University of
Nottingham

Electromechanical devices MM2EMD

Lecture 4 – Analog electronics
“every idiot can count to one” - Bob Widlar

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Outline of the lecture

- **No recap of last lecture :)**
  - Finish off digital electronic- Race times

- Analog electronics

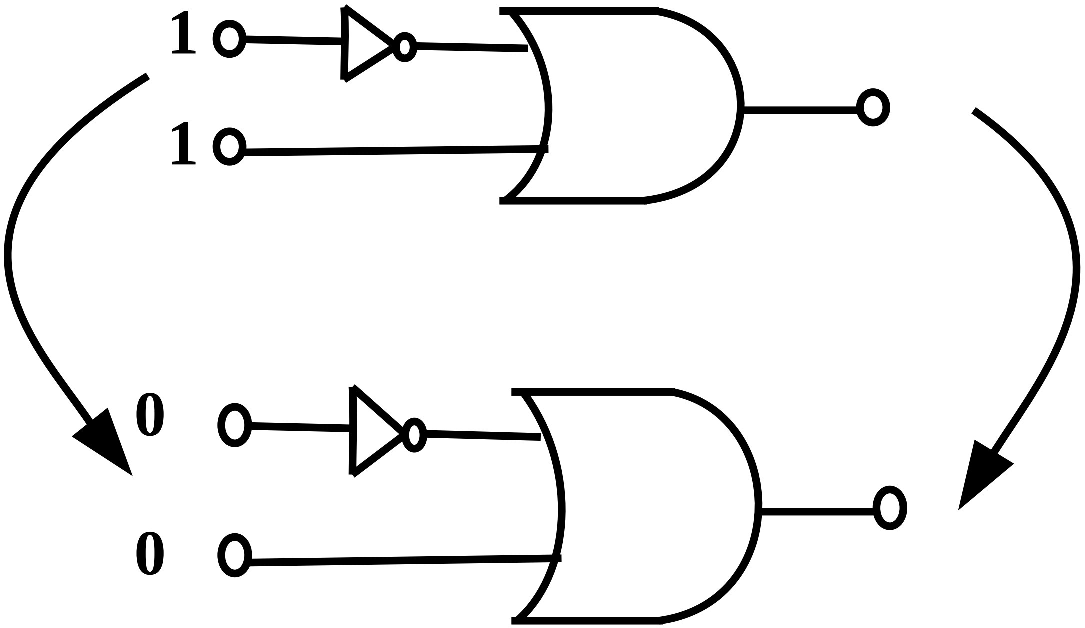
  - Operational Amplifiers
    - What is an op-amp and what are they used for?

    - Two fundamental op-amp circuits
      - Inverting amplifier
      - Particle op-amps
      - Summing amplifier

- Summary

Last tip on digital electrons **race times**

•Think about this circuit...

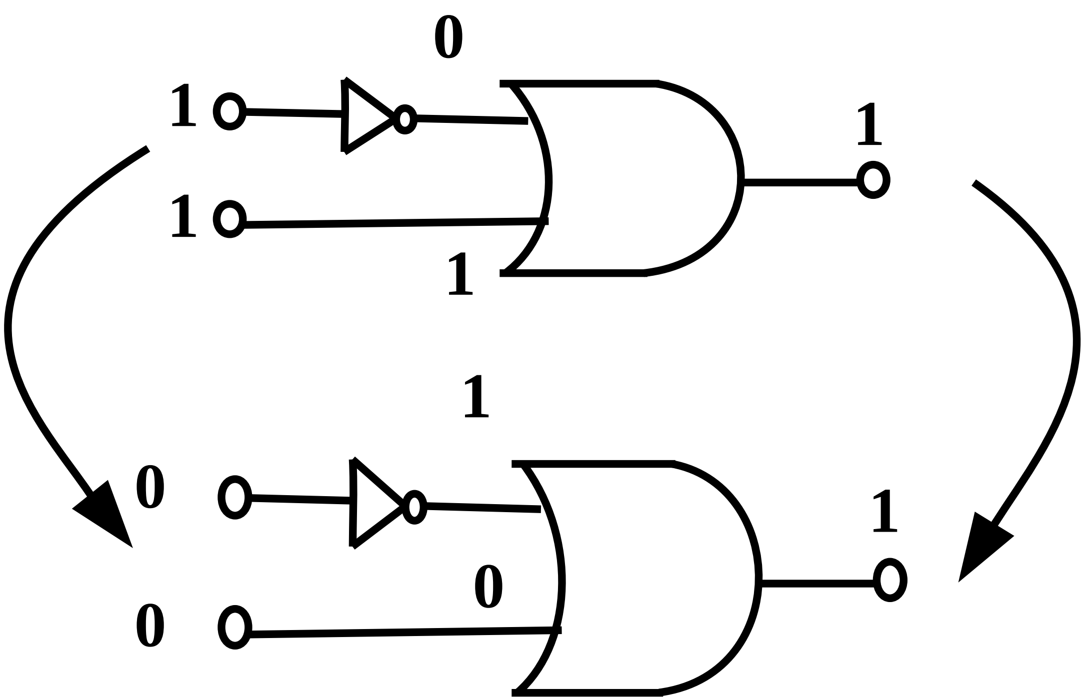


Slooby from Chicago

•Let's draw this out in detail

Last tip on digital electrons **race times**

•If you changed the inputs from 11 to 00 the outputs would not change.

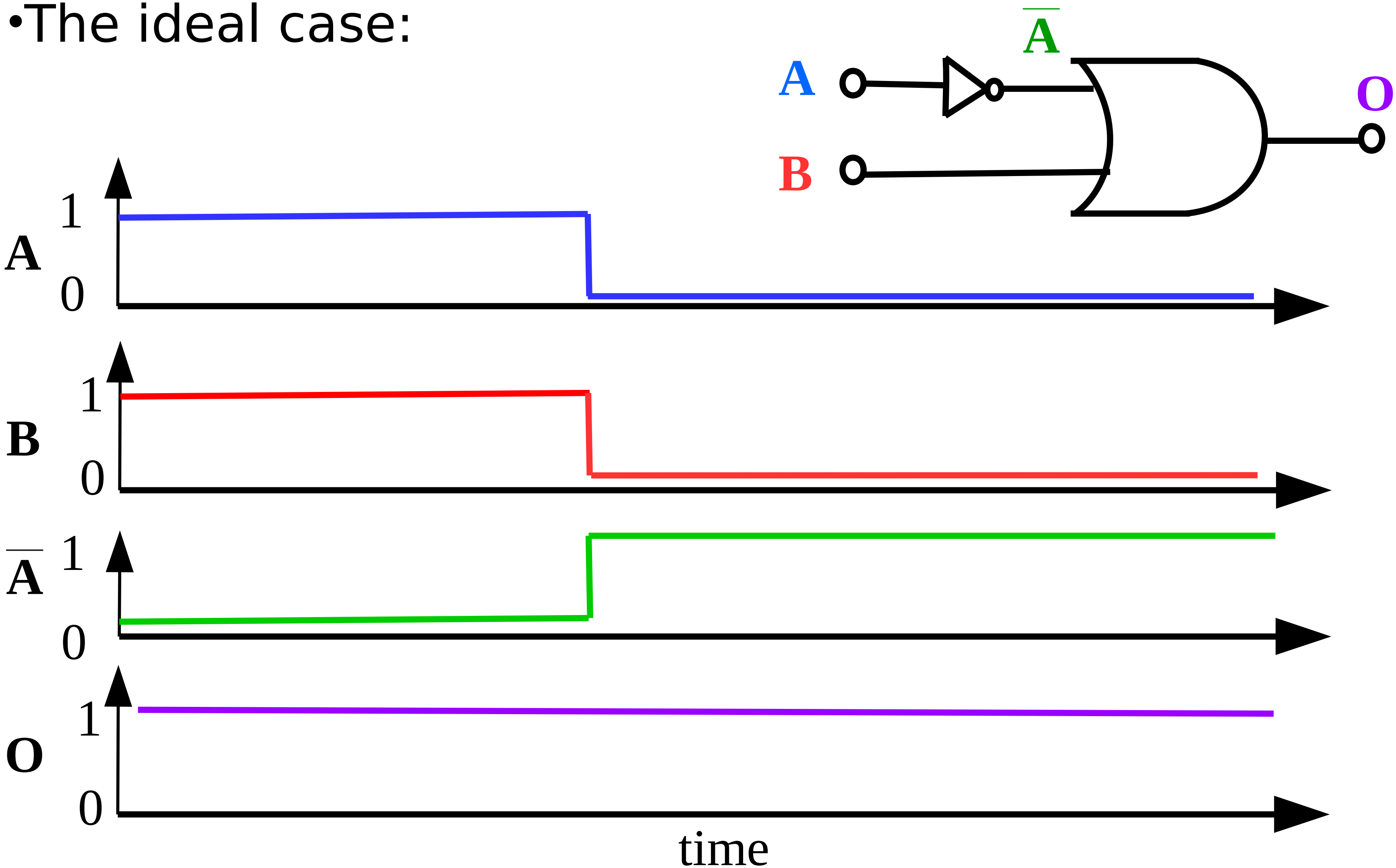


Slooby from Chicago

•Let's draw this out in detail

Last tip on digital electrons **race times**

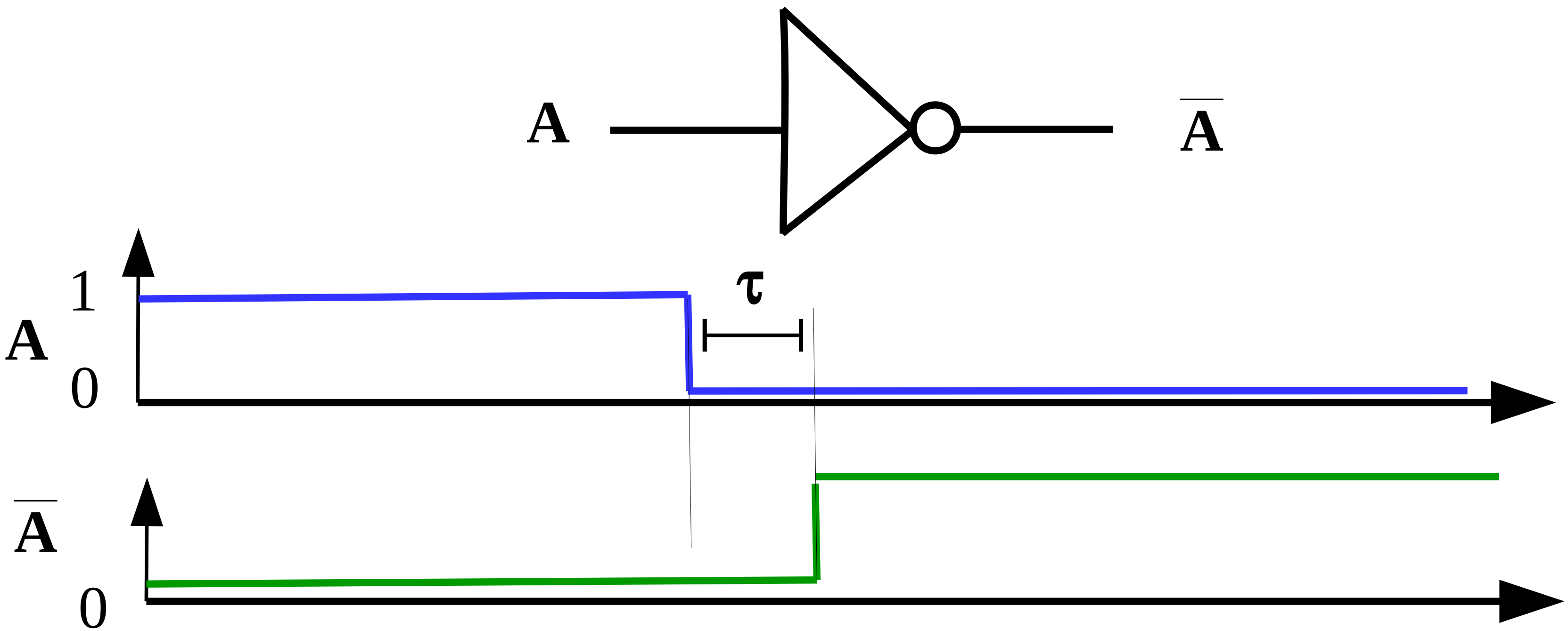
- The ideal case:



However, you should know that....

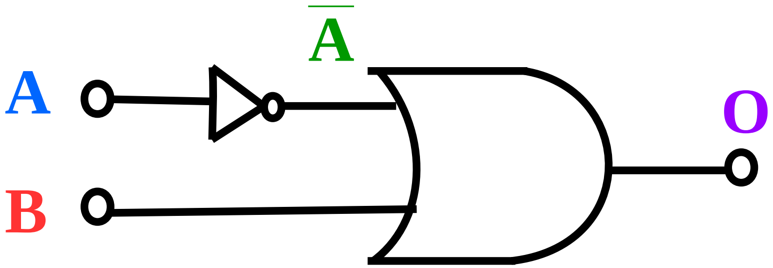
•All gates have a 'turn on' and 'turn off' time.

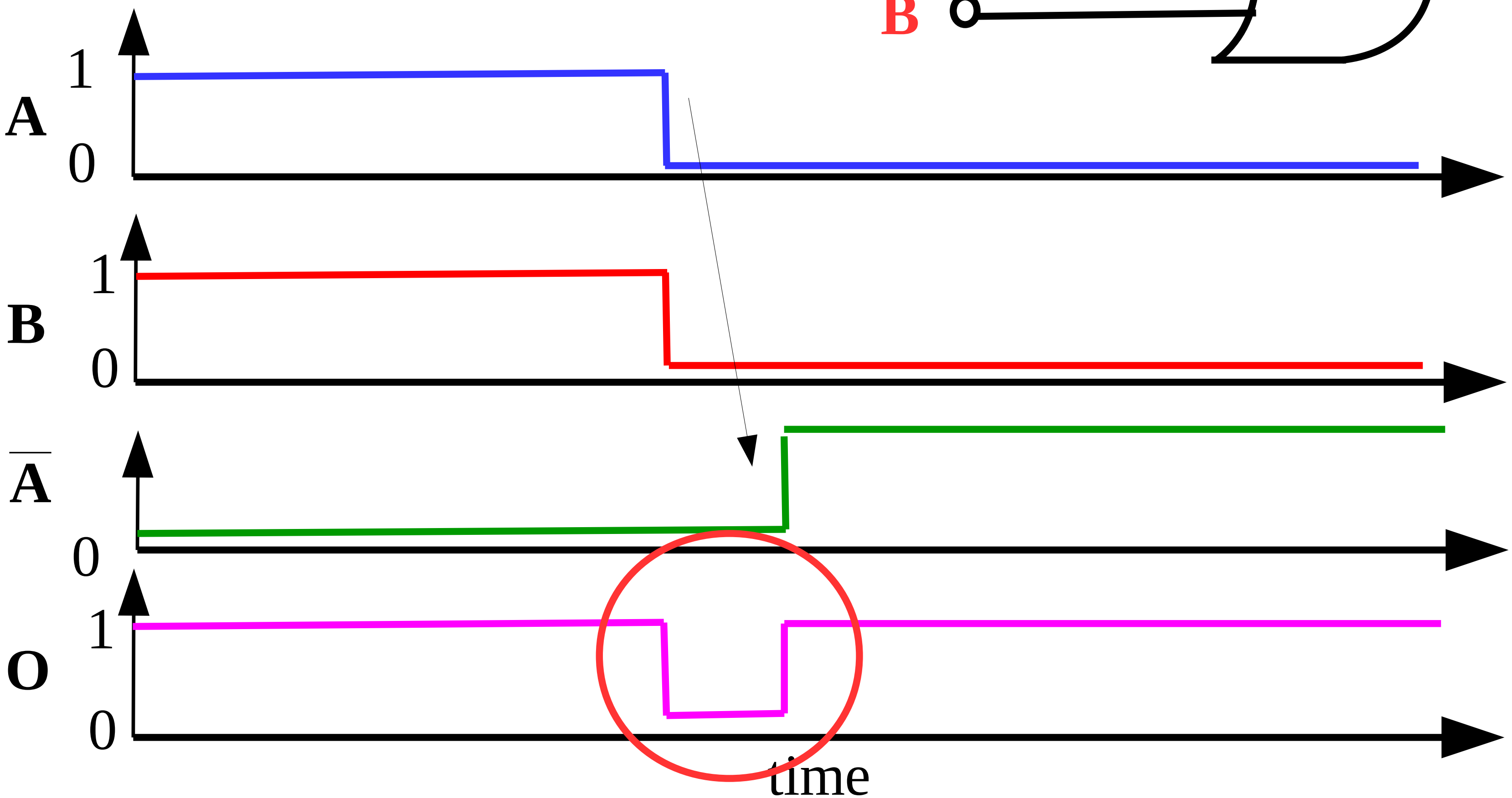
•This is in effect a time it takes the gate to react to an input - **τ**.



Last tip on digital electrons **race times**

•However every gate takes a finite time to respond (micro seconds).





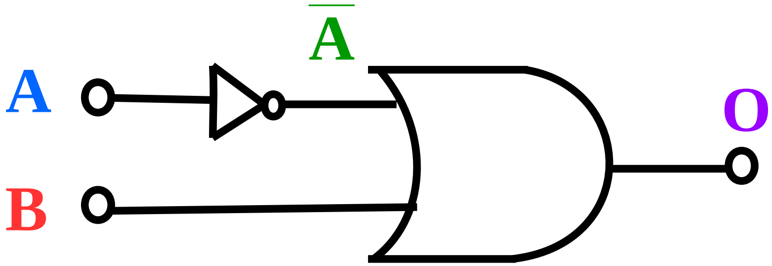
Last tip on digital electrons **race times**

- Gates take microseconds to respond.

- This means your output can be wrong for up to a microsecond.

- The more gates you have the longer theses effects will last for.

- Often glitches don't matter, but if you are designing sensitive (fast) circuits, they can be really really important.



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- **Analog electronics**
    - Operational Amplifiers
        - What is an op-amp and what are they used for?
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            - Inverting amplifier
            - Particle op-amps
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Book chapter

- Everything you need for the exam is in this lecture and the example sheet.

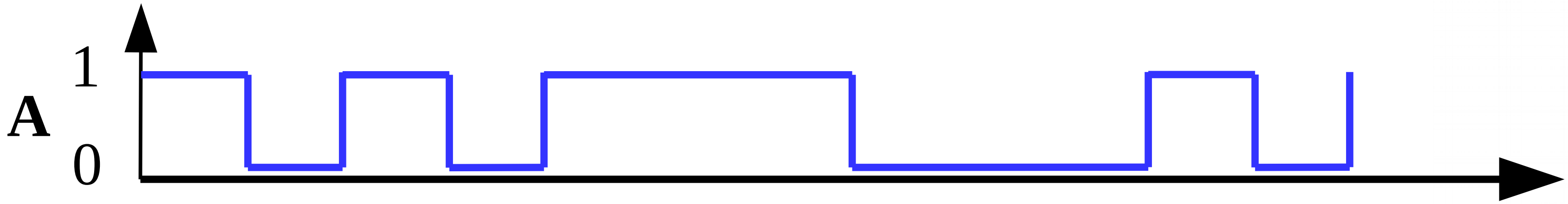
- However if you would like to read more in depth about this subject:

  - **An Introduction to Mechanical Engineering: Part 1 pages 365 to 371**

Digital signals

•Until now I have only taught you how to use **digital electronics** to process information.

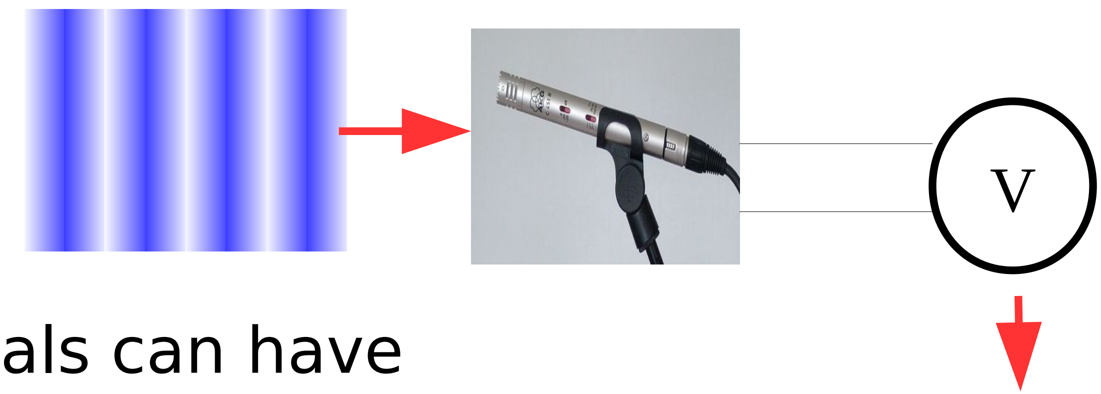
•In digital electronics signals can either be ***on*** (1) or ***off*** (0) and all information is transmitted and stored using binary numbers.



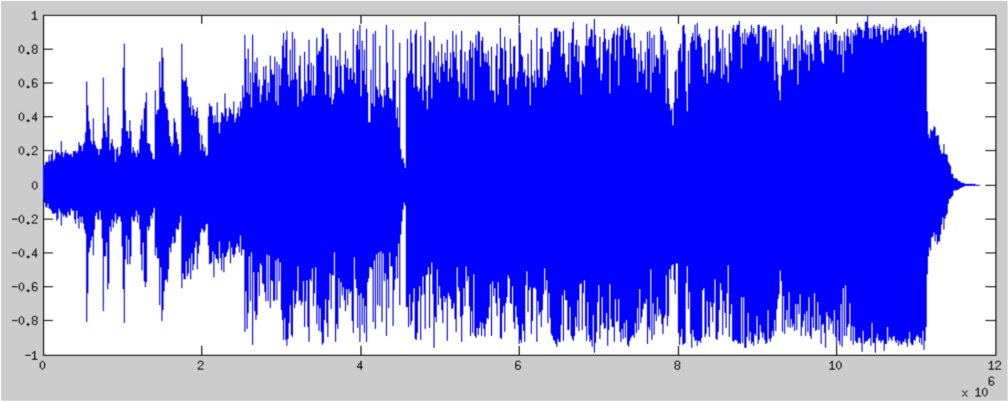
•However the **real world** is not binary, think of playing a music on a guitar.....

Analog signals.

•Your guitar produces compression waves in the air that a microphone can pick up.



•These signals can have any value and are called **analog signals**.



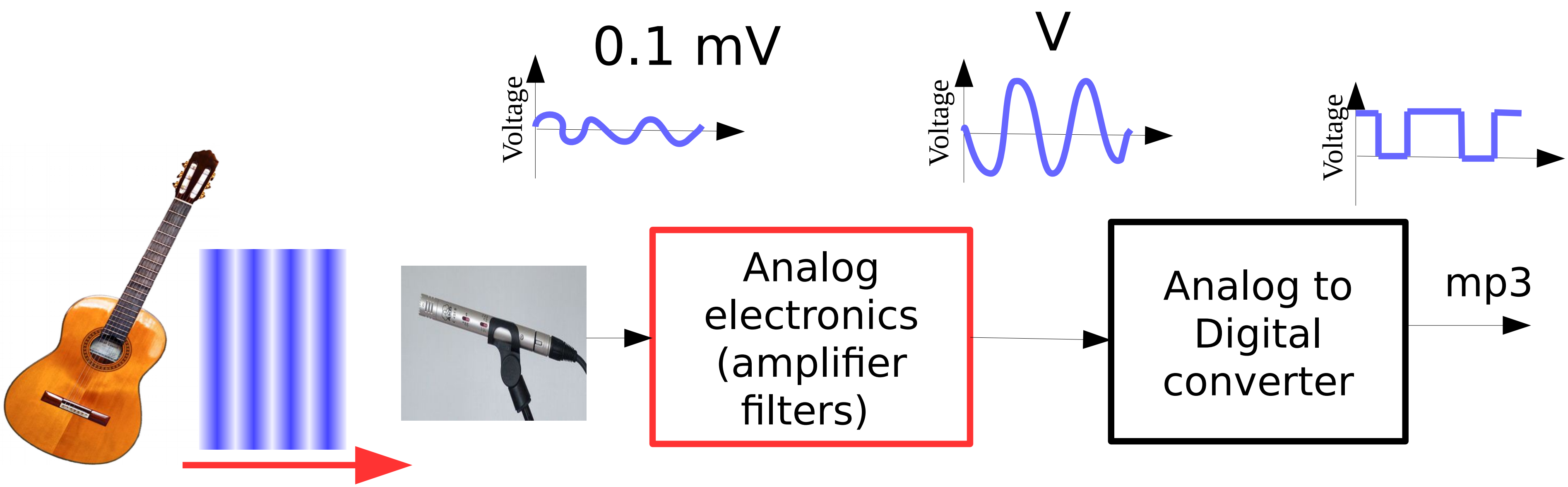
Analog electronics – why?

- Why are you going to teach us about analog electronics, is not everything digital nowadays?
    - **TV**, **music**, **radio** etc.

- Yes, but there is always an analog part to any circuit interacting with the real world.

- Example....

An MP3 recorder as an example of a modern analog and digital system.



•Being able to process analog signals is very important.

•And this is what I am going to teach you about in this lecture.

Where else will we find analog electronics?

- Common applications include:
  - Audio and video pre-amplifiers
  - **Filters – clean up signals.**
  - Voltage regulators
  - Analog to digital converters (data acquisition)
  - **Amplifying small signals from sensors before sending the data to a computer**

- To make all theses circuits you use something called an operation amplifier

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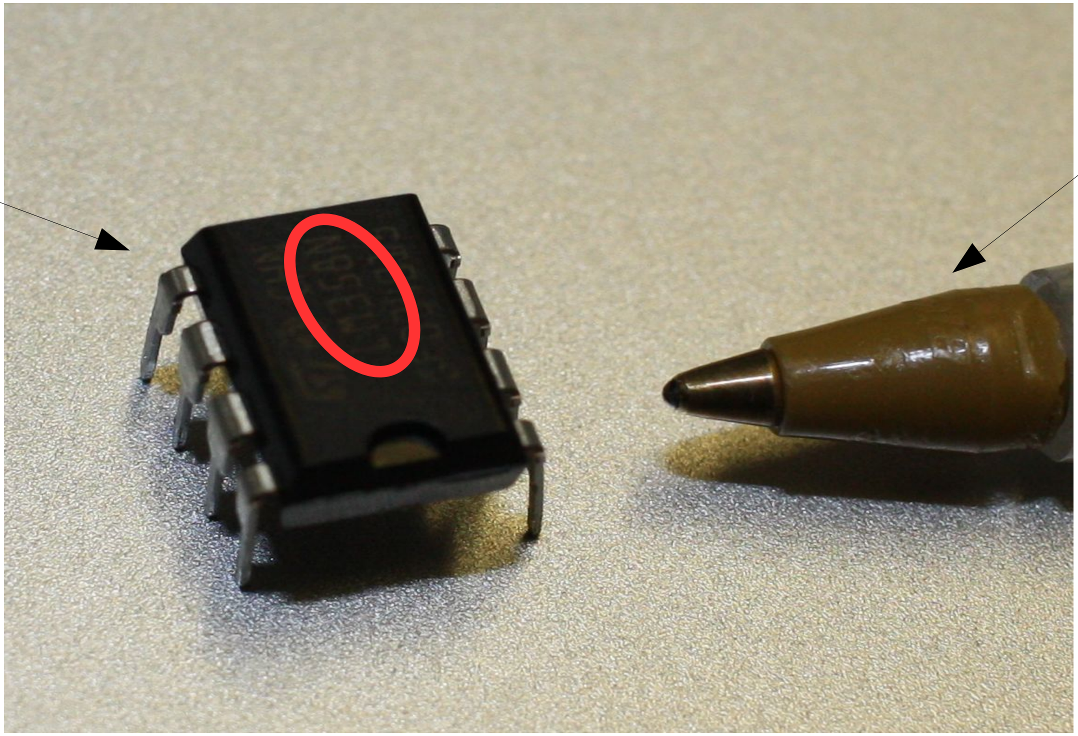
The operational amplifier

One of the most useful/versatile and widely used analog chips is the operation amplifier.

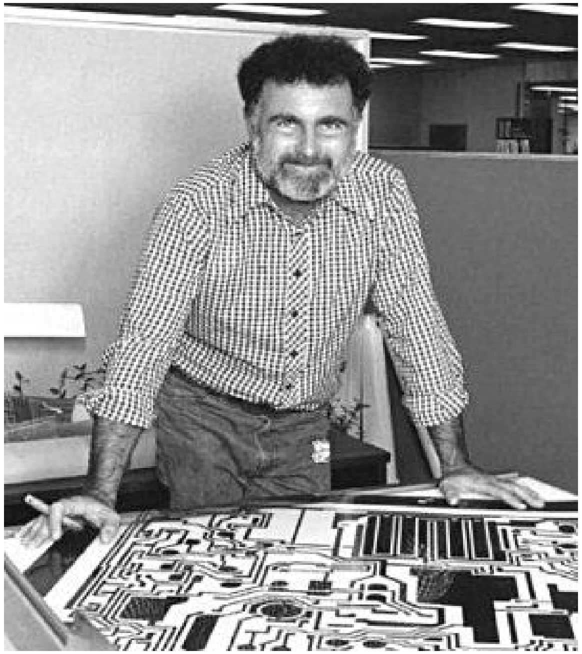
Op-amp in 8 pin DIP package



Biro

“every idiot can count to one”

•This is the farther of modern analog electronics - Bob Widlar

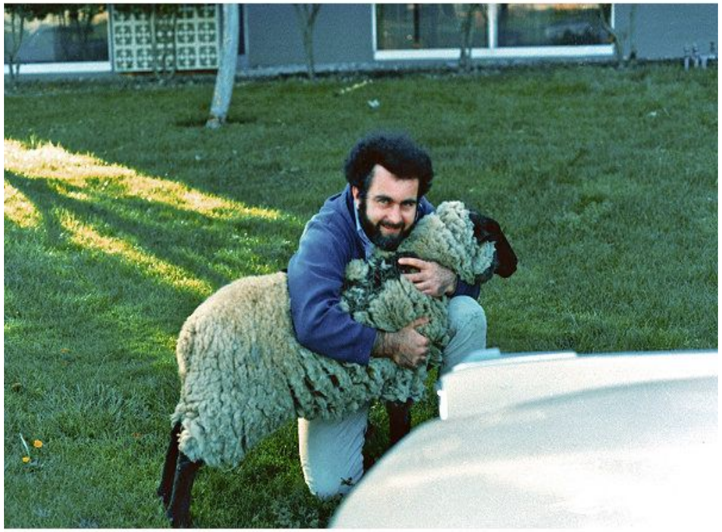


•He was a genius and eccentric who spent his life designing the very first versions of **all the analog chips we are going to learn about in the next couple of lectures**.

•He said “***every idiot can count to one***”, meaning that analog electronics hard is harder than digital electronics but often more worth while.

The human aspect

•"Widlar lived the life of an alcoholic loner, who went on all-night-long bar binges. He liked to fight others when drunk, but regularly overestimated his own abilities in such confrontations. On one occasion he was "absolutely clocked" by the offended Mike Scott, a future CEO of Apple Inc."



•However, the story about Widlar bringing a goat to trim the lawn in front of his office, was incorrect. It was a sheep. He brought her in his Mercedes-Benz convertible for just one day, he later abandoned her in the nearest bar.

•Let's look at some of this character designed..

What is the purpose of an op-amp

We can guess what they do by the name:

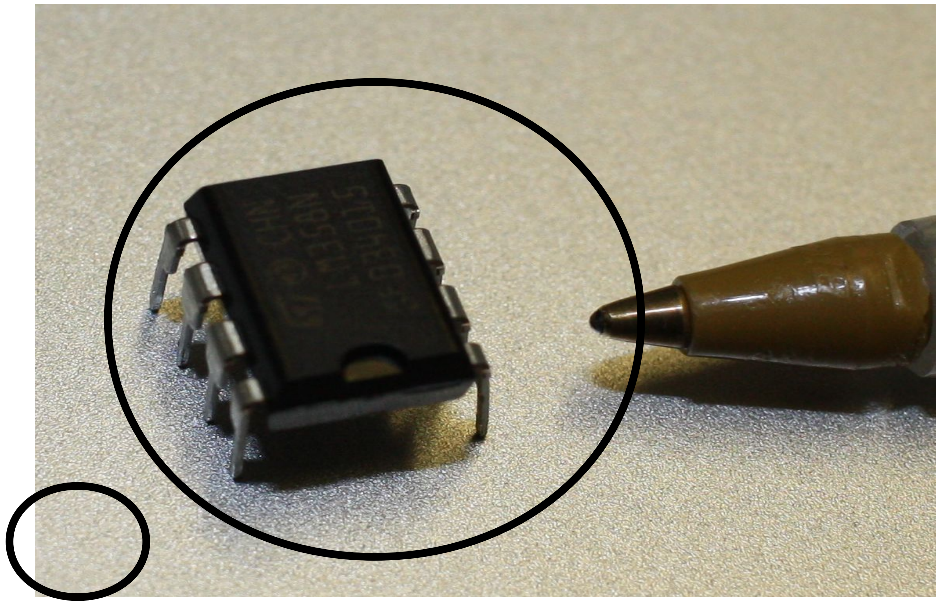
Operational amplifier

And 'operation', think of a mathematical operation.

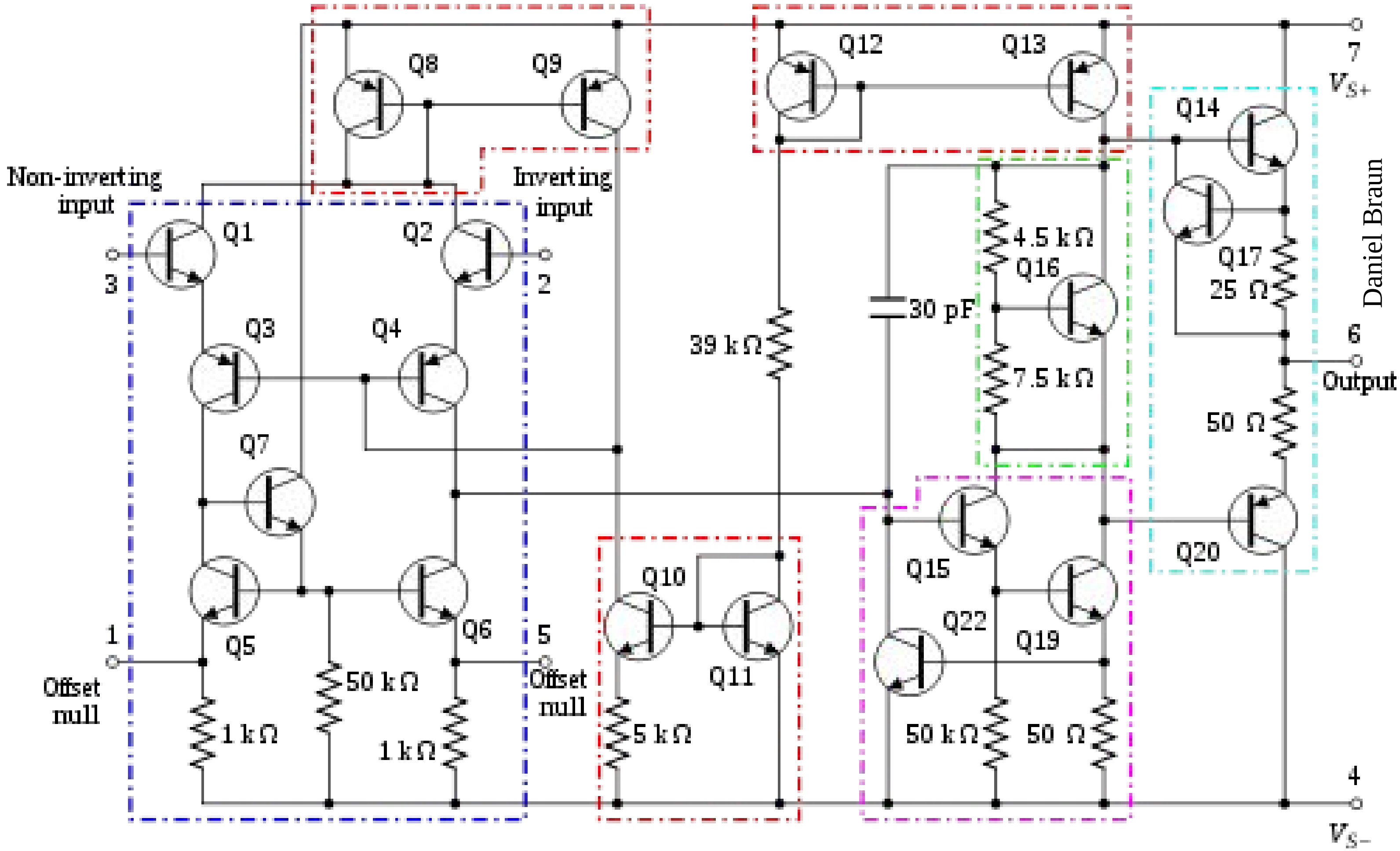
An amplifier i.e. something that makes a signal bigger.

In effect they are an amplifier that does maths.

But what is inside this op-amp?



Ahhh...

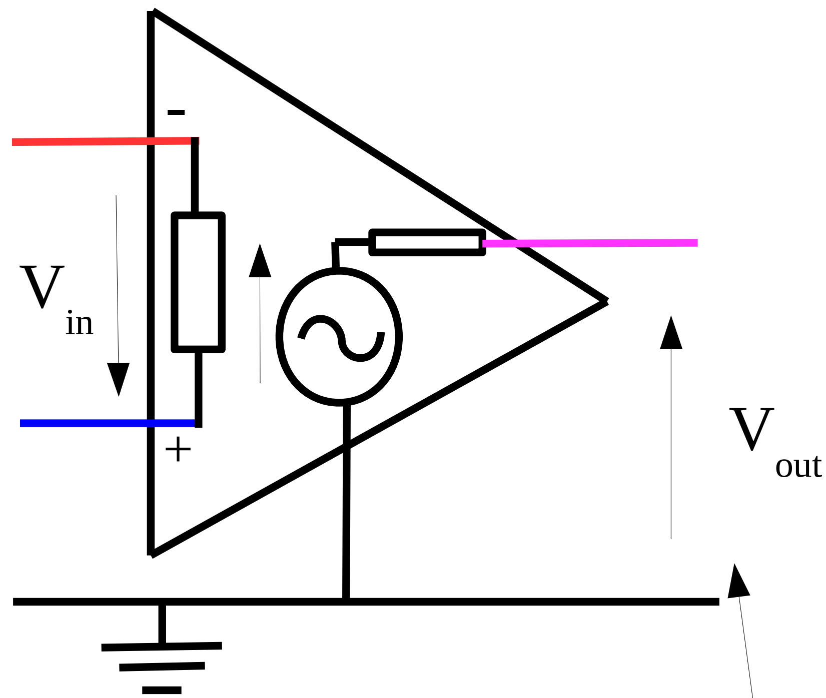


This is far too complex to understand, so let's just make a model of this complex circuit...

A model of an op-amp (equivalent circuit)

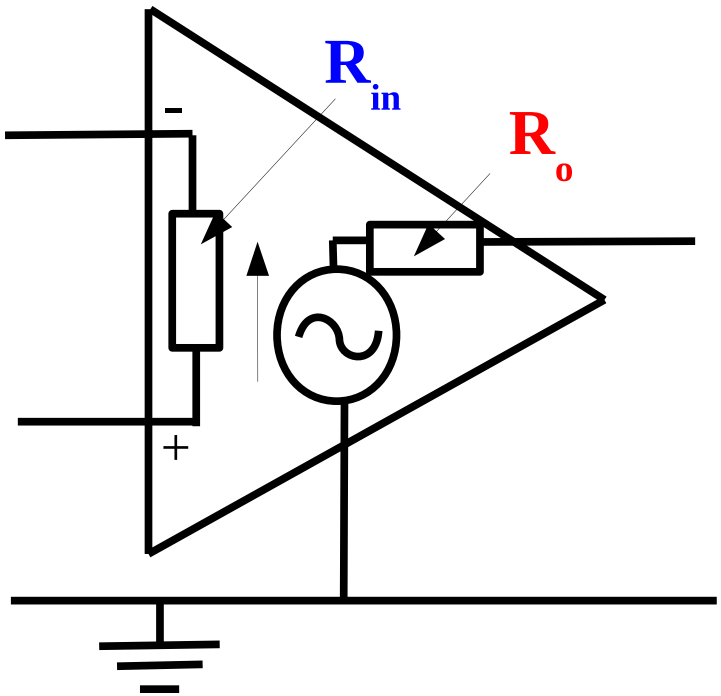
The Op-amp equivalent circuit has two inputs:

- Inverting input (-)
- Non-inverting input (+)



And an single output V_{out}.

It contains two resistors

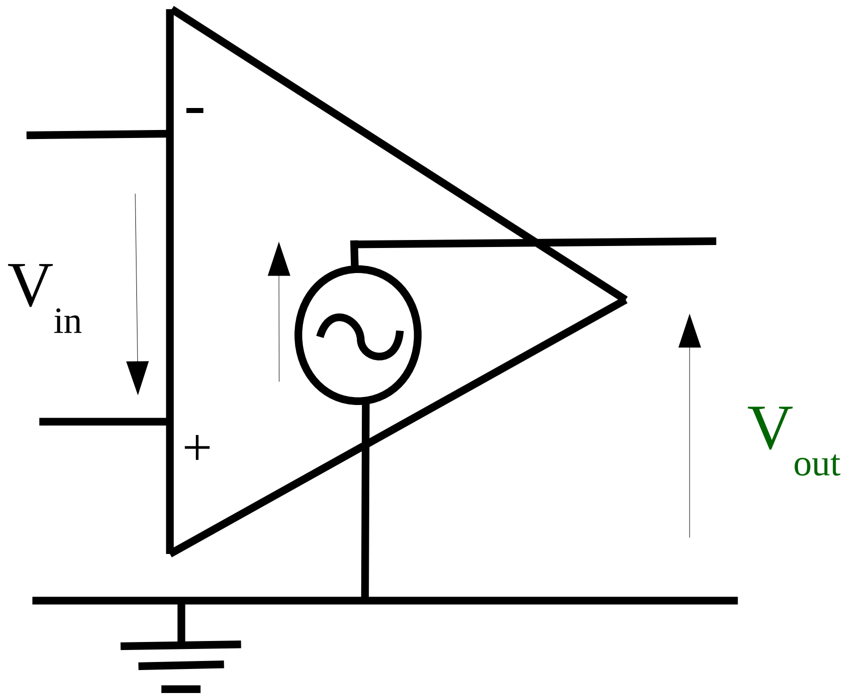


R_{in} = an input resistance – very high – we can assume this is infinite.

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

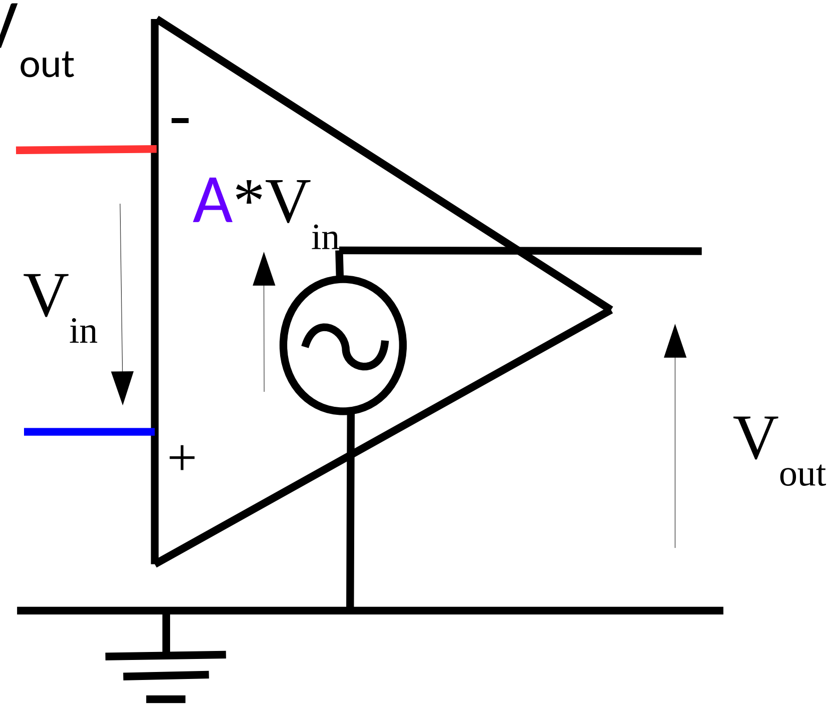
So let's further simplify our circuit taking into account the high R_{in} and the low R_o.

That's better



A model of an op-amp (equivalent circuit)

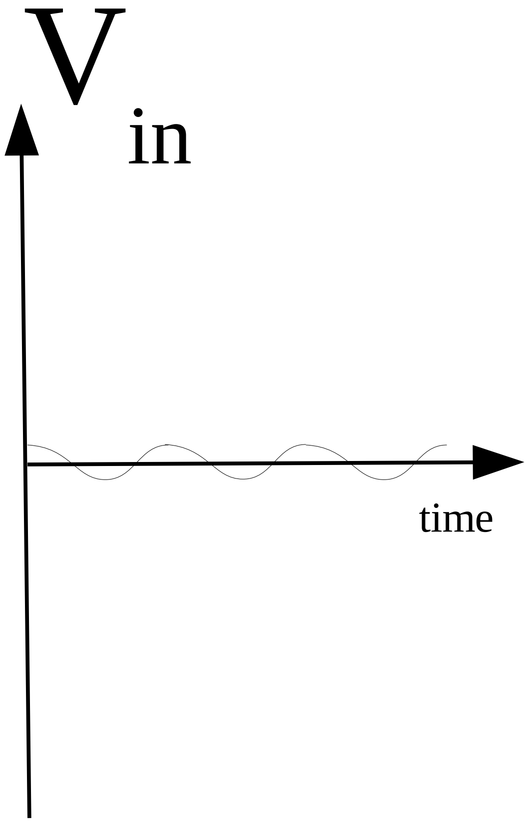
- The op-amp produces a voltage V_{out}
- A times bigger than V_{in}

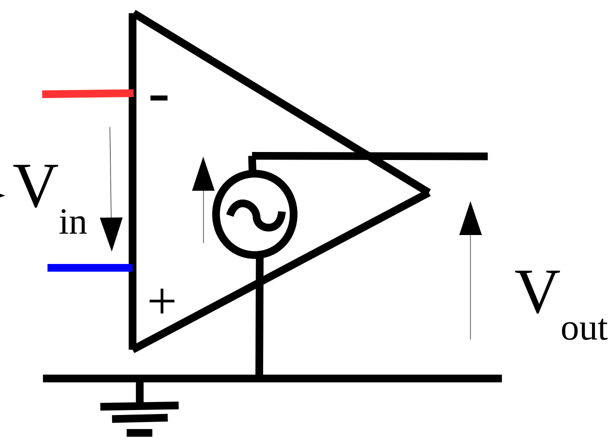


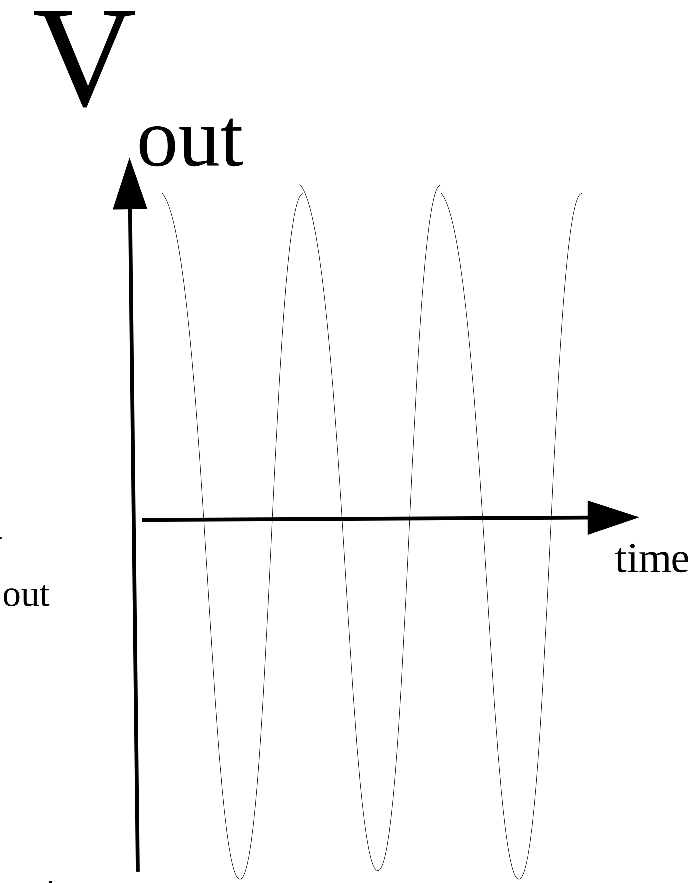
$$V_{in} A = V_{out}$$

- Where A is the gain (or amplification) of the op-amp.

'A' tells us how much bigger the output signal will be compared to the input signal.



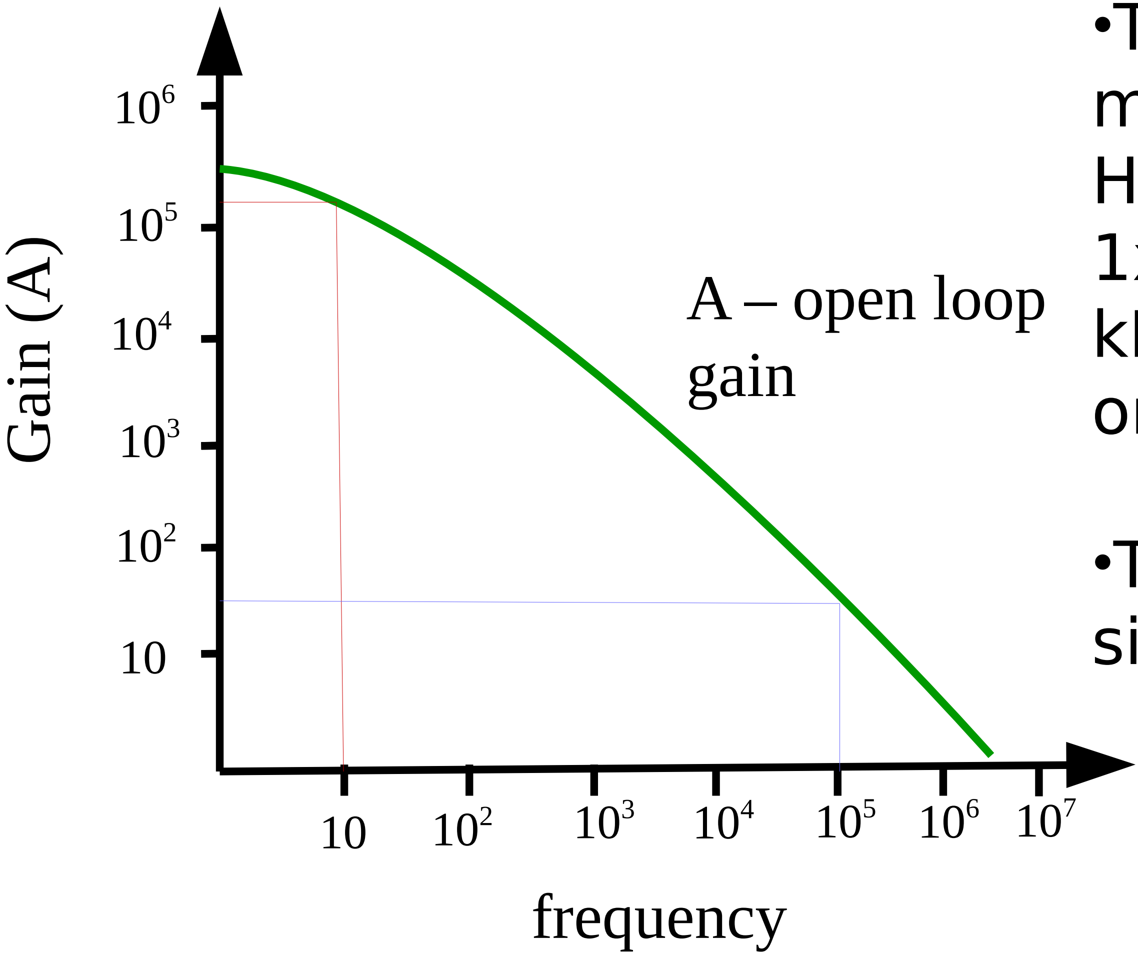




$$V_{in} \, A = V_{out}$$

- But what is A for a typical opamp?

That depends upon the frequency of input signal...

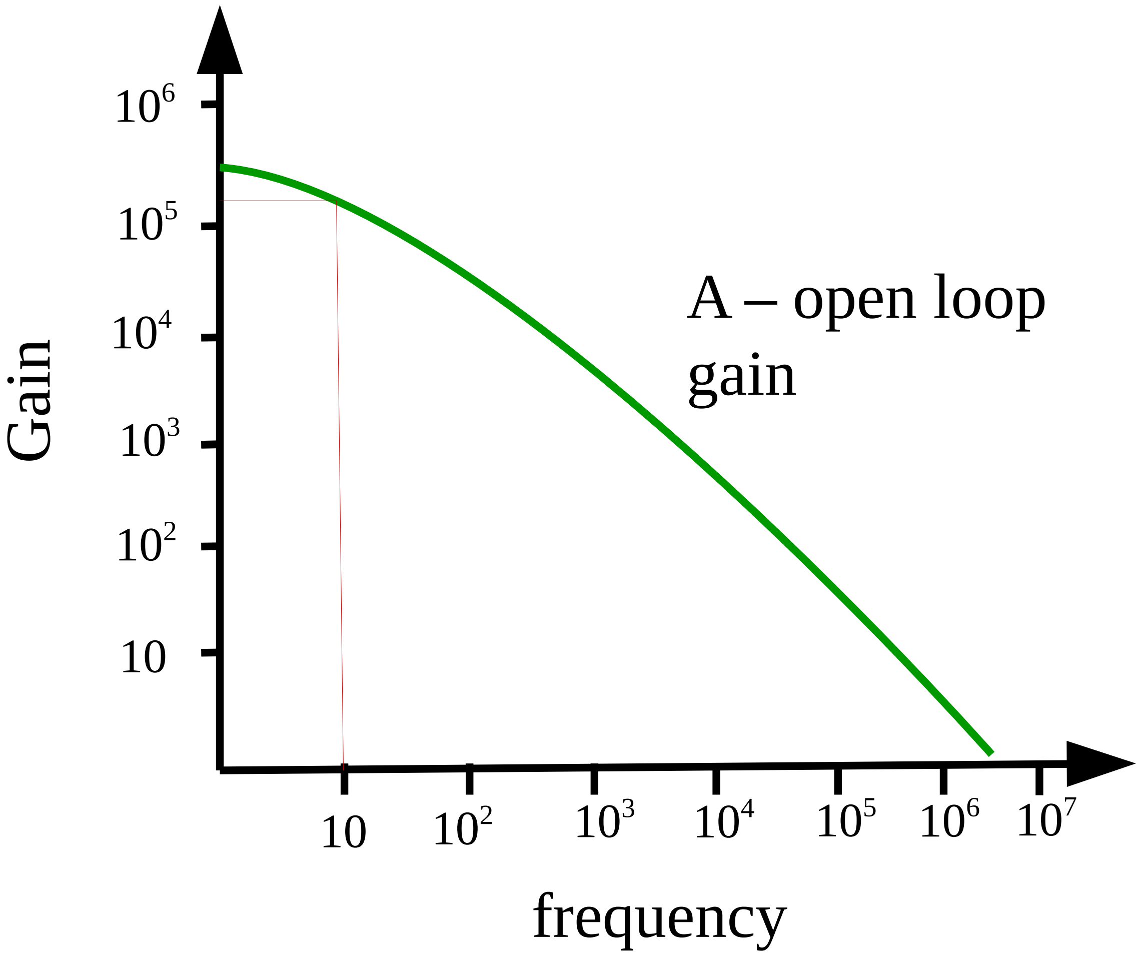


- The gain is non linear, meaning a signal at 10 Hz, will be amplified by $1x10^5$, but signal at 10 kHz will be amplified by only 100.

- This will mean your signal will be distorted.

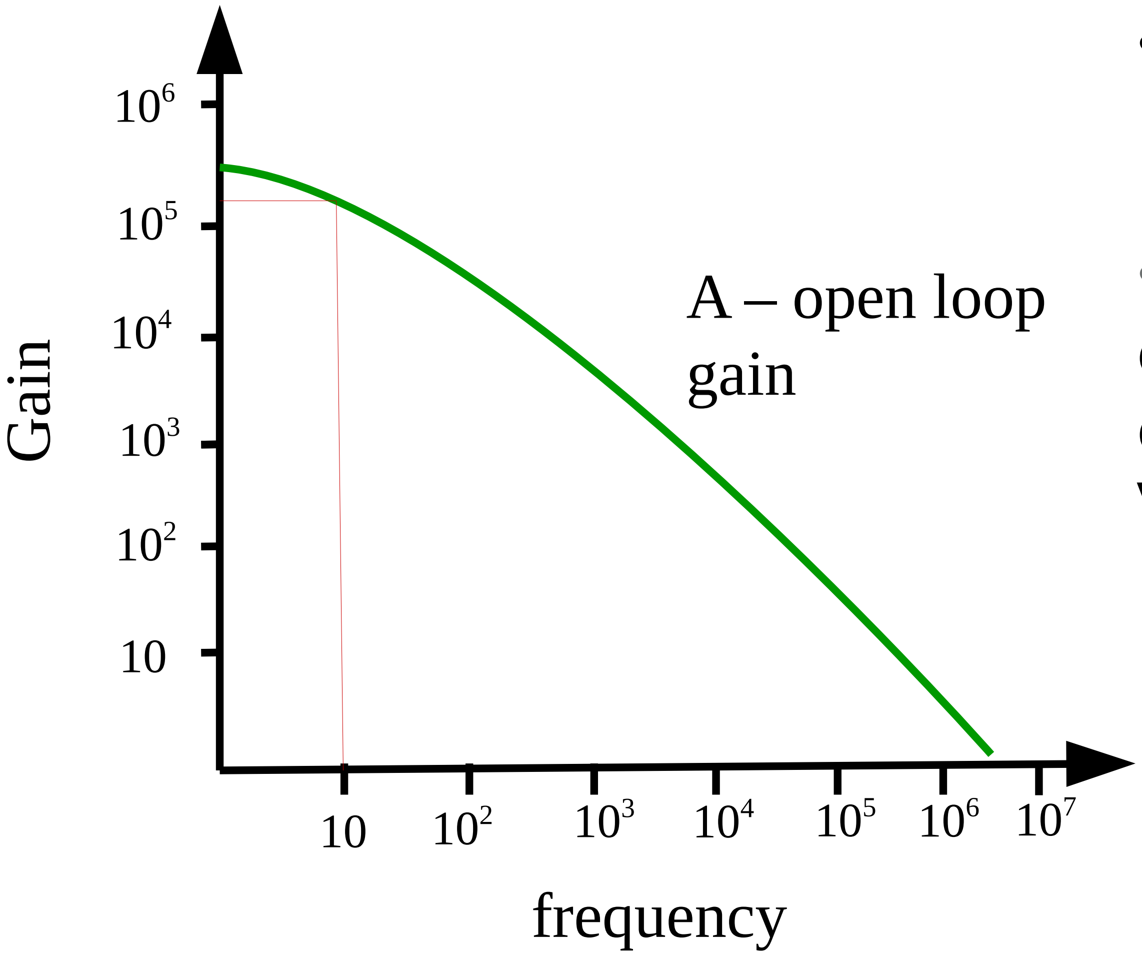
Hartmut Häfele

Another problem with this op-amp...



- Imagine we had a 0.01V signal at 10 Hz.
- What is the gain (A) at 10 Hz?
- $V_{out}=V_{in}A$
- What will V_{out} be?

Another problem with this op-amp…

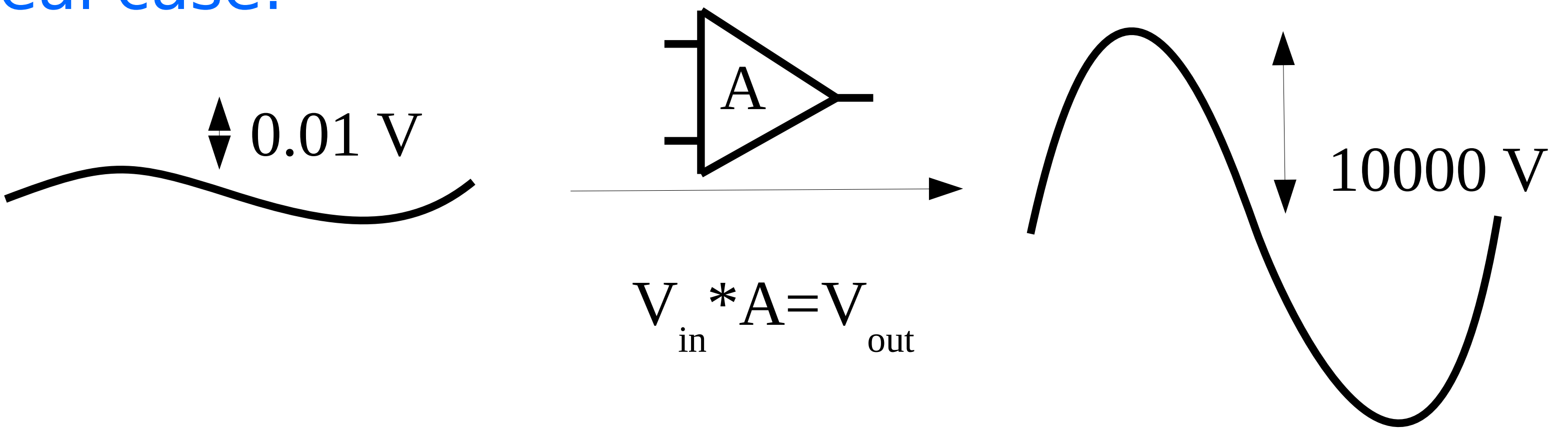


- An output voltage of 10000 Volts?

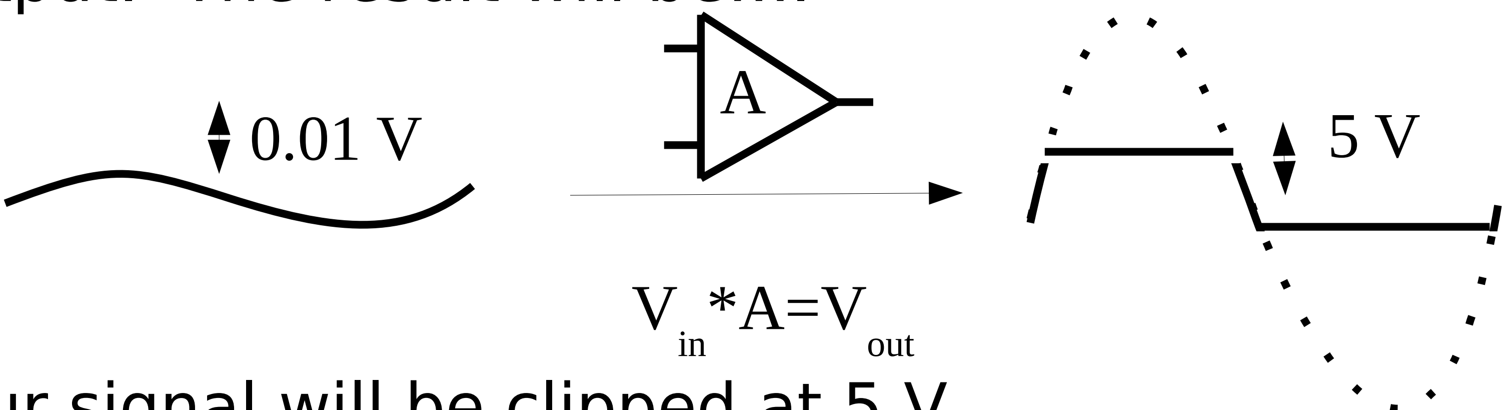
- This seems quite high, especially as op-amps can only run of 5 Volts???

Saturating your amplifier ($A=1x10^5$)

• Ideal case:

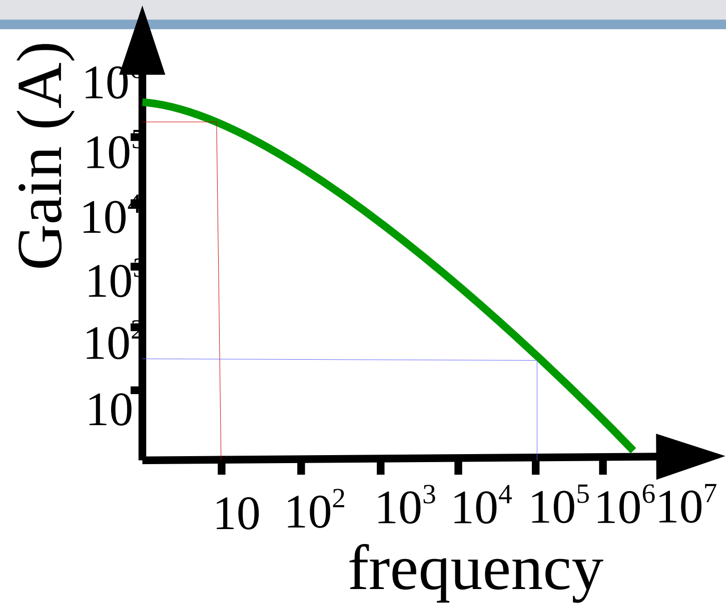


• What will really happen: Your op-amp runs from a 5V supply it will not be able to generate 1000V on the output. The result will be....



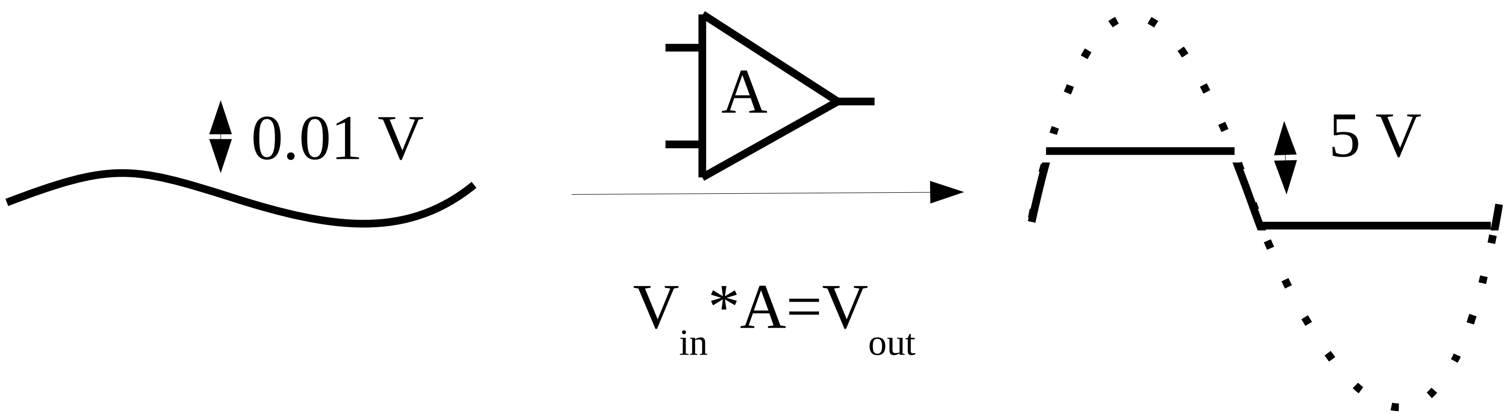
Your signal will be clipped at 5 V.

Problems with the op-amp..



- Non linear gain

- Output clipping



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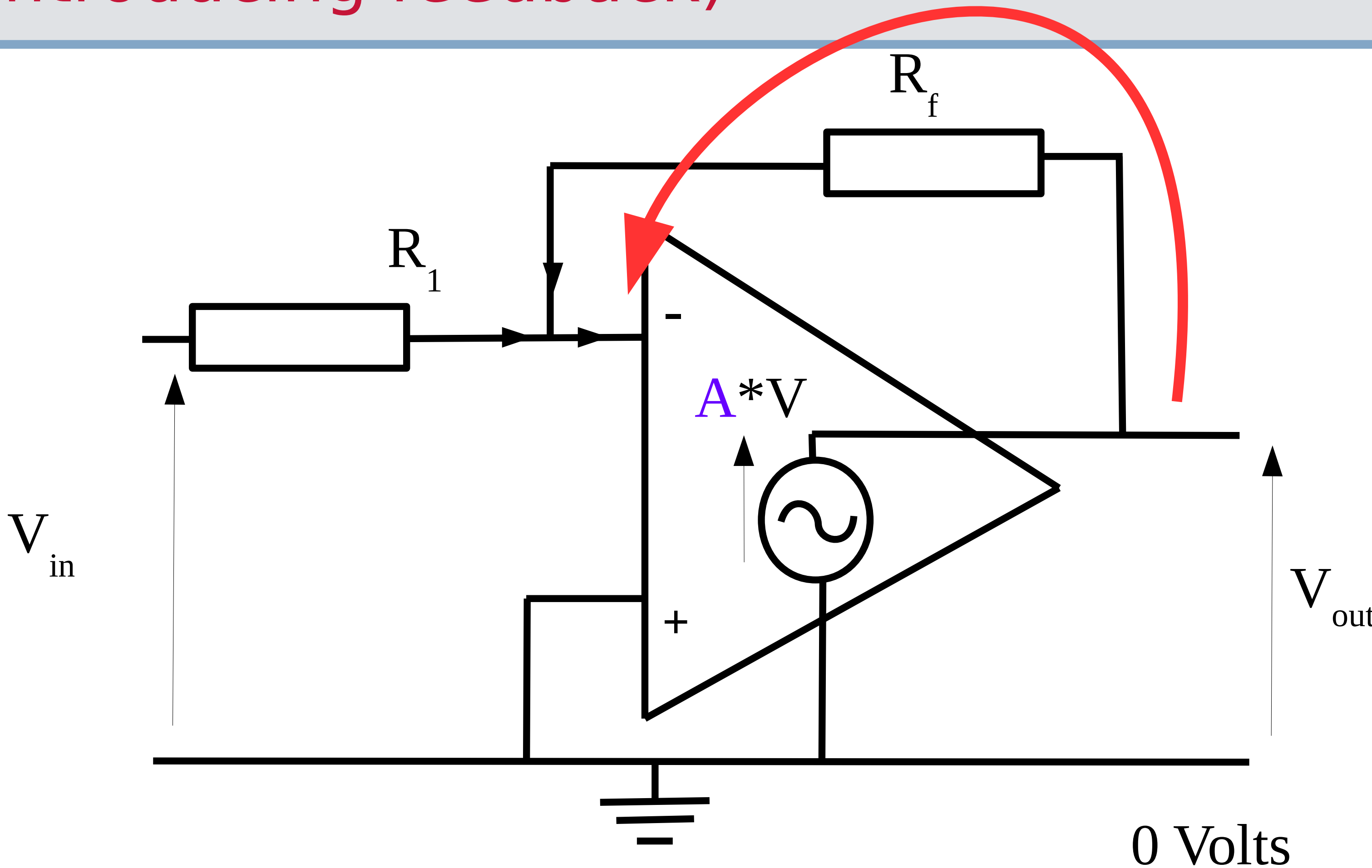
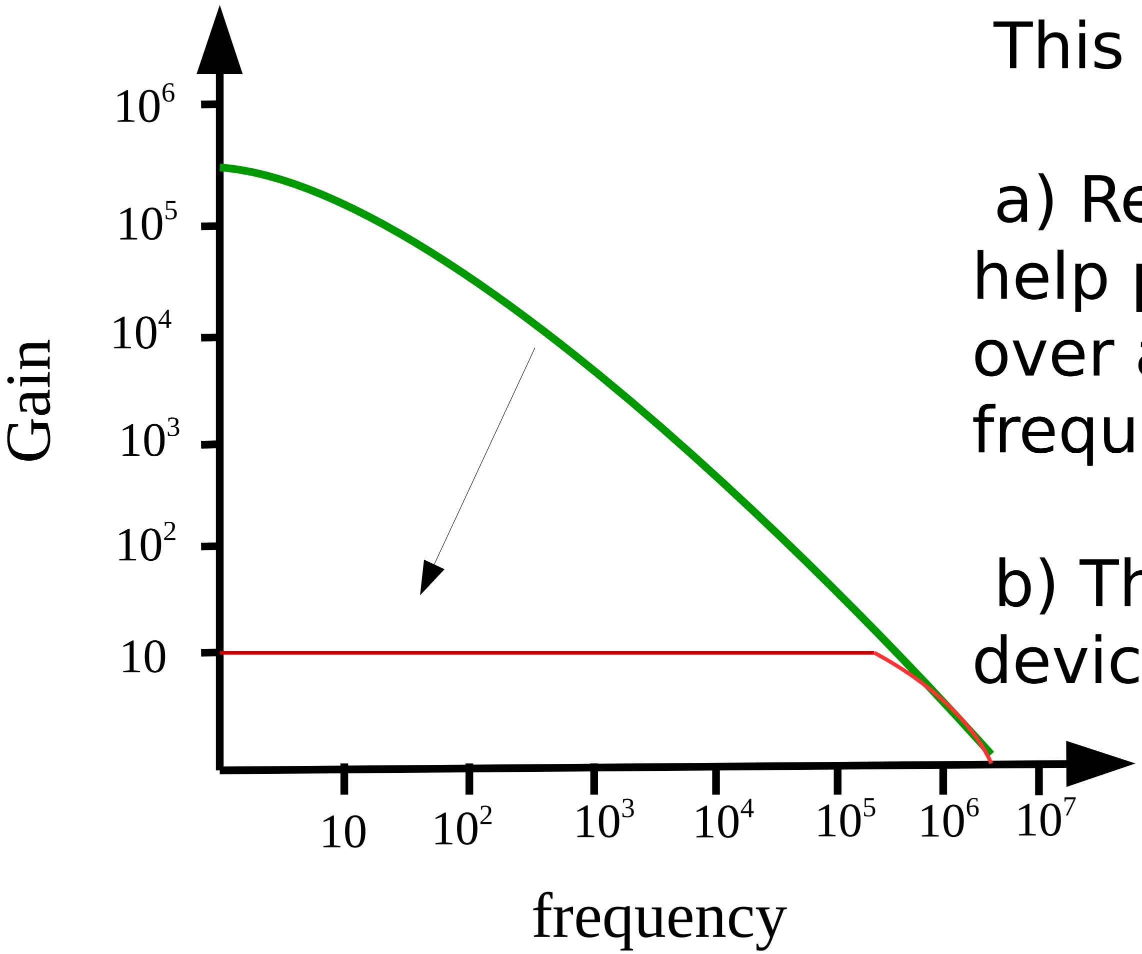
The inverting amplifier (introducing feedback)



To try and solve this problem. We take a proportion of the output and feed it back to the negitave input to reduce the overall gain. Negative feedback loop.

The result is a flatter lower gain curve:



This will:

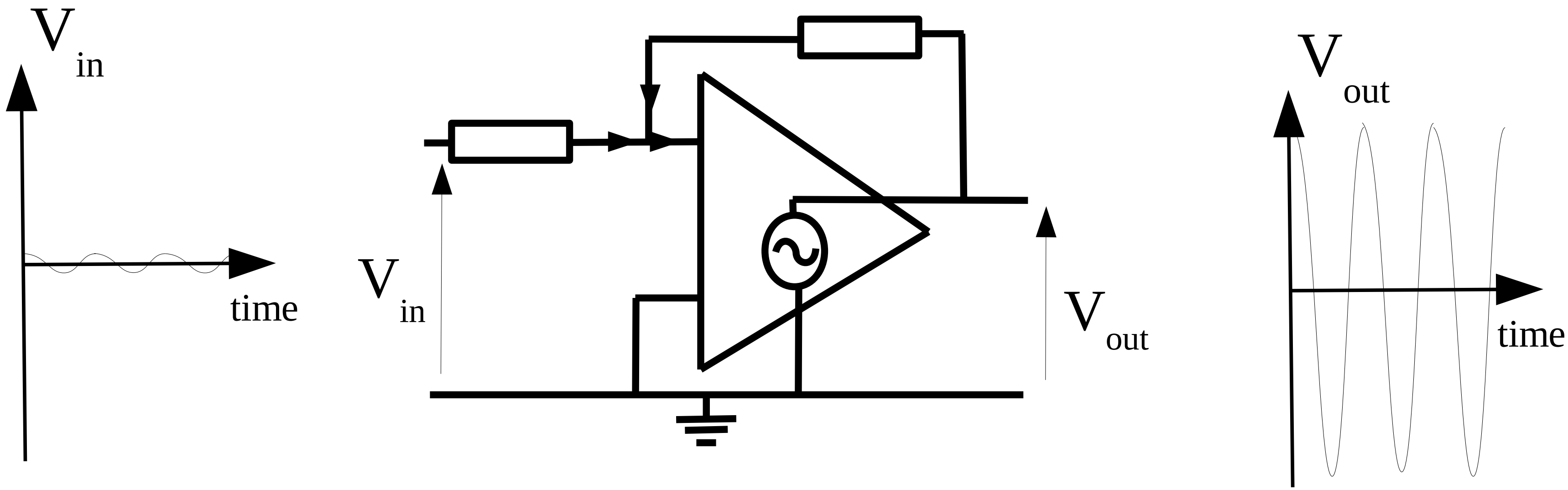
a) Reduce the gain, and help produce a flat gain over a wide range of frequencies.

b) The gain is lower so your device won't saturate.

Let's analyze this circuit in a bit more detail ....

How much gain will this circuit with feedback give us?

- To do this we need to write an expression linking the input voltage (V_{in}) to the output voltage (V_{out}).



- We are going to use Kirchhoff's Current and Voltage Laws to derive this expression.

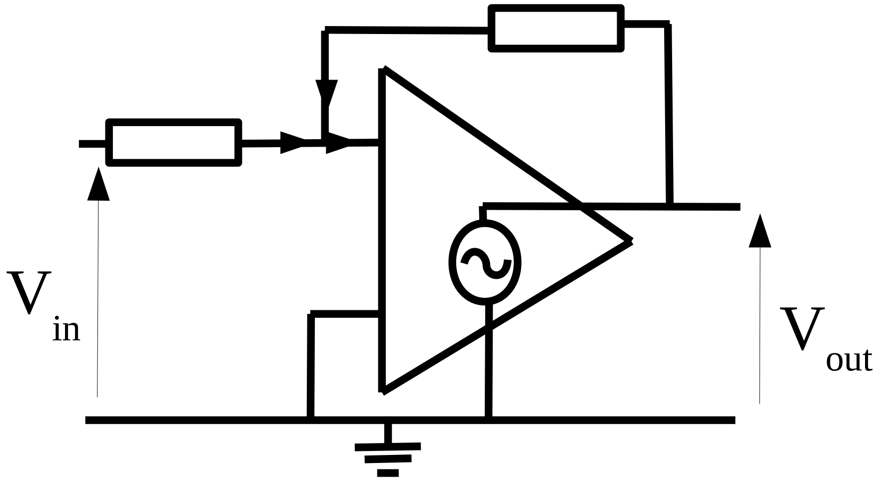
Our strategy to derive an equation describing this circuit.

- Write an expression relating the input voltages to the voltages at the terminals of the op-amp

- Write an expression relating the output of the op-amp to the input terminals of the op-amp

- Relate the two expressions

- Get the answer



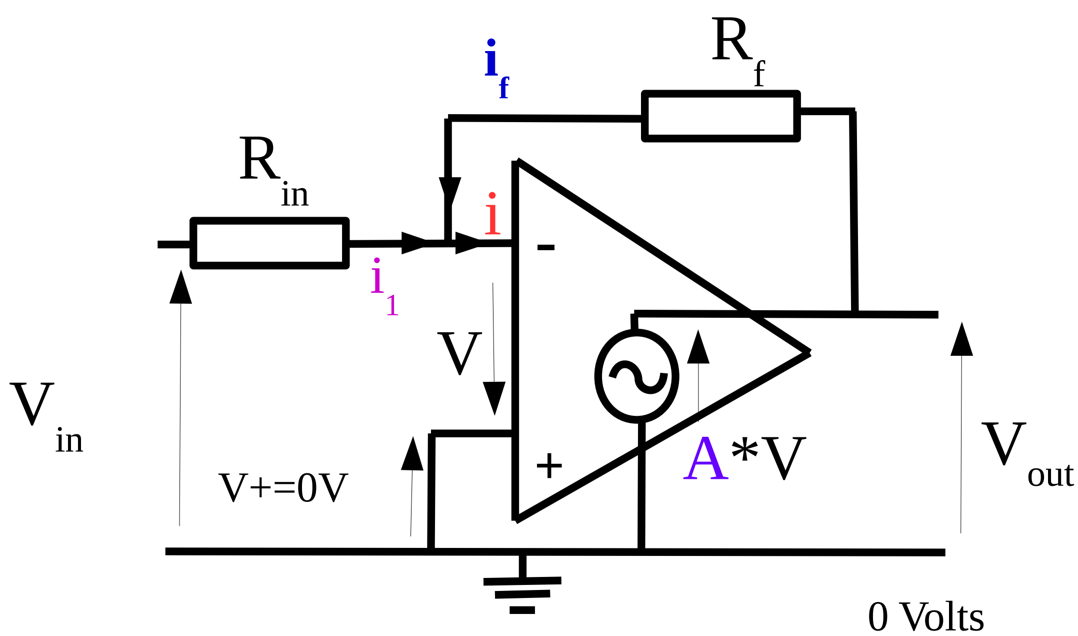
The inverting amplifier

- The inverting amplifier has two external resistors:
  - Feedback resistor R_f , Input resistor R_{in}

•The input resistance to an op-amp is always very high so we can assume it is infinite so $i = \mathbf{0}$.

- Looking at the inverting input we can write input

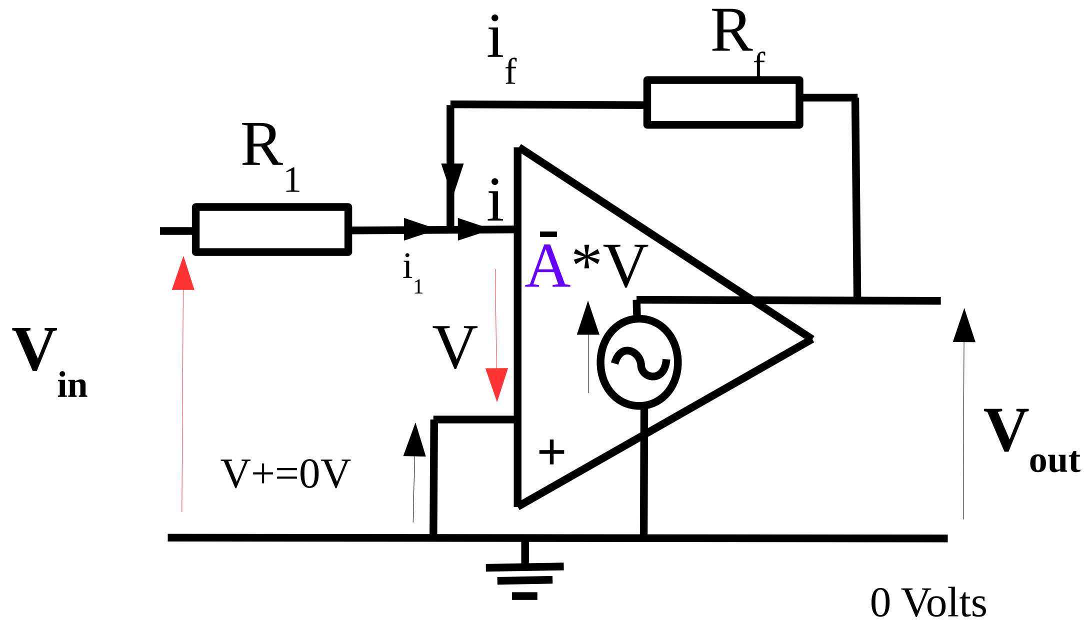
① $i_1 = -i_f$



Look at the front end of the circuit

- Apply Kirchhoff's Voltage Law linking the input voltage V_{in} to the negative input terminal.

$$V_{in} = i_1 R_1 - V$$

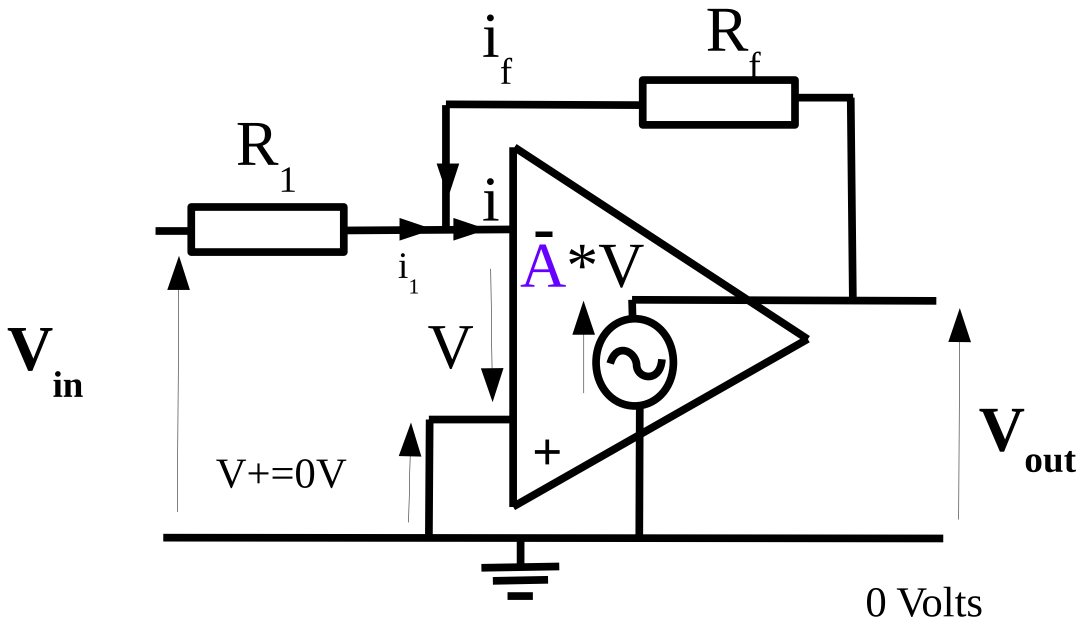


Look at the front end of the circuit

$$V_{in} = i_1 R_1 - V$$

- V is an unknown so let's get rid of it with V_{out}=AV.

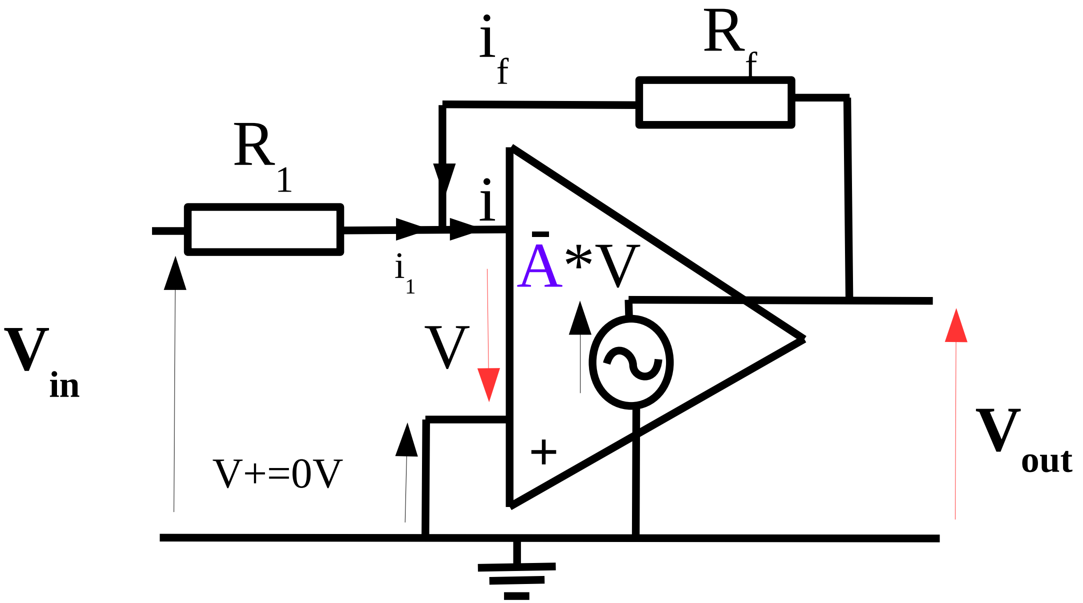
$$② \quad V_{in} = i_1 R_1 - \frac{V_{out}}{A}$$



- But we still don't know i_1.

Now, apply Kirchhoff's Voltage Law linking the output V_{out} to the negative terminal.

$$V_{out}=i_f R_f - V$$

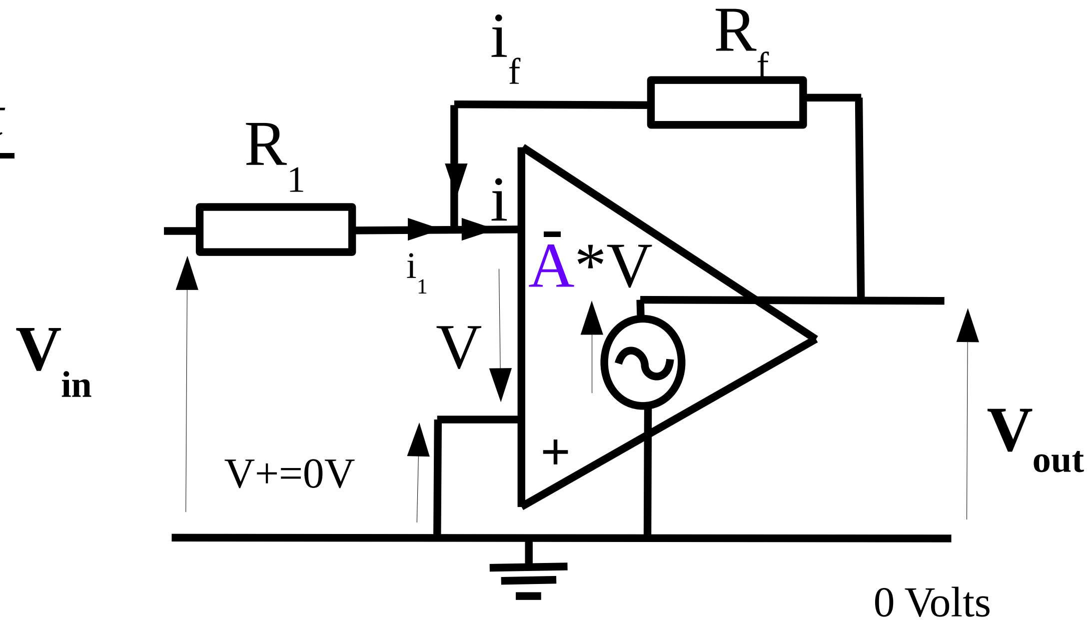


Look at the back end of the circuit

$$V_{out} = i_f R_f - V$$

- Again V is an unknown so let's get rid of it with V_{out}=AV.

③ $$V_{out} = i_f R_f - \frac{V_{out}}{A}$$



- But we still don't know i_f.

Look at the back end of the circuit

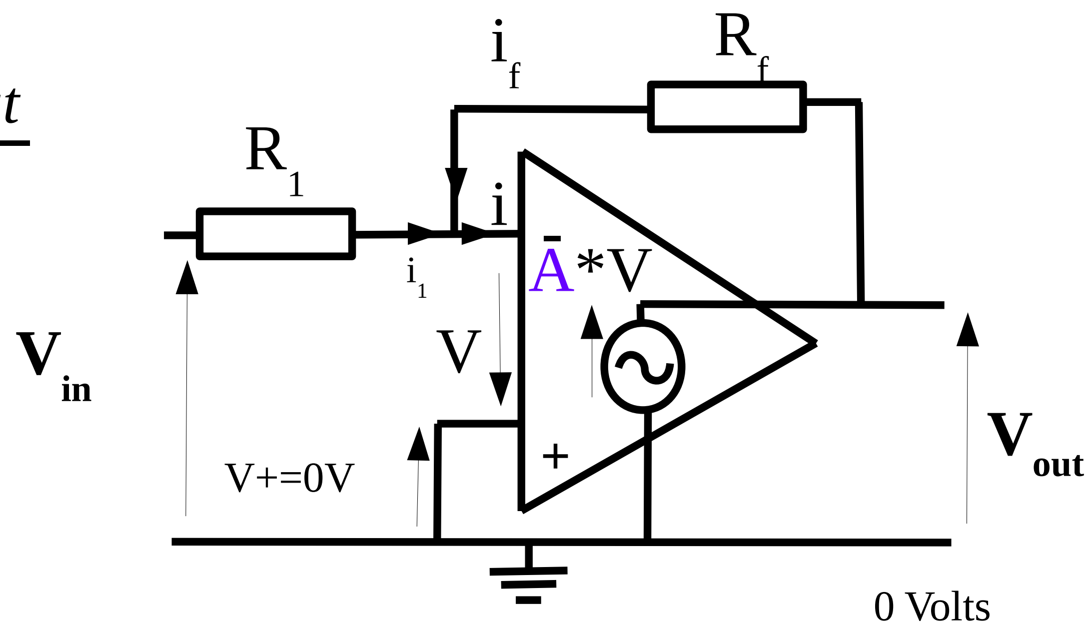
- Now we have two equations with three unknowns

② $$V_{in} = i_1 R_1 - \frac{V_{out}}{A}$$

③ $$V_{out} = i_f R_f - \frac{V_{out}}{A}$$

But we know that...

① $$i_1 = -i_f$$

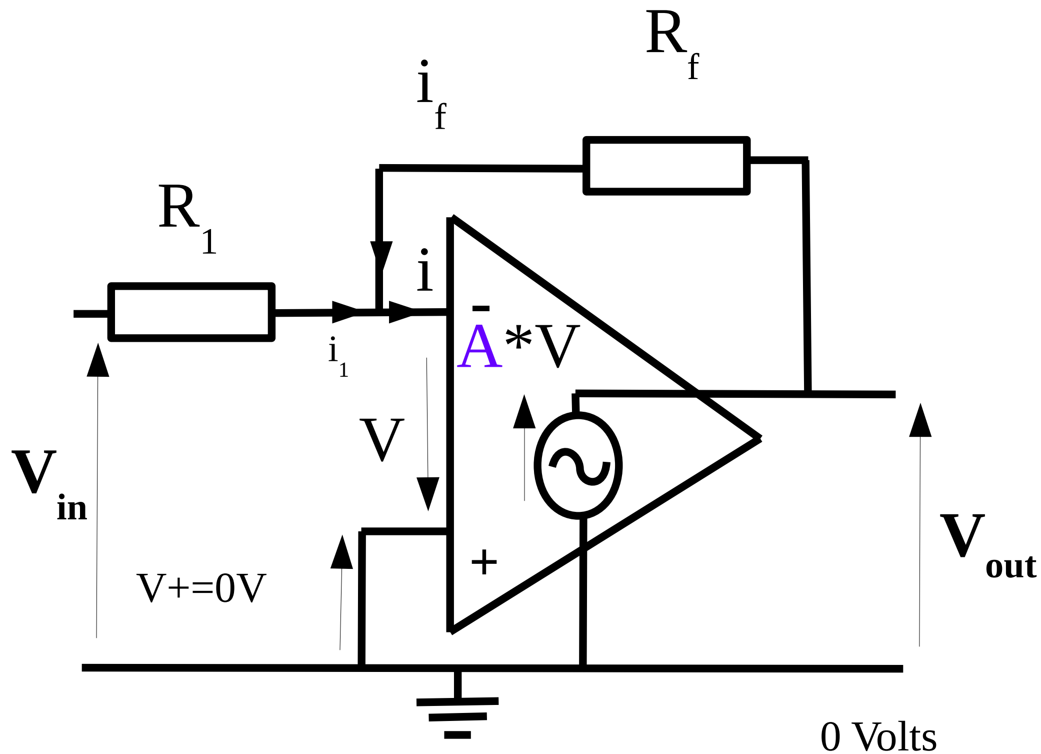


Deriving an expression to relate input and output voltage.

$$V_{in} = i_1 R_1 - \frac{V_{out}}{A}$$

$$V_{out} = -i_1 R_f - \frac{V_{out}}{A}$$

- And after some work...



$$V_{in} = \frac{V_{out}\left[R_1(A+1)+R_f\right]}{-R_f A}$$

Calculating closed loop gain

- Rearrange this expression to get the output over the input or the closed loop gain:

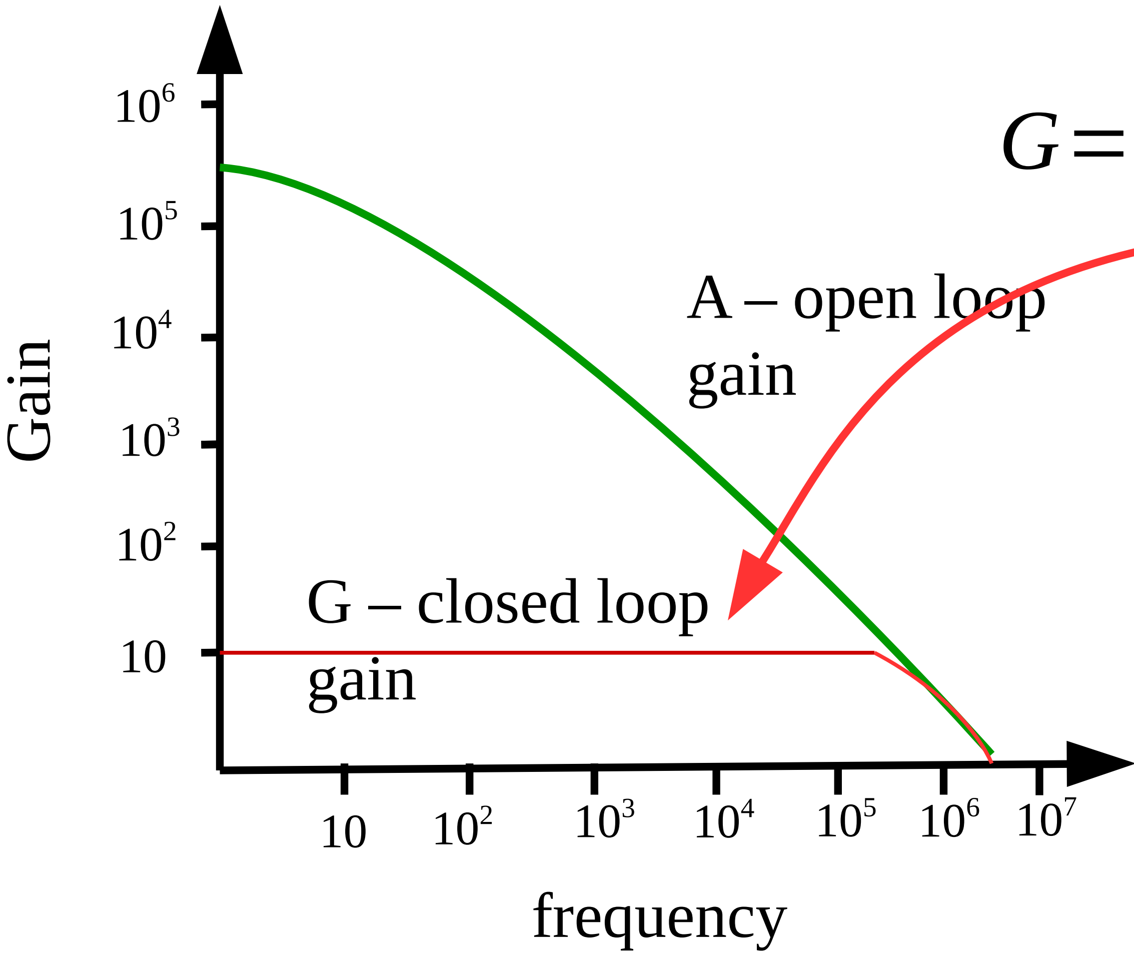
$$\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{-R_f A}{\left[R_r (A+1) + R_f\right]}$$

$$G = \frac{V_{\text{out}}}{V_{\text{in}}}$$

- Note the negative sine indicates that the output voltage is negative.

Closed loop gain:

$$G=\frac{V_{out}}{V_{in}}=\frac{-R_f A}{[R_r(A+1)+R_f]}$$



At low frequencies we can simplify the equation...

$$\frac{V_{\text{out}}}{V_{\text{in}}}=\frac{-R_f A}{[R_r(A+1)+R_f]}$$

when A>>1, we can write..

$$G=\frac{V_{\text{out}}}{V_{\text{in}}}=-\frac{R_f}{R_1}$$

You can now build and design any small signal amplifier with any gain by carefully picking the values of R_f and R_1.

Example exam question

- An inverting amplifier circuit has an input resistance R_1=10 k Ohm and a feedback resistance of R_f =1M Ohm.
- Using the open circuit gain v.s. frequency plot for the 741 op-amp calculate the ***exact*** close loop gain G at 10 Hz.

Rearrange the closed loop gain equation

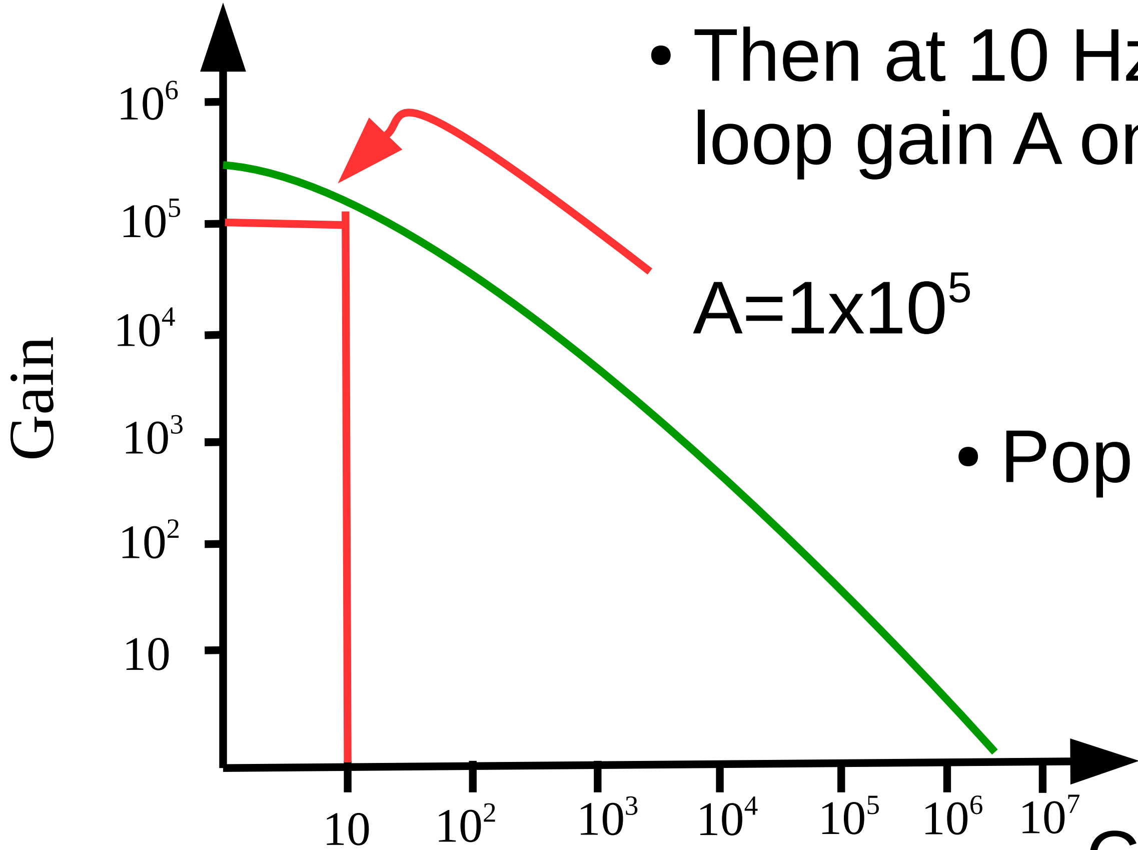
$$G = \frac{V_0}{V_i} = \frac{-R_f A}{R_1 (A+1) + R_f}$$

$$R_f = 1 M\Omega = 10^6 \Omega$$

$$R_1 = 1 k\Omega = 10^4 \Omega$$

$$G = \frac{-100 A}{(A+101)}$$

Example question



- Then at 10 Hz, look up the open loop gain A on the graph.

$A=1x10^5$

- Pop A into the equation:

$$G=\frac{-100\,A}{(A+101)}$$

Calculate the closed loop gain G:

G=99.899

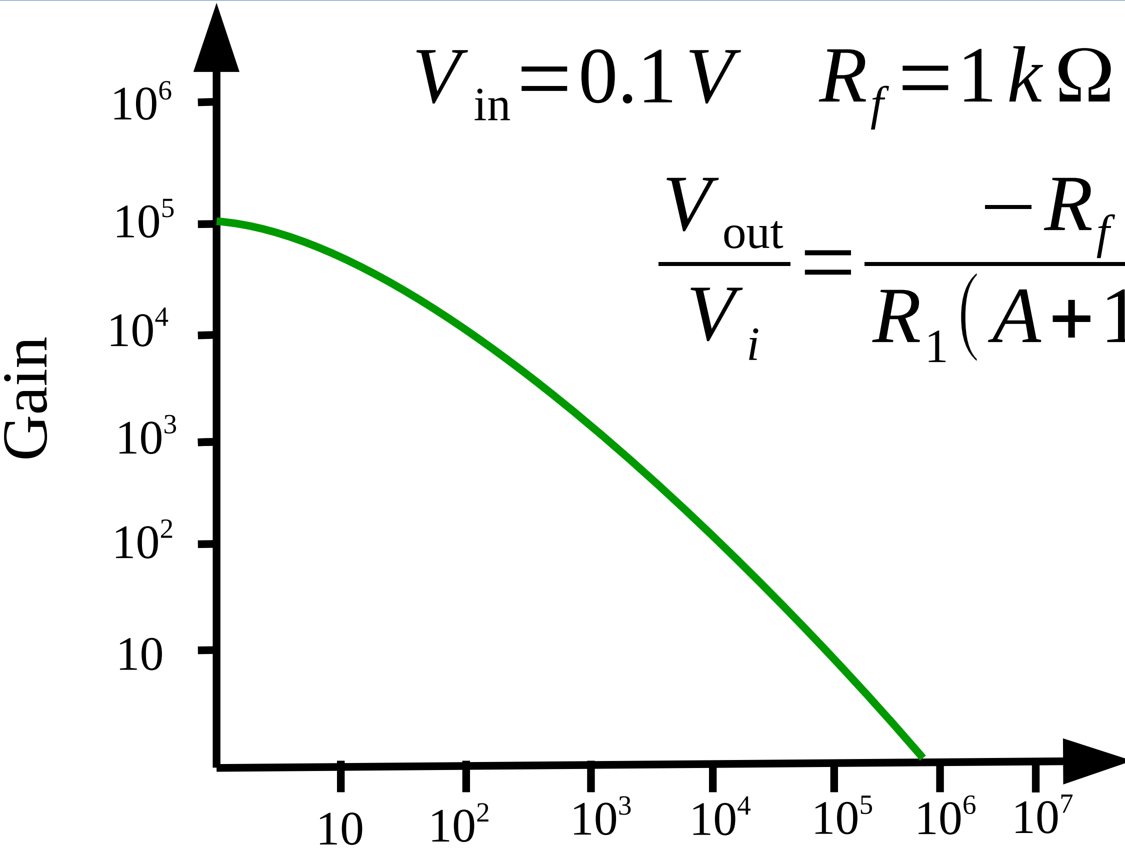
Your turn

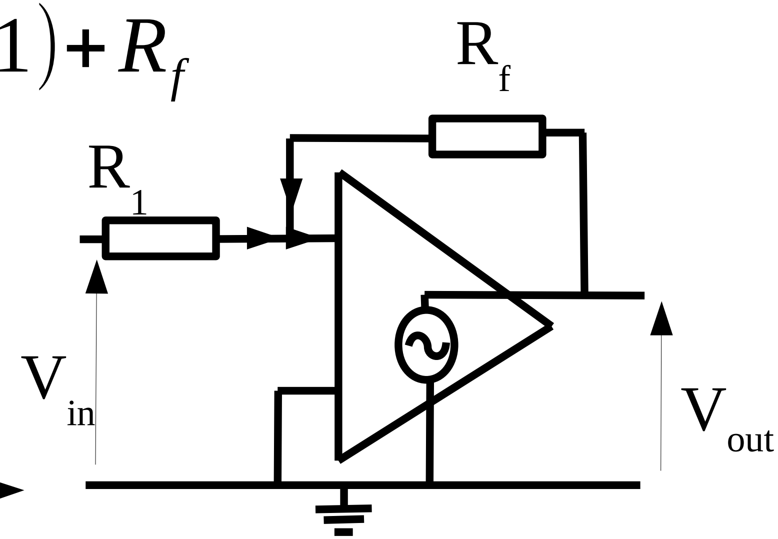
- High speed trains must stop when there is an earth quake or the trains will de-rail.
- You are designing an earthquake detection system for a new generation of high speed trains.
- You are listening for earthquakes with a microphone attached to the side of the tracks.
- Earthquakes produce a lot of vibrations at 1000 Hz.
- During an earthquake your microphone will produce a 0.1 V sin wave at 1000Hz.
- You have designed an amplifier circuit with R_f=1000 Ohm, R_1=10 Ohm. What will the output voltage of the amplifier be when an earth quake hits?

Your turn

$$V_{in}=0.1\,V \quad R_f=1\,k\Omega \quad R_1=10\,\Omega \quad f=1000\text{ Hz}$$

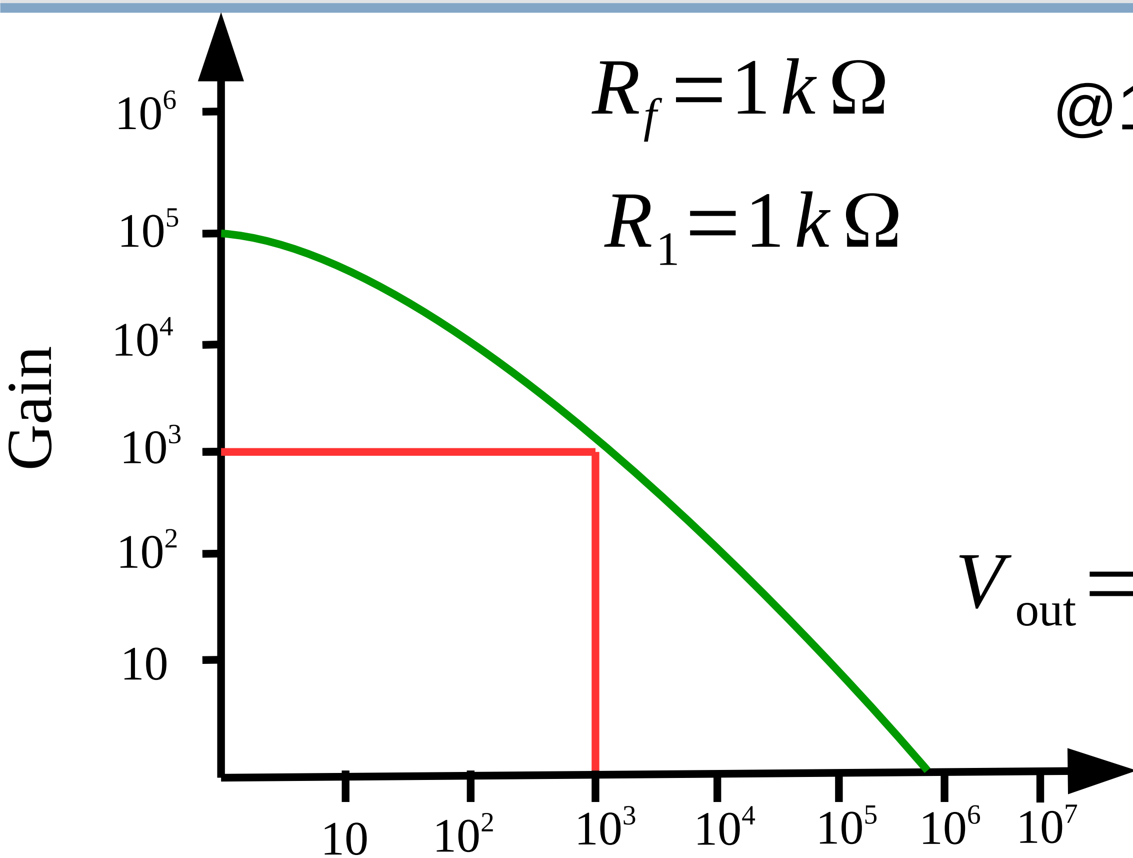
$$\frac{V_{out}}{V_i}=\frac{-R_f\,A}{R_1(A+1)+R_f}$$





- We are looking for the value of V_{out}.

Your turn



$$R_f = 1\,k\Omega$$

$$R_1 = 1\,k\Omega$$

@1000 Hz, $A=1\text{x}10^3$

$$V_0 = \frac{-R_f A V_i}{R_1(A+1)+R_f}$$

$$V_{out} = \frac{-1000\,x\,1\,x\,10^3\,0.1}{10(1\,x\,10^3+1)+1000.0}$$

$$V_{out} = -9.082$$

Outline of the lecture

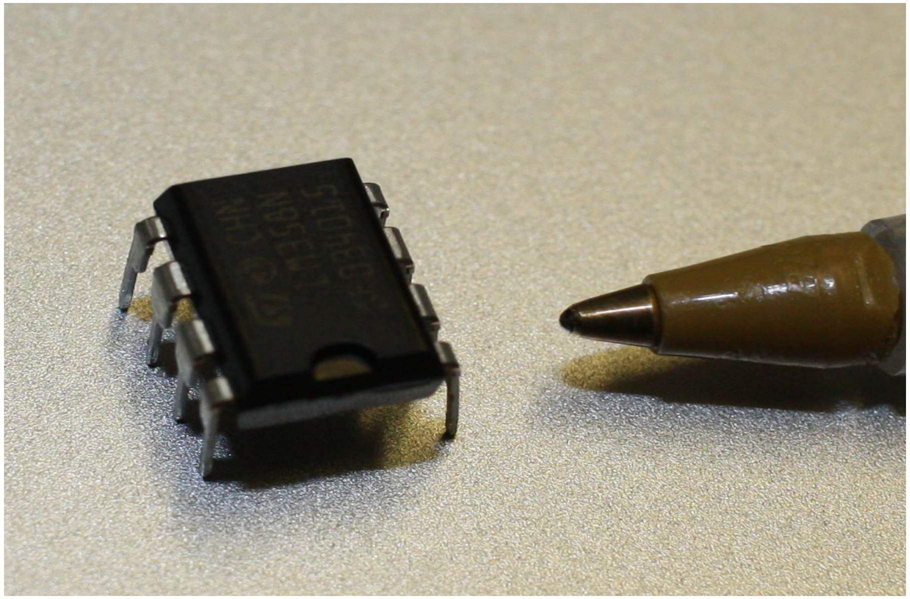
- Recap of last lecture

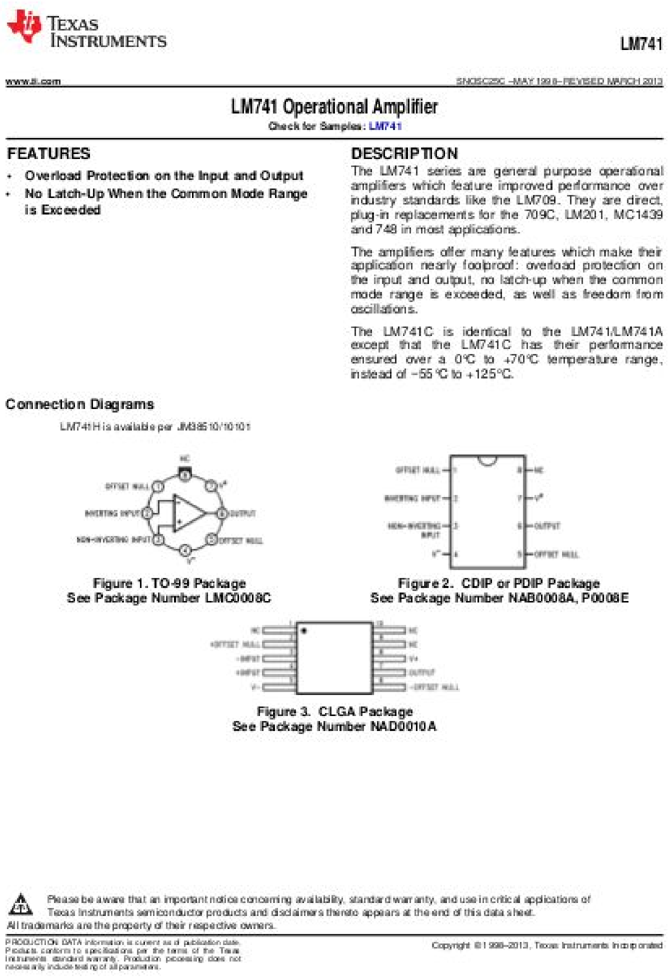
- What is an op-amp and what are they used for?

- **Three fundamental op-amp circuits**
    - Inverting amplifier
    - **Practical op-amps**
    - Summing amplifier

- Summary

Piratical considerations when designing op-amp circuits





TEXAS INSTRUMENTS

LM741

www.ti.com SNOSC25C –MAY 1998–REVISED MARCH 2013

LM741 Operational Amplifier

Check for Samples: LM741

FEATURES

- Overload Protection on the Input and Output
- No Latch-Up When the Common Mode Range is Exceeded

DESCRIPTION

The LM741 series are general purpose operational amplifiers which feature improved performance over industry standards like the LM709. They are direct, plug-in replacements for the 709C, LM201, MC1439 and 748 in most applications.

The amplifiers offer many features which make their application nearly foolproof: overload protection on the input and output, no latch-up when the common mode range is exceeded, as well as freedom from oscillations.

The LM741C is identical to the LM741/LM741A except that the LM741C has their performance ensured over a 0°C to +70°C temperature range, instead of −55°C to +125°C.

Connection Diagrams

LM741H is available per JM38510/10101

Figure 1. TO-99 Package
See Package Number LMC0008C

Figure 2. CDIP or PDIP Package
See Package Number NAB0008A, P0008E

Figure 3. CLGA Package
See Package Number NAD0010A

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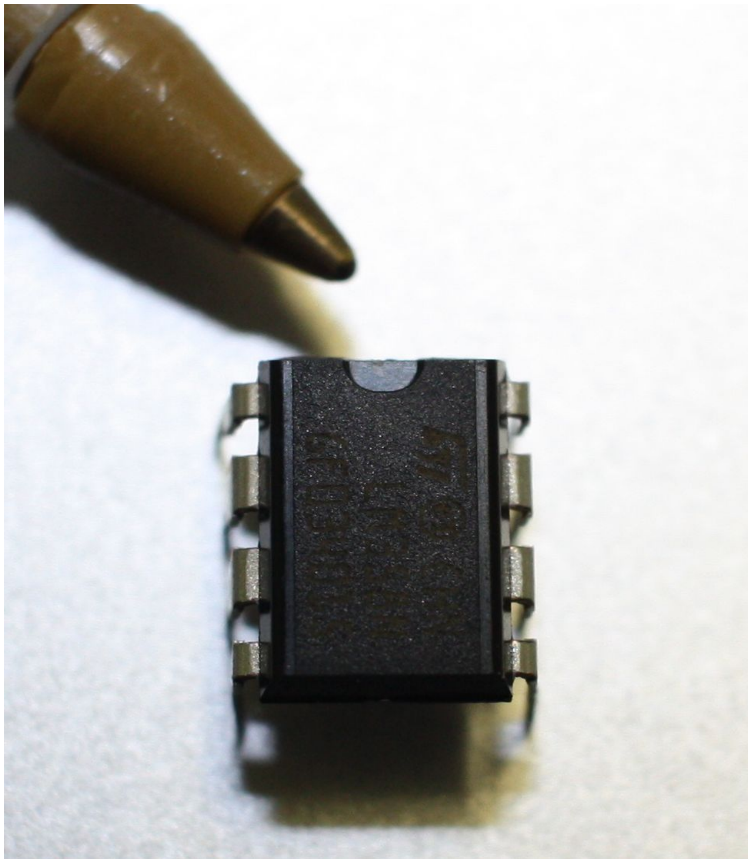
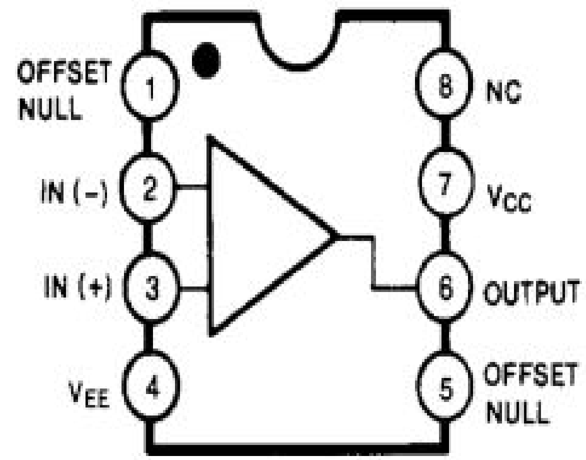
Using op-amps in the real world.

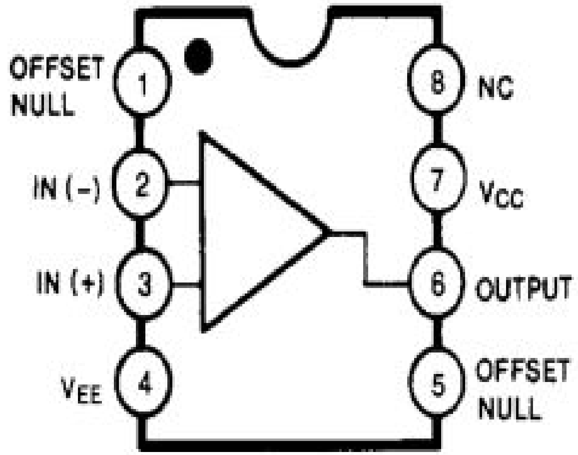


- They all have a small hole in them so you know which way around they go.



- Page 1 in the data sheet.

Using op-amps in the real world.



- NC means not connected
- V_{cc} means a positive supply voltage.
- V_{EE} means earth.

- You know what IN(-), and IN(+) do, and what output do.
- Ignore, the offset pins.

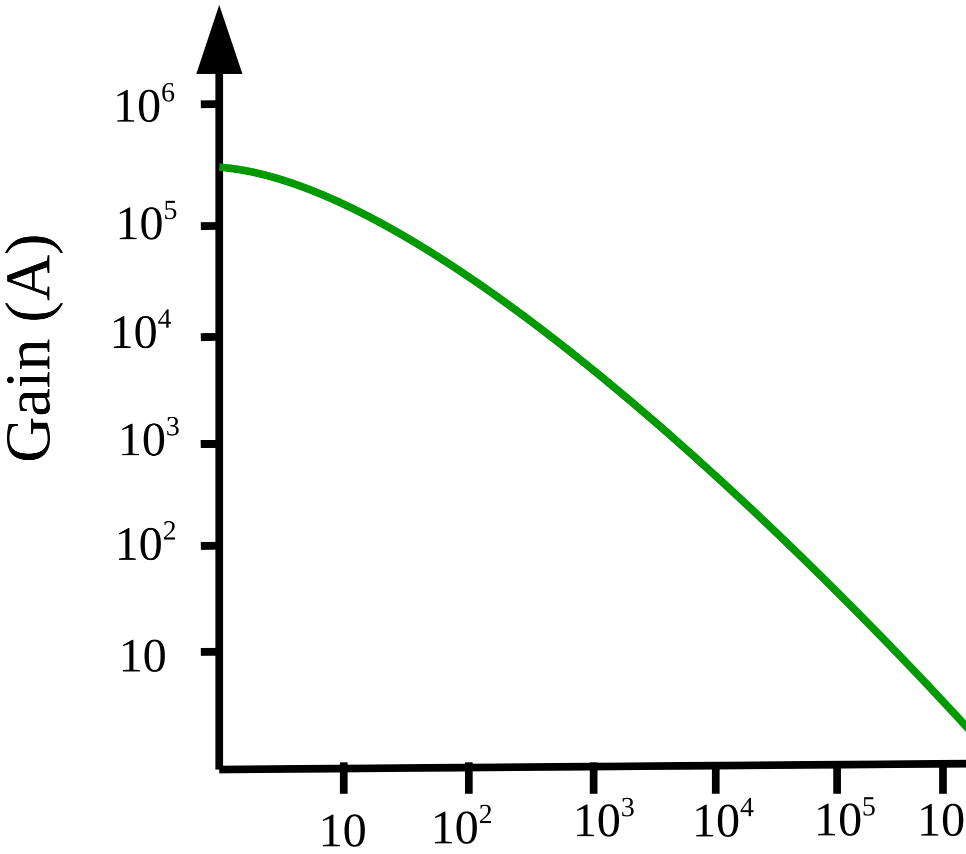
Page 2: Information on how to break it.

Absolute Maximum Ratings (T_A = 25°C)

Parameter	Symbol	LM741	Unit
Supply Voltage	V_{CC}	±18	V
Differential Input Voltage	$V_{I(DIFF)}$	30	V
Input Voltage	V_I	±15	V
Output Short Circuit Duration	-	Indefinite	-
Power Dissipation	P_D	500	mW
Operating Temperature Range	T_{OPR}	0 ~ + 70	°C
Storage Temperature Range	T_{STG}	-65 ~ + 150	°C

- Or how to avoid breaking it.
- Notice the temperate ranges – not that low..

Page 3: Gain graphs



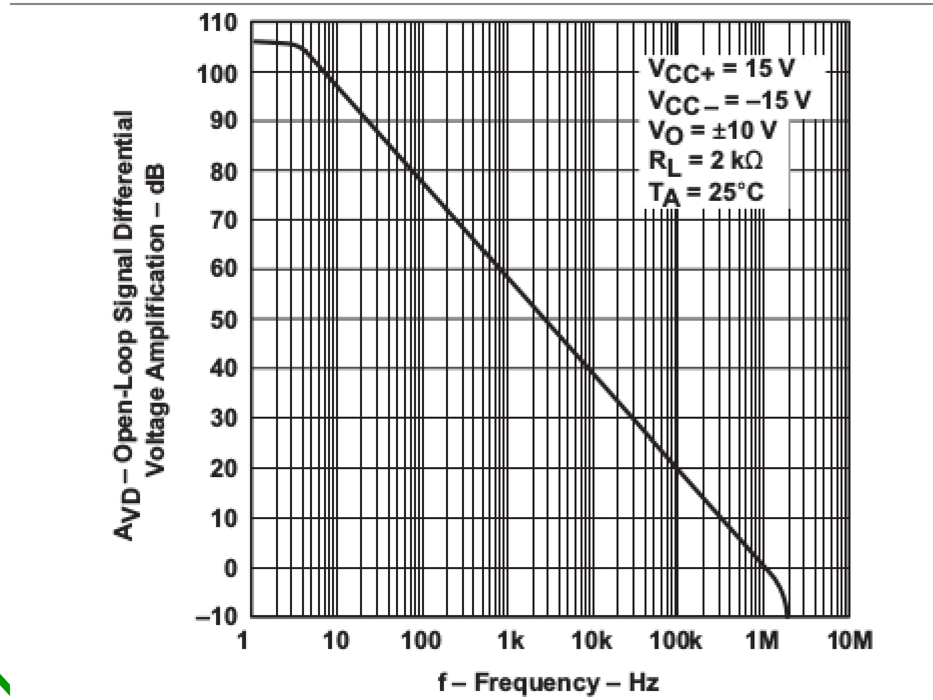


Figure 7. Open-Loop Large-Signal Differential Voltage Amplification vs Frequency

Outline of the lecture

- No recap of last lecture :)
  - Finish off digital electronic- Race times

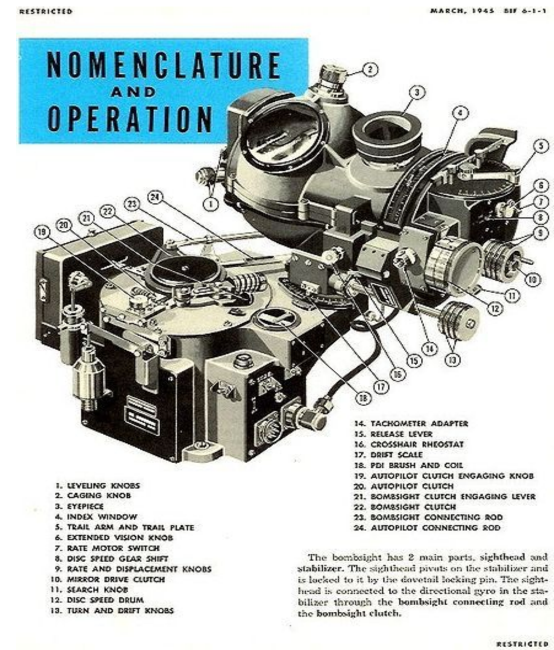
- Analog electronics

- Operational Amplifiers
  - What is an op-amp and what are they used for?

  - Two fundamental op-amp circuits
    - Inverting amplifier
    - Particle op-amps
    - **Summing amplifier**
- Summary

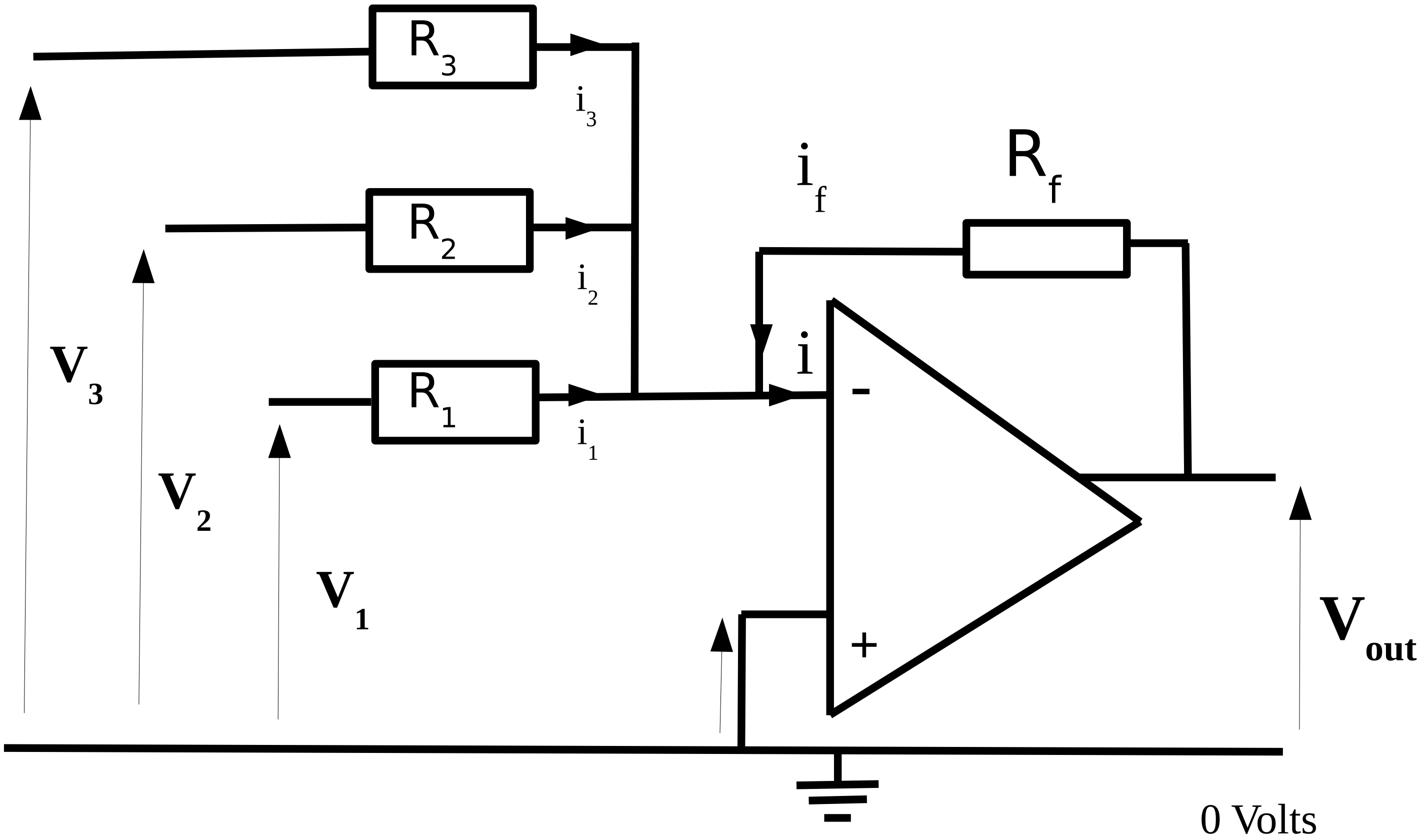
Mathematics with op-amps

- I said at the beginning of the lecture that one major application for op-amps is to do mathematics.

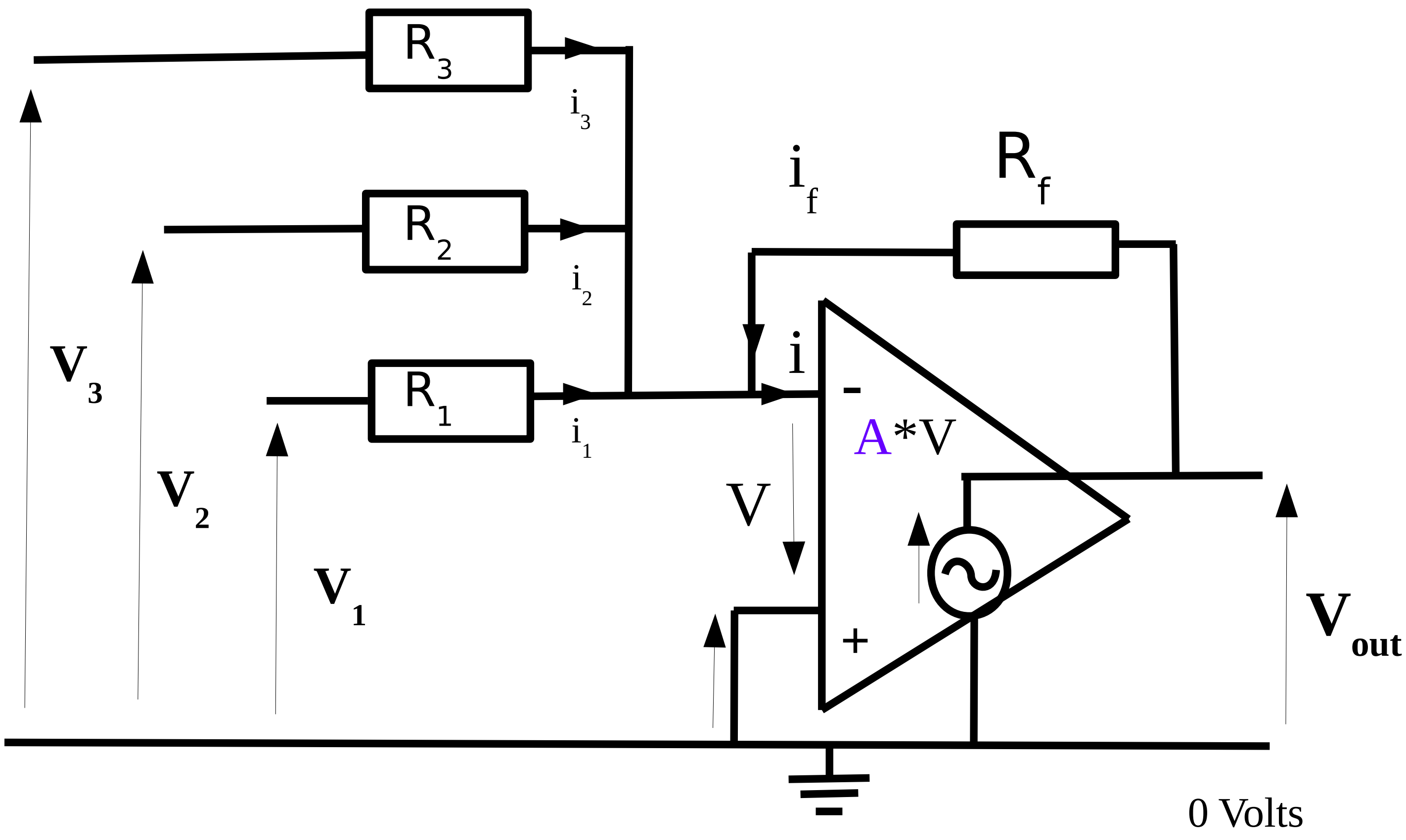


- Adding signals together is something you very often have to do in electronics and this is how you do it with an op-amp.

The summing amplifier

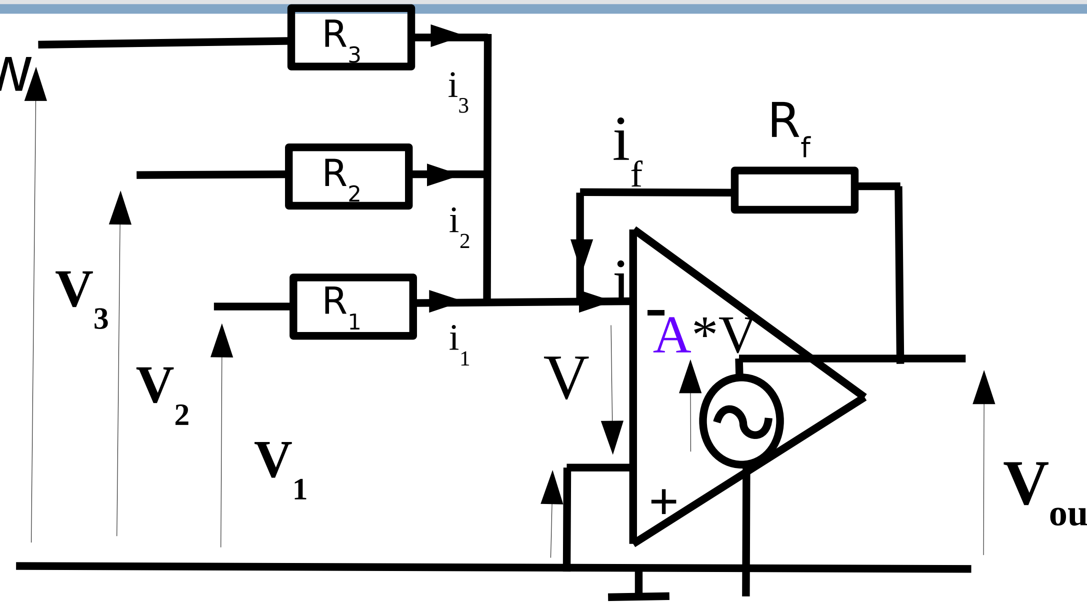


Mathematics with op-amps



Mathematics with op-amps

Using Kirchhoff's Voltage Law



$$V_1 = i_1 R_1 - V$$
$$V_2 = i_2 R_2 - V$$
$$V_3 = i_3 R_3 - V$$
$$V_{out} = i_f R_f - V$$

If $R_o = 0$ and $V = \frac{V_{out}}{A}$

As A is very large, v tends to zero and the voltage equations may be simplified to:

$$V_1 = i_1 R_1$$
$$V_2 = i_2 R_2$$
$$V_3 = i_3 R_3$$
$$V_{out} = i_f R_f$$

Mathematics with op-amps

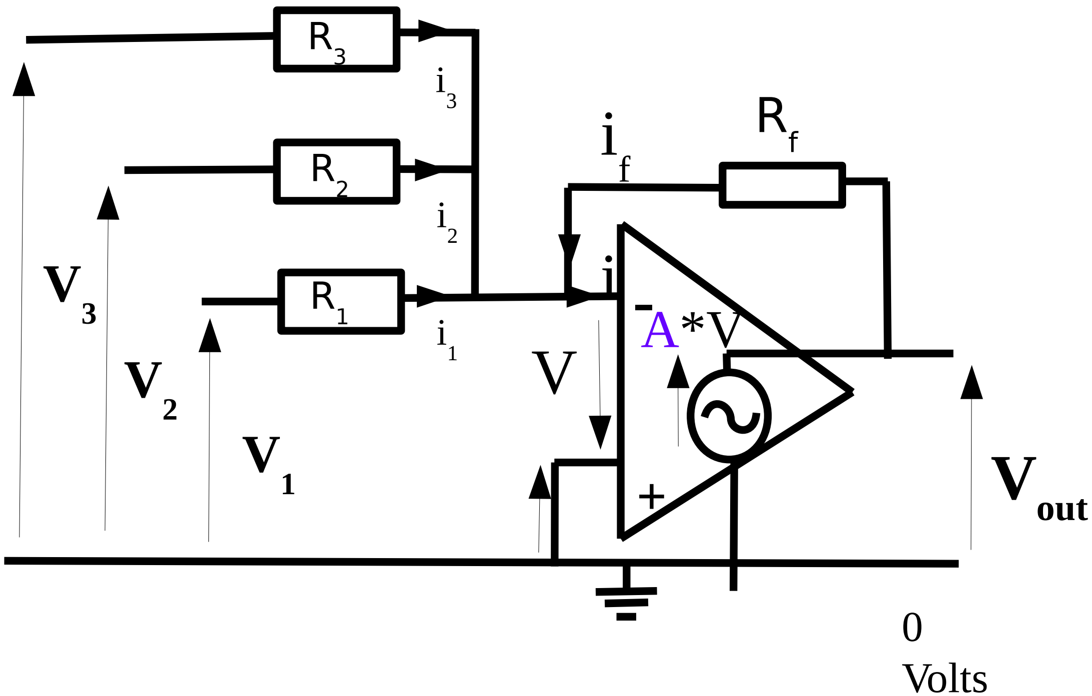
If the input resistance of the op-amp is high i=0.

Therefore we can write:

$$i_1 + i_2 + i_3 = -i_f$$

$$\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} = \frac{-V_0}{R_f}$$

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



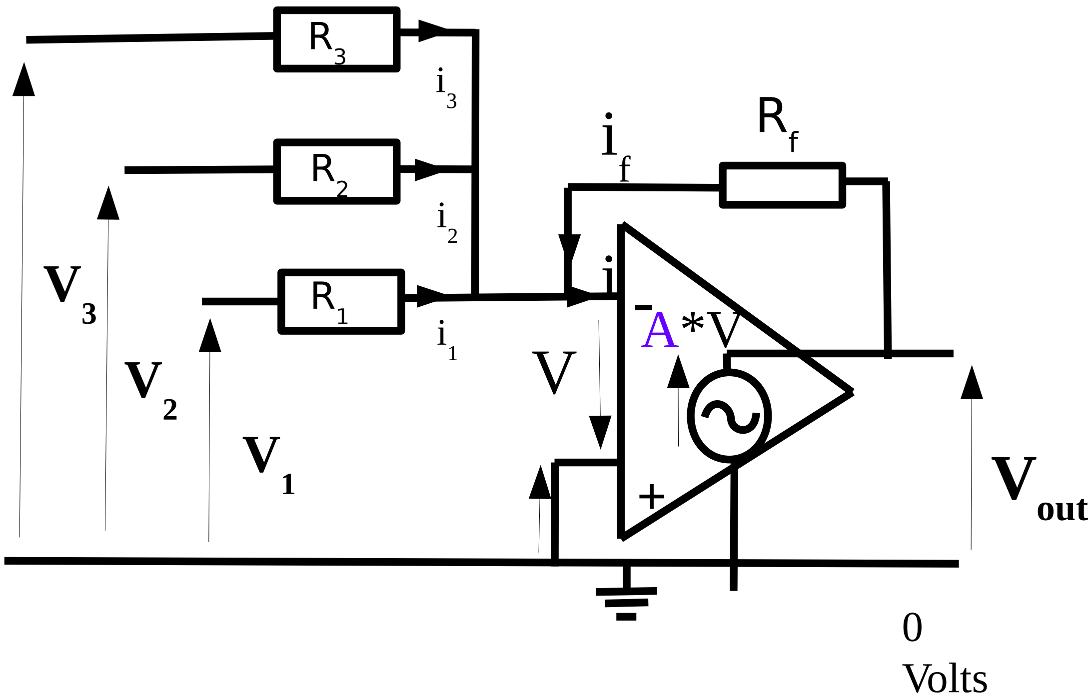
Mathematics with op-amps

If $R_1 = R_2 = R_3$

and

$$R_f = R_1 + R_2 + R_3$$

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



i.e. the output voltages are the sum of the input voltages

$$V_{out} = -\sum V_{in}$$

Summary of today's lecture

- No recap of last lecture :)
    - Finish off digital electronic- Race times

- Analog electronics

- Operational Amplifiers
    - What is an op-amp and what are they used for?

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