University of Nottingham

Electromechanical devices MM2EMD

Lecture 5 – Using Operational Amplifiers (opamps) in the real world

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Summer 2015

@rcimackenzie

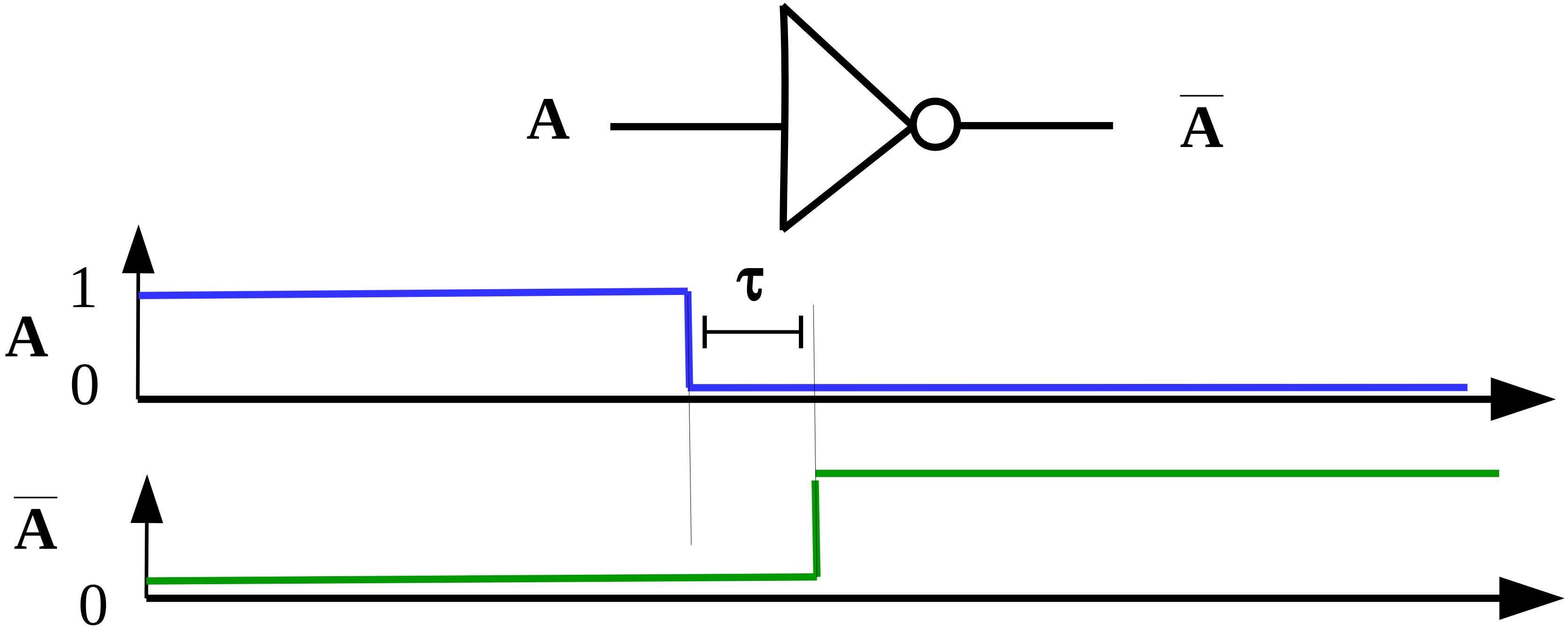
Outline of the lecture

- **Recap of last lecture**
- Mini Quiz
- Books and resources
- Op-amps used in the real world
    - Measuring acceleration
    - Measuring stress and strain.
- Summary

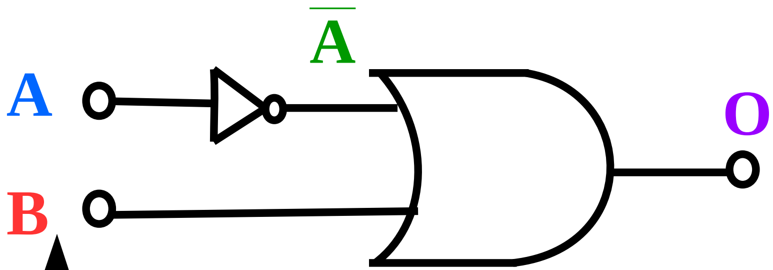
Recap: Race times

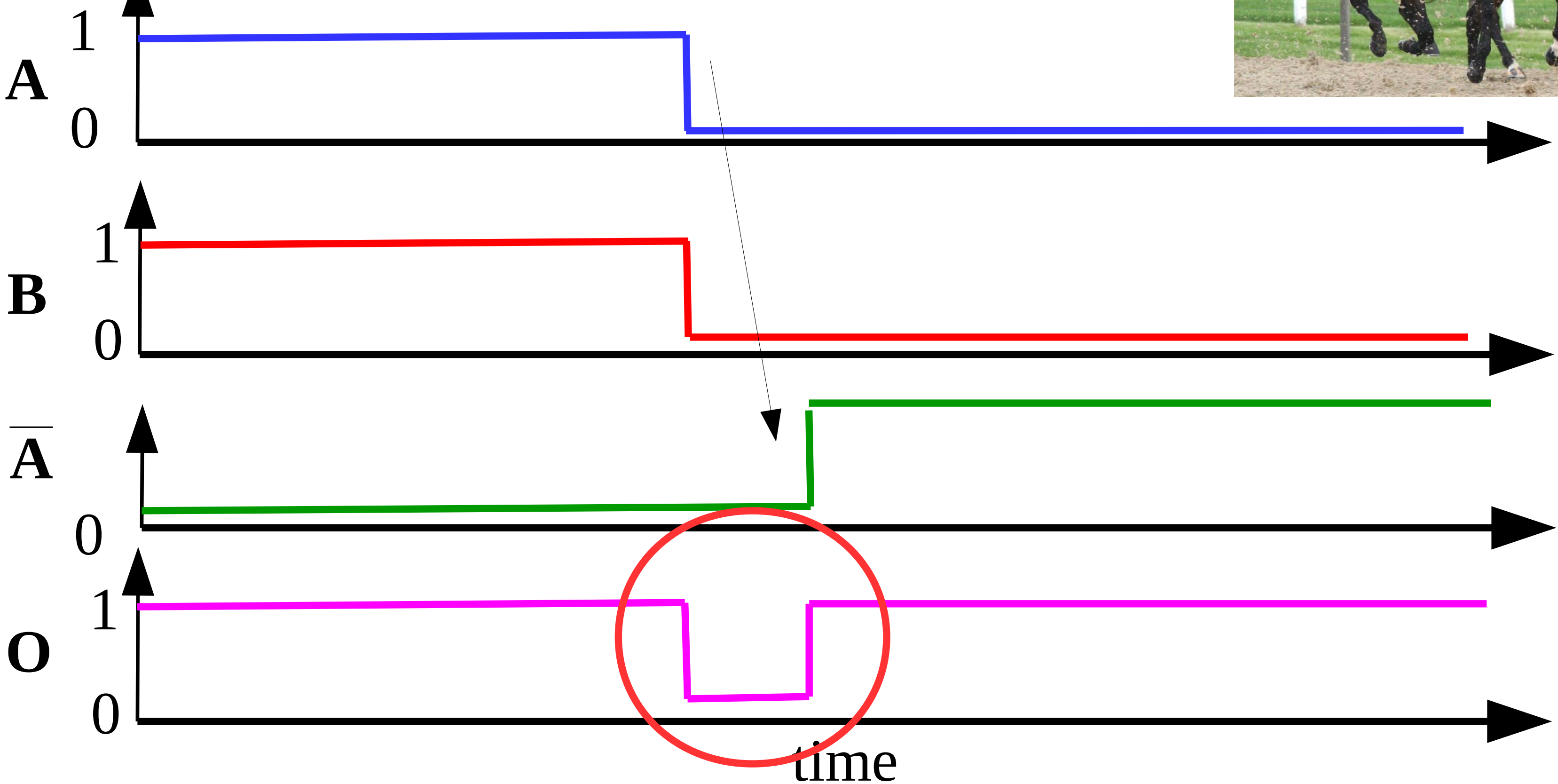
•All gates have a 'turn on' and 'turn off' time.

•This is in effect a time it takes the gate to react to an input - **τ**.



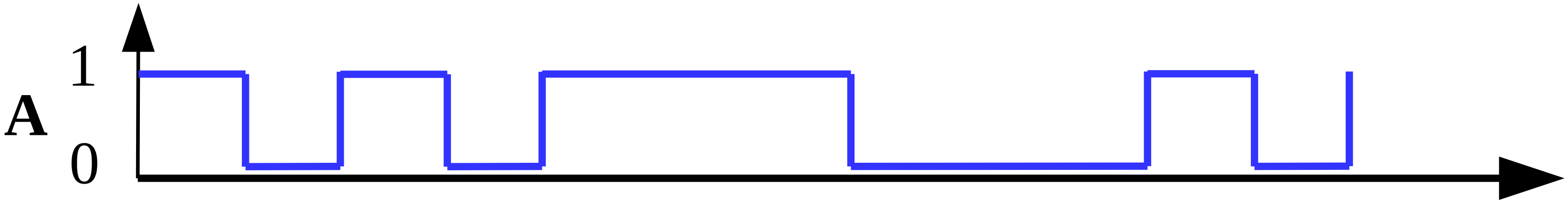
Recap: Race times





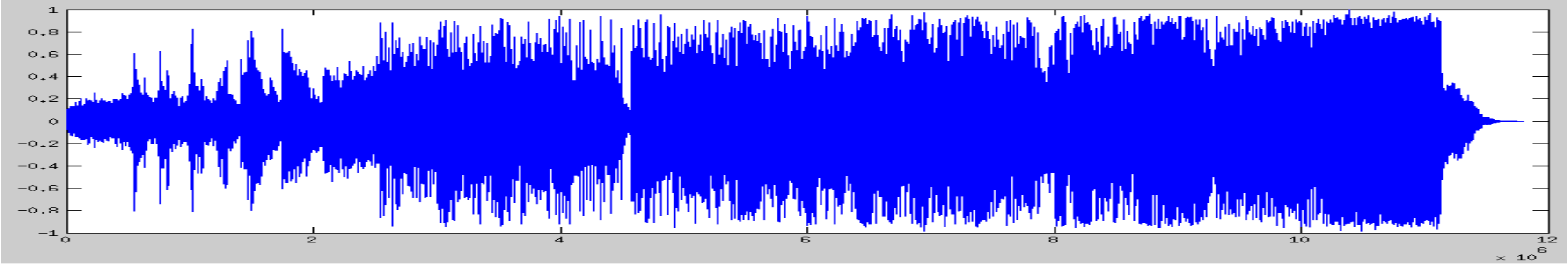
Recap: digital v.s. analog signals

•Digital signal can only have two values on and off.



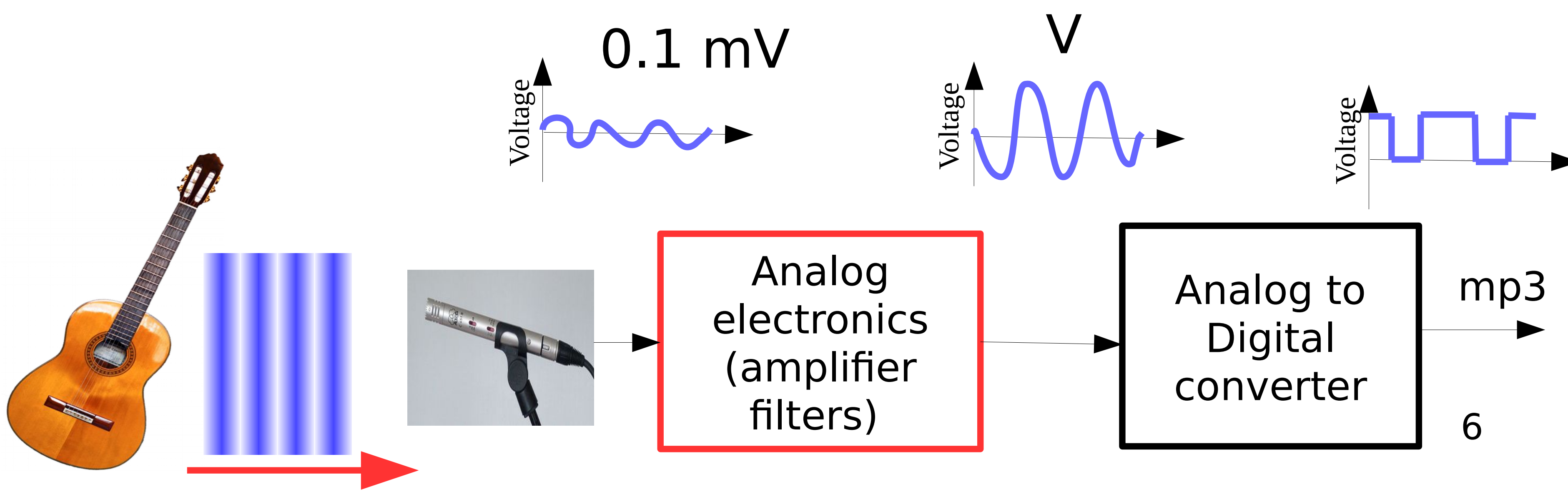
•Analog signals can take any value.

•You find analog signals in the real world, think of sound or vibration signals.

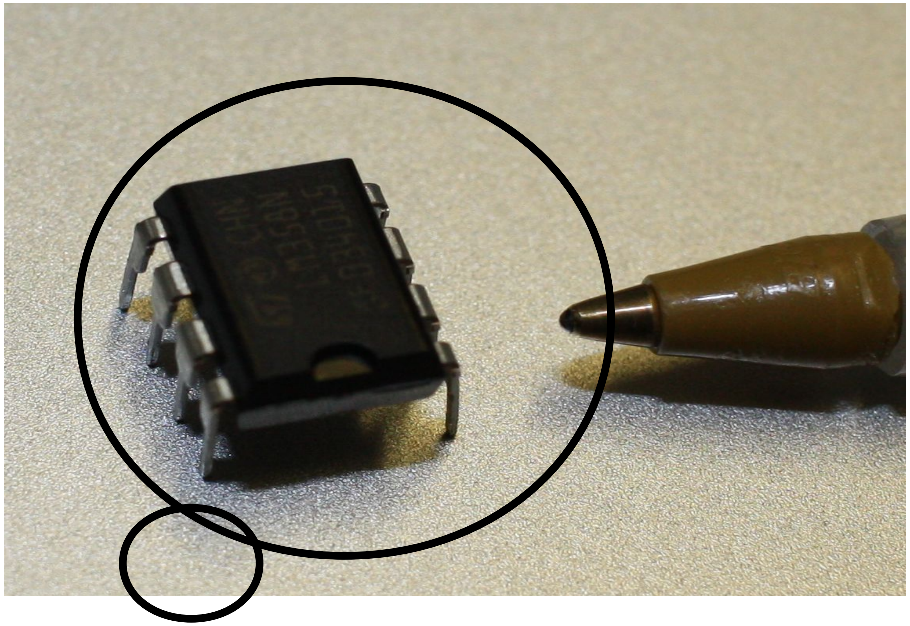


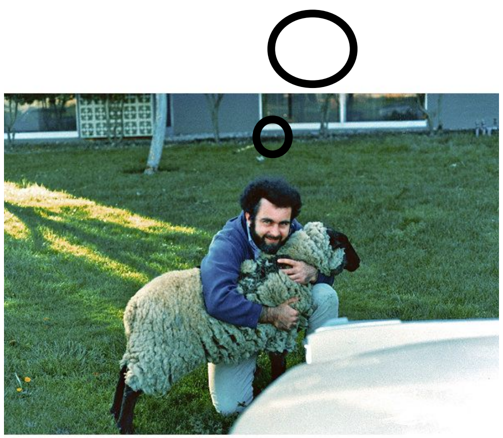
Recap: Modern analog systems an mp3 recorder.

•Many modern digital systems have analog electronic preprocessing of data.



Recap: The op-amp (Bob Widlar)



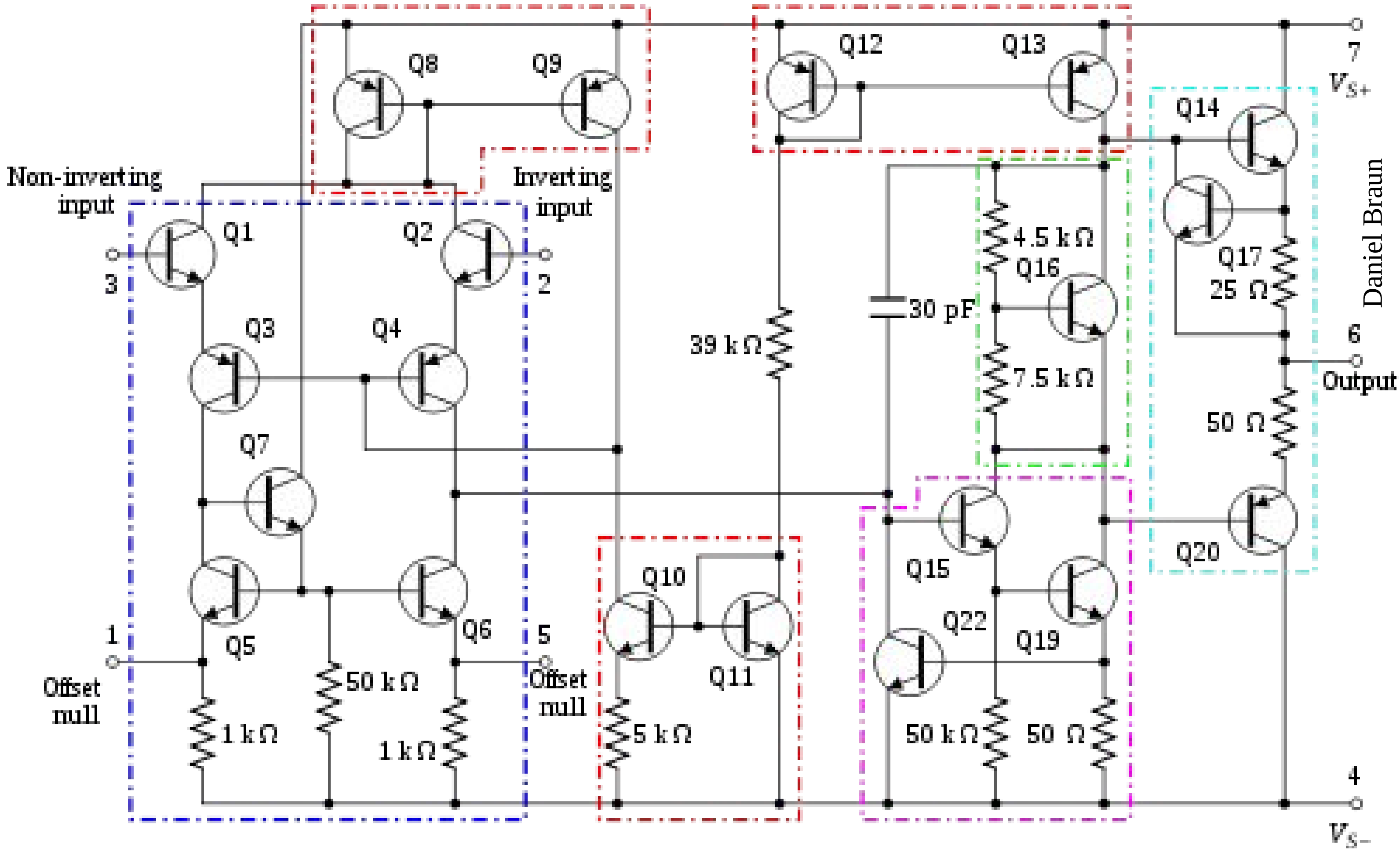


Operational amplifier

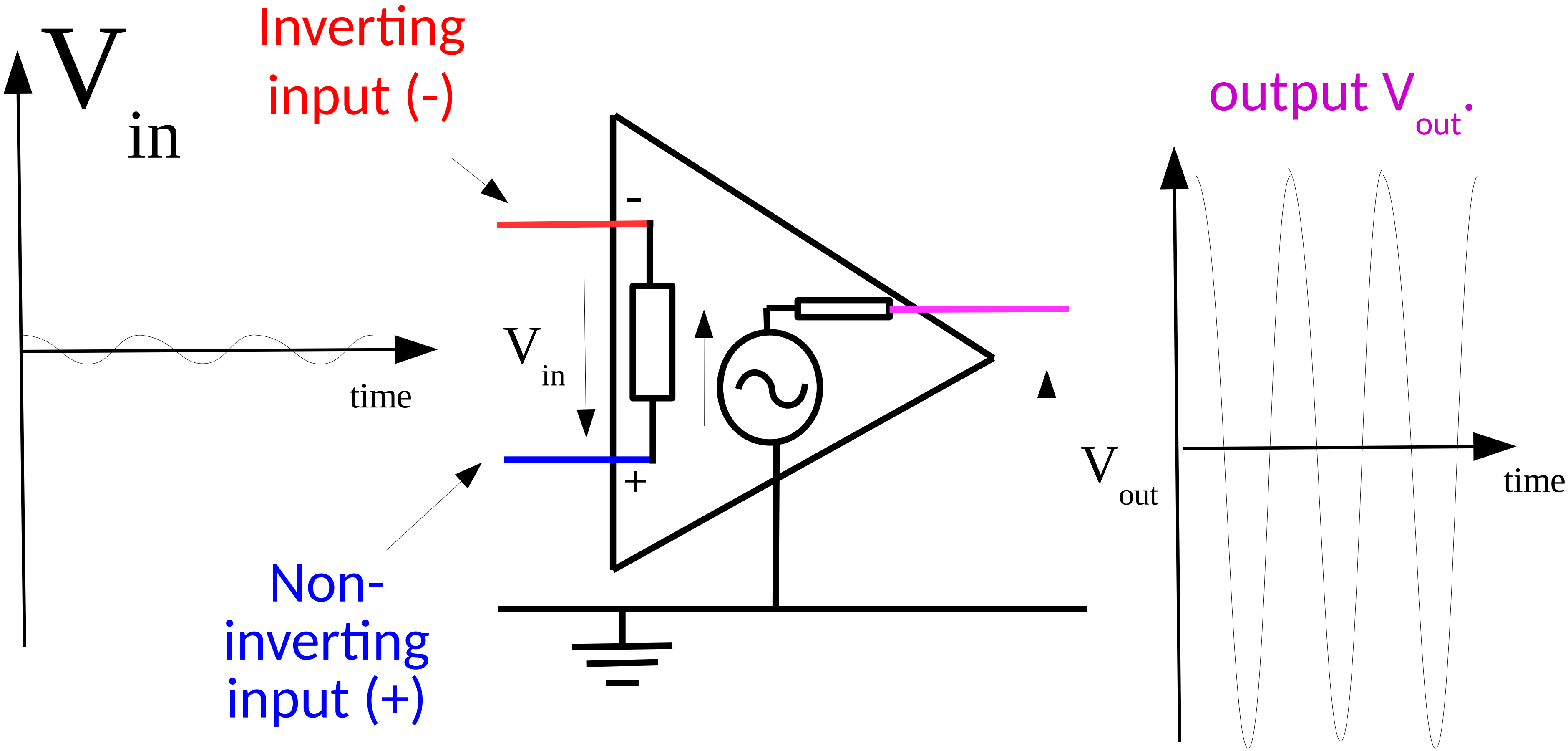
And 'operation', think of a mathematical operation.

An amplifier i.e. something that makes a signal bigger.

Recap: What's inside... ahhh..

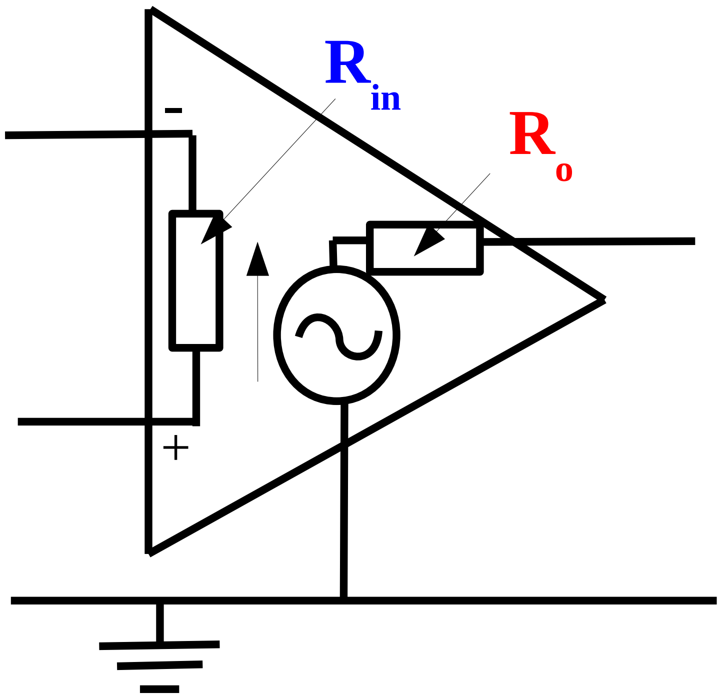


Recap: op-amp equivalent circuit



$$V_{in} A = V_{out}$$

Recap: It contains two resistors

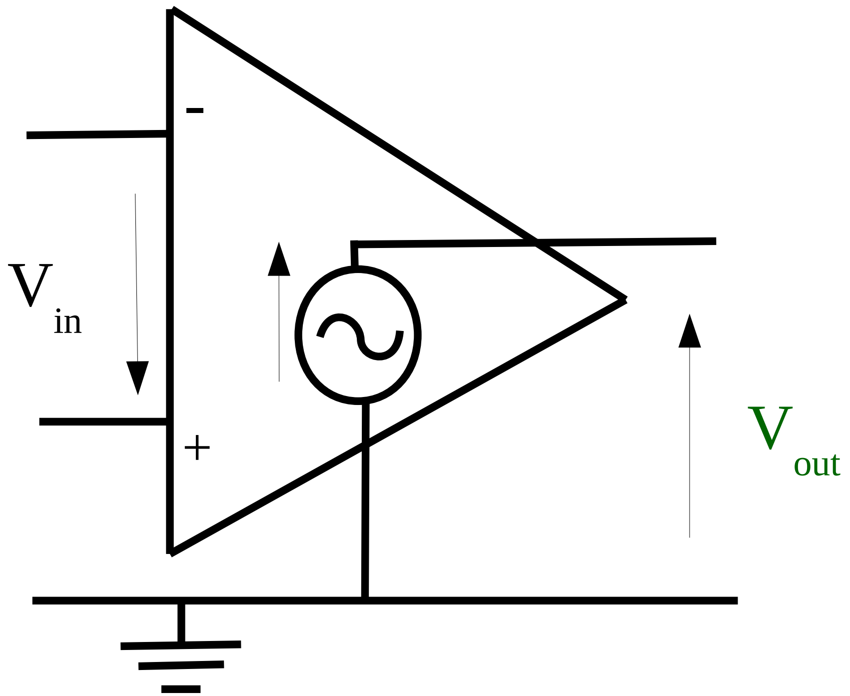


R_{in} = an input resistance – very high – we can assume this is infinite.

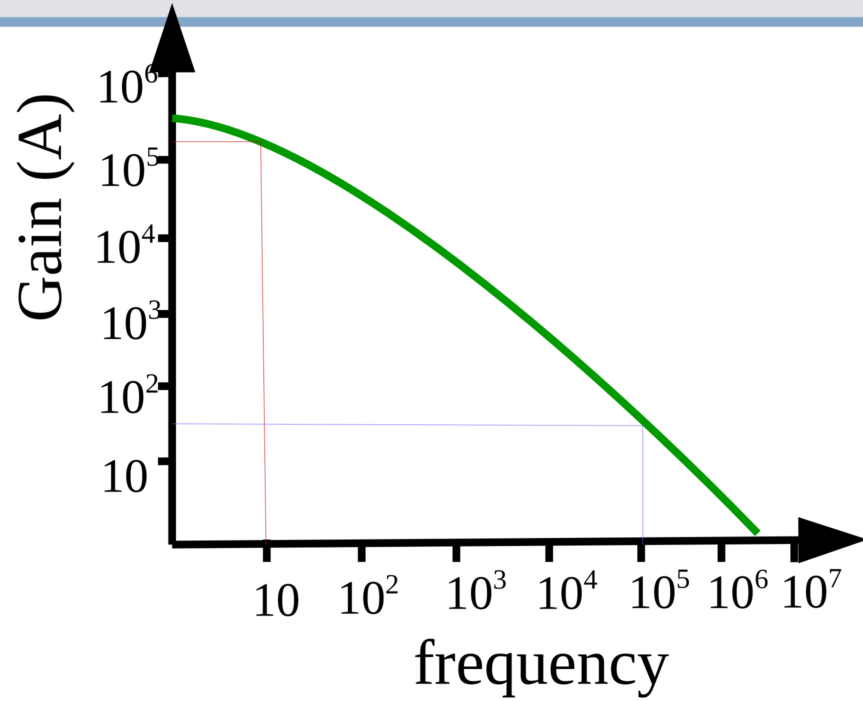
R_o = output resistance – very low – we can assume this is zero (i.e. a short circuit)

So let's further simplify our circuit taking into account the high R_{in} and the low R_o.

Recap: A simple op-amp circuit

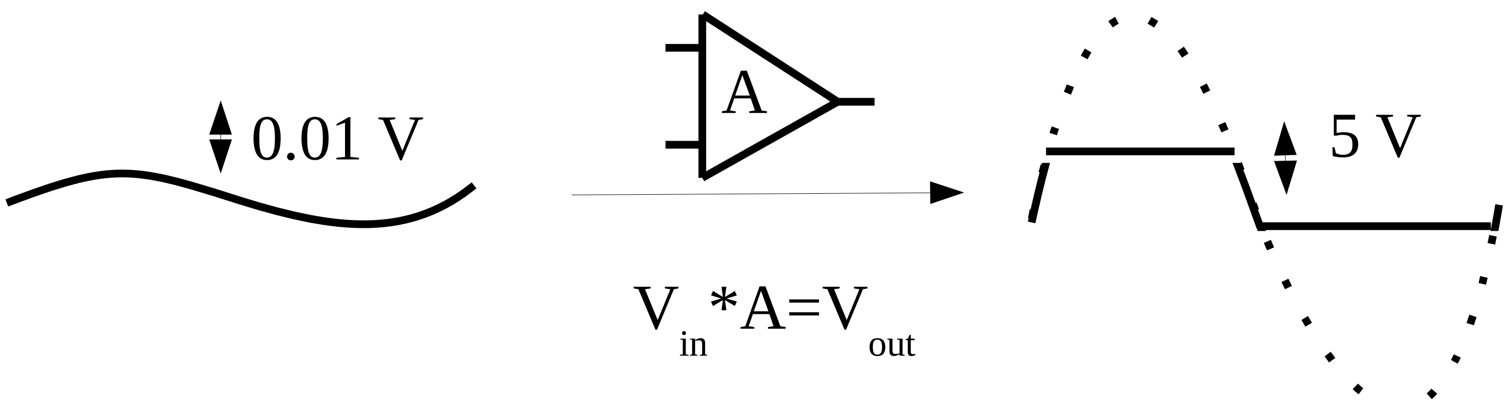


Recap: Problems with the op-amp..

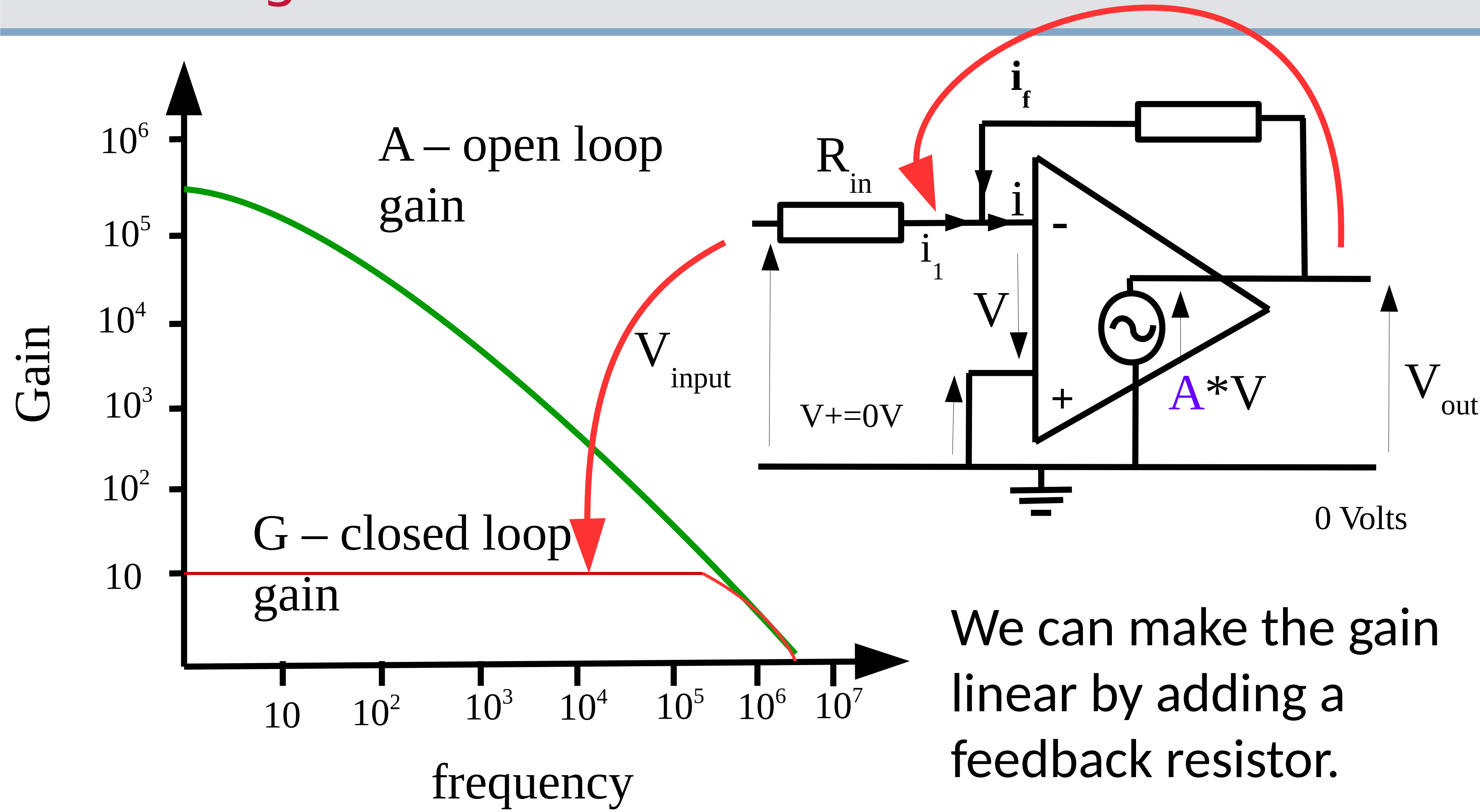


•Non linear gain

•Output clipping

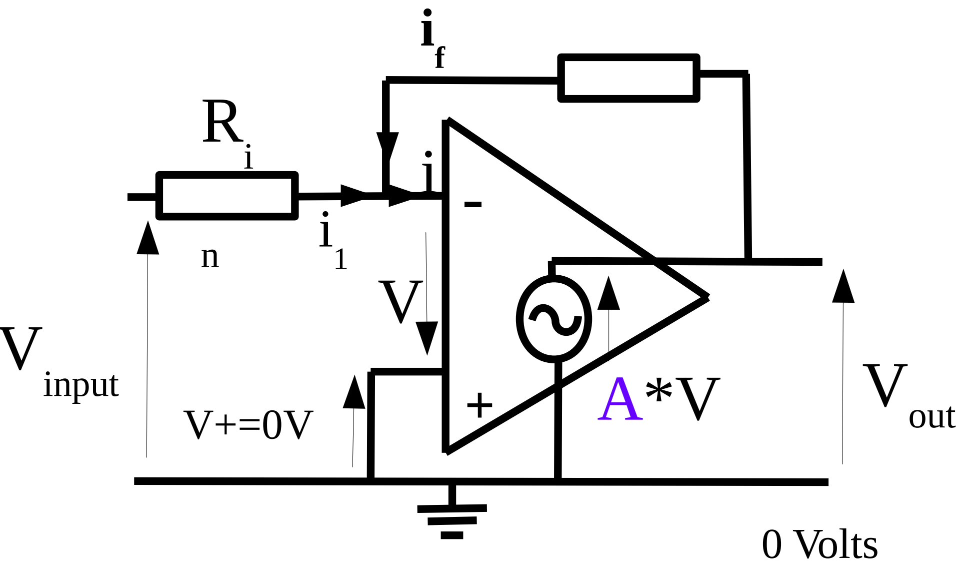


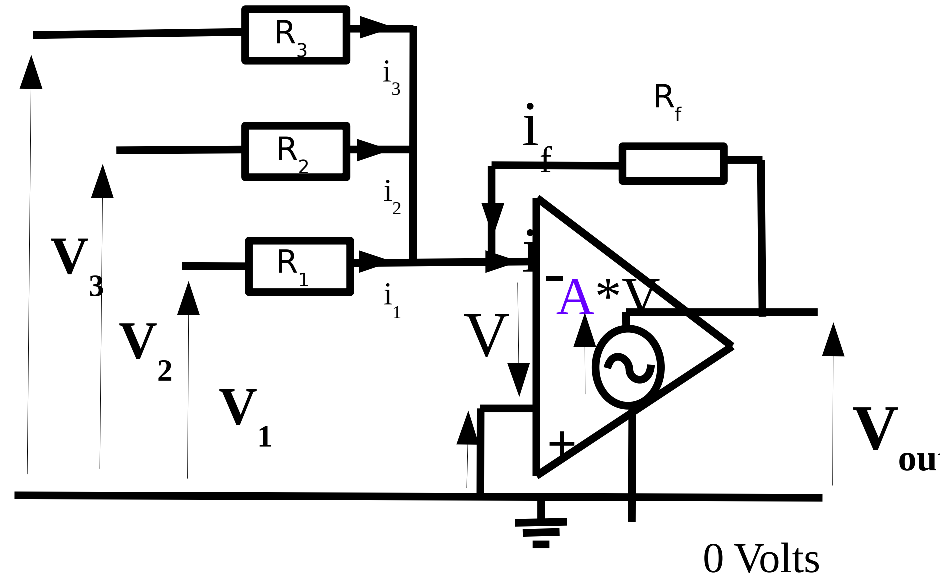
Recap: Op-amps give a lot of non-linear gain.



We can make the gain linear by adding a feedback resistor.

Recap: Inverting amplifier and adding amplifier





$$\frac{V_0}{V_i}=\frac{-R_f A}{[R_r(A+1)+R_f]}$$

$$G=\frac{V_0}{V_i}=-\frac{R_f}{R_1}$$

$$V_{out}=-[V_1+V_2+V_3]$$

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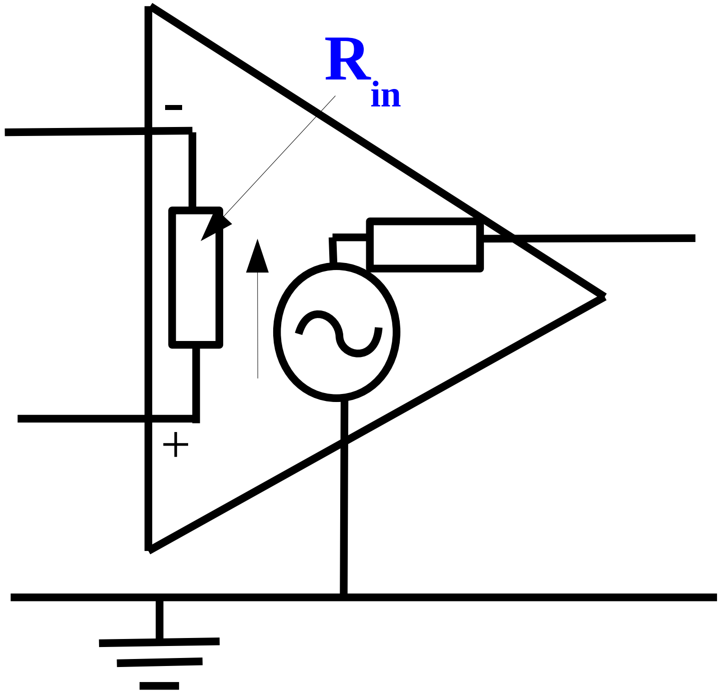
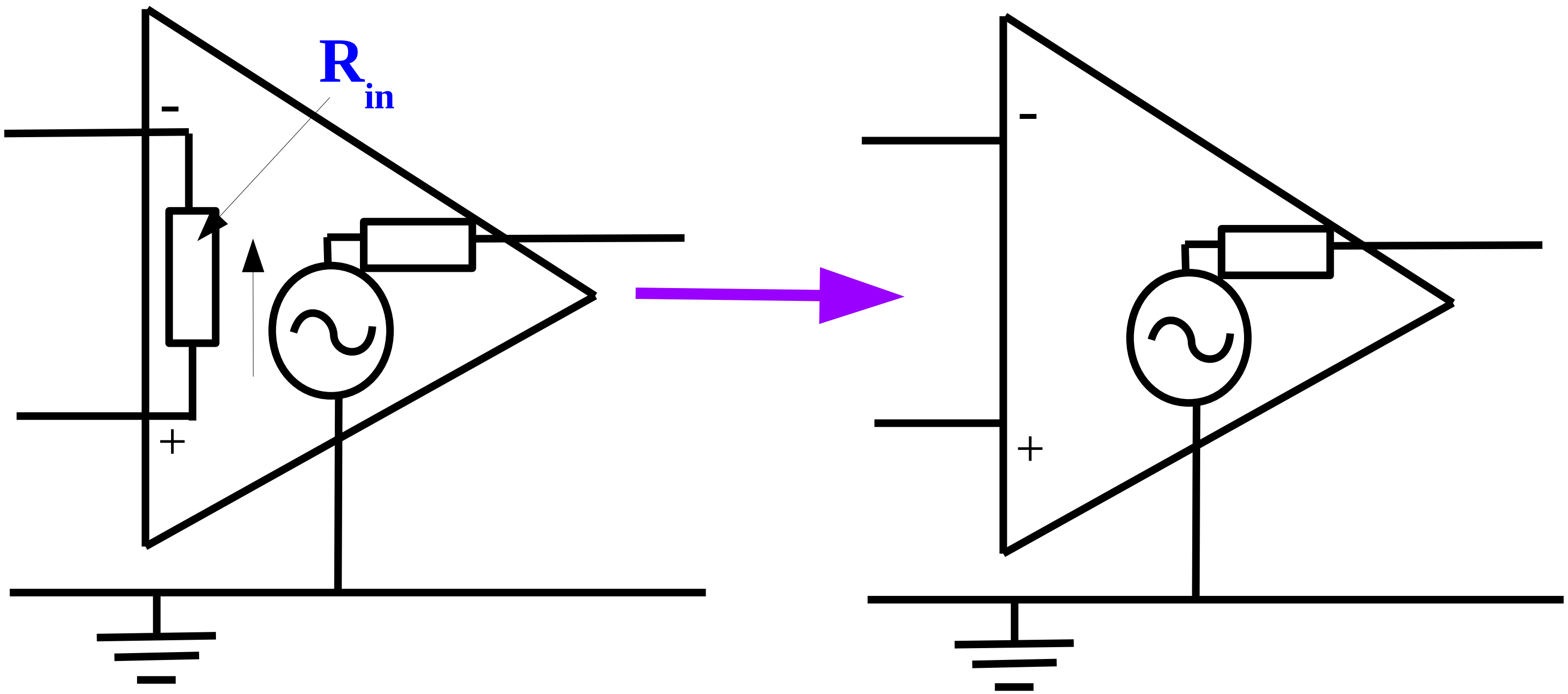
Quiz Q1:

Q: What can we assume the input resistance of an op-amp is?



Quiz A1:

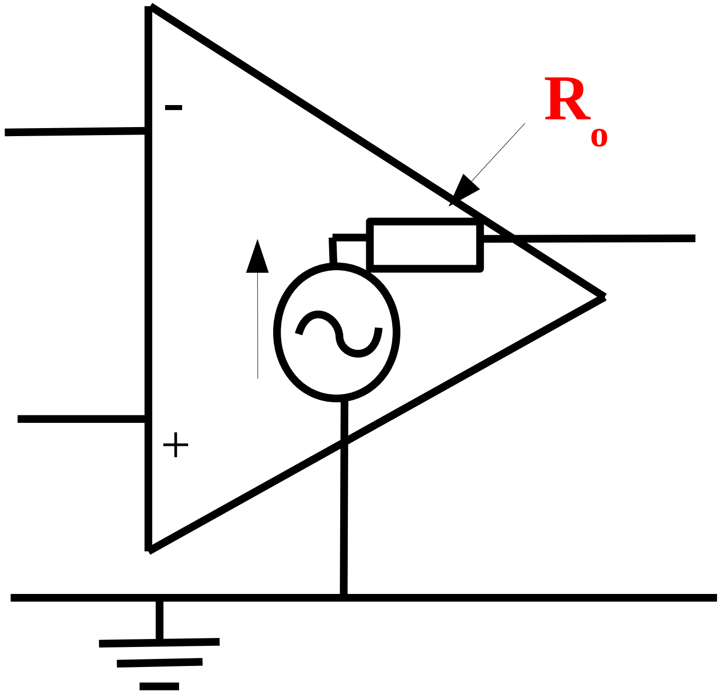
•Q: What can we assume the input resistance of an op-amp is? **Infinite**



In fact it's so big we can assume it's not there!

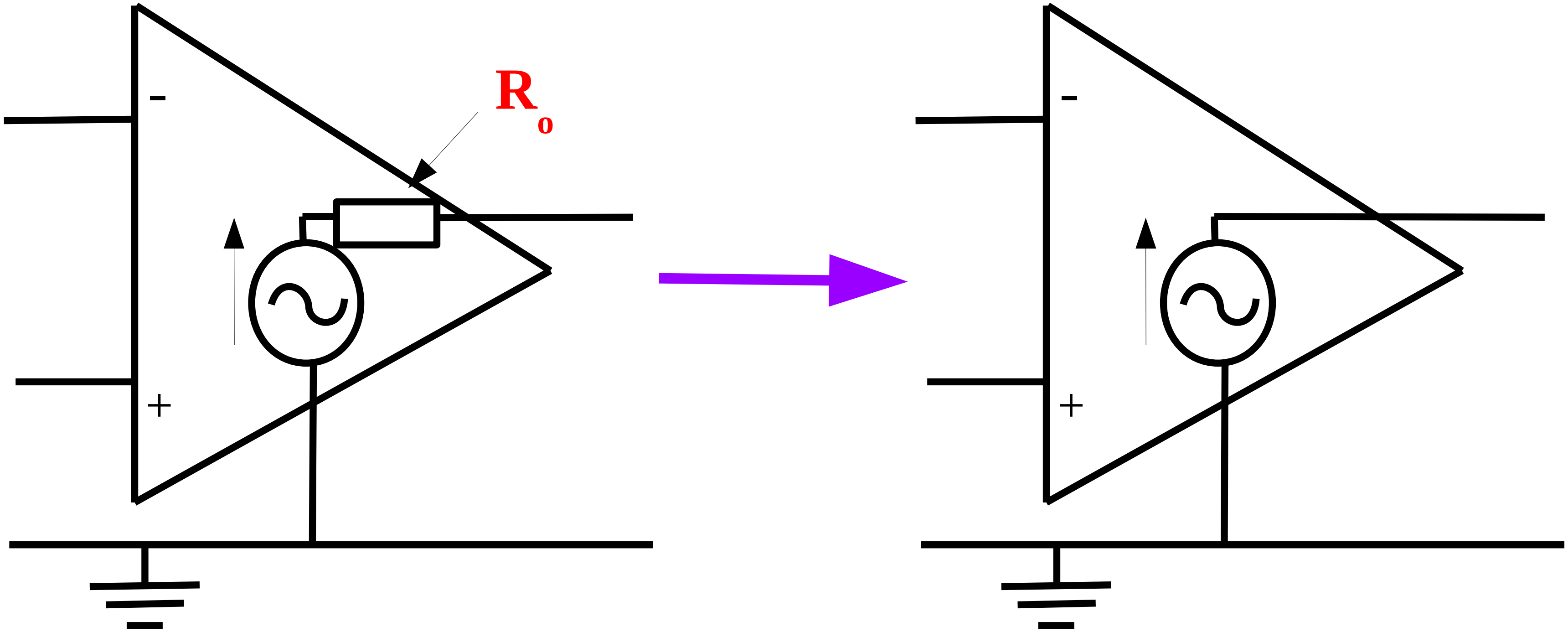
Quiz Q2:

Q: What can we assume the output resistance of an op-amp is?



Quiz A2:

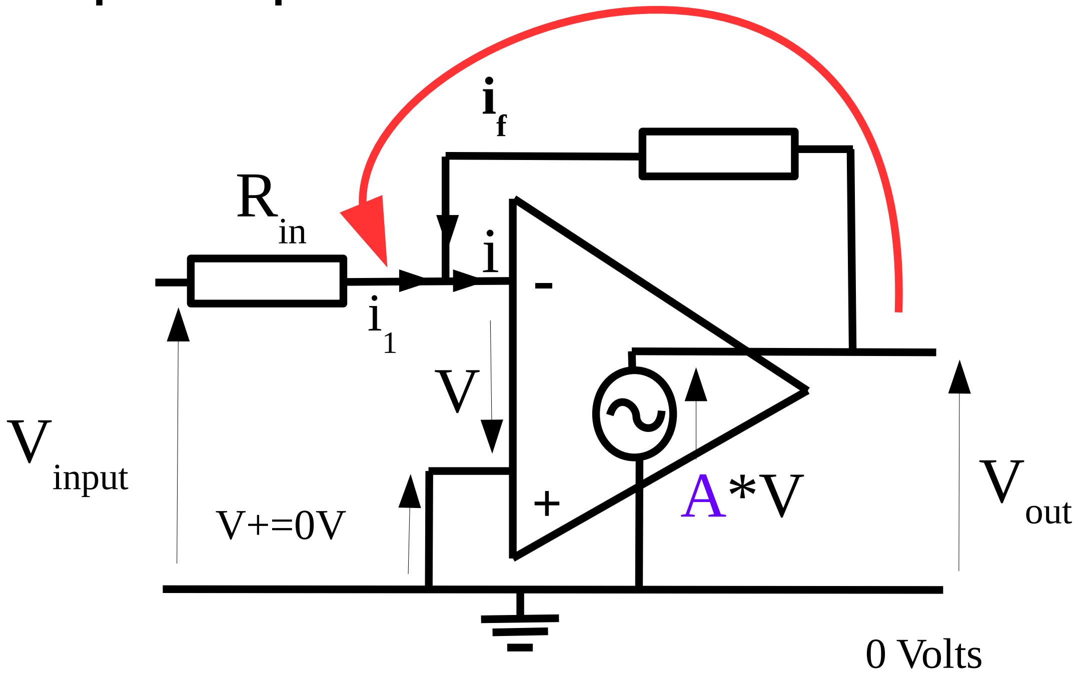
Q: What can we assume the output resistance of an op-amp is? zero



In fact it's so small we can assume it's not there!

Quiz Q3:

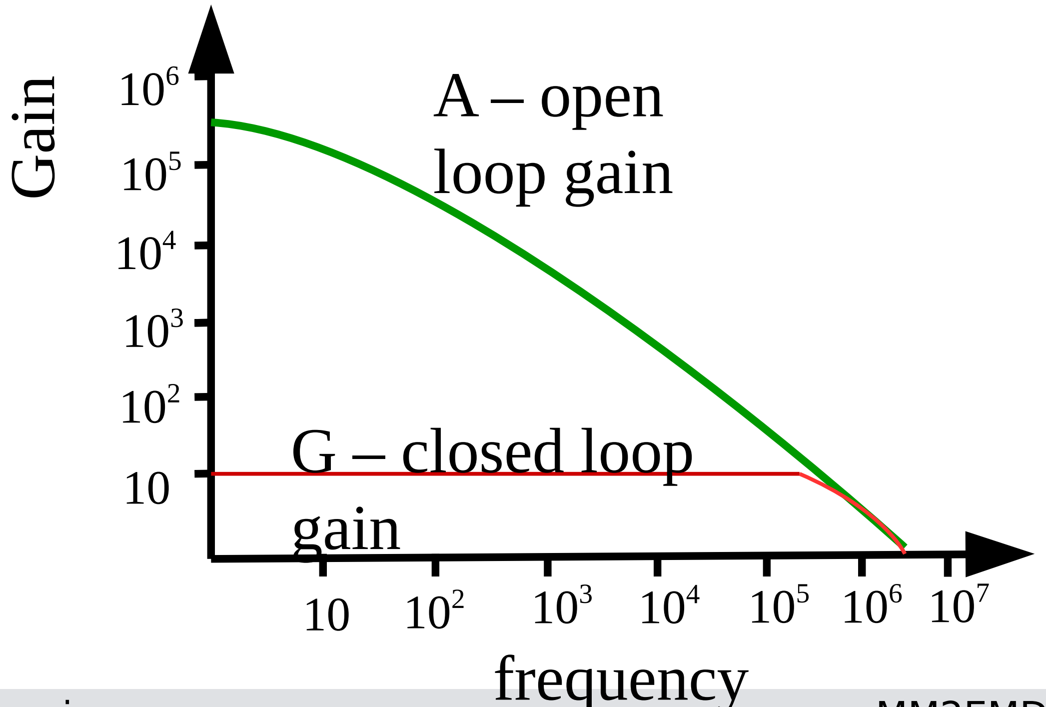
Q: Why do we need to use a feedback resistor in an op-amp circuit?



Quiz A3:

Q: Why do we need a feedback resistor to use an op-amp?

A1) The gain is too high to be useful
A2) The gain is non-linear.



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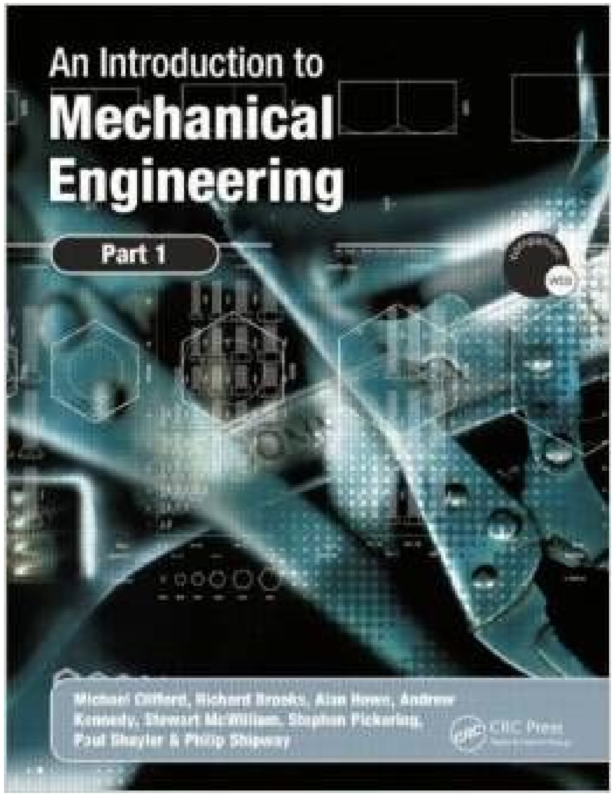
Recommended reading: A general text book

If you feel you need a text book and only want to buy one – get this one:

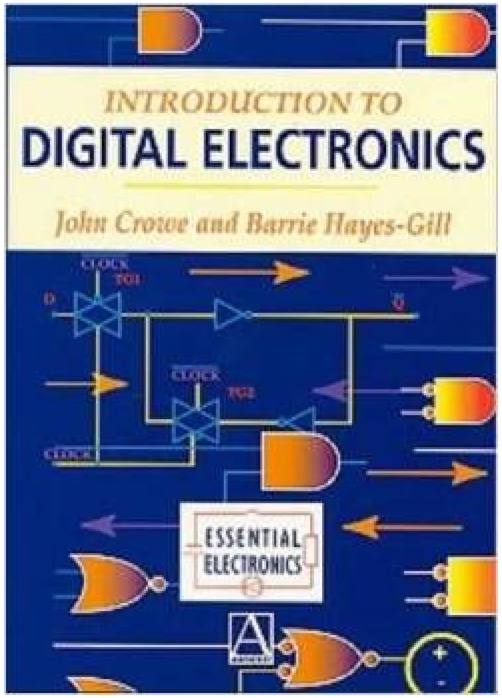
An introduction to Mechanical Engineering, Part 1 pp. 365-371



£42

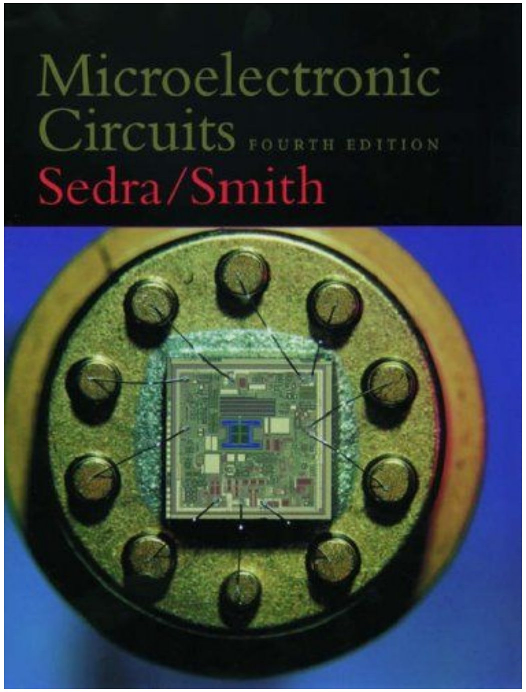
Recommended reading: Useful for later in industry or now if you are interested

A little more in depth on digital electronics:



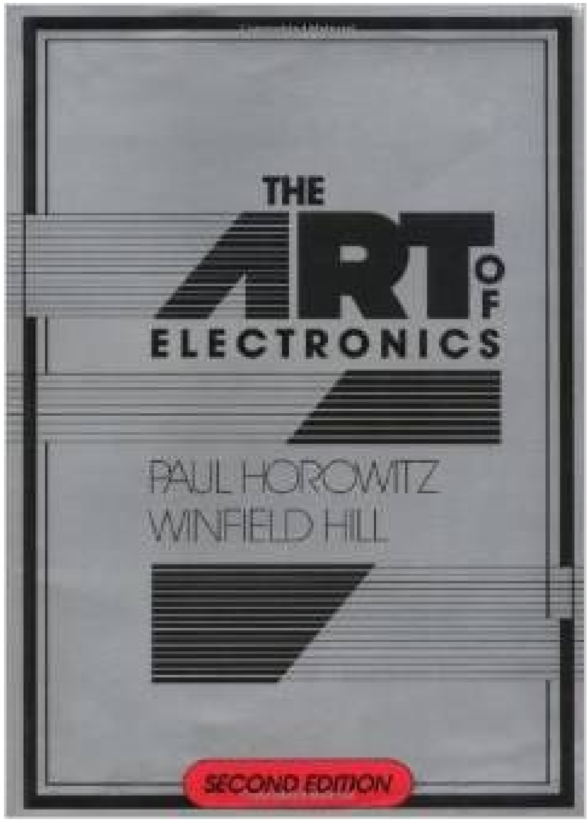
£29-£42

Lots of in depth stuff on analog circuits – classic text book.



£30-£60

Recommended reading: Useful for later in industry or now if you are interested



£28-60

- This is the classical ***practical*** electronics book.
- Every electronic engineer has this on his shelf.

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Let's think about measuring acceleration

- Often we need to measure acceleration

- Because acceleration can tell us a lot about our environment

$$\int acceleration\, dt = velocity$$

$$\int velocity\, dt = position$$

Now let's think about the crystal quartz

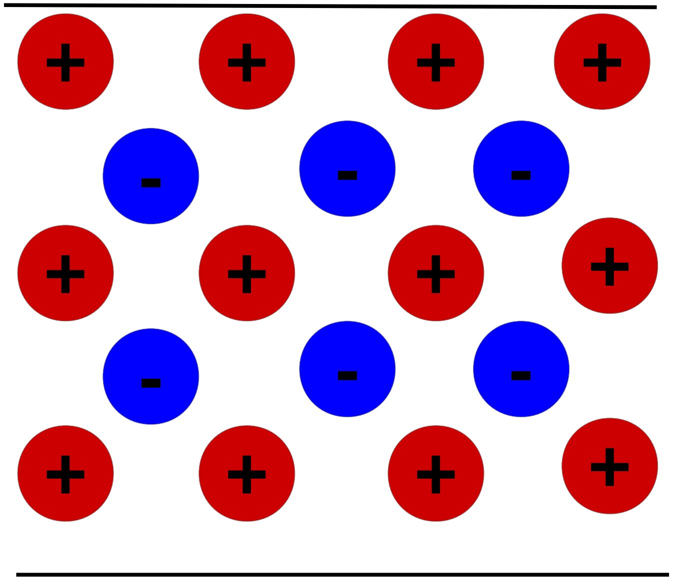
Quartz

AlaskaMining

The pizoelectric effect in quartz

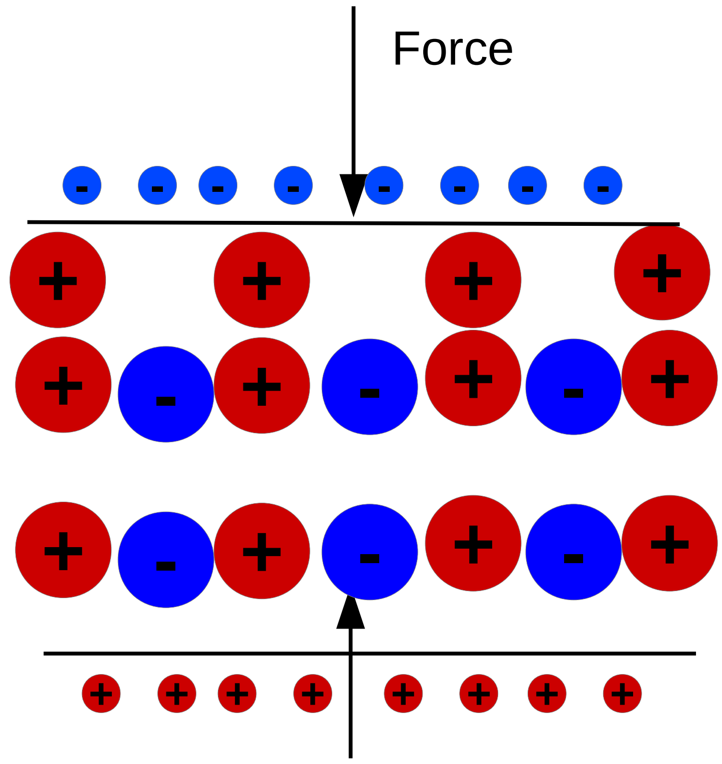
- Normally quartz has a regular arrangement of positive and negative ions:

JJ Harrison



quartz

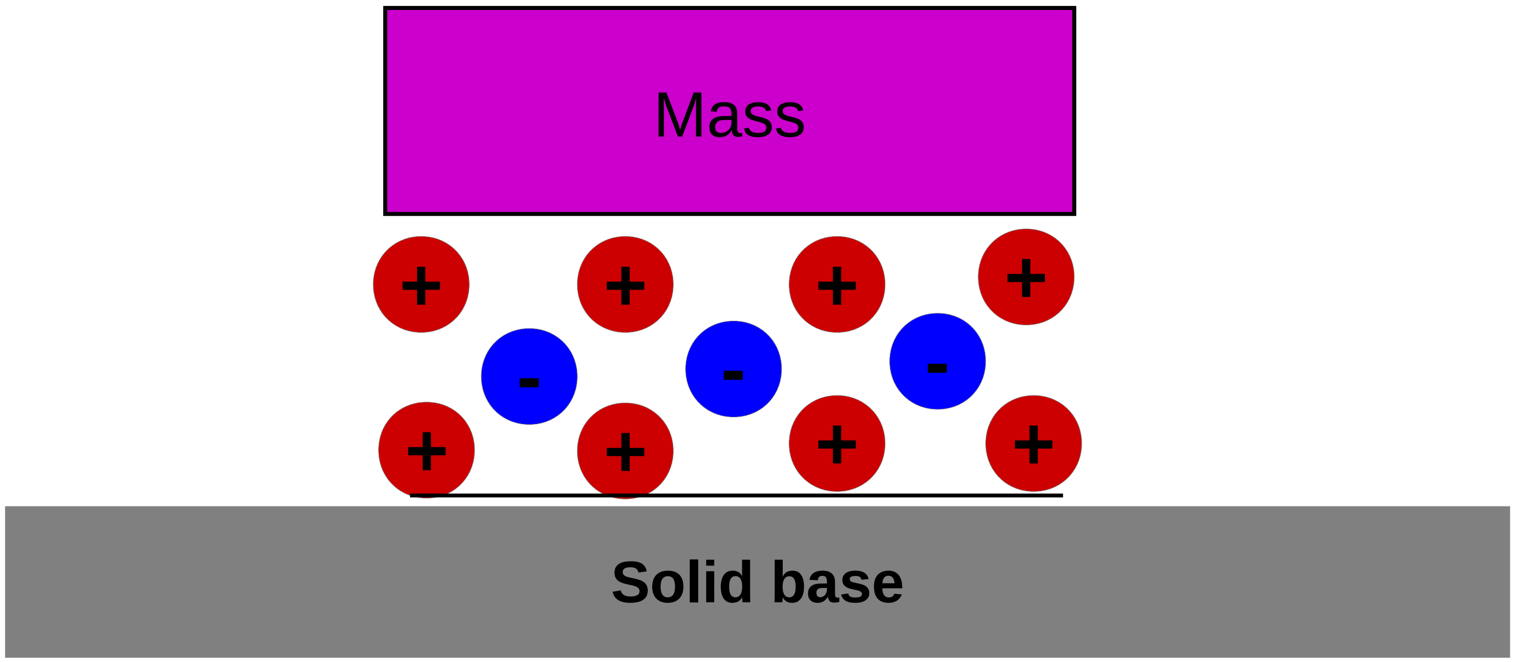
The pizoelectric effect in quartz



But what has this got to do with measuring acceleration?

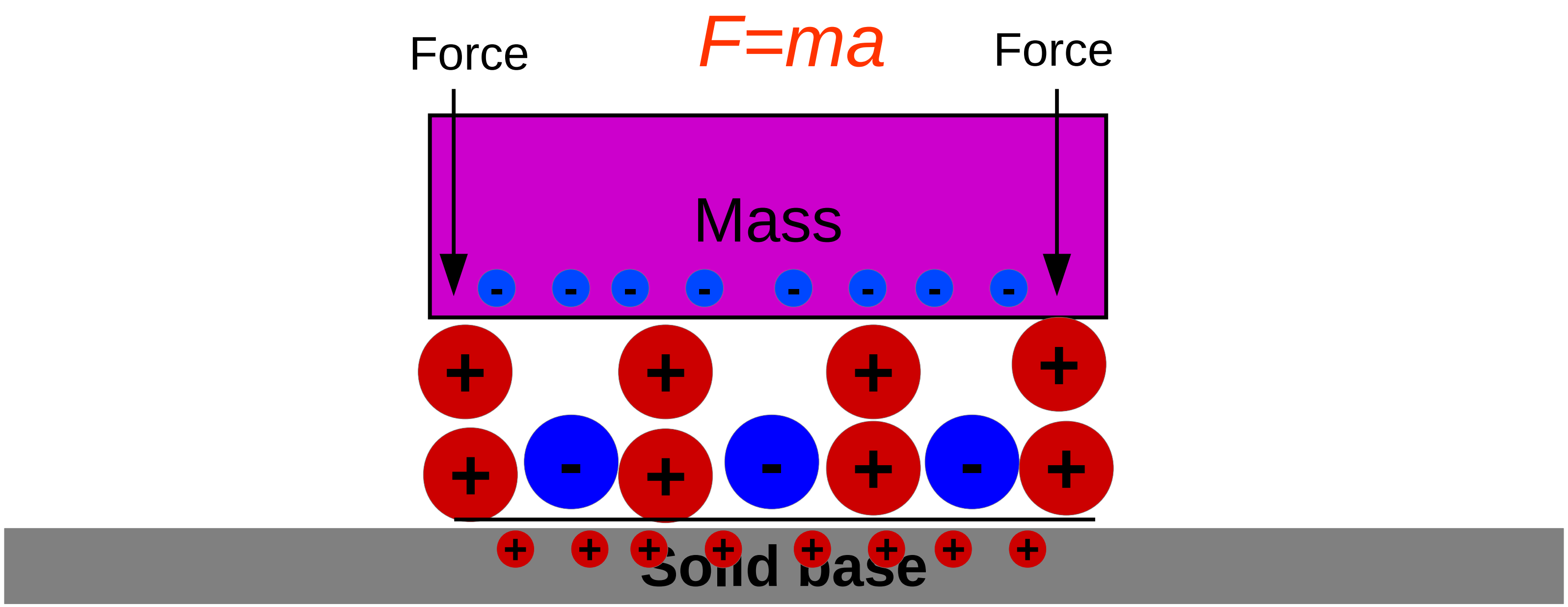
Detecting acceleration with quartz crystal

Let's put a mass on top of the quartz crystal



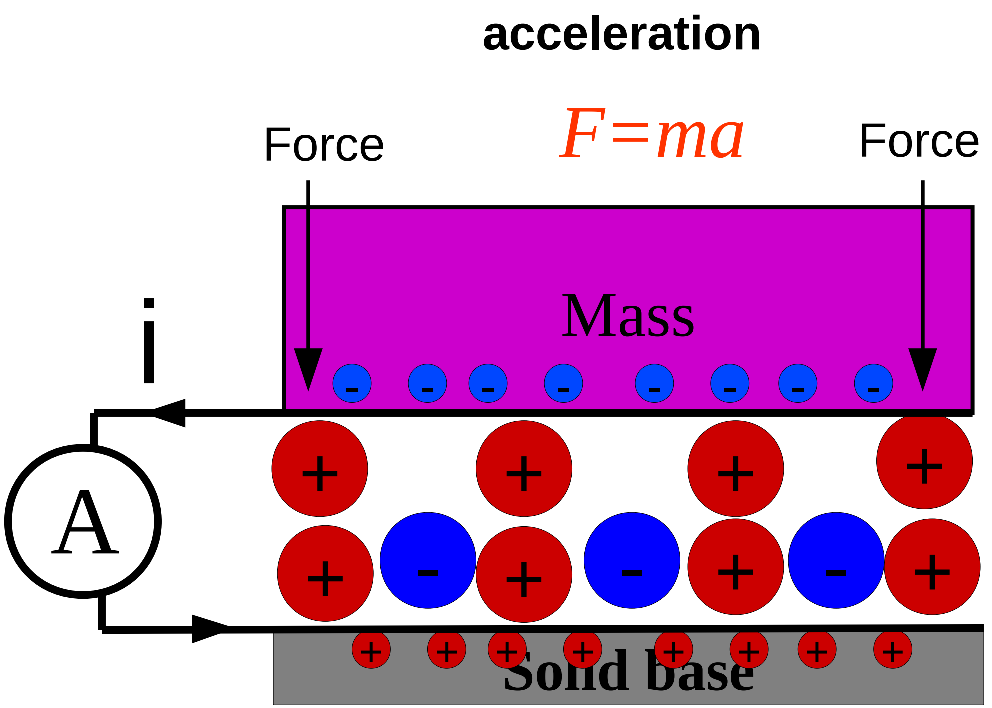
Detecting acceleration with quartz crystal

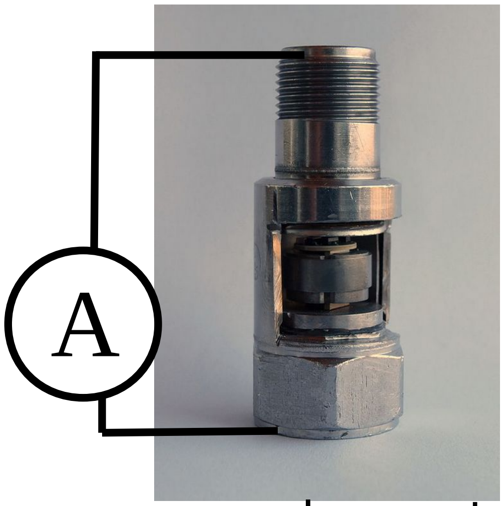
Acceleration *a produces force (F=ma)*



The movement causes the output charge from the piezoelectric crystal to change producing a current.

This is how you make an accelerometer



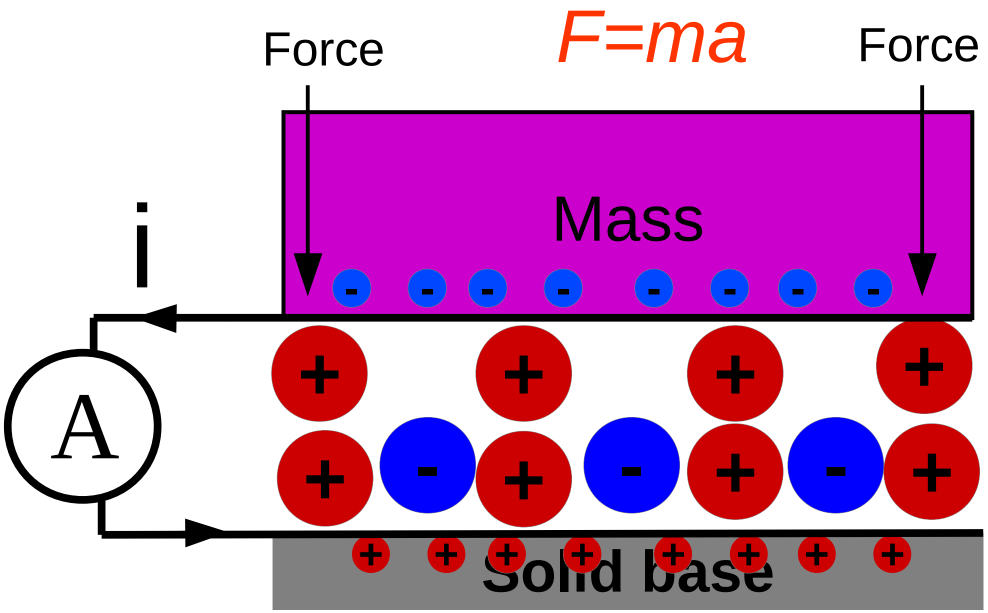


accelerometer

- The current changes when the sensor experiences acceleration

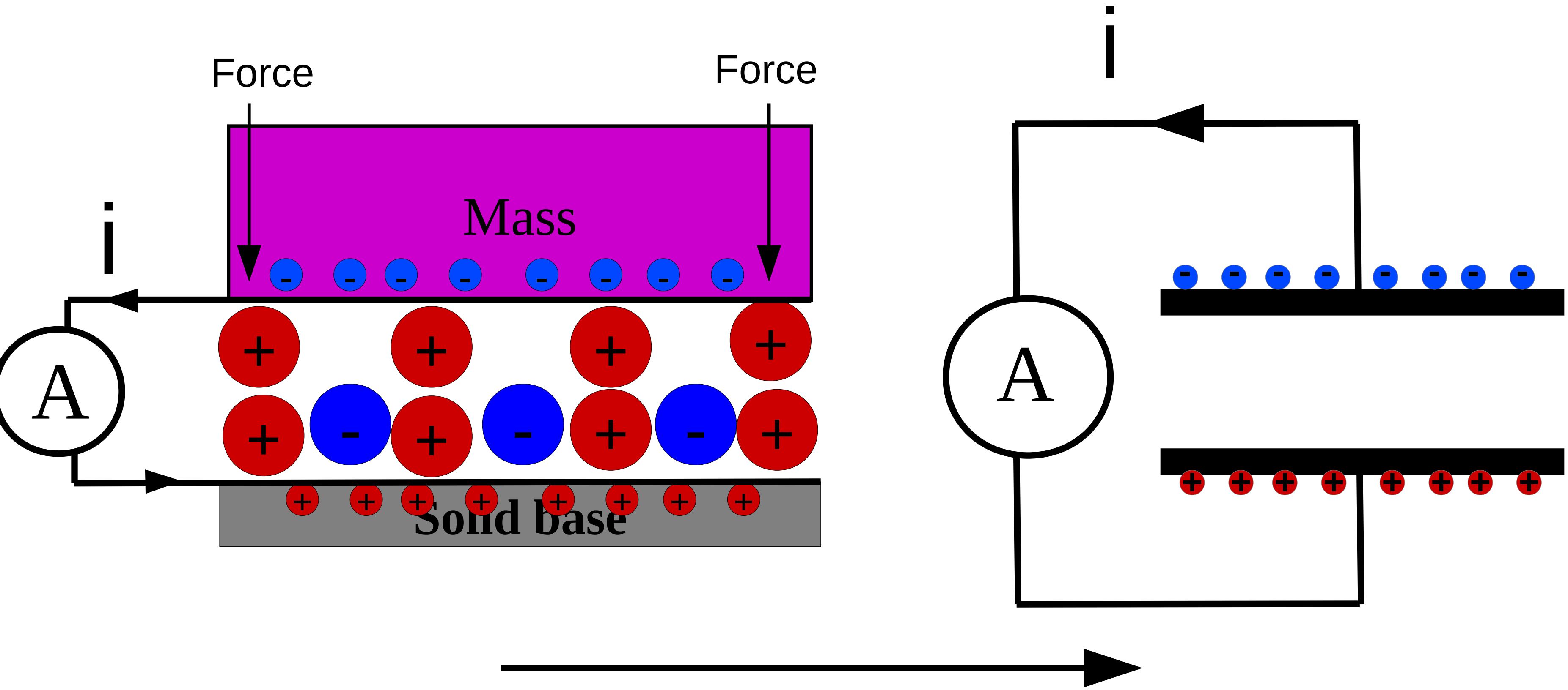
- Let's have a look at this effect in more detail....

We have two problems....



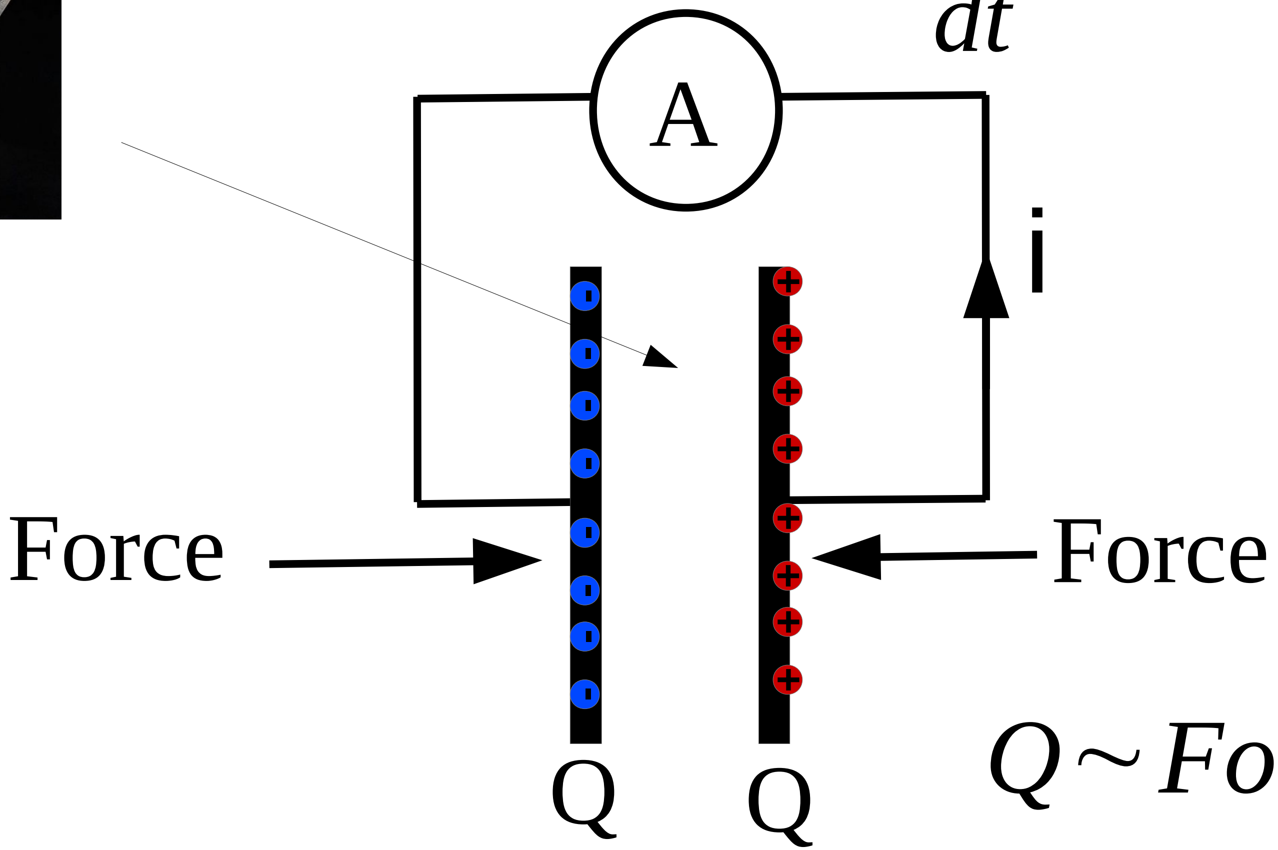
- **Problem 1:** ***i*** is very small.. too small to be used.... how might we fix that??
- **Problem 2:** ***i*** is not proportional to the acceleration, it's actually a bit more complex.. let's have have a look at this first...

Simplification of accelerometer



You can think of a piezoelectric crystal as a capacitor

$$i = \frac{dQ}{dt}$$



$$Q \sim Force$$

We can therefore we can write...

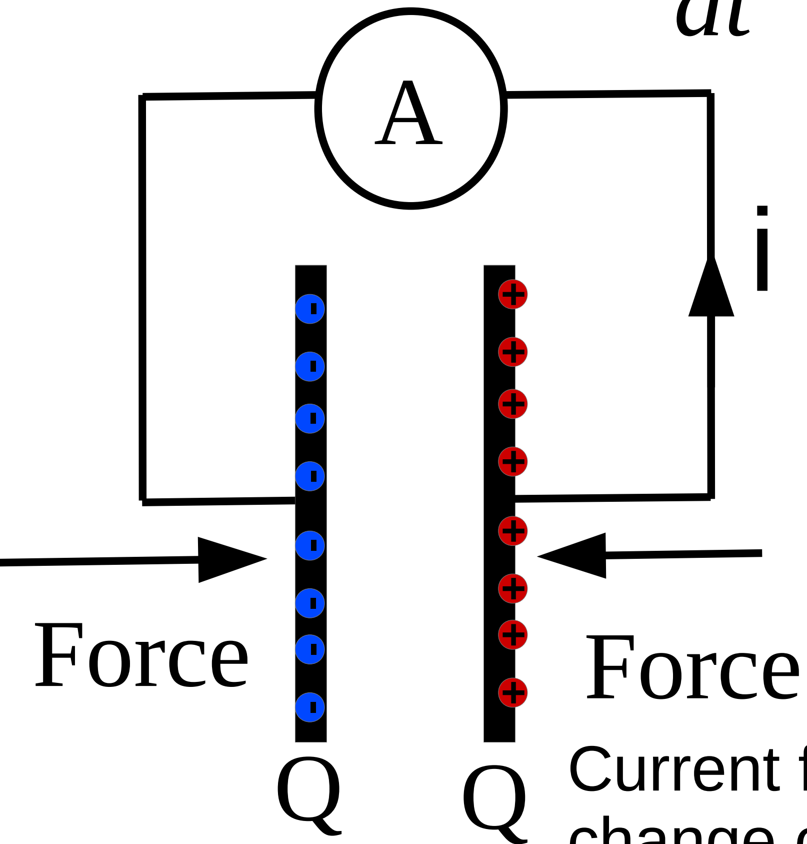
$$i=\frac{dQ}{dt}$$

$$Q \sim Force$$

$$i \sim \frac{d\,Force}{dt}$$

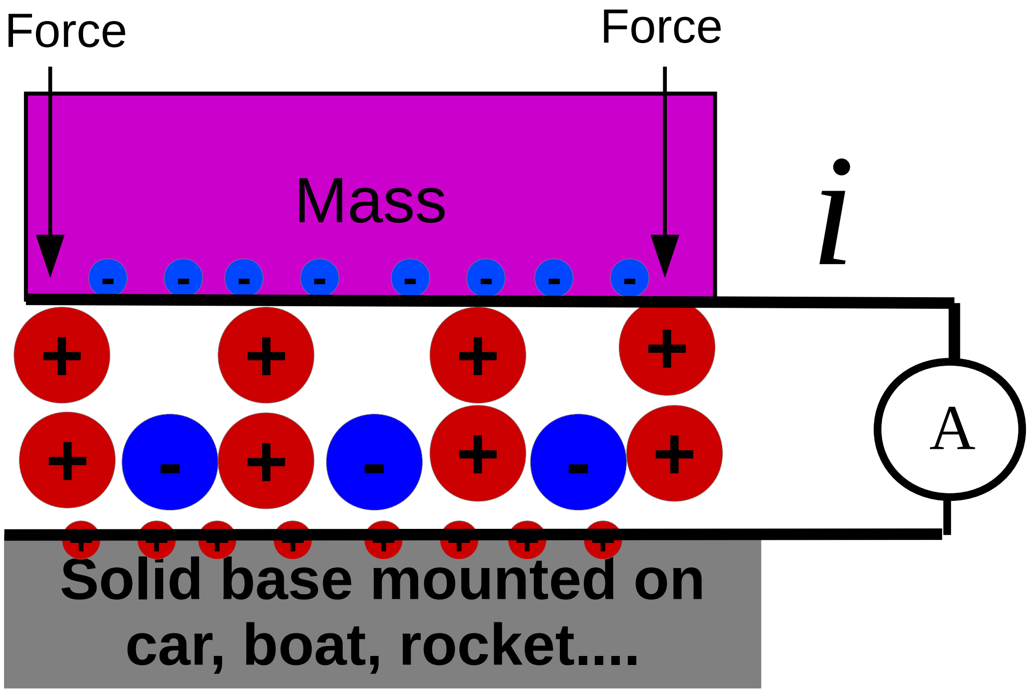
$$Force = ma$$

$$i \sim \frac{d\,a}{dt} m$$



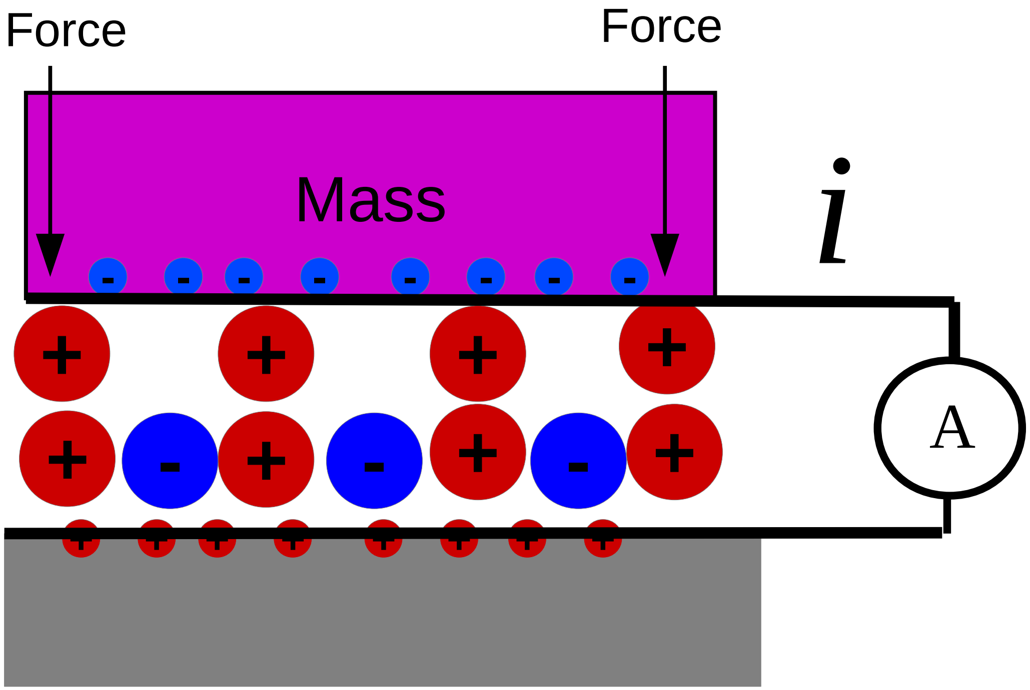
Current from accelerometer is proportional to change of charge with time

How would you solve this equation for 'a'?



$$i \sim \frac{d\,a}{dt} m$$

To solve this equation we need to integrate...



$$i \sim \frac{da}{dt} m$$

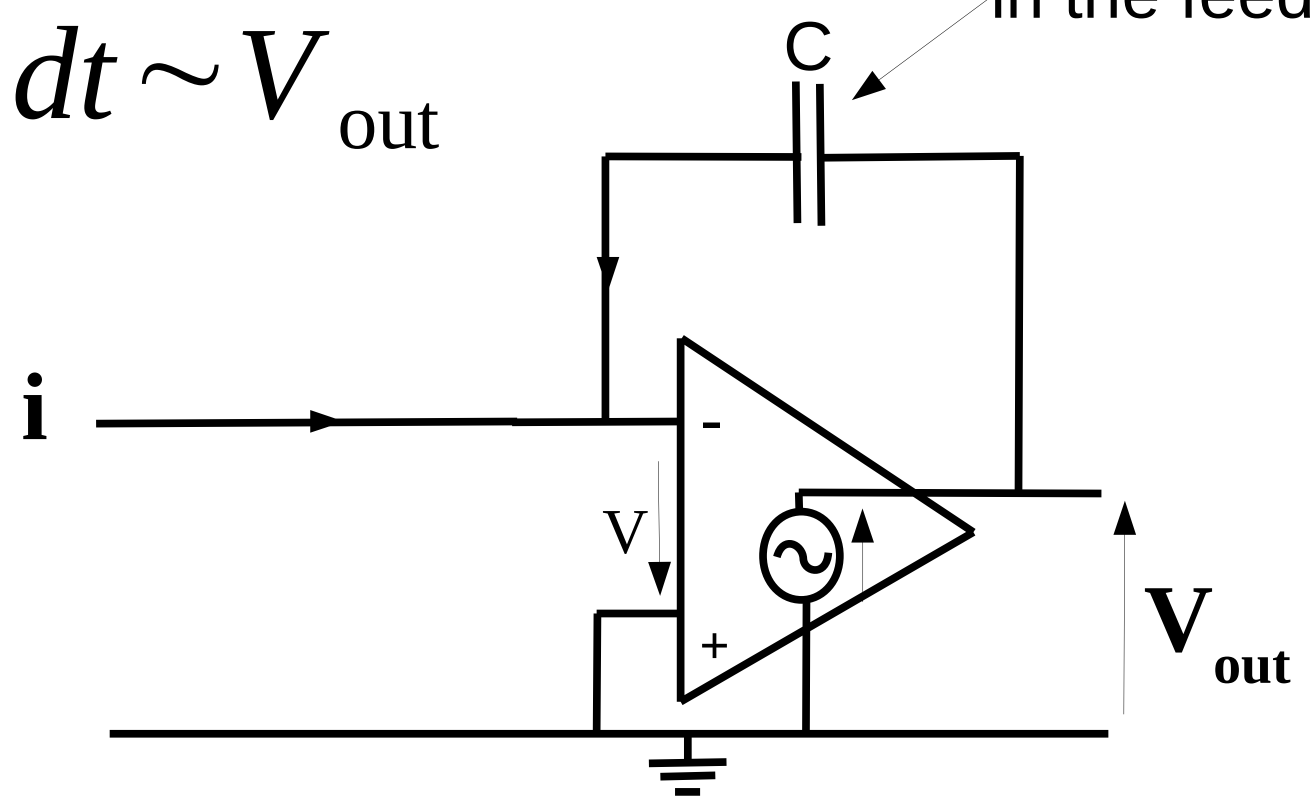
$$\frac{1}{m} \int i\,dt \sim a$$

- To calculate the acceleration we need to integrate the current.
- To do this we need an integrator circuit.........

An op-amp based integrator circuit

Notice the capacitor in the feedback loop

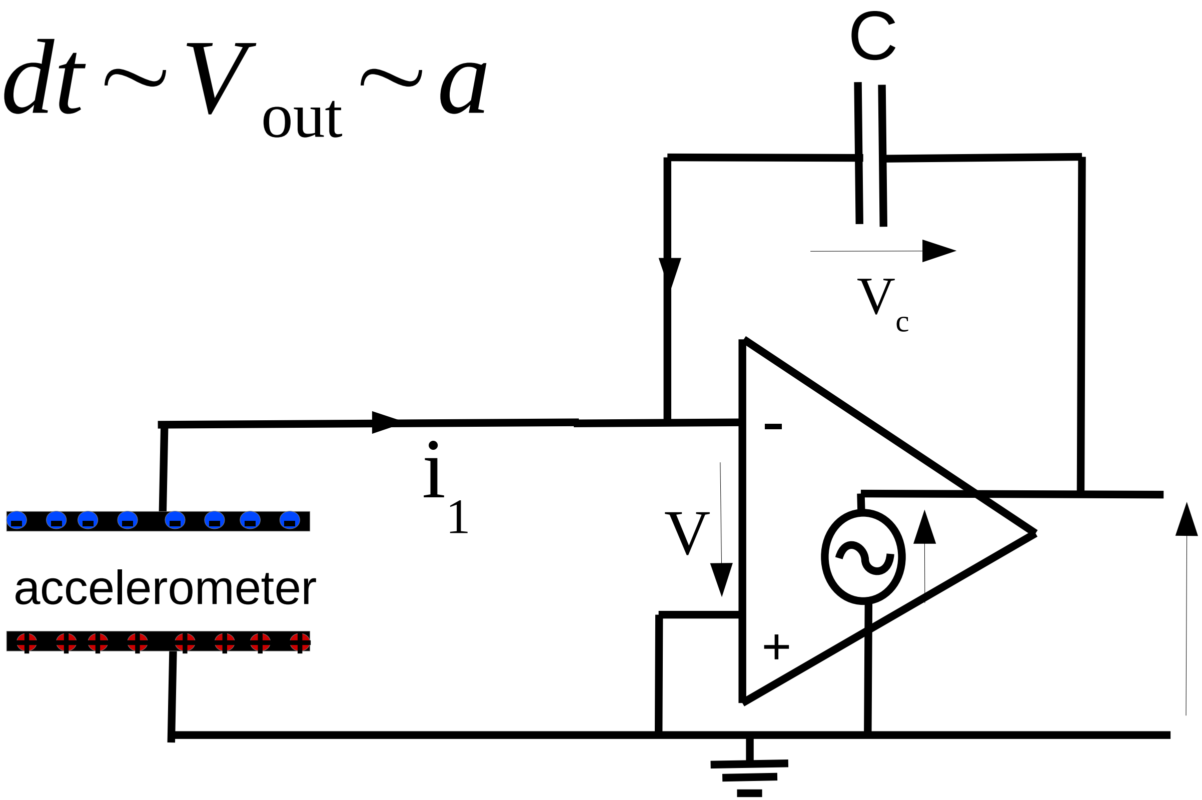
$$\int i\,dt \sim V_{out}$$



This will integrate current i, and V_{out} will be proportional to the sum of the integration.

An integrator circuit

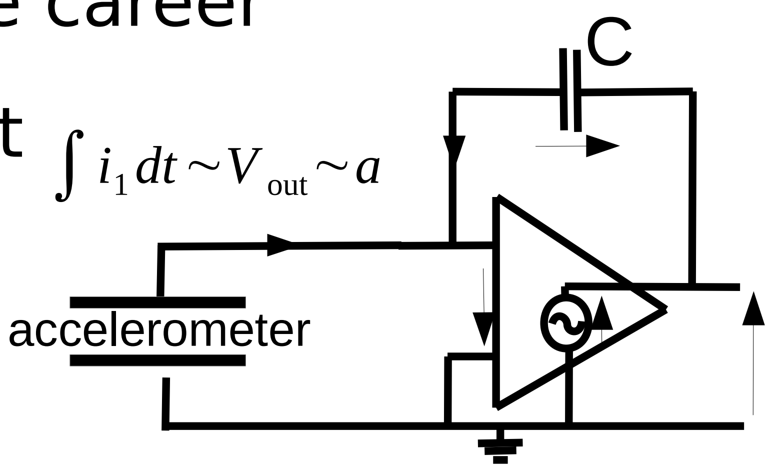
$$\int i_1 dt \sim V_{out} \sim a$$



$$V_{out} \sim a$$

Question

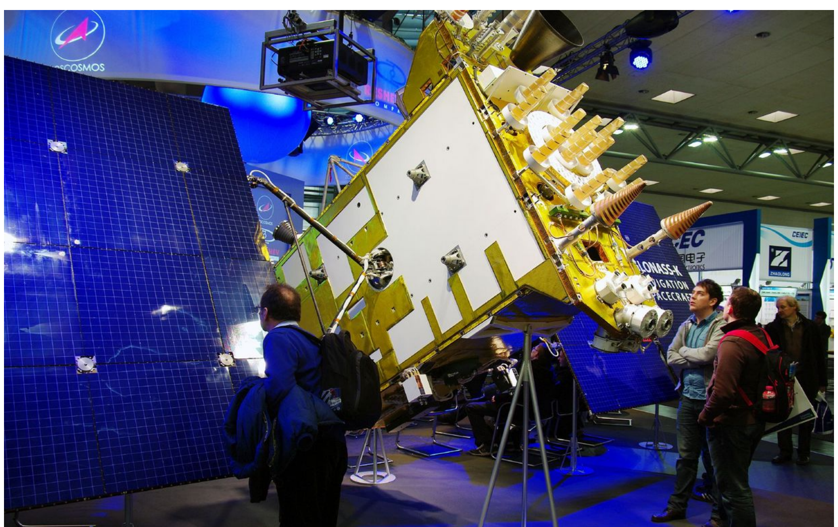
- How many people think understanding the accelerometer/integrator circuit is:
  - Boring and pointless
  - Important to my future career
  - Very important to my future career
  - Possibly the most important thing I will learn at university!!



An example of an accelerometer and integrator circuit in action.

An example is in this Russian proton M rocket.

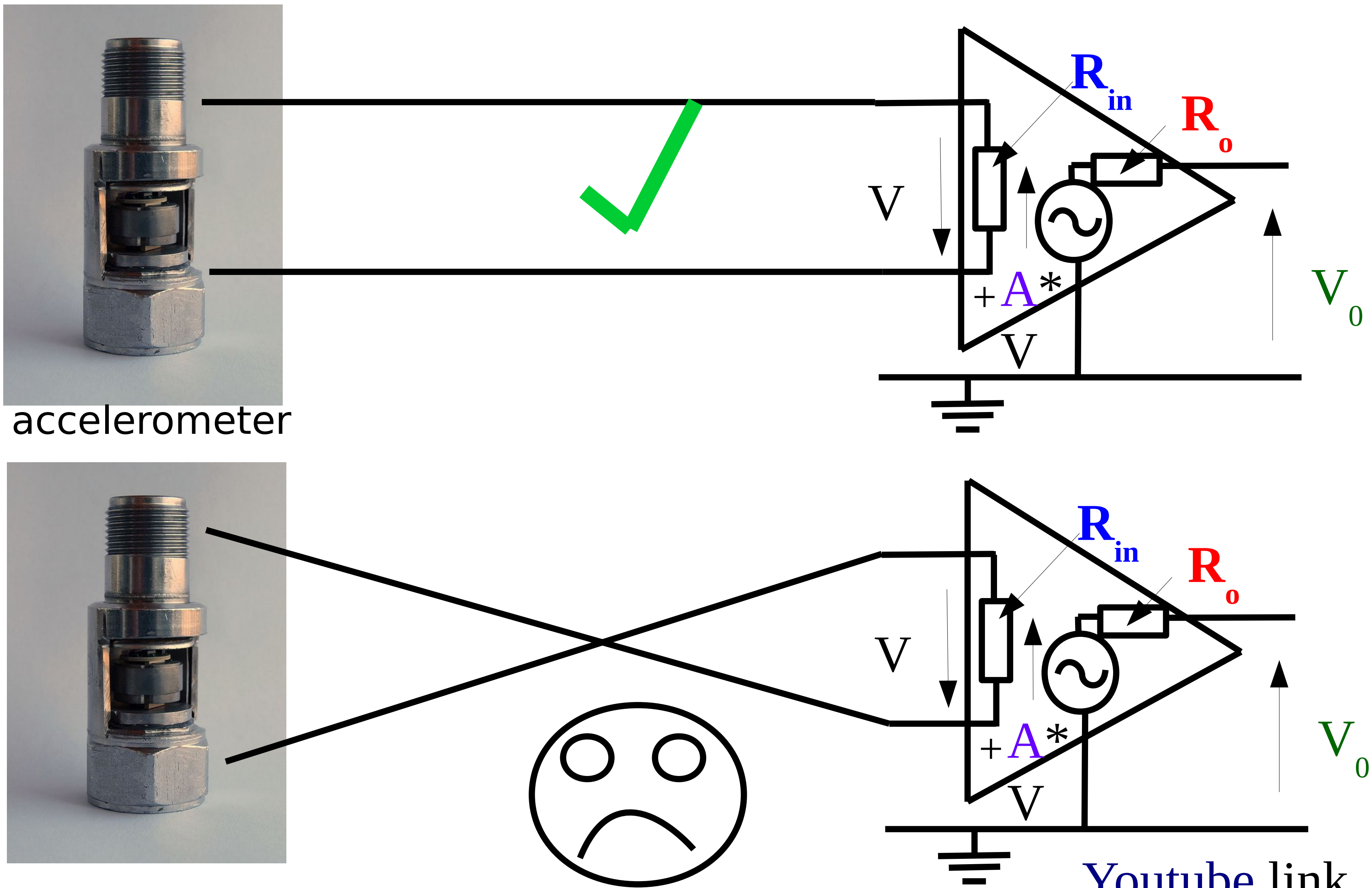
Pavel Kolotilov



- GLONASS satellite (Russian GPS)

•On the 1st July 2013 it was put on top of a Proton M rocket - combined cost costs 4.4 billion rubles.

An engineer coupled the accelerometer the wrong way around to the op-amp.



Youtube link

So..

- Op-amps in general are very important to know about and get correct.

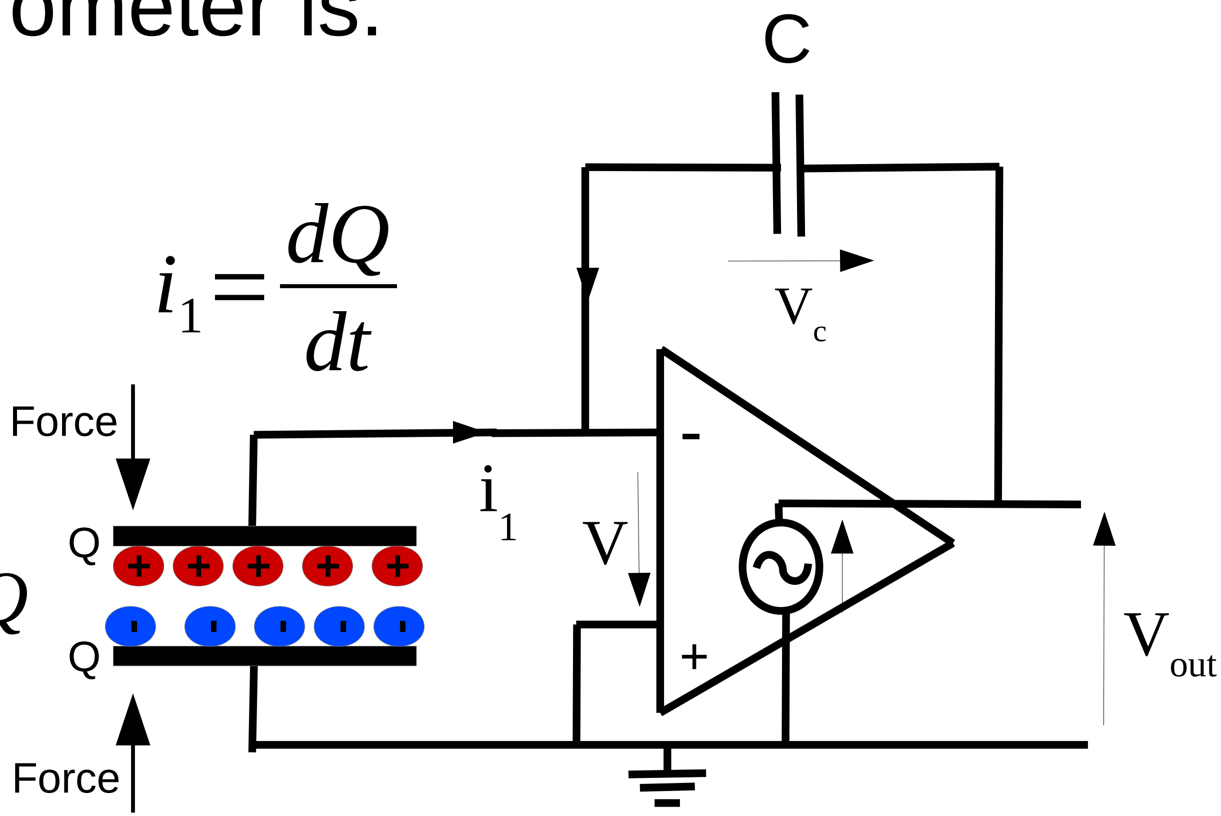
- It's too important to just leave everything up to the electronic engineer.

- With this in mind we are going to spend a little time deriving the equation describing this circuit and linking acceleration to V_{out}.

Input current from the accelerometer is:

$$i_1 = \frac{dQ}{dt}$$

$$Force \sim Q$$



Examine the current node at the inverting input

The amplifier has infinite input resistance so...
i=0, therefore:

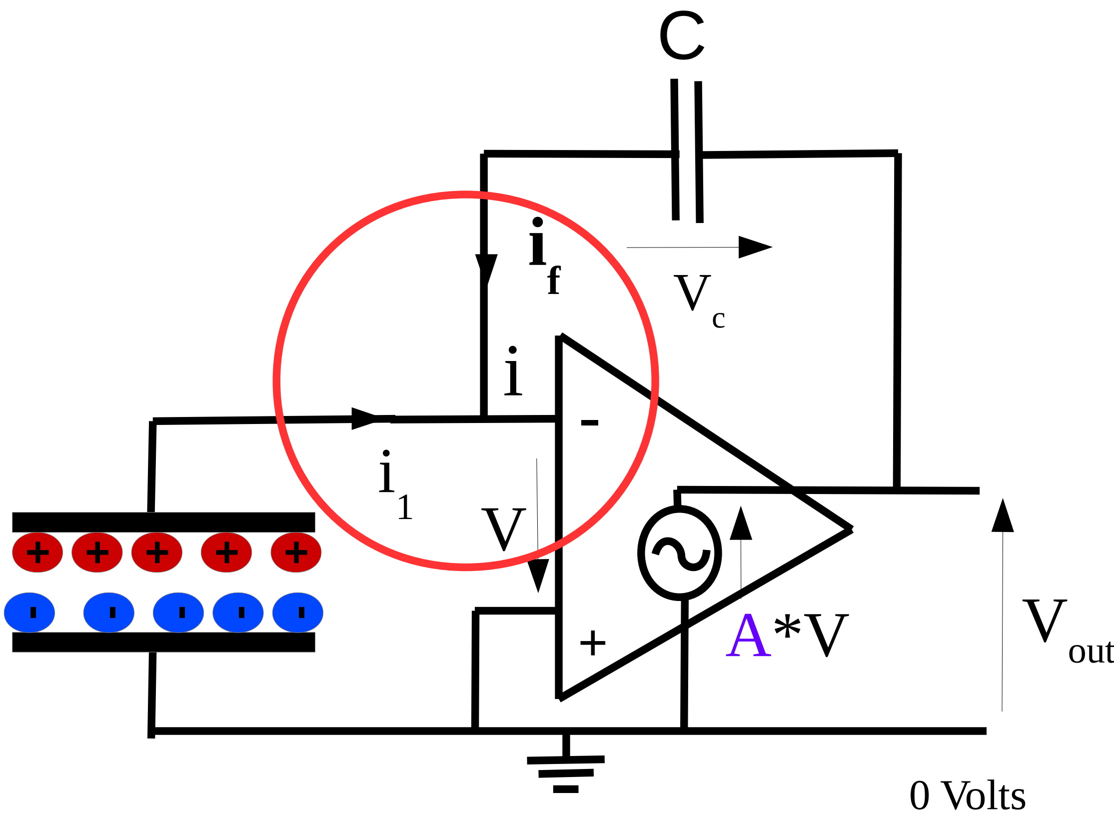
$$i_f = -i_1$$

But we already know..

$$i_1 = \frac{dQ}{dt}$$

Therefore,

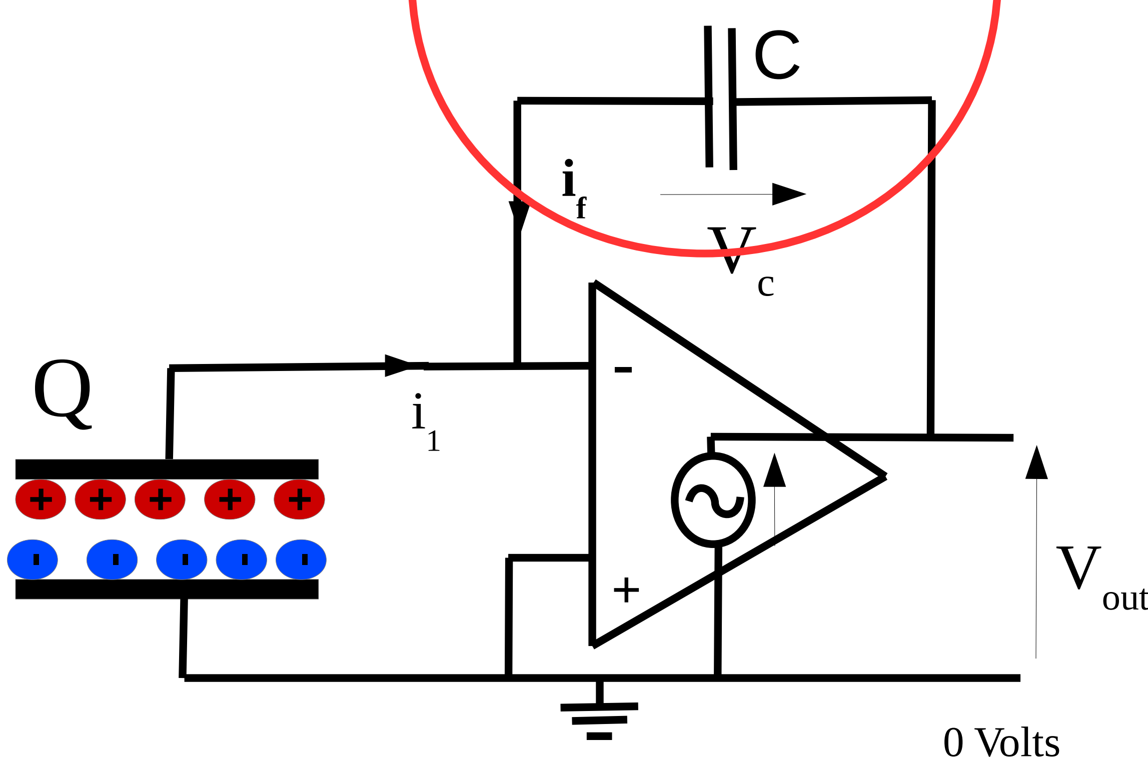
(1) $$i_f = -\frac{dQ}{dt}$$



Examine the capacitor...

From your notes on capacitance:

$$i_f = C\frac{dV_c}{dt}$$



Examine the capacitor...

From your notes on capacitance:

(2)

$$i_f = C\frac{dV_c}{dt}$$

But we already know

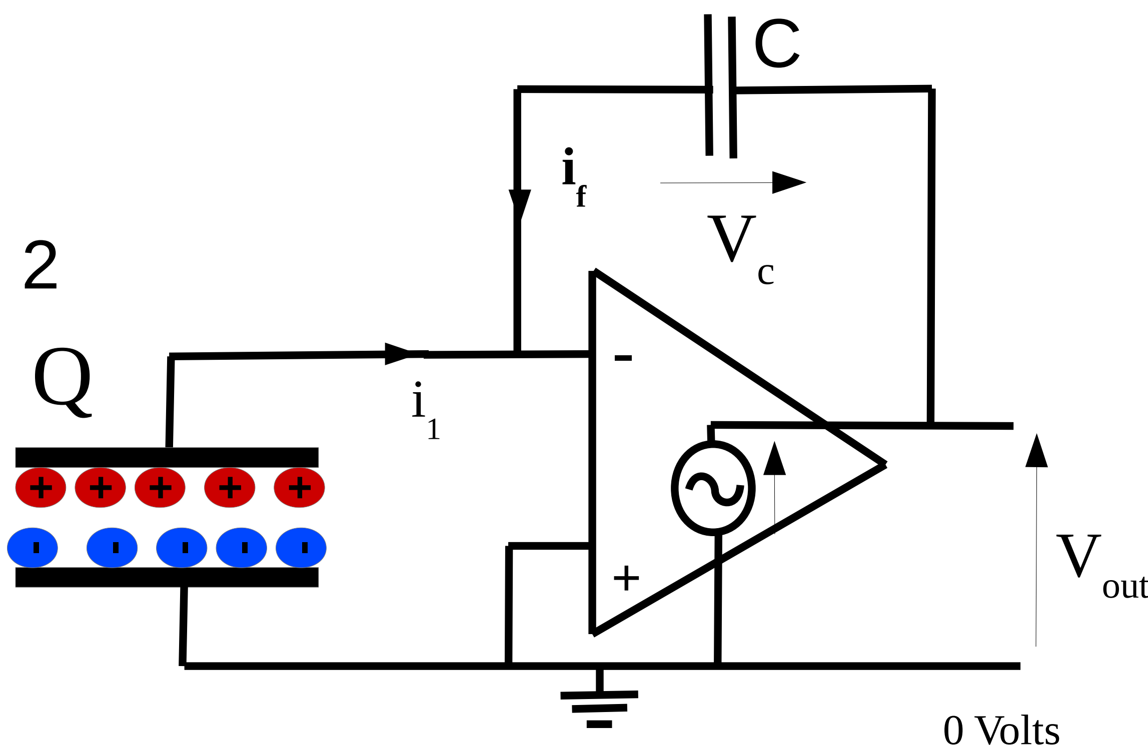
(1)

$$i_f = -\frac{dQ}{dt}$$

Equate equations 1 and 2

$$\frac{dQ}{dt} = -C\frac{dV_c}{dt}$$

$$\frac{dV_c}{dt} = -\frac{1}{C}\frac{dQ}{dt}$$

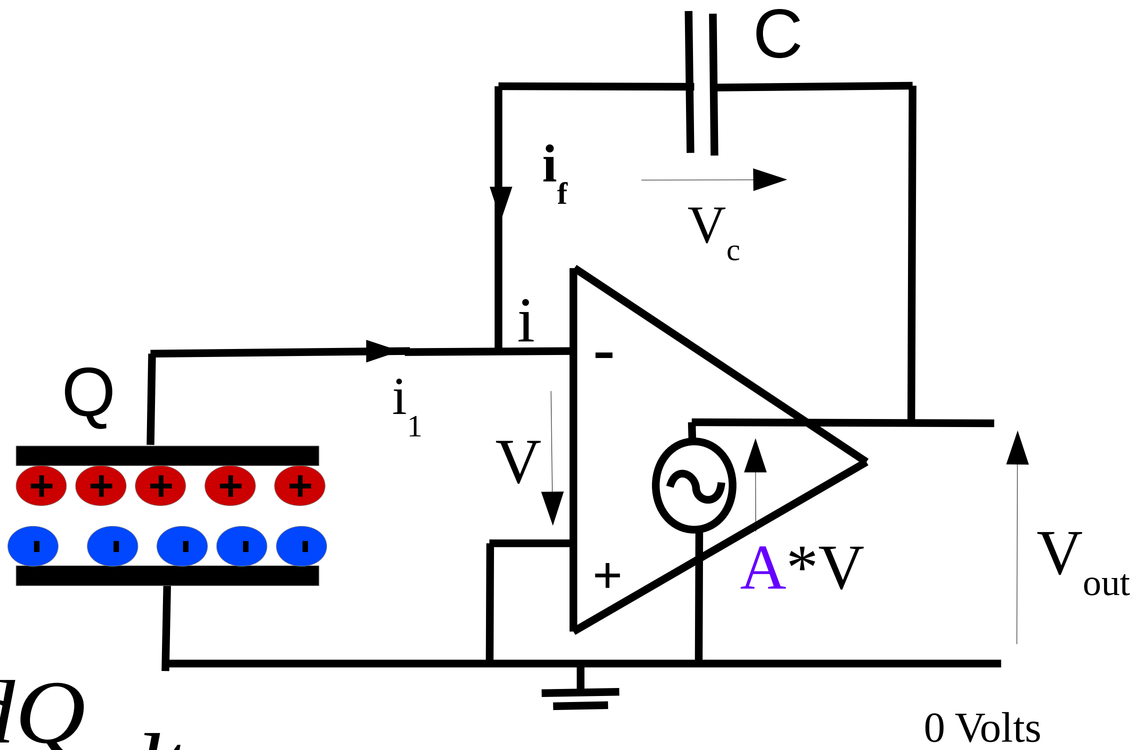


Integrate both sides

$$\frac{dV_c}{dt} = -\frac{1}{C}\frac{dQ}{dt}$$

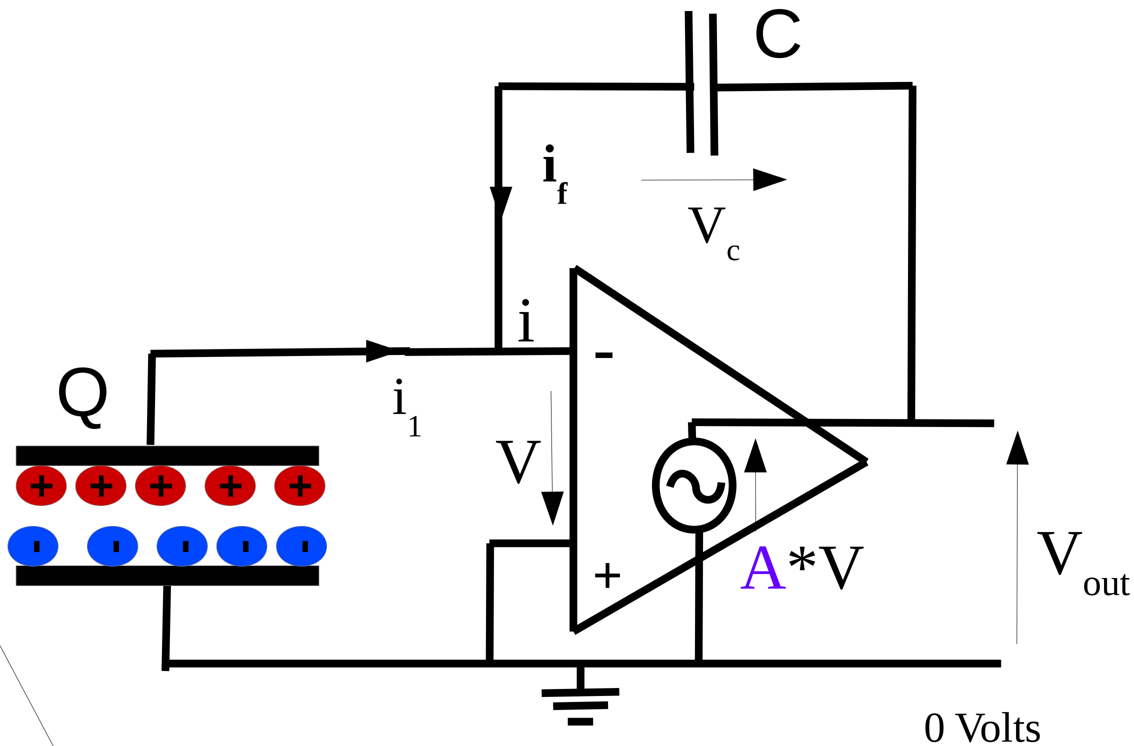
$$\int \frac{dV_c}{dt} dt = -\int \frac{1}{C}\frac{dQ}{dt} dt$$

$$V_c = -\frac{1}{C} Q$$



Integrate both sides

$$V_c = -\frac{1}{C} Q$$



We also know that

$$V_c - V = V_{out}$$

and

$$V_{out} = AV$$

$$-\frac{1}{C} Q - \frac{V_{out}}{A} = V_{out}$$

The final step…

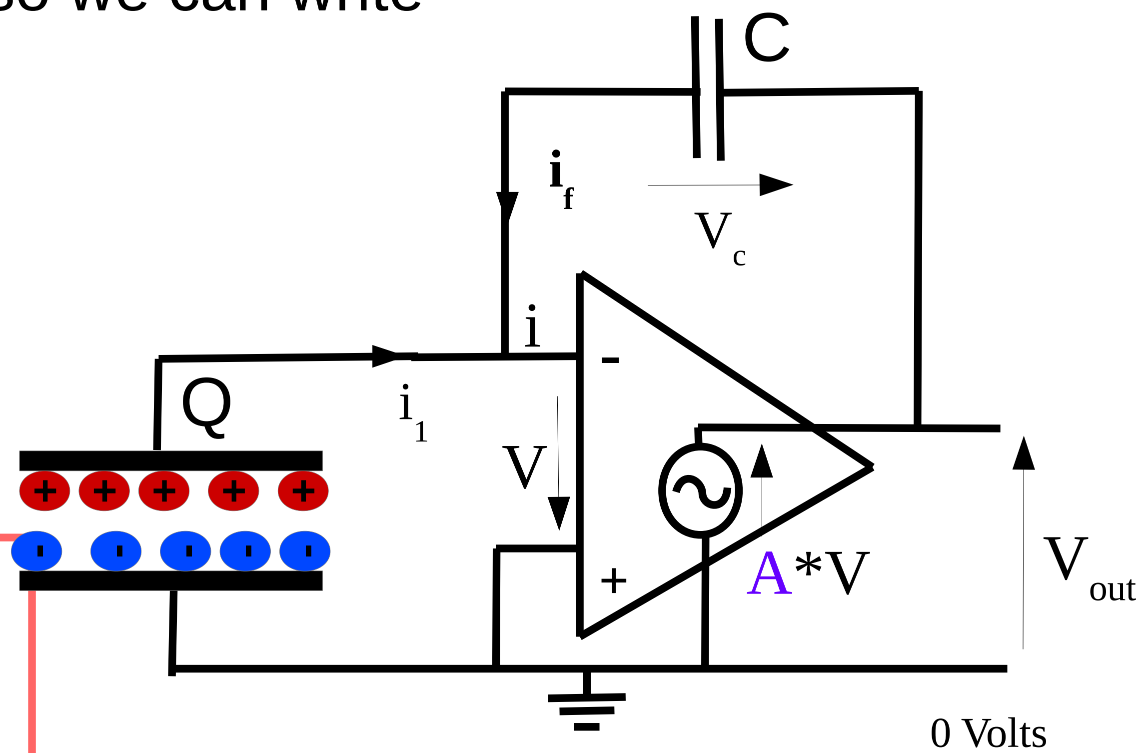
$$-\frac{1}{C}Q-\frac{V_{out}}{A}=V_{out}$$

$$V=\frac{V_{out}}{A}\rightarrow 0$$

However, A is very large so we can write

Therefore,

$$V_{out}=-\frac{1}{C}Q$$



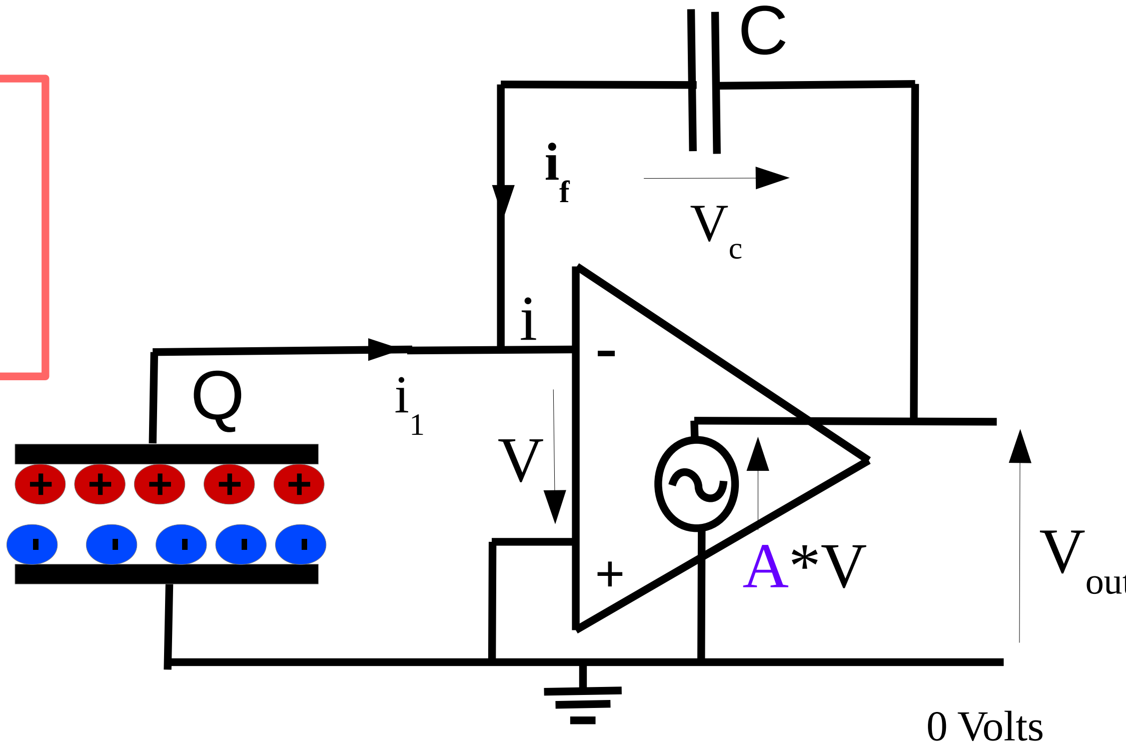
Amplifier output voltage

$$V_{out}=-\frac{Q}{C}\sim\frac{F}{C}\sim\frac{a}{C}$$

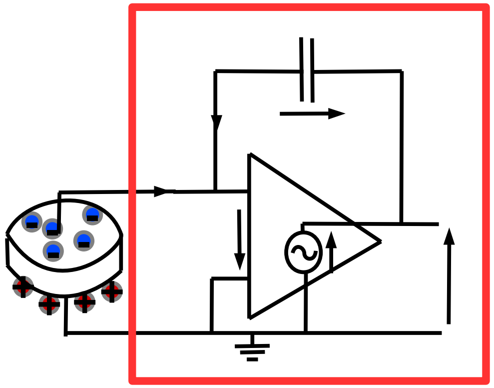
Question:

If you wanted to make your circuit more sensitive to small changes in acceleration (or Q) what would you change?

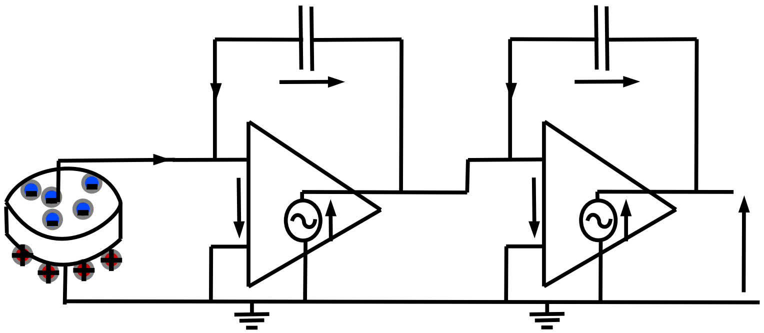
$$V_{out} = -\frac{Q}{C} \sim \frac{F}{C} \sim \frac{a}{C}$$



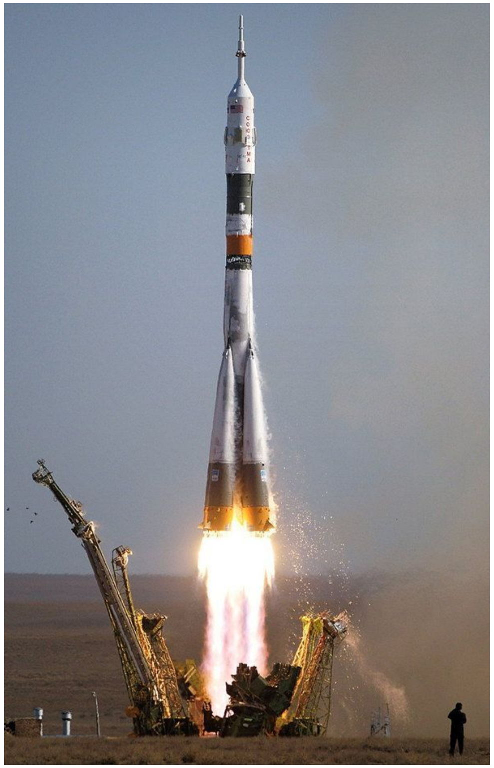
We can cascade these integrator elements

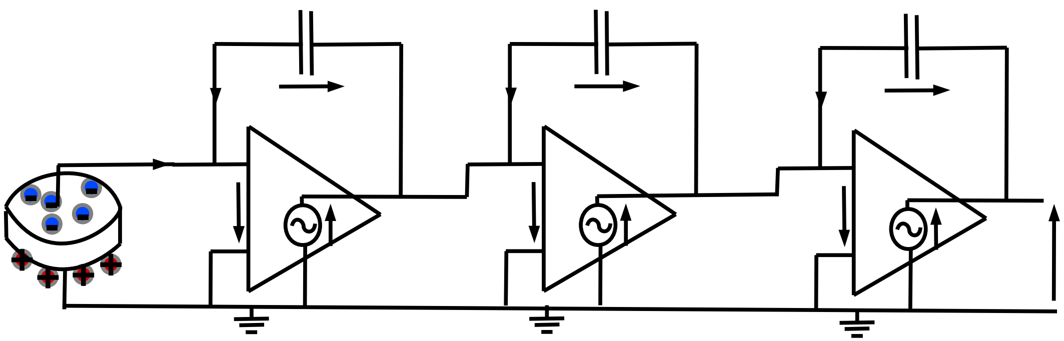


$$V_0 = -\frac{Q}{C} \sim \frac{F}{C} \sim \frac{a}{C}$$



$$V_0 \sim velocity$$



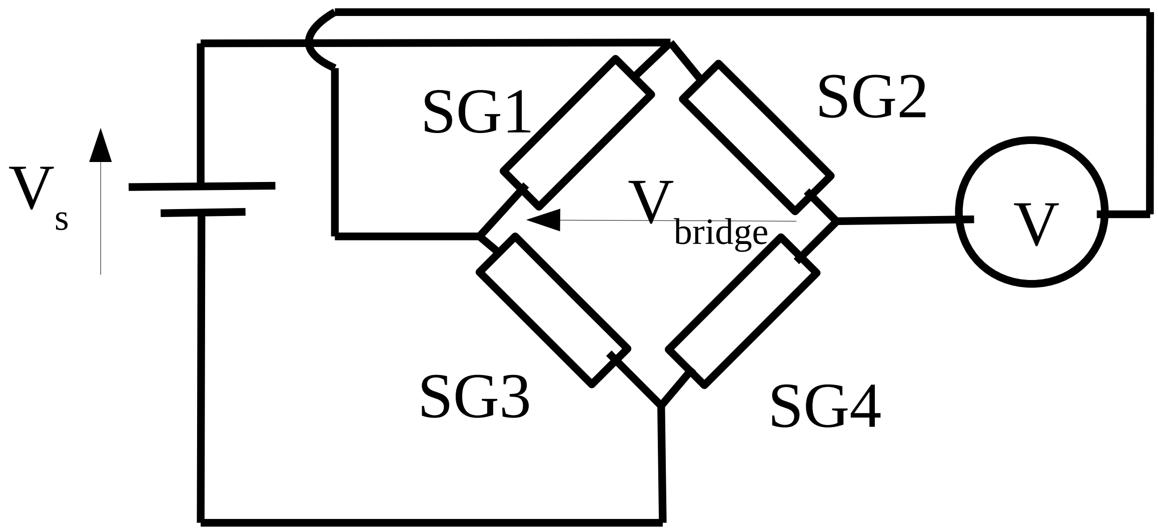


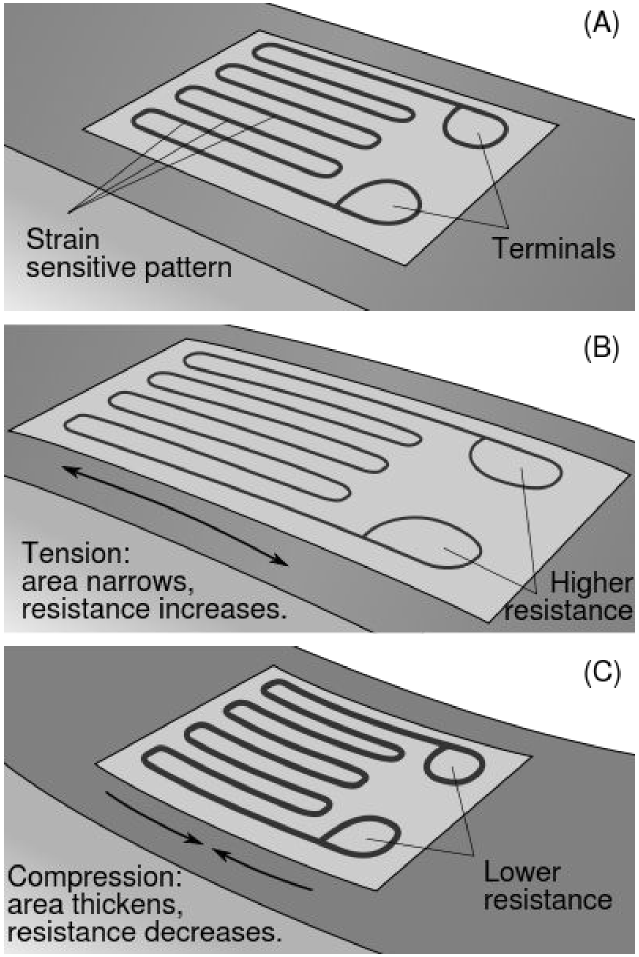
$$V_0 \sim distance$$

Outline of the lecture

- Recap of last lecture
- Mini Quiz
- Books and resources
- **Op-amps used in the real world**
    - Measuring acceleration
    - **Measuring stress and strain.**
- Summary

A strain gauge

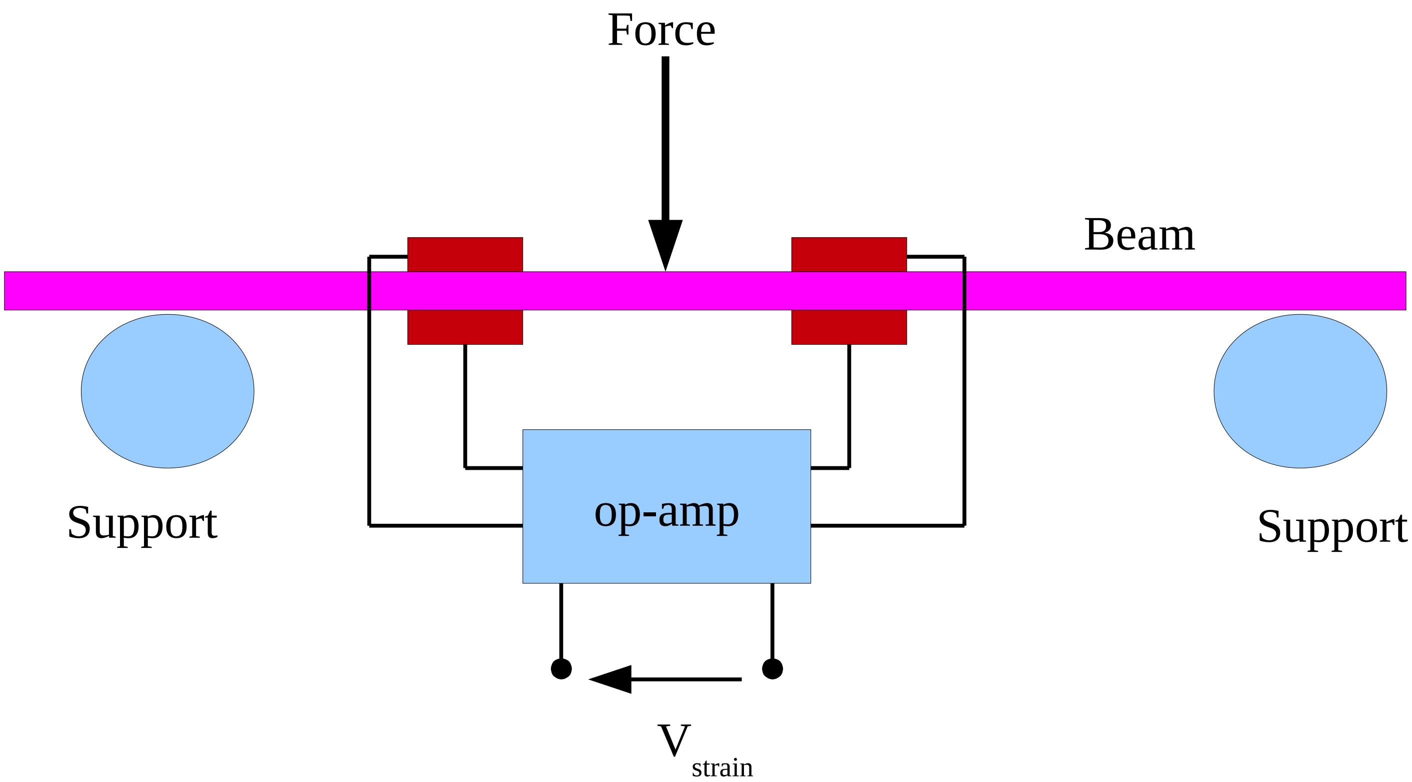




- The voltage V_{bridge} is very small... so we need to amplify it..

- And what do we use to amplify it?????

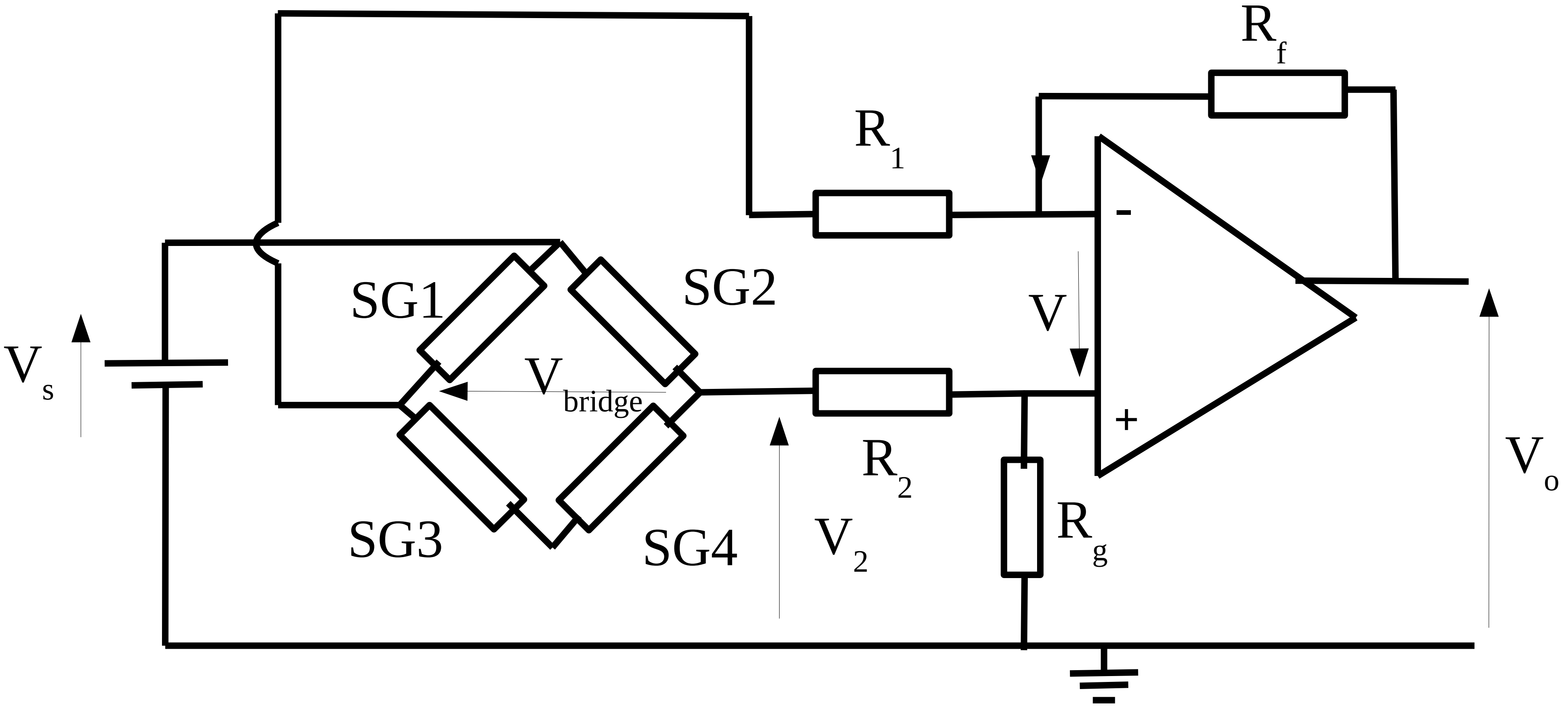
Application of op-amps to strain gauges..



Practical applications could be measuring strain on an aeroplane wing.

Video of lab....

Using an op-amp to amplify the output of a strain gauge



We need to derive an expression relating V_{bridge} to V_{out}.

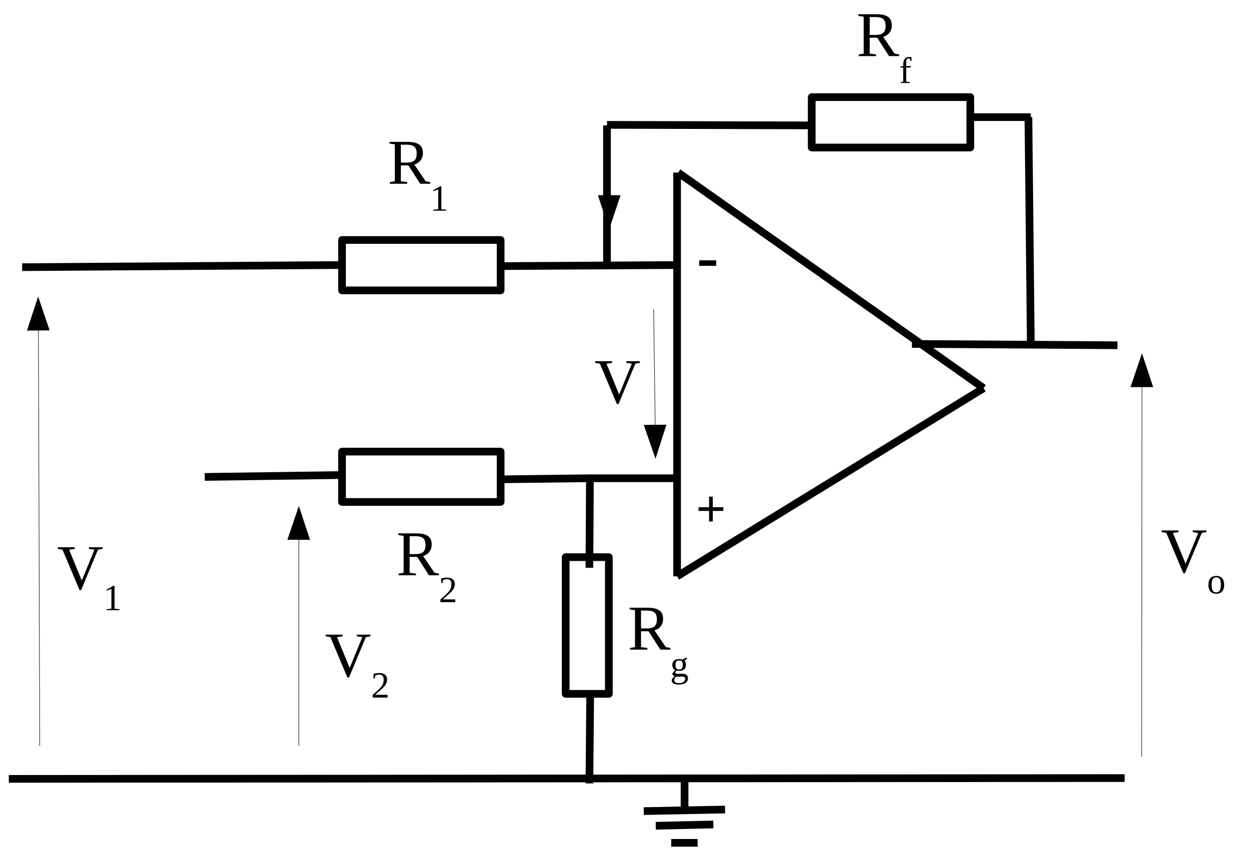
Relate the inputs to the outputs

The general idea is to write expressions **relating the input terminals to the inputs of the op-amp.**

Then to write an expression relating the **input terminals of the op-amp to the output of the op-amp**.

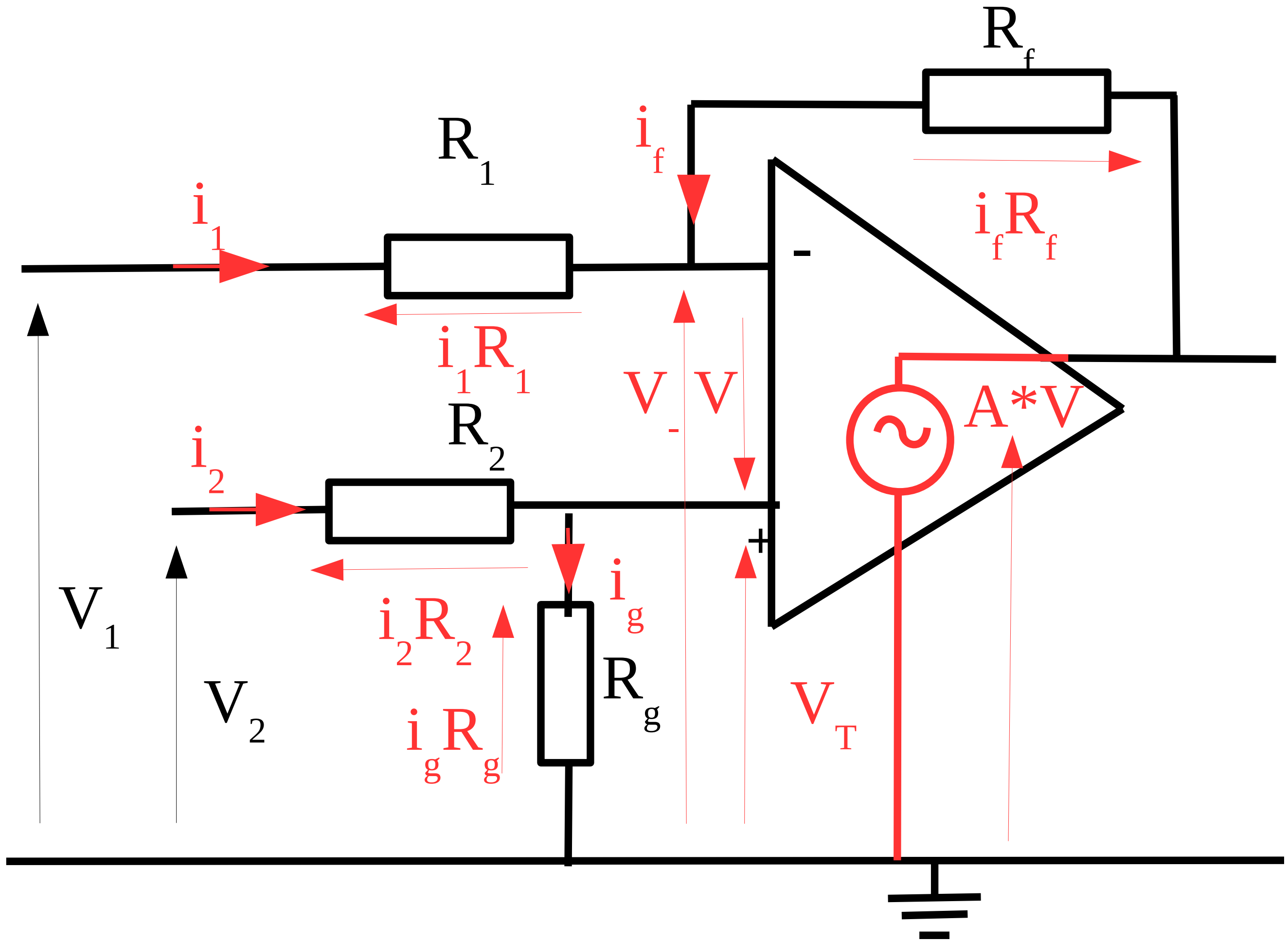
Let's have a go..

Let's just start off by looking at the op-amp.



Write on all current and voltage arrows.

Annotate the diagram with arrows, currents and voltages



First write an expression relating V_1 of the circuit to the inverting input of the op-amp.

$$V_- = V_1 - i_1 R_1$$

$$i_1 = \frac{V_1 - V_-}{R_1} \quad \mathbf{1}$$

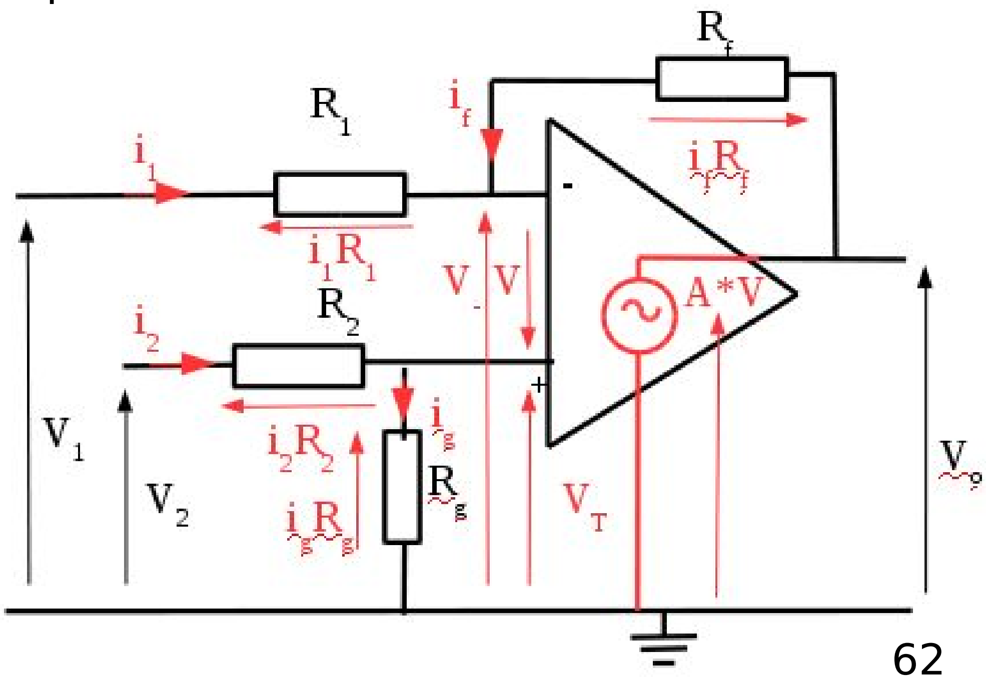
$$V_- = V_0 - i_f R_f$$

$$i_f = \frac{V_0 - V_-}{R_f} \quad \mathbf{2}$$

Equating equation 1 and 2

$$i_f = -i_1$$

$$\frac{V_1 - V_-}{R_1} = \frac{V_1 - V_0}{R_f}$$



Rearrange the equations to get the voltage V_-

$$\frac{V_1 - V_-}{R_1} = \frac{V_1 - V_0}{R_f}$$

$$V_1 R_f - V_- R_f = V_1 R_1 - V_0 R_1$$

$$V_1 R_f + V_0 R_1 = V_1 [R_1 + Rf]$$

$$V_- = \frac{V_1 R_f + V_0 R_1}{R_1 + R_f}$$

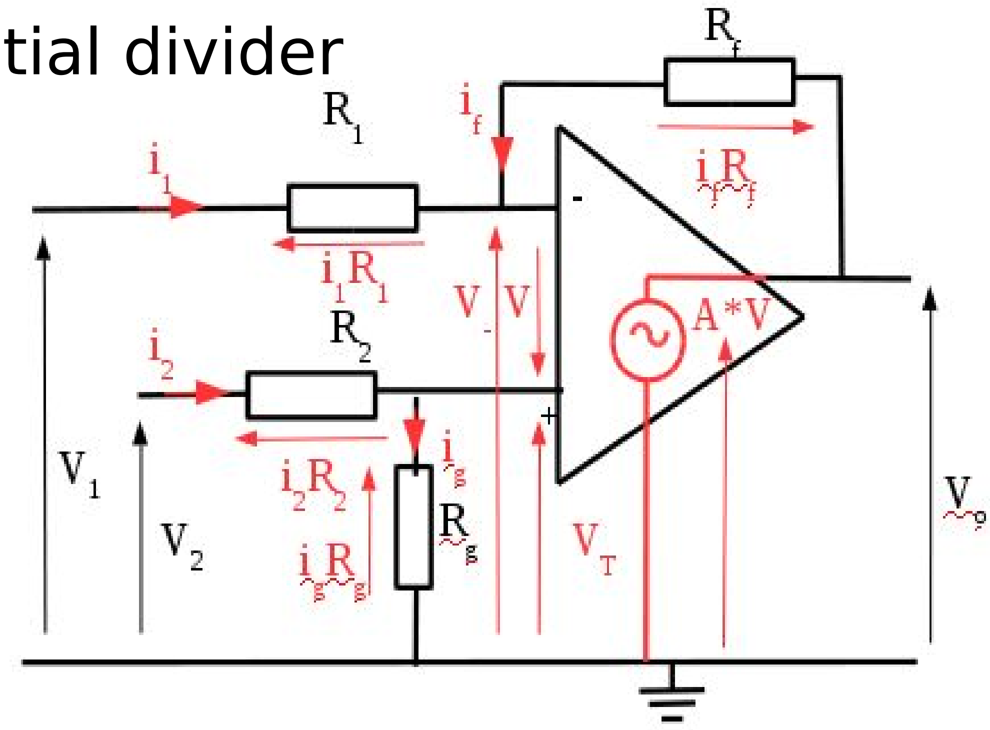
Then write an expression relating input V_2 to the non-inverting input of the op-amp.

As the input resistance of the op-amp R_{in}=infinity

$$i_g = i_2$$

And R_2 and R_g from a potential divider

$$V_+ = \frac{R_g}{R_2 + R_g} V_2$$



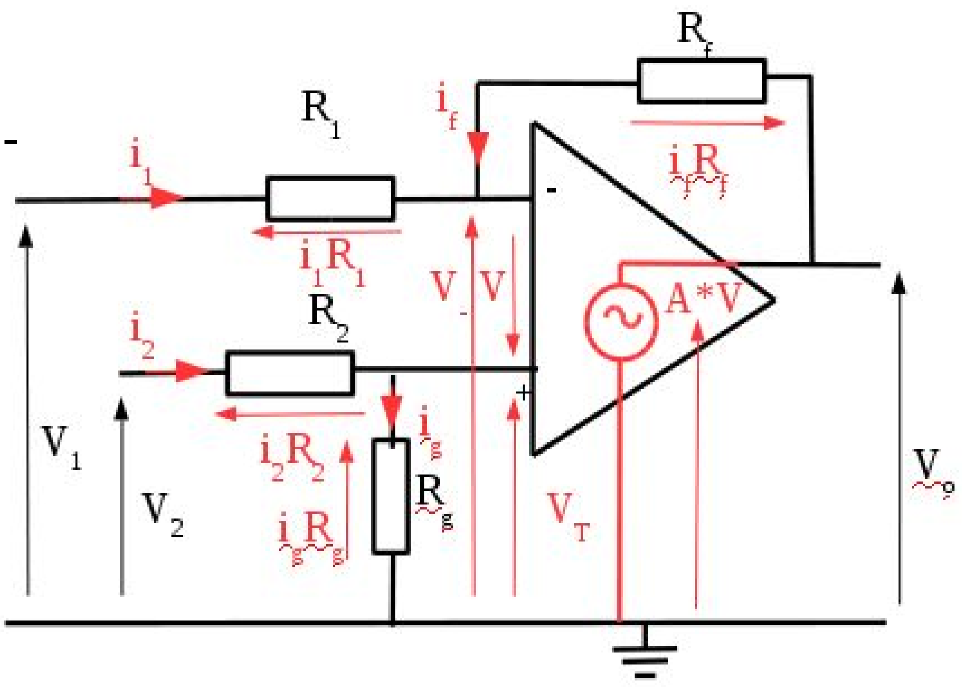
Now write an expression relating the inputs of the op-amp to the output of the circuit

We know that, $V_0 = VA$ **5**

We also know, $V = V_+ - V_-$ **4**

Therefore $\frac{V_0}{A} = V_+ - V_-$

We now have an expression **relating the inputs of the op-amp to the output** and we have **expressions relating the input terminals to the inputs of the op-amp**.



Recap and rearranging our equations……

$$\frac{V_0}{A} = V_+ - V_- \qquad V_- = \frac{V_1 R + V_0 R_1}{R_1 + R_\mathrm{f}} \qquad V_+ = \frac{R_g}{R_2 + R_g} V_2$$

Substituting 3,4 and 6 in 5 we get

$$\frac{V_0}{A} = \left[\frac{R_g}{R_2 + R_g}\right] V_2 - \left[\frac{V_1 R_f + V_0 R_1}{R_1 + R_f}\right]$$

$$V_0 \left[\frac{1}{A} + \frac{R_1}{R_1 + R_f}\right] = V_2 \left[\frac{Rg}{R_2 + R_g}\right] - V_1 \left[\frac{R_f}{R_1 + R_f}\right] \qquad \mathbf{7}$$

Let's make a few assumptions..

$$V_0\left[\frac{1}{A}+\frac{R_1}{R_1+R_f}\right]=V_2\left[\frac{Rg}{R_2+R_g}\right]-V_1\left[\frac{R_f}{R_1+R_f}\right]$$

If A>> 0, $R_2=R_1$ and $R_g=R_f$

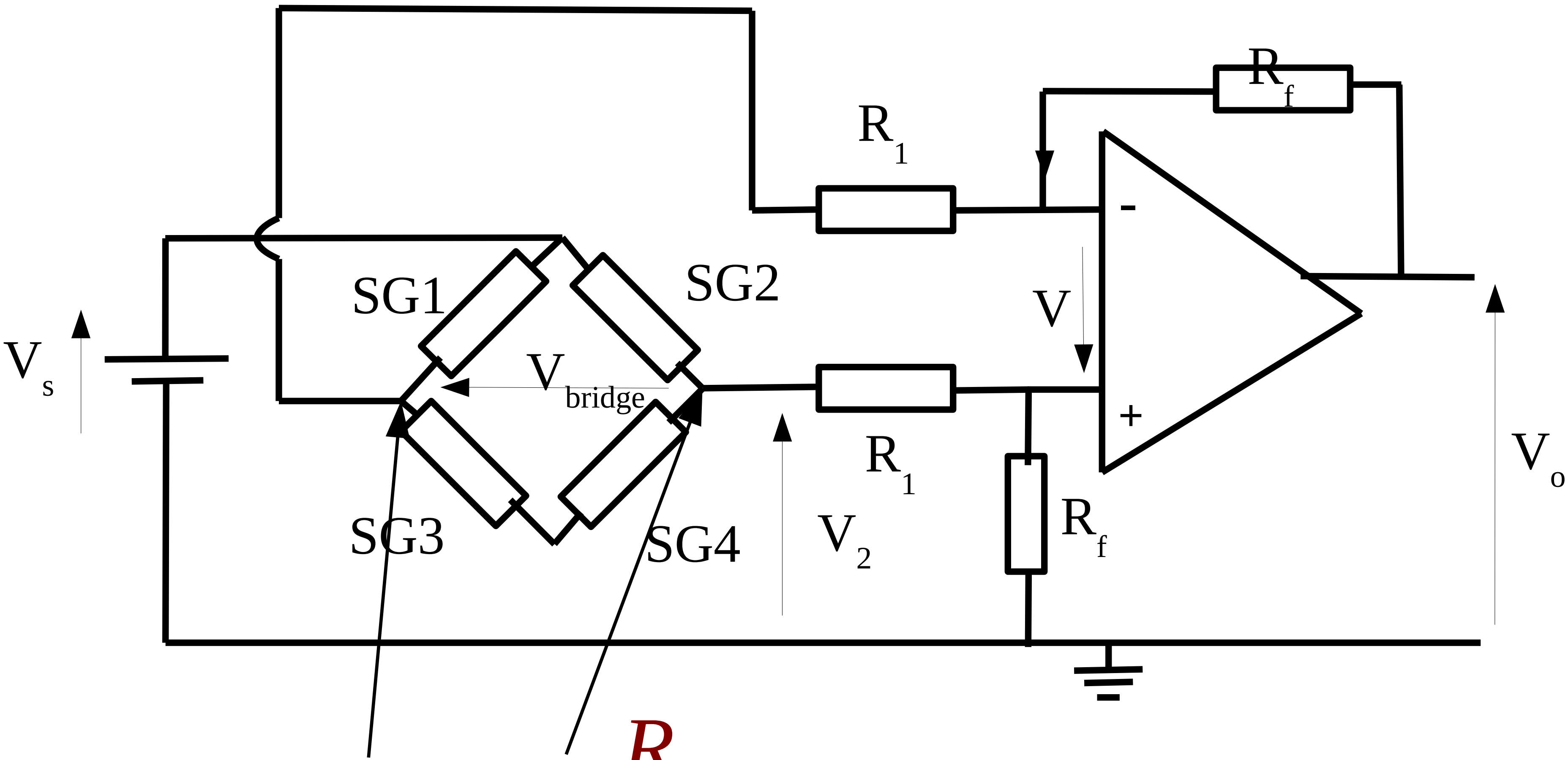
Which is generally true for difference amplifiers

$$V_0\left[\frac{R_1}{R_1+R_f}\right]=V_2\left[\frac{Rg}{R_2+R_g}\right]-V_1\left[\frac{R_f}{R_1+R_f}\right]$$

$$V_0\left[R_1\right]=V_2\left[R_f\right]-V_1\left[R_f\right]$$

$$V_0=[V_2-V_1]\frac{R_f}{R_1}$$

Questions



$$V_0 = [V_2 - V_1] \frac{R_f}{R_1}$$

Typical exam question:

a) Explain why you would need to use an operational amplifier when using a strain gauge?

b) Your strain gauge is attached to an operational amplifier with $R_1 = R_2 = 10\,k\Omega$ and $R_g = R_f = 1\,M\Omega$ calculate the output voltage when the wheatstone bridge produces 0.1 V across it.

$$V_0 = [V_2 - V_1]\frac{R_f}{R_1}$$

Typical values

a) Strain gauges produces very small voltages which need to be amplified.

b) $R_1 = R_2 = 10\, k\,\Omega$ $R_1 = R_2 = 1\, M\,\Omega$

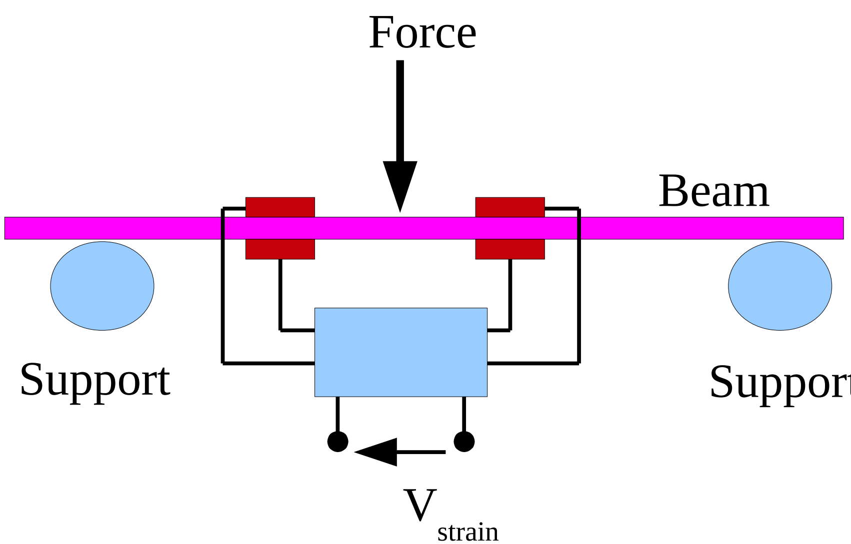
Therefore

$$V_0 = [V_2 - V_1]\frac{1\,x\,10^6}{1\,x\,10^4}$$

$$V_0 = 100\,[V_2 - V_1]$$

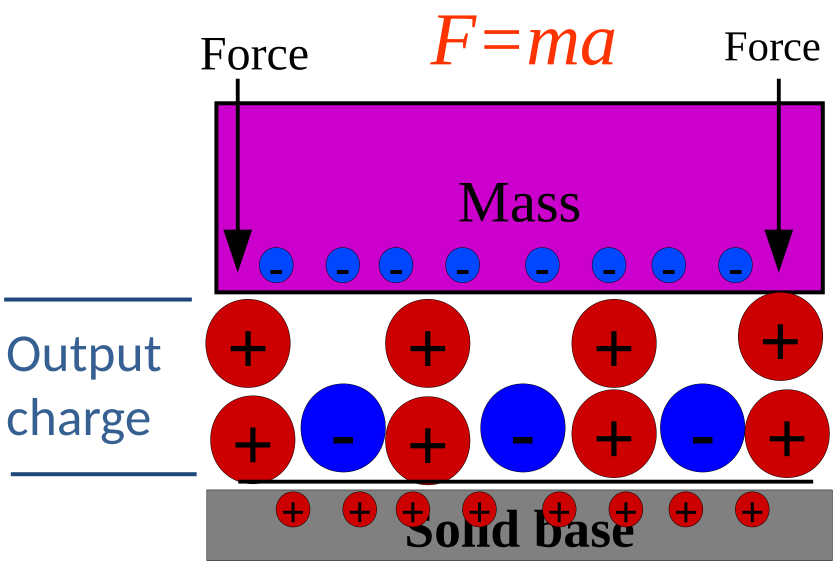
Summary

We can now analyse the circuit for strain gauges and accelerometers



Strain gauge

acceleration



Accelerometer