  - Op-amp as a feedback controller
  - Applications of control
  - Course Revision
  - Final exam details

Amplifiers

- Amplifiers take information at a low power level, and increase it to a high power level.
- They can do this by amplifying the voltage **and/or** the current of the signal.
- Key applications of electronic amplifiers:
  - Communications: To amplify a signal received from a distant location (i.e. an RF amplifier in a mobile phone).
  - Instrumentation: To amplify a small signal generated by a sensor (i.e. a strain gauge to measure the load on a structure, or torque on a rotating shaft).
  - Transducers: Convert information (i.e. low energy signal) to a physical signal (i.e. audio amplifier to control volume at a speaker); convert the low power output from a microcontroller to a high power output to drive a motor.

Amplifier Model: 2-Port Network



$$V_2(t) = G \times V_1(t)$$

- In the simplest case, the gain, G is a constant, e.g. G=10
- Unless the two port network contains an **"active"** amplifier device, the gain magnitude will always be less than 1.
- If the two port network includes inductors or capacitors, this will be a complex (frequency dependant) transfer function:

$$V_2(t) = H(\omega) \times V_1(t)$$

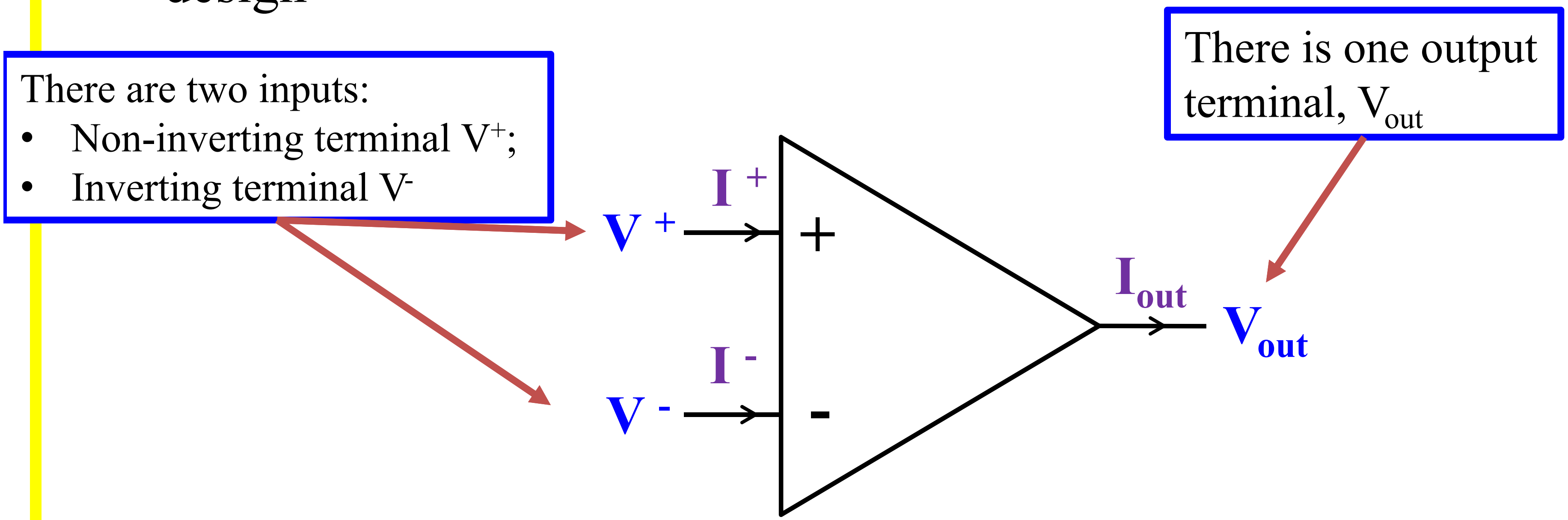
Amplifier Gain

- Note that we can refer to three types of gain:-
  - Voltage gain: $G_v = \frac{|V_2|}{|V_1|}$
  - Current gain: $G_I = \frac{|I_2|}{|I_1|}$
  - Power gain: $G_p = \frac{|P_2|}{|P_1|} = G_v \times G_I$

- In ENGG1300, if not otherwise specified, you can assume "gain" means voltage gain.

Operational Amplifier ("op-amp")

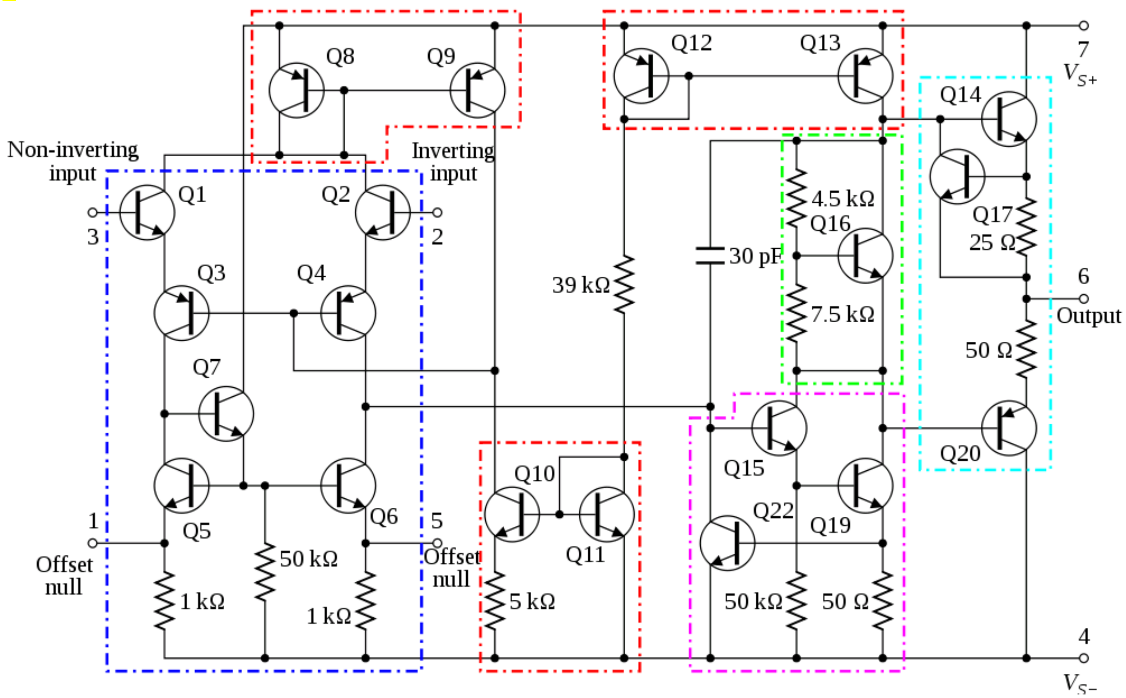
- Op-amps are a general purpose building block for amplifier design

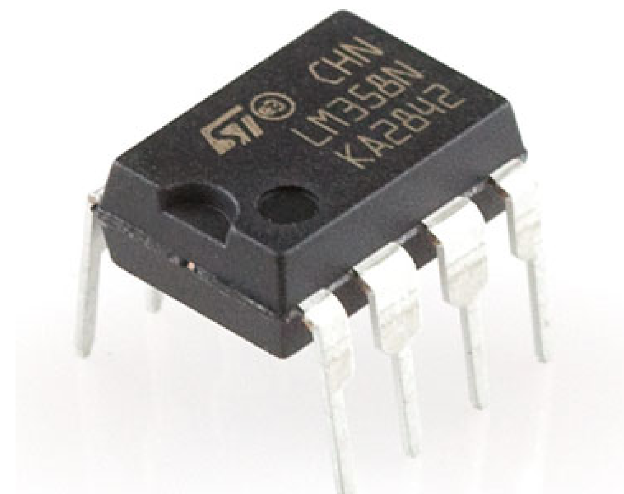


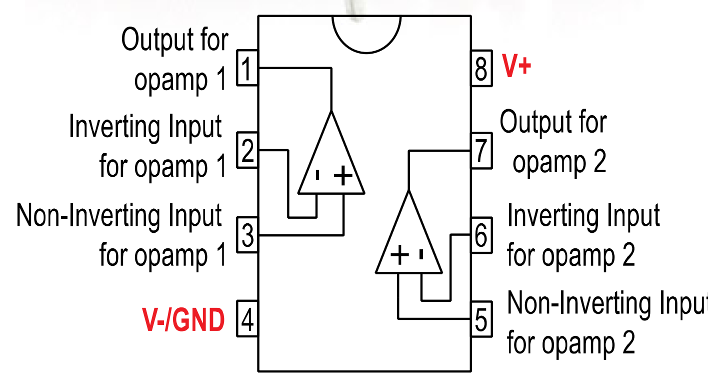
- All voltages are relative to a ground reference
- Op-amps require power connections to operate (although these are not normally shown in the circuit schematic model).

The Op-Amp

- Op-amps are "integrated circuits" – a complex circuit composed of semi-conductors (transistors, diodes) and "passives" (resistors, small number of capacitors)
- Manufactured on a silicon chip which is normally encapsulated in a resin case.

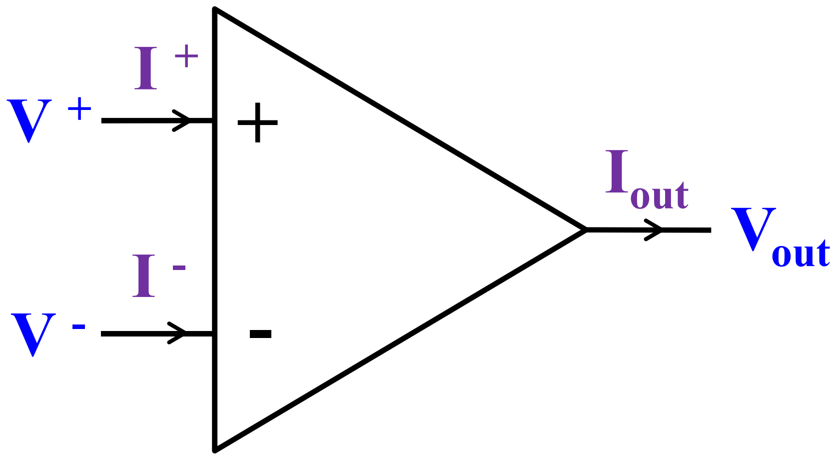




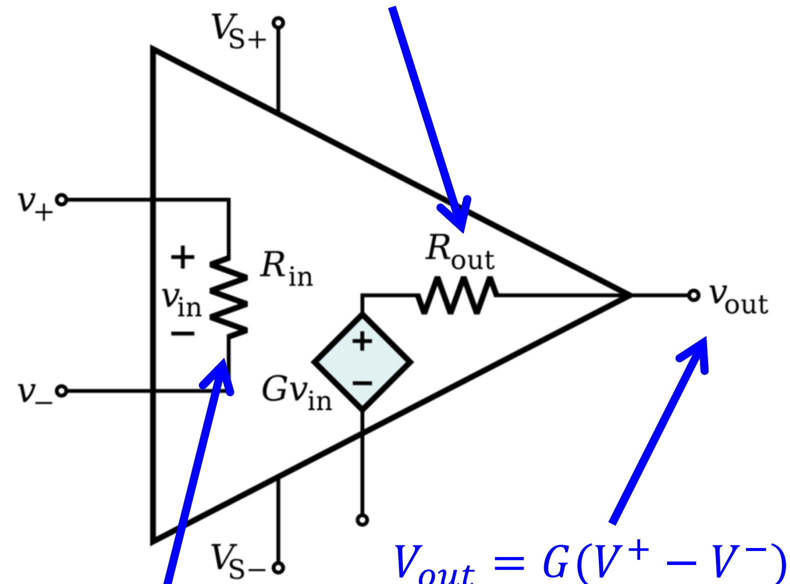


You'll be using these in labs this week!

Modelling Op-amp behaviour:



R_{out}=0 : The output voltage will be independent of any load connected to Vo



$R_{in}=\infty$: No current goes into, or out of the input terminals

- No Current enters the input terminals:
  - $\boldsymbol{I^+ = I^- = 0}$ (nA in practice)
- We can relate input to output voltages:
  - $\boldsymbol{V_{out} = G(V^+ - V^-)}$
  - "Ideally" **G=∞**; (in practice, G=10^4-10^6)

If $V^+>V^-$, V_{out} goes UP!
If $V^+<V^-$, V_{out} goes DOWN!
If $V^+=V^-$, V_{out} STAYS THE SAME

So, If we connect **negative feedback** (i.e. some network which connects the output terminal to the V^- terminal) the output will reach a steady state when the output remains constant, i.e. when **$V^+=V^-$**

In a circuit with negative feedback we can say: $I^+ = I^- = 0$ and $V^+=V^-$

Standard Op-amp Circuits

- We rarely use an op-amp by itself – we almost always use it in a negative feedback configuration.
- We will briefly examine five standard op-amp configurations in today's lecture.
  - Unity gain buffer
  - Inverting amplifier
  - Non-inverting amplifier
  - Summing Amplifier
  - Active filter
- Please use the pre-reading resources for the corresponding lab activities to understand these in detail.

Non- Inverting Amplifier

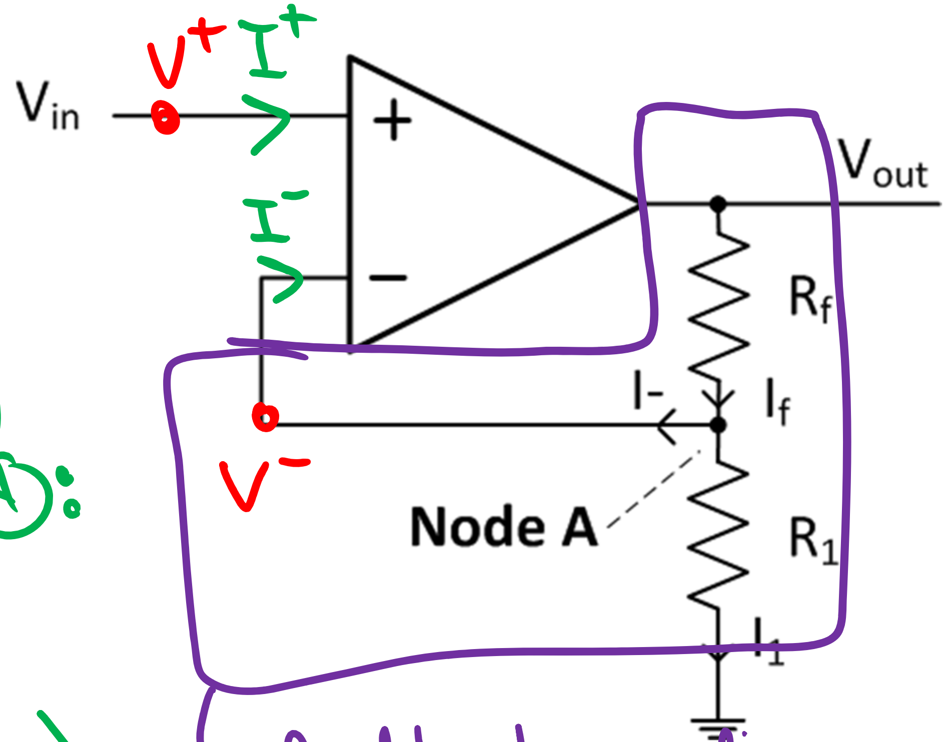
Op-amp rules:

* $I^+ = I^- = 0$
* $V^- = V^+ = V_{in}$.

Because $I^- = 0$, we can apply voltage divider at node A:

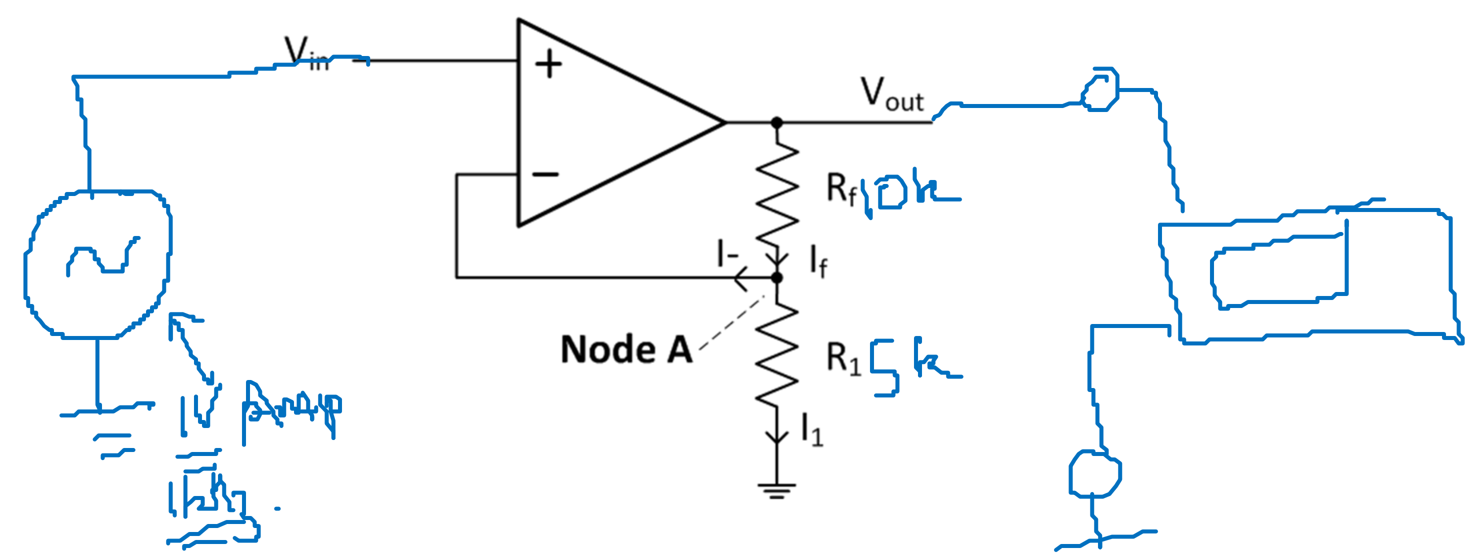
* $V^- = V_{out}\left(\frac{R_1}{R_1+R_f}\right)$
* $V^- = V_{in}$, $V_{in} = V_{out}\left(\frac{R_1}{R_1+R_f}\right)$

Thus $\frac{V_{out}}{V_{in}} = \frac{R_1+R_f}{R_1} = 1 + \frac{R_f}{R_1}$

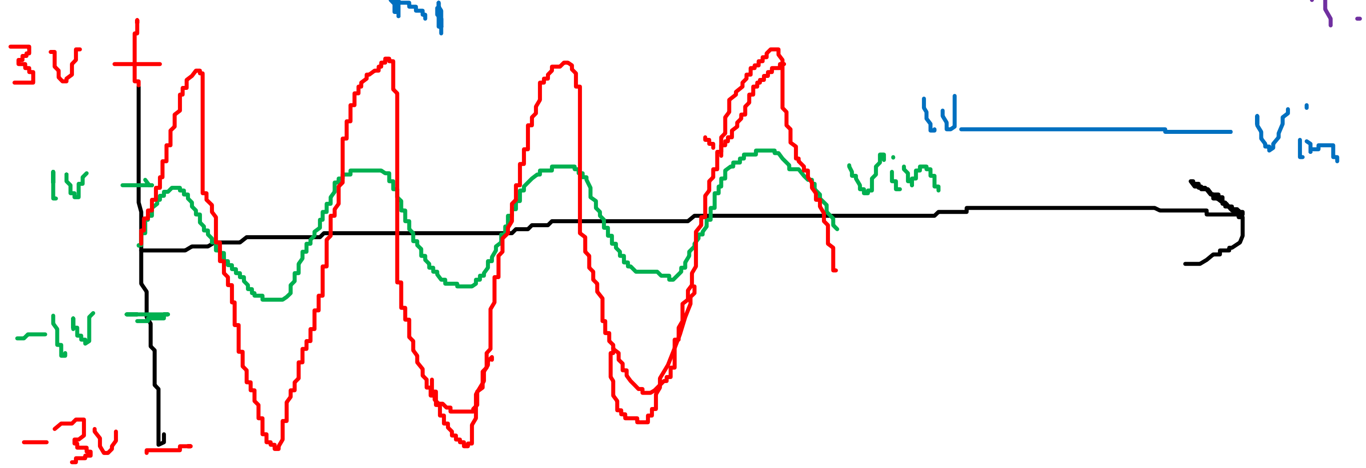


→ feed back connecting V_{out} to V^-

i.e. we can design the gain of the amplifier by choosing R_f and R_1 (in kΩ range). The gain is always positive, with magnitude greater than 1. i.e. for gain of 3, choose R_f, = 10 kΩ, R_1 = 5 kΩ



$$\text{Gain} = 1 + \frac{R_f}{R_1} = 1 + 2 = 3.$$



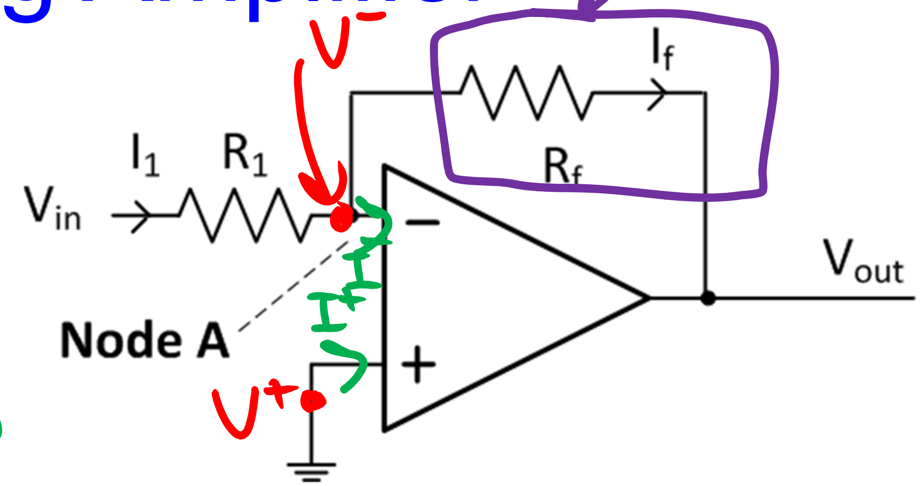
Inverting Amplifier

Op-amp rules:

* $I^+ = I^- = 0$
* $V^- = V^+$

V^+ is connected to ground, and we can say:

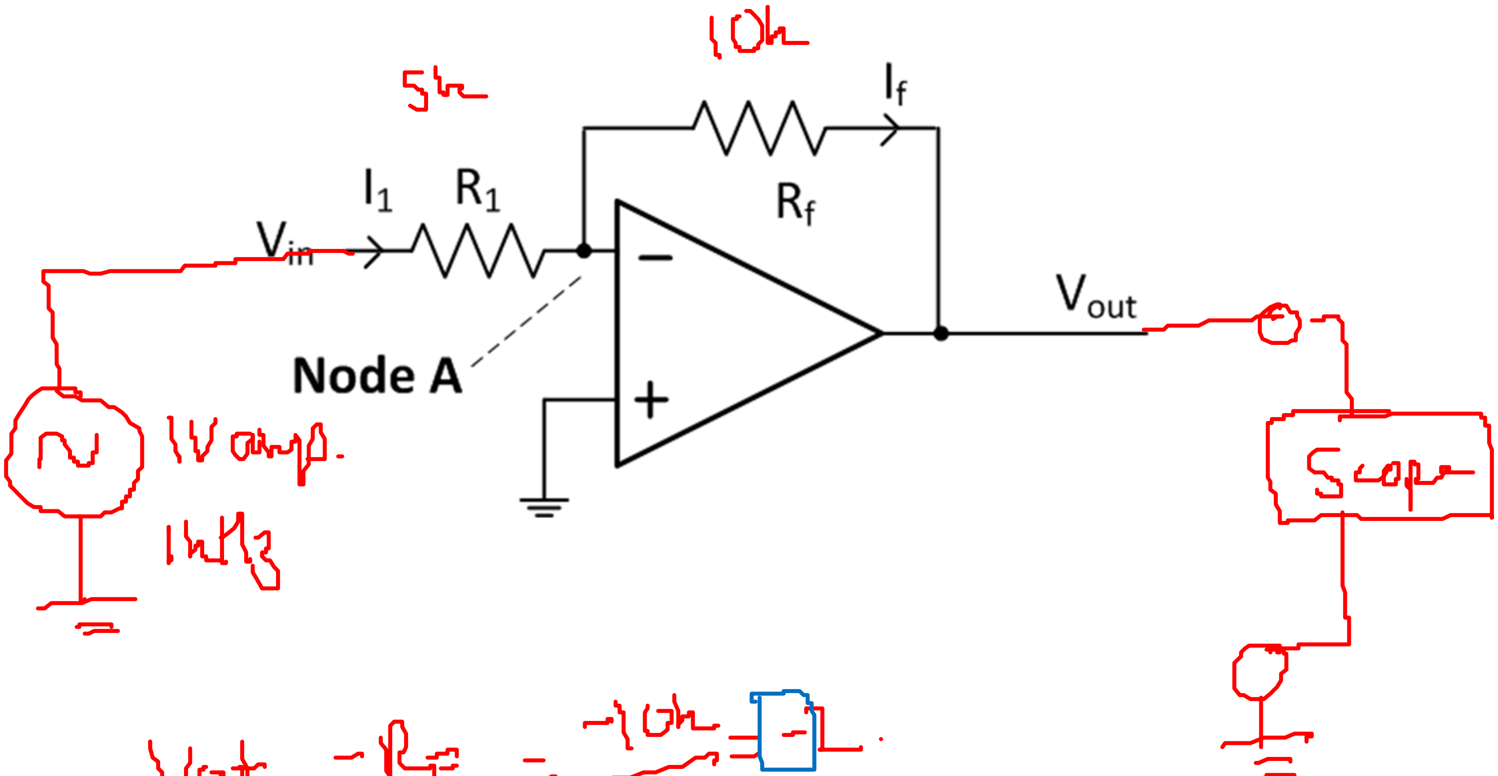
* $V^+ = V^- = 0V$.



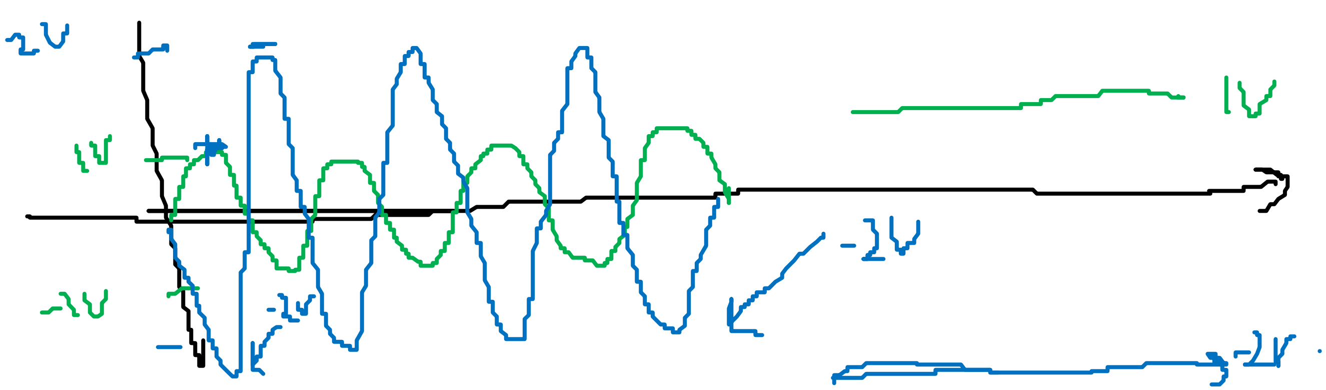
We can apply nodal analysis at A. With $I^- = 0$:

* $\frac{V_{in} - 0}{R_1} = \frac{0 - V_{out}}{R_f}$ $\Rightarrow$ Thus: $\frac{V_{out}}{V_{in}} = -\frac{R_f}{R_1}$

i.e. We can design the gain of the amplifier by choosing R_f and R_1. However, in this circuit, the gain is always negative, with magnitude that can be both greater or less than 1



$$\frac{V_{out}}{V_{in}} = -\frac{R_f}{R_1} = \frac{-10k}{5k} = \boxed{-2}$$



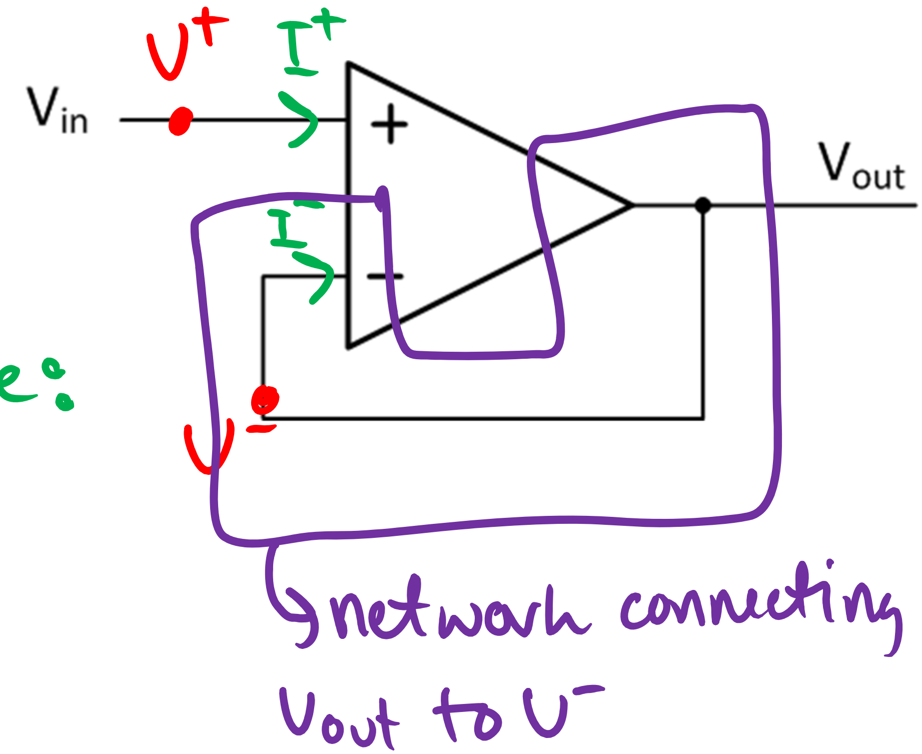
Unity Gain Buffer

Op-amp rules:

* $I^+ = I^- = 0$
* $V^- = V^+$

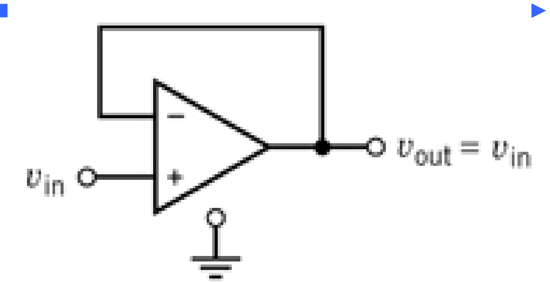
And, $V_{out} = V^-$, we have:

$$V_{out} = V_{in} \Rightarrow \frac{V_{out}}{V_{in}} = 1$$

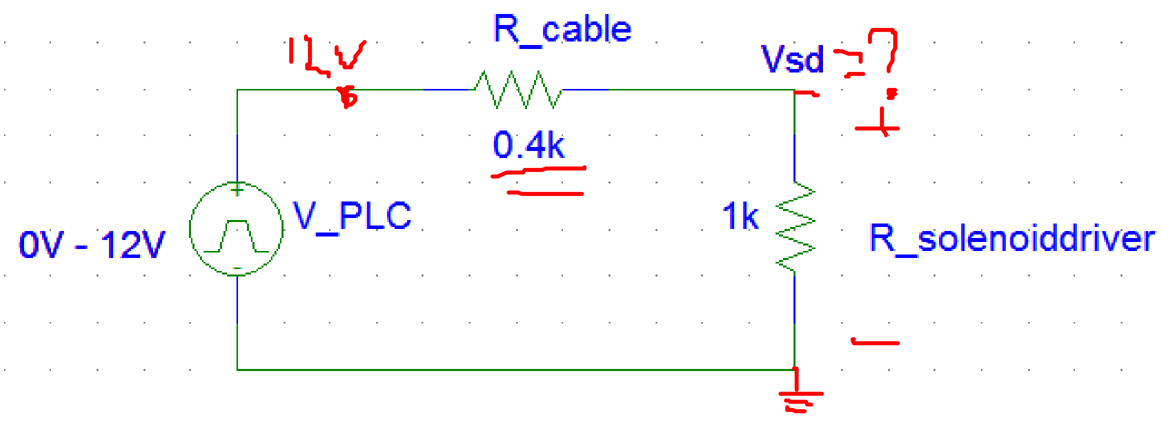


- So, if all it does is make the output equal the input, what is the Application??
- *Because it has infinite input impedance and zero output impedance, it is Used to provide **current gain**. i.e. for low-power sensors, to this ensures output current is provided by the amplifier, not the sensor*
- Prevents "loading" effects

What is this circuit for?

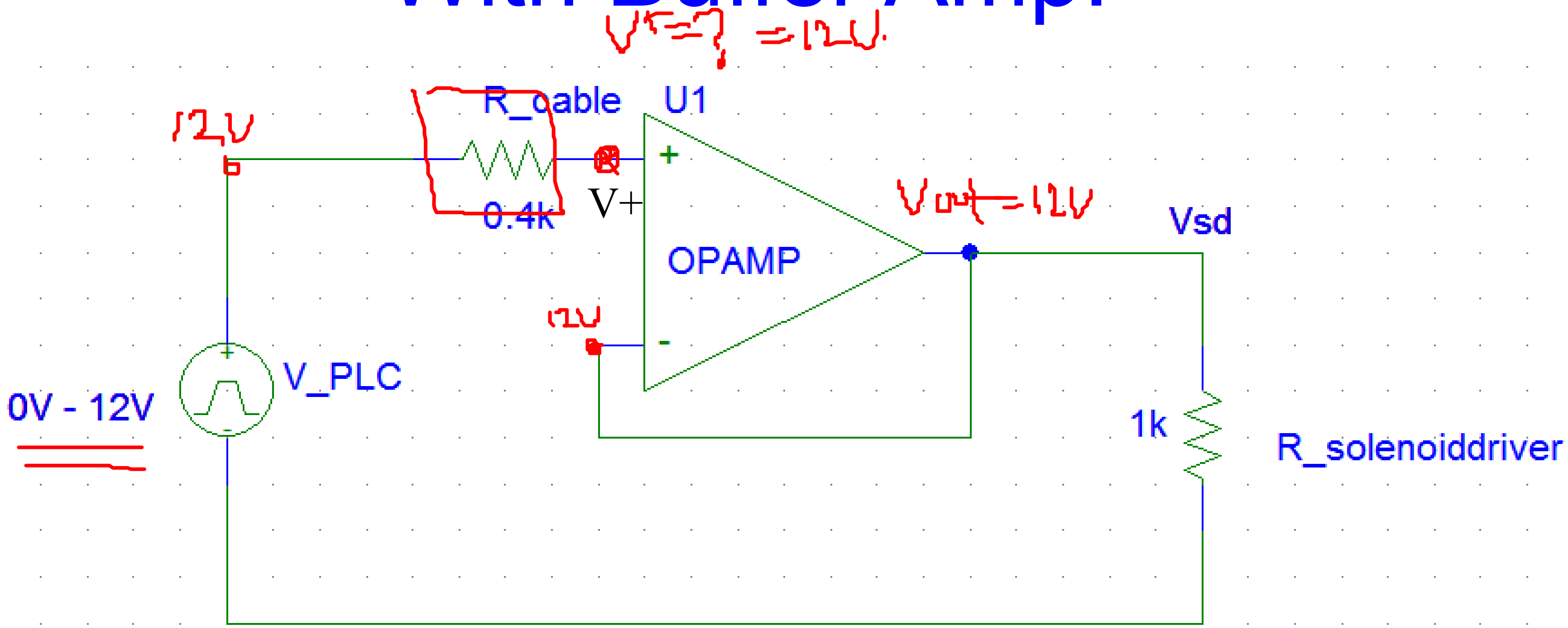


- Prevents **“Loading”** effects in your circuit
- Suppose you have a control system in a manufacturing system, where you are required to control fluid through a pressured pipe to a reaction chamber:
  - To do this, you have a PLC (programmable logic computer), which **provides a digital signal (0-12V)** to a solenoid driver which drives a solenoid valve.
  - The solenoid driver has an input resistance of 1k ohm **(i.e. appears like a 1k Resistor**), and requires **at least 9V** to switch on.
  - However, the factory is a big place, and we have 800m of cable between our central control system, and the solenoid driver. This cable has which has a resistance of 0.4kOhm



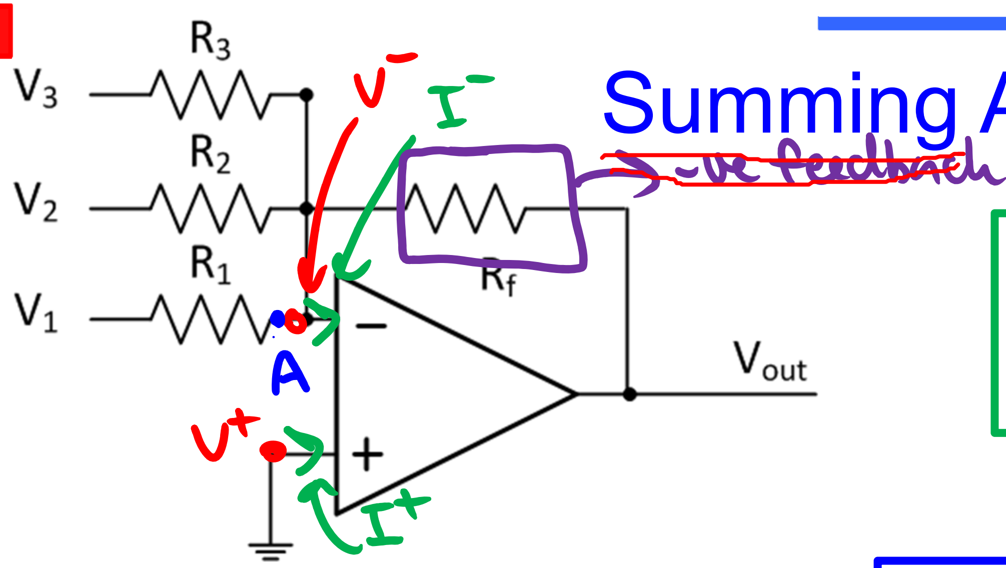
- When V_{plc}=12V:
- $V_{sd} = 12\left(\frac{1k}{1k+0.4k}\right) = 8.57V$
- **Thus, V_{sd}=8.57<9V and thus solenoid won’t switch on!!!**

With Buffer Amp:



- Since input impedance of op-amp is infinite, I^{+}=0A, and **V^{+}=12V** (since there is no current, there no voltage drop across R_cable).
- Using Ideal op-amp rules, **V^{+}=12V** and thus **V^{-} = 12V**; and **V_{out} = 12V**
- Our voltage is now sufficient to switch on the solenoid driver.

Summing Amplifier



This is a generalisation of inverting amplifier with multiple inputs, each with its own resistor

So, inputs are summed and inverted. This can be extended to as few, or as many inputs as is required for the application.

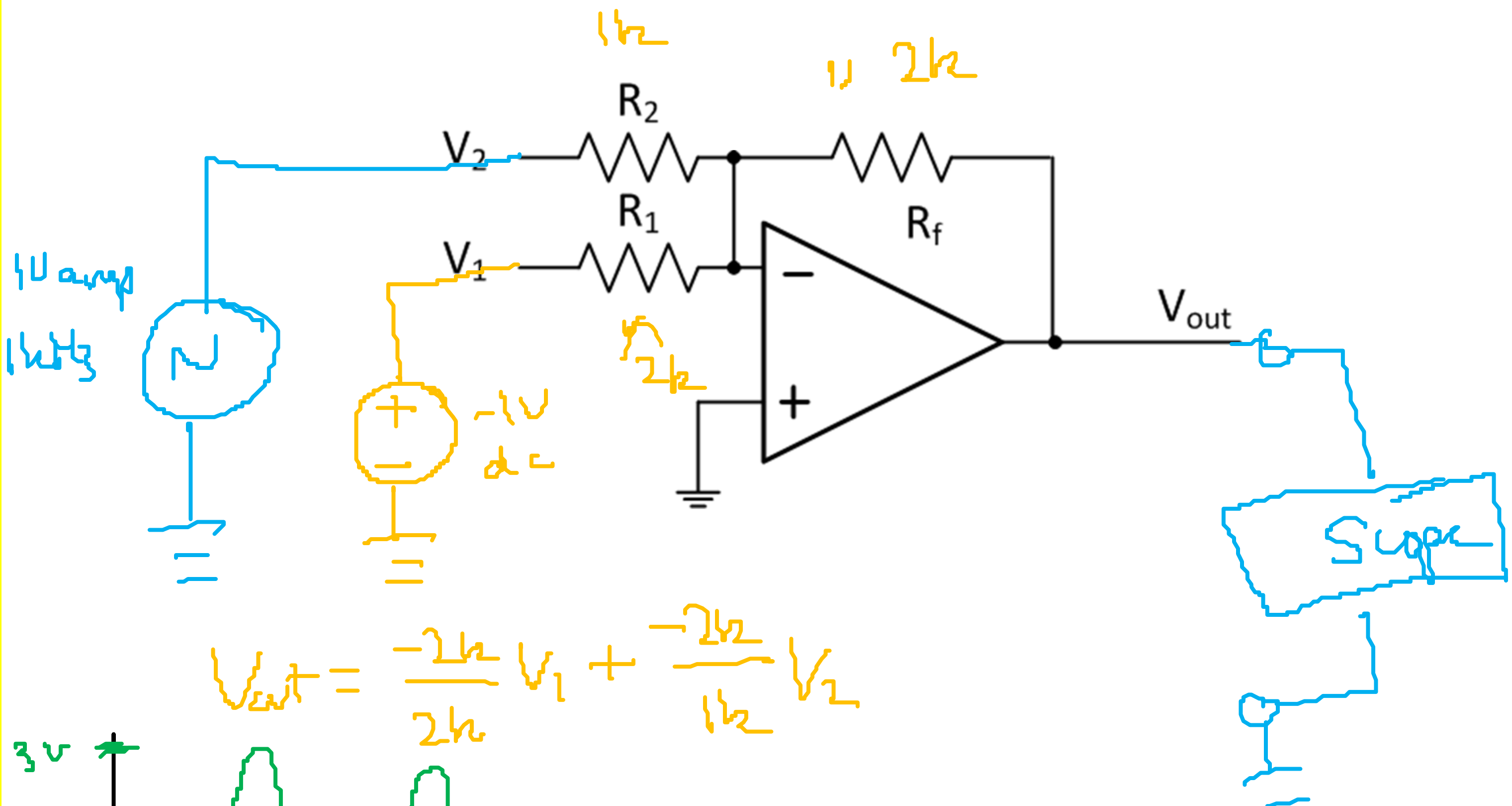
Op-amp rules:

* $I^+ = I^- = 0$
* $V^- = V^+ \Rightarrow V^- = V^+ = 0V$.
  ("virtual earth")

Applying KCL at node A:

$$\frac{V_3 - 0}{R_3} + \frac{V_2 - 0}{R_2} + \frac{V_1 - 0}{R_1} = \frac{0 - V_{out}}{R_f}$$

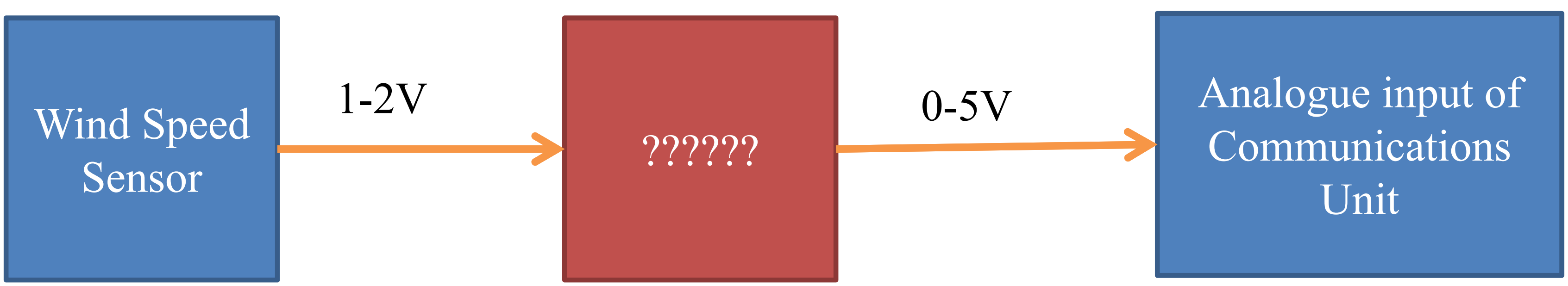
Thus: $V_{out} = -\frac{R_f}{R_1} V_1 + -\frac{R_f}{R_2} V_2 + -\frac{R_f}{R_3} V_3$

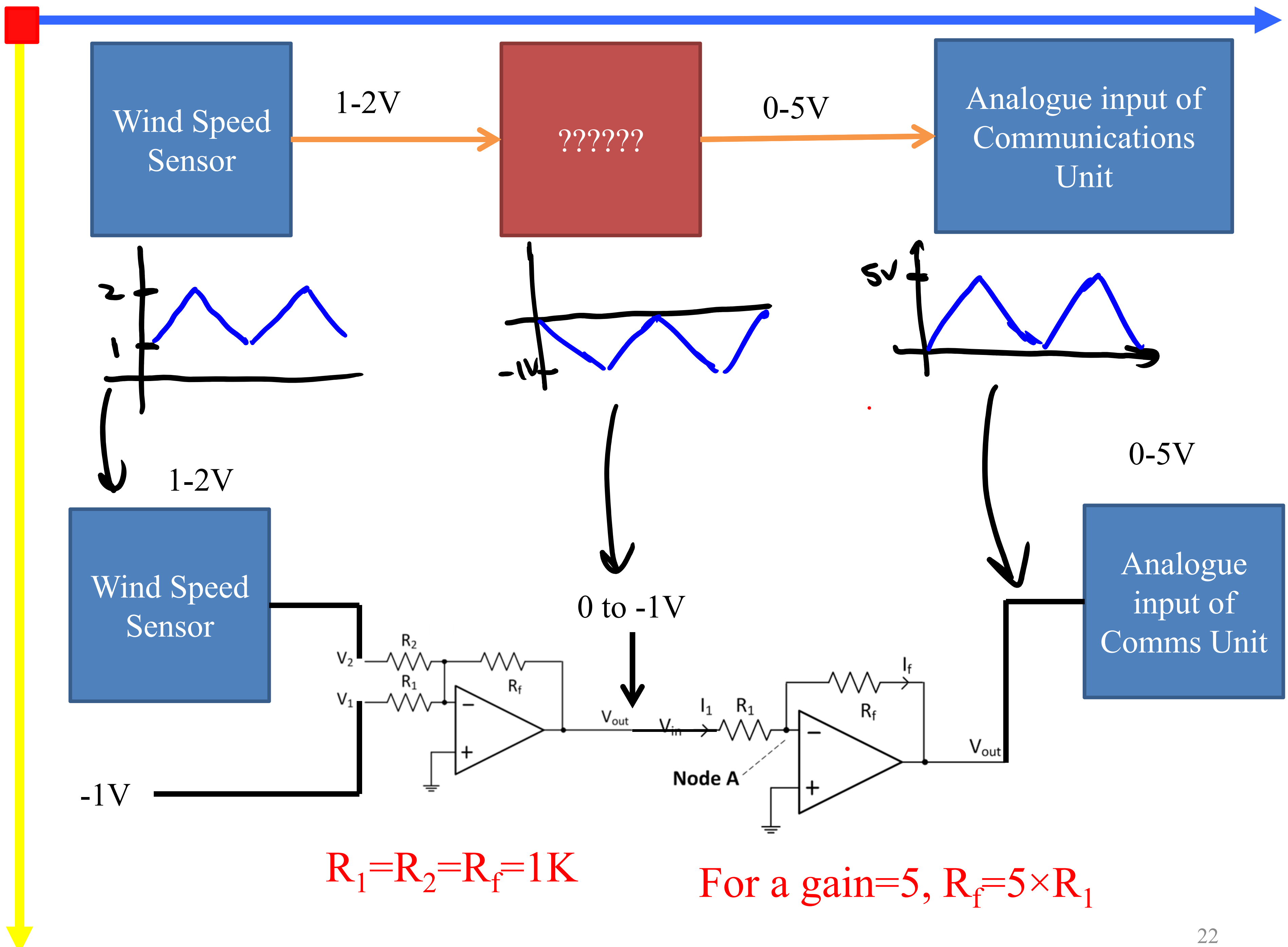


$$V_{out} = \frac{-2k}{2k} V_1 + \frac{-2k}{1k} V_2$$

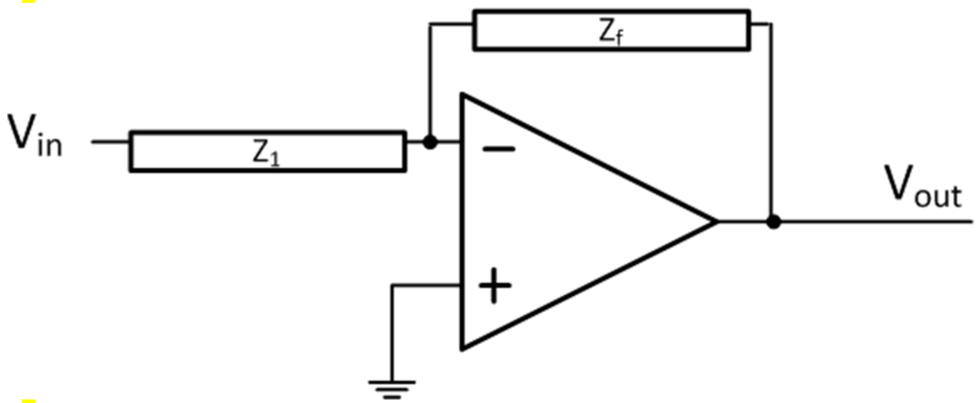
Application of Summing Amp:

- You are a graduate engineer at Powerlink. As part of their monitoring systems, they would like to be able to track the wind speed across the transmission network.
- To do this, you plan to install wind speed measurement devices on a 275kV power line poles, and need to input the measurement to a communications unit with an analogue input.
- The wind speed sensor provides an analogue voltage output between 1V (indicating 0knots of wind) and 2V (indicating 45knots of wind).
- The analogue input of the communications unit has a voltage input range of 0-5V.
- You need to convert the 1-2V dynamic range to be a 0-5V dynamic range [0V=0 Knots; 5V=45 Knots]




Wind Speed Sensor
1-2V
??????
0-5V
Analogue input of Communications Unit
2
1
-1V
5V
1-2V
Wind Speed Sensor
0 to -1V
0-5V
Analogue input of Comms Unit
R2
R1
V2
V1
Rf
Vout
Vin
I1
R1
If
Rf
Node A
Vout
-1V
R1=R2=Rf=1K
For a gain=5, Rf=5×R1

Active Filter



Generalisation of the inverting amplifier with the resistors replaced by frequency dependent impedances (inductors, capacitors)

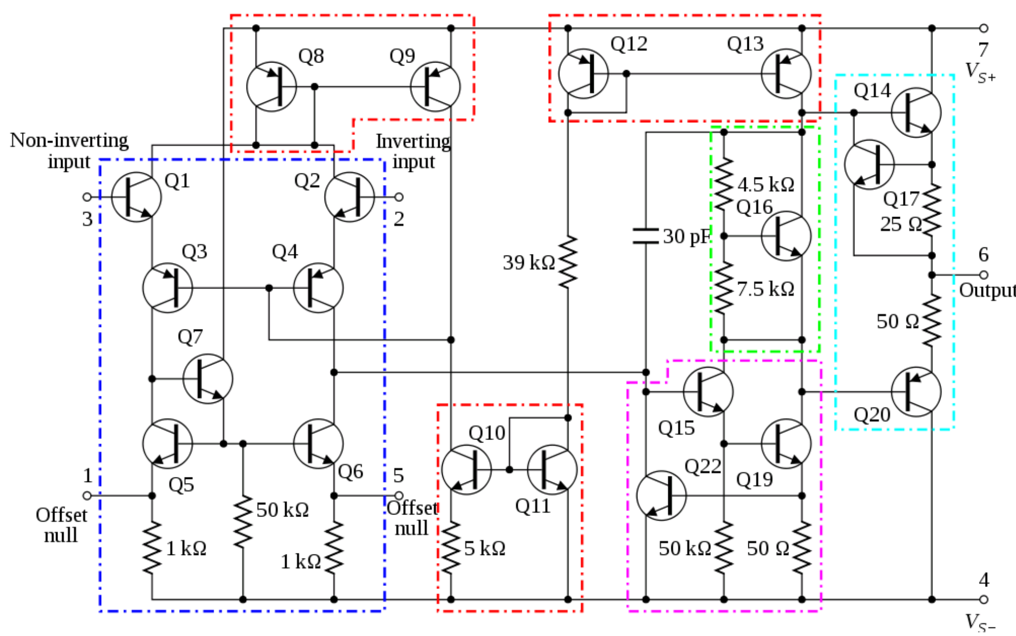
The analysis is exactly the same as for inverting amplifier, except using phasor voltages and current and complex impedances:

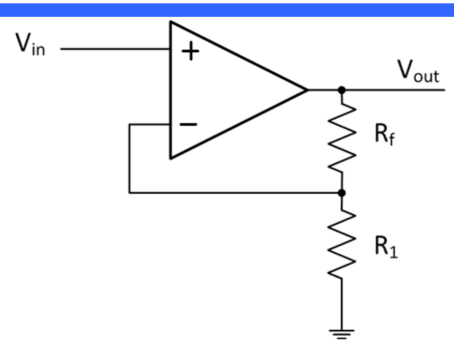
- $\underline{V}_{out} = -\underline{V}_{in} \times \left(\frac{Z_f}{Z_1}\right)$
- Or: $G(\omega) = -\left(\frac{Z_f}{Z_1}\right)$

- *We can plot frequency response as Bode plot, and build low pass, high pass filters, etc. – see lab 12B*

Why Op-amps instead of "discrete" amplifiers?

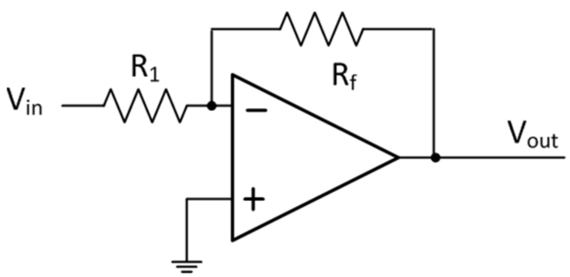
- We can also build amplifiers using "discrete" components – i.e. transistors, resistors, capacitors.
- So why use an op-amp?
  - Op-amps have extremely complex internal engineering to make their application less complex!
  - Complex internal circuit designs to provide a circuit element which is predictable, stable, amplifies linearly to allow "black box" style circuit construction





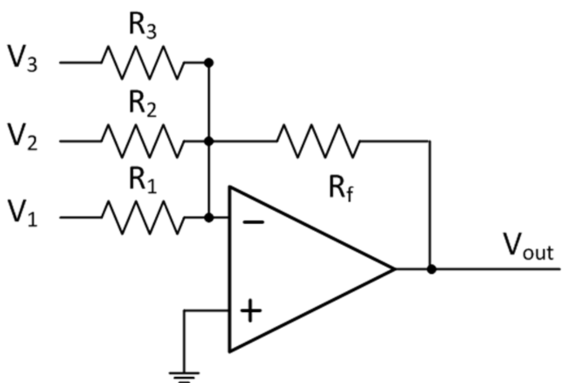
Non-inverting Amplifier:

$$V_{out} = V_{in} \times \left(1 + \frac{R_f}{R_1}\right)$$



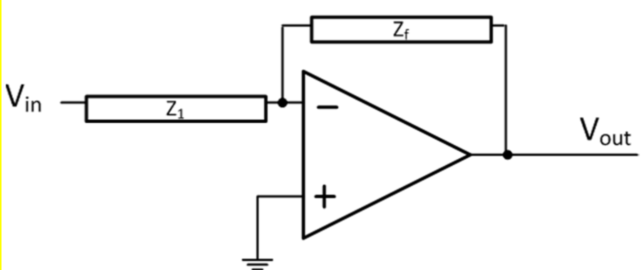
Inverting Amplifier:

$$V_{out} = -V_{in} \times \left(\frac{R_f}{R_1}\right)$$



Summing Amplifier:

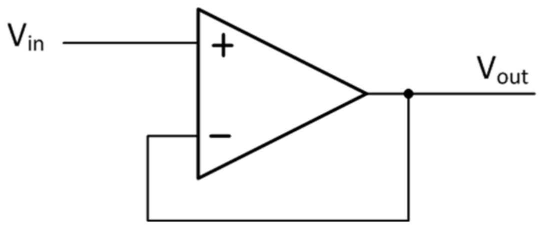
$$V_{out} = -\left[V_1 \times \left(\frac{R_f}{R_1}\right) + V_2 \times \left(\frac{R_f}{R_2}\right) + V_3 \times \left(\frac{R_f}{R_3}\right) + \cdots\right]$$



Active Filter:

$$V_{out} = -V_{in} \times \left(\frac{Z_f}{Z_1}\right)$$

$$G(\omega) = -\left(\frac{Z_f}{Z_1}\right)$$



Buffer:

$\underline{V}_{out} = \underline{V}_{in}$