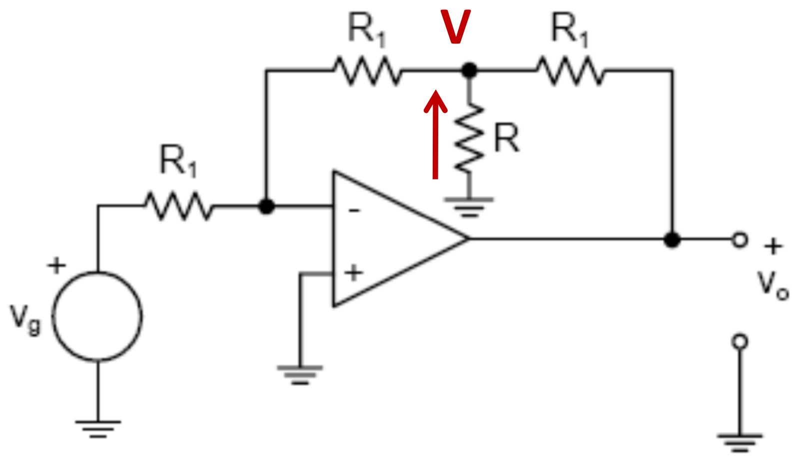
# Problems op-amps (see Vital)

6. Find R such that $\frac{v_o}{v_g}$ = -100 when $R_1$ = 10k




$$\frac{V_g - 0}{R_1} = \frac{0 - V}{R_1}$$

$$V = -V_g$$

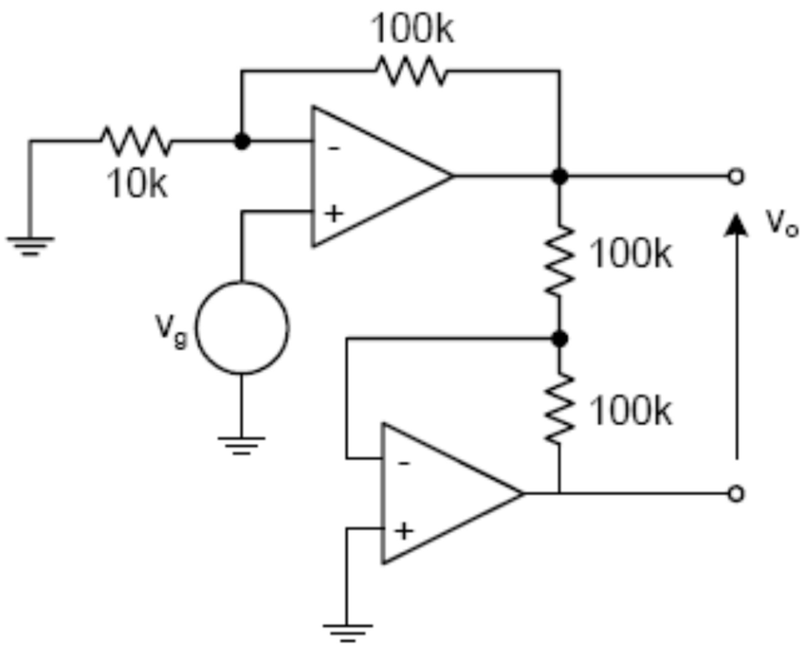
$$\frac{0 - V}{R_1} = \frac{V}{R} + \frac{V - V_o}{R_1} \Rightarrow \frac{V}{R_1} + \frac{V}{R} + \frac{V}{R_1} = \frac{V_o}{R_1}$$

$$\frac{V_o}{V_g} = -(2 + \frac{R_1}{R})$$

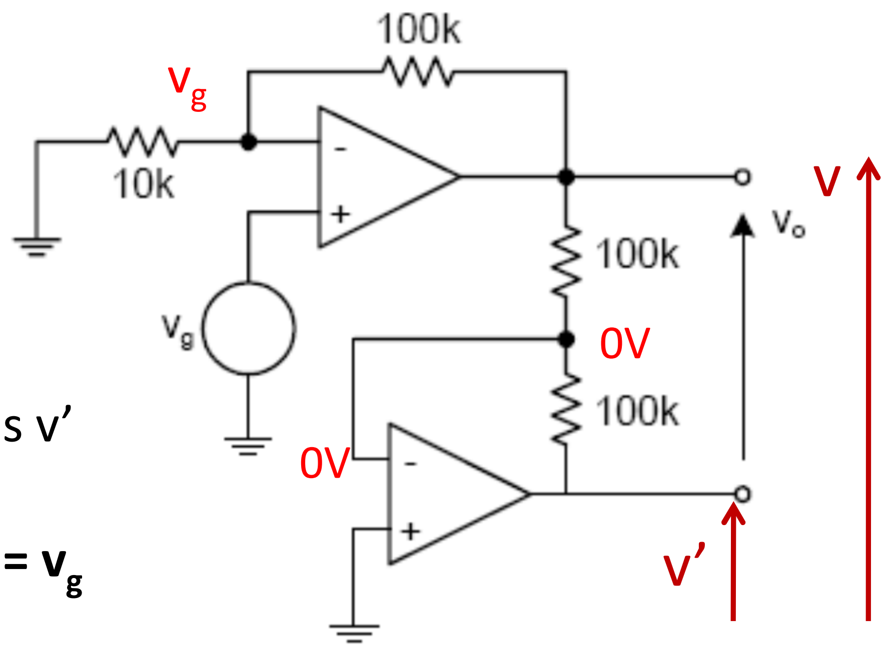
**Hence R=102 Ω.**

**A method of getting high gain with small resistors!**

7. Find $\dfrac{v_o}{v_g}$ for



## 7. Find $\dfrac{v_o}{v_g}$ for




### Solution

Label o/p of **top op-amp** as v and bottom as v'

Then $\mathbf{v_o = v - v'}$. Also, for top op-amp, $\mathbf{v_n = v_p = v_g}$

Then, for top op-amp: $\dfrac{0 - v_g}{10k} = \dfrac{v_g - v}{100k}$ giving $\dfrac{v}{v_g} = 11$

For **bottom op-amp**, $v_n = v_p = 0$

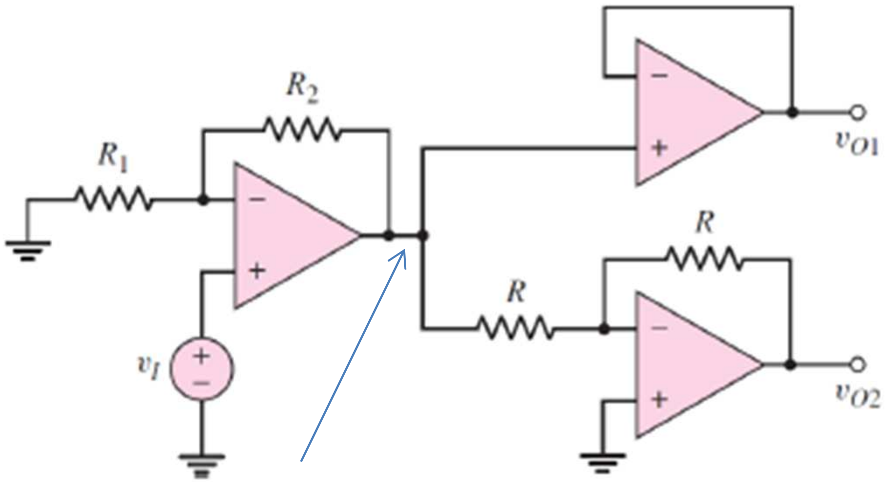
so $\dfrac{v - 0}{100k} = \dfrac{0 - v'}{100k}$ giving $v = -v'$

so, $v_o = v + v = 2v = 22v_g$ giving $\boxed{\dfrac{v_o}{v_g} = 22}$

*Note that $\dfrac{v'}{v_g} = -11$

'phase splitter' $\dfrac{v}{v_g} = 11$

A 'phase splitter'




$$\frac{v_{O1}}{v_I} = \left(1 + \frac{R_2}{R_1}\right)$$

$$\frac{v_{O2}}{v_I} = -\left(1 + \frac{R_2}{R_1}\right)$$

$$v_I \times \left(1 + \frac{R_2}{R_1}\right)$$

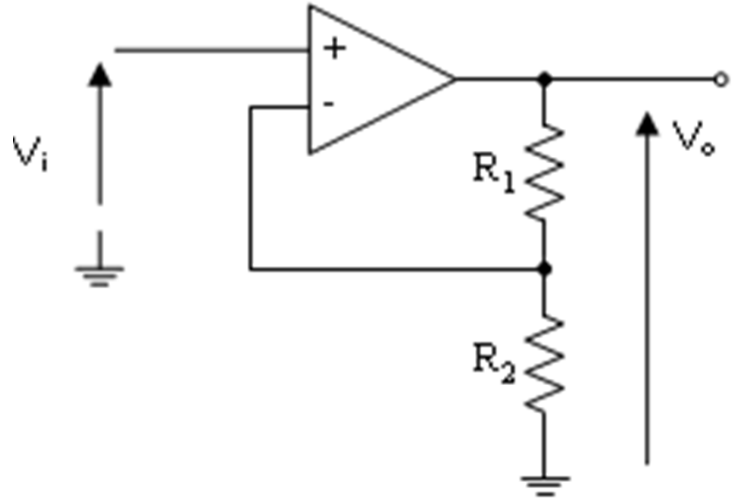
# Worked Example FROM PART 13

An amplifier with an **open loop gain of 500** operates in an environment where temperature rise causes the open loop gain to increase to 550.

i) Treating the amplifier as a negative feedback system, find the necessary feedback fraction, β to ensure that that the closed loop gain does not change by more than 0.2%. Assume that β does not change with temperature.

**Answer was β = 0.089**

A practical circuit to implement the amplifier is shown opposite.. design the amplifier to achieve the required β.




Solution: $$\frac{V_0}{V_i} = \frac{R_1 + R_2}{R_2}$$

Loop gain, $T = A_{ol}\,\beta = 500 \times 0.09 = 45$

Consider T >> 1, so write $$A_f = \frac{1}{\beta}\frac{T}{1+T} \sim \frac{1}{\beta}$$ $1/\beta \approx 11$

$$A_f = \frac{R_1 + R_2}{R_2} = 11$$

Set $\mathbf{R_2 = 10\ k}$ (say) then $R_1 = 10 \times R_2$

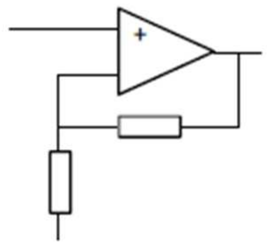
$\mathbf{R_1 = 100\ k}$

# Electronic circuits and systems
# ELEC271

## Part 17
## Input and output resistances of feedback amplifiers

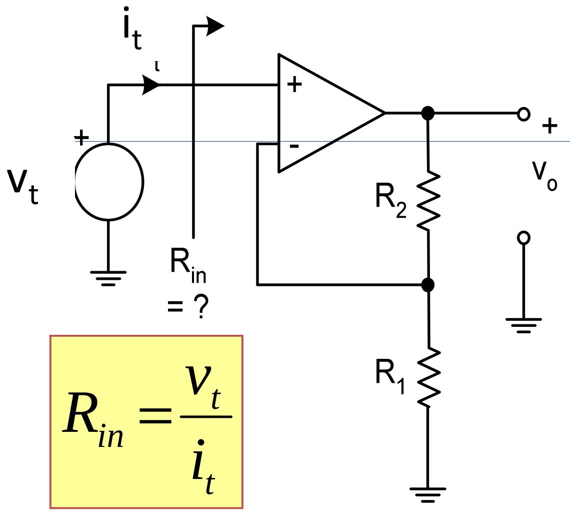
How does the feedback 'adjust' $R_{in}$ and $R_{out}$ as we have assumed so far?

Use the non-inverting amp as an example

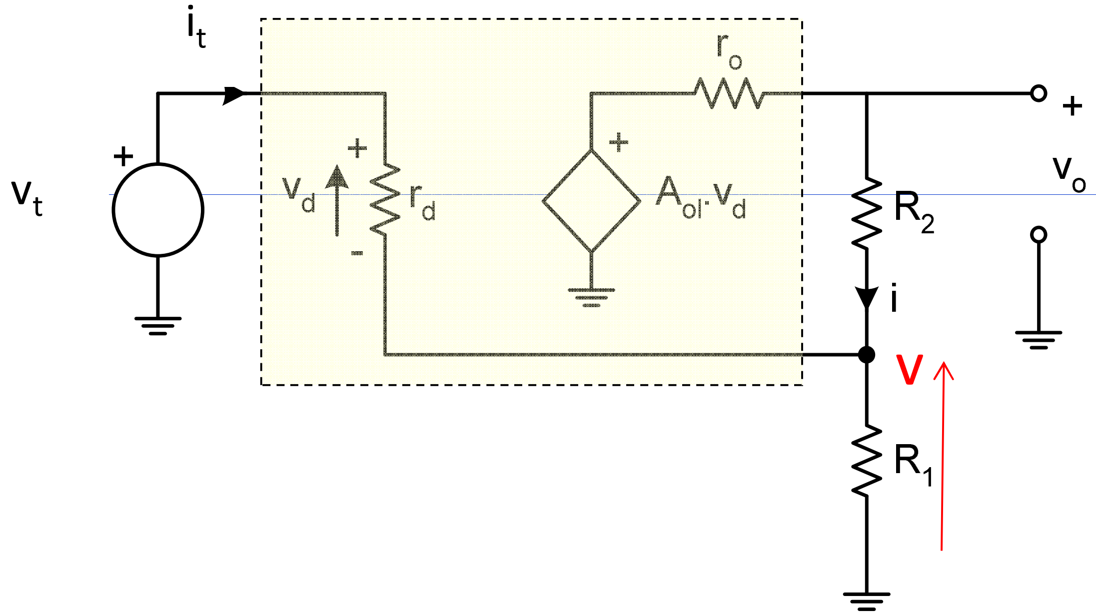


# Input and output resistances of feedback amplifiers

1. Input Resistance of Non-Inverting Amp (**voltage sampling, voltage summing**)




$$R_{in} = \frac{v_t}{i_t}$$




We can write: $v_t = i_t r_d + v$ $\quad v_d = i_t r_d$

$$v = (i_t + i) R_1 \qquad i = \frac{[A_{ol} v_d - v]}{r_o + R_2}$$

The solution of which gives:

$$R_{in} = \frac{v_t}{i_t} = r_d \left[ 1 + \frac{A_{ol}}{1 + (R_2 + r_o)/R_1} \right] + R_1 \| (R_2 + r_o)$$

I leave it to an exercise for you to prove this equation.....

# Input resistance of feedback amplifiers (contd)

**Can we simplify...**

$$R_{in} = \frac{v_t}{i_t} = r_d \left[ 1 + \frac{A_{ol}}{1 + (R_2 + r_o)/R_1} \right] + R_1 \| (R_2 + r_o)$$

Note that $A_{ol}$ is BIG, $r_O$ is in series with $R_2$ and usually $r_O << R_2$ so:

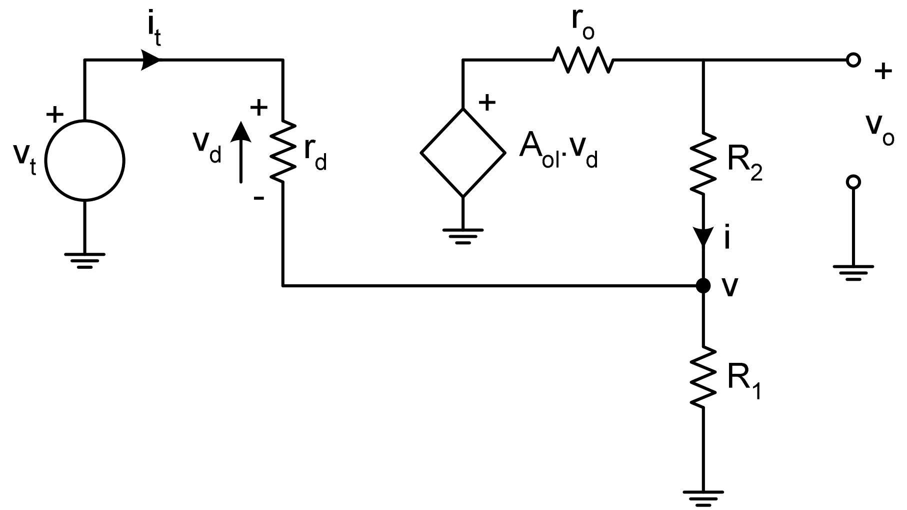
$$R_{in} = \frac{v_t}{i_t} \approx r_d \left[ 1 + \frac{A_{ol}}{\underbrace{1 + R_2/R_1}} \right] + R_1 \| R_2$$

$$= r_d \left[ 1 + \frac{A_{ol}}{1/\beta} \right] + R_1 \| R_2$$

Feedback fraction

$$= r_d \left[ 1 + A_{ol}\beta \right] + R_1 \| R_2$$

$$\approx r_d \left[ 1 + A_{ol}\beta \right]$$

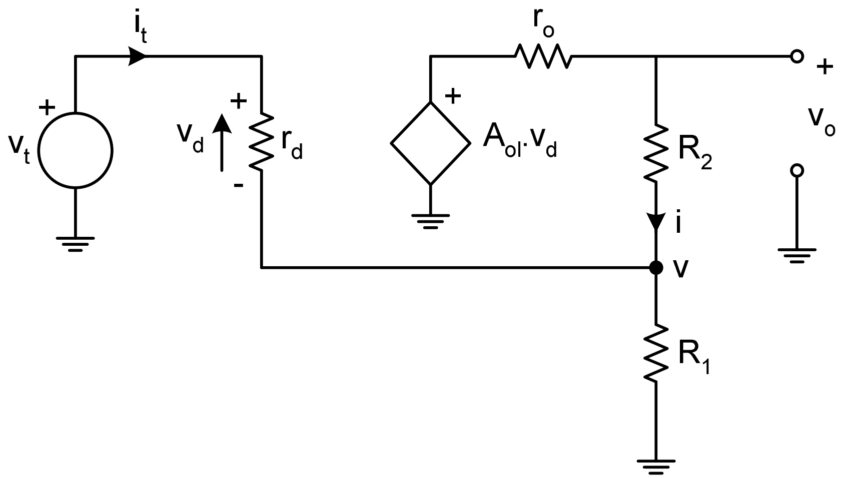



So effective input resistance ***of the amplifier*** is increased from $r_d$ to $r_d \left[ 1 + A_{ol}\beta \right]$ as a result of the feedback

Big numbers!

# Check assumptions with some numbers

$R_1$ = 1 kΩ, $R_2$ = 10 k Ω, $r_o$ = 75 R, $r_d$ = 2 MΩ



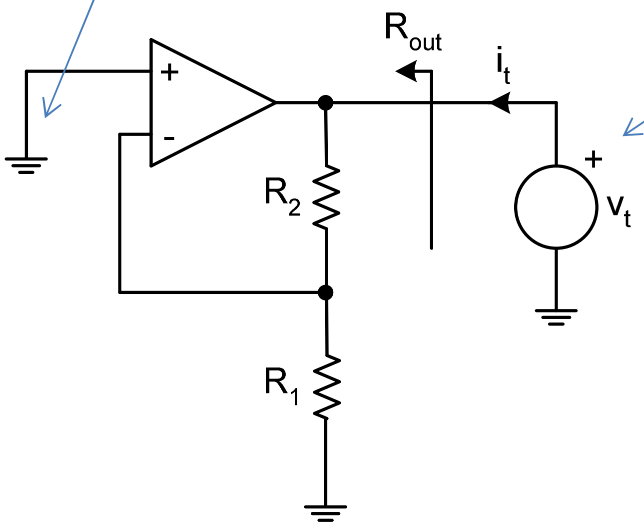

$$R_{in} = \frac{v_t}{i_t} = \underbrace{r_d\left[1 + \frac{A_{ol}}{1 + (R_2 + r_o)/R_1}\right]}_{\textbf{36 G}\boldsymbol{\Omega}\textbf{!!}} + \underbrace{R_1 \| (R_2 + r_o)}_{\substack{\textbf{970 }\boldsymbol{\Omega} \\ \textbf{Small!}}}$$

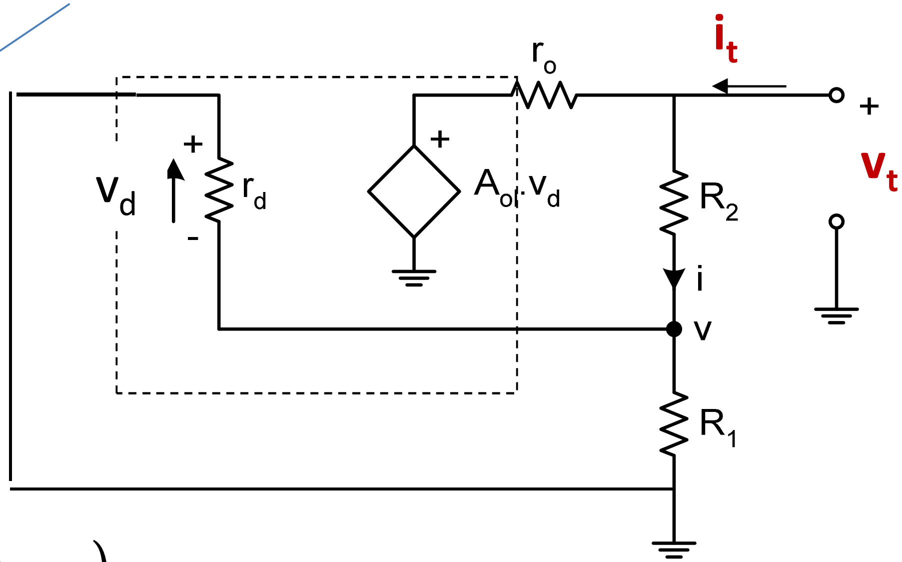
$R_{in} \sim r_d\,(1 + T) = 36\ \mathrm{G\Omega}$

Approximations justified!

# Output Resistance

**Suppress input ; apply a test voltage, $v_t$ at output and force in a current, $i_t$**




$$v_d = -i \times R_1 // r_d \qquad i_t = \frac{(v_t - A_{ol} v_d)}{r_O} + i \qquad v_t = i\left(R_2 + R_1 // r_d\right)$$

Solving gives

$$\boxed{R_0 = \frac{v_t}{i_t} = \frac{r_o}{1 + \left(\dfrac{A_{ol} R_1 // \cancel{r_d} + \cancel{r_O}}{R_2 + R_1 // \cancel{r_d}}\right)}} \Rightarrow \boxed{R_0 \approx \frac{r_o}{1 + \beta A_{ol}}}$$

if $r_O << R_1 // r_d$

and $r_d >> R_1$

so $R_1 // r_d \sim R_1$

**So output resistance is reduced by the feedback factor [1 + $\beta A_{ol}$] when output voltage sampling is used!**

# Note

$R_1 = 1\ k\Omega$, $R_2 = 10\ k\Omega$, $r_d = 2\ M\Omega$, $r_o = 75\ \Omega$, $A_{ol} = 2 \times 10^5$

$r_d >> R_1, R_2$

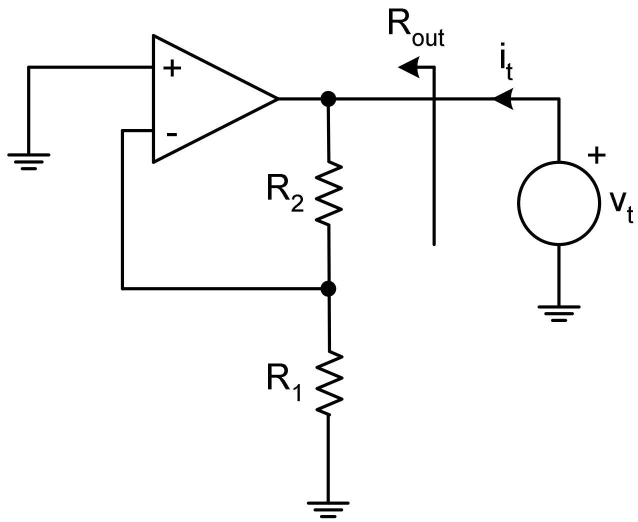
$$R_0 = \frac{v_t}{i_t} = \frac{r_o}{1 + \left( \dfrac{A_{ol} R_1 // r_d + r_O}{R_1 // r_d + R_2} \right)}$$

$$R_0 = \frac{r_o}{1 + \dfrac{A_{ol} + r_0 / R_1 + r_o / r_d}{1 + \dfrac{R_2}{R_1} + \dfrac{R_2}{r_d}}}$$

$$R_1 // r_d \approx R_1$$

$A_{ol}\ R_1 // r_d \sim A_{ol}\ R_1$

$A_{ol}\ R_1 >> r_o$




$$R_0 \approx \frac{r_o}{1 + \left( \dfrac{A_{ol} R_1}{R_1 + R_2} \right)}$$

$$R_0 \approx \frac{r_o}{1 + \beta A_{ol}}$$

$$R_0 \approx \frac{75}{1 + \dfrac{1k}{1k + 10k} 2 \times 10^5}$$

**$R_o \sim 0.4\ m\Omega$**

**We estimate that the output resistance of the V-amp is a fraction of a milli-ohm!**

# Input Resistance of Inverting Amp

(**output voltage sampling, current summing**)

We can use the same method to obtain expressions for $R_{in}$ and $R_{out}$ for an **inverting amplifier.**

(Recall that the feedback topology is associated with a *transresistance* amplifier – so do you expect $R_{in}$ and $R_{out}$ to be large or small?).

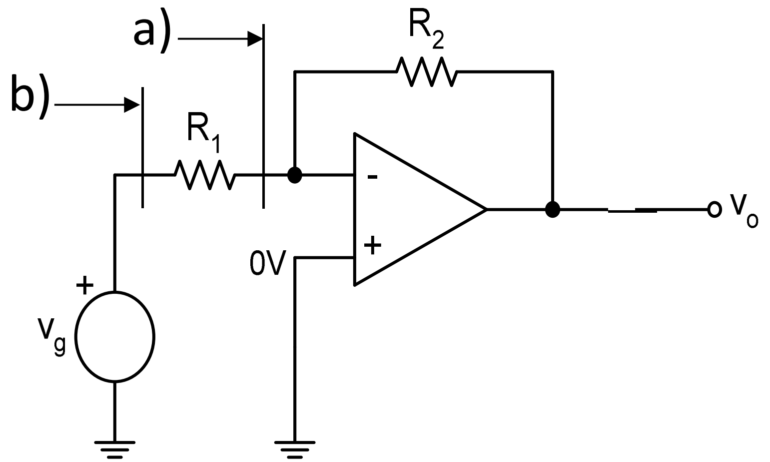
Can determine the input resistance of the inverting amplifier

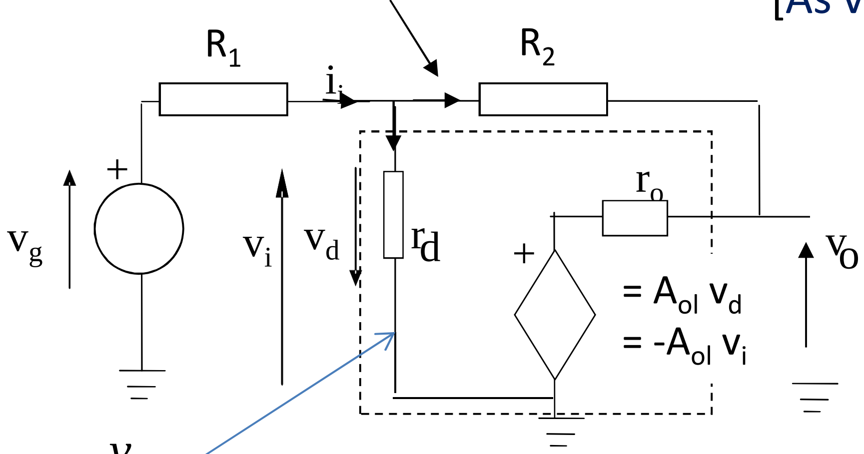
a) looking into the negative terminal ($R_{in}$')

b) looking from the source, $v_g$ ($R_{in}$)

$$i_{R2} = \frac{v_i - A_{ol} v_d}{R_2 + r_o} = \frac{v_i (1 + A_{ol})}{R_2 + r_o}$$

[As $v_d = -v_i$]



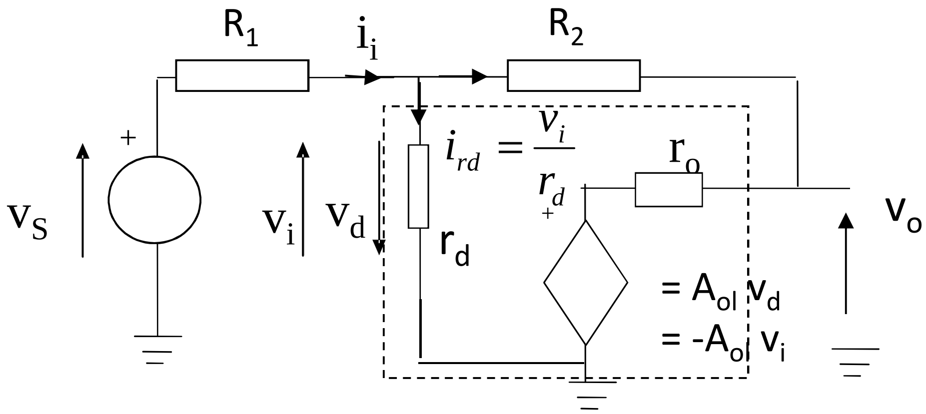




$$i_{rd} = \frac{v_i}{r_d}$$

$v_d = (v_p - v_n) = -v_i$

# Input Resistance of Inverting Amp - analysis

**a) looking into the negative terminal ($R_{in}'$)**




$$R_{in}' = \frac{v_i}{i_i} = -\frac{v_d}{i_i}$$ also, $$i_i = i_{rd} + i_{R2}$$ so $$i_i = \frac{v_i}{r_d} + \frac{v_i - (-A_{ol} v_i)}{R_2 + r_o}$$

$$\boxed{\rightarrow i_i = \frac{v_i}{r_d} + \frac{v_i(1+A_{ol})}{R_2 + r_o}}$$

$$\frac{i_i}{v_i} = \frac{1}{R_{in}'} = \frac{1}{r_d} + \frac{(1+A_{ol})}{R_2 + r_o}$$ so $$R_{in}' \equiv \frac{v_i}{i_i} = r_d \,//\left(\frac{R_2 + r_o}{1+A_{ol}}\right)$$

(Because $\frac{(1+A_{ol})}{R_2 + r_o}$ has units of '1/R')

Note that the input impedance has been reduced by feedback through the influence of a *resistance* $(R_2+r_O)/(1+A_{ol})$.

e.g. for example if: $R_2 = 10$ k, $R_1 = 1$ k (gain of 10); $r_o \sim 75\ \Omega$, $A_{ol} = 2\times10^5$, $r_d = 2\ \text{M}\Omega$

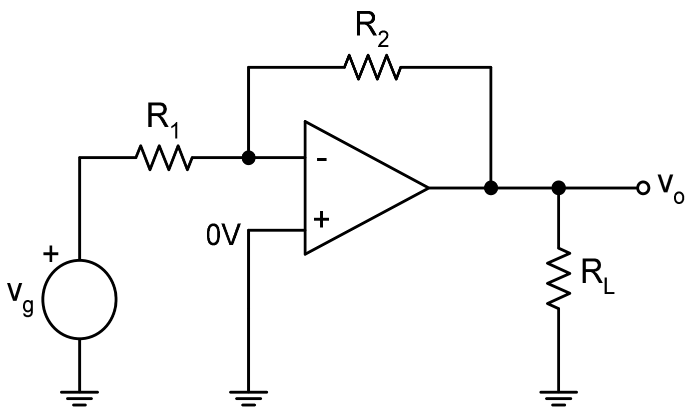
Then **$R_{in}' \sim 0.1\ \Omega$ *which is small - as expected!***

# Input resistance of inverting op-amp (contd)

Then **$R_{in}'$ = 0.1 Ω *which is small - as expected!***

$$R_{in}^{'} \equiv \frac{v_i}{i_i} = r_d \,//\left(\frac{R_2 + r_o}{1 + A_{ol}}\right) \quad \Rightarrow \quad R_{in}^{'} \approx \frac{R_2}{1 + A_{ol}}$$

b) **Looking from the source,** we see **$R_1 + R_{in}'$ ~ $R_1$ = 1 kΩ** that is, the input resistance of this *trans-resistance* amplifier ***is equal to $R_1$***




**So when designing a circuit of this type, choose $R_1$ to meet the required input resistance and then choose $R_2$ to meet the required gain ($-R_2/R_1$)**

# Electronic circuits and systems
# ELEC271

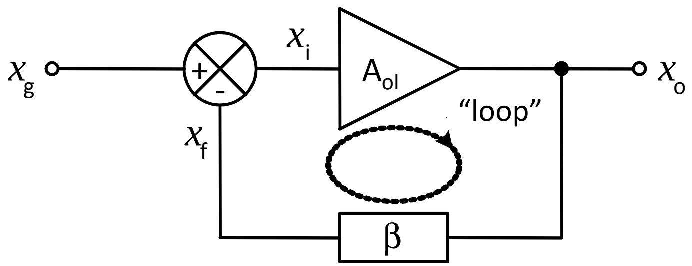
## Part 18
## Finding the loop gain

# Finding the loop gain

We have seen that the feedback factor $(1+\beta A_{ol})$ is a very important quantity that determines the behaviour of a feedback amplifier in many ways.

To determine its effect in a given amplifier it is first necessary to calculate the loop gain $\beta A_{ol}$. This can be done as follows:

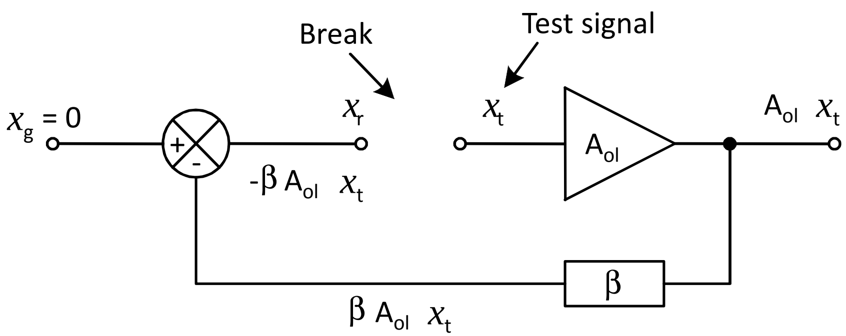
1) Suppress $x_g$ (turn down to zero)
2) Break loop at some convenient point
3) Inject a test signal $x_t$
4) Trace round loop to find return signal $x_r$




$$x_r = -\beta A_{ol}\ x_t$$

Then

$$\frac{x_r}{x_t} = -\beta A_{ol}$$



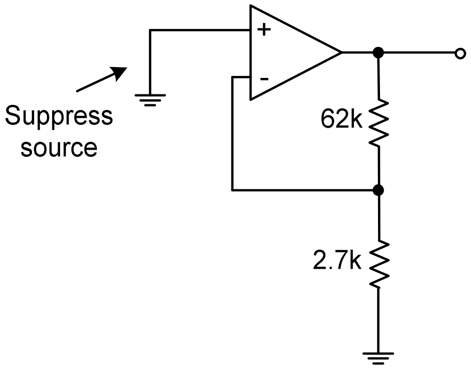

Note

- it should be negative, (otherwise the feedback is positive!)
- It doesn't matter **where** in loop break is made (but it is best done after a generator)

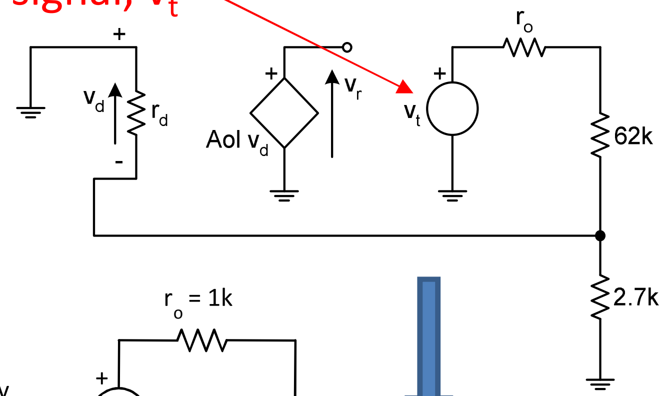
# Example 1

Consider the non-inverting amplifier below and suppose $r_o = 1k, \quad r_d = 10k, \quad A_{ol} = 10^2$

(not a very good op-amp!)




Break the loop and insert a test signal, $v_t$



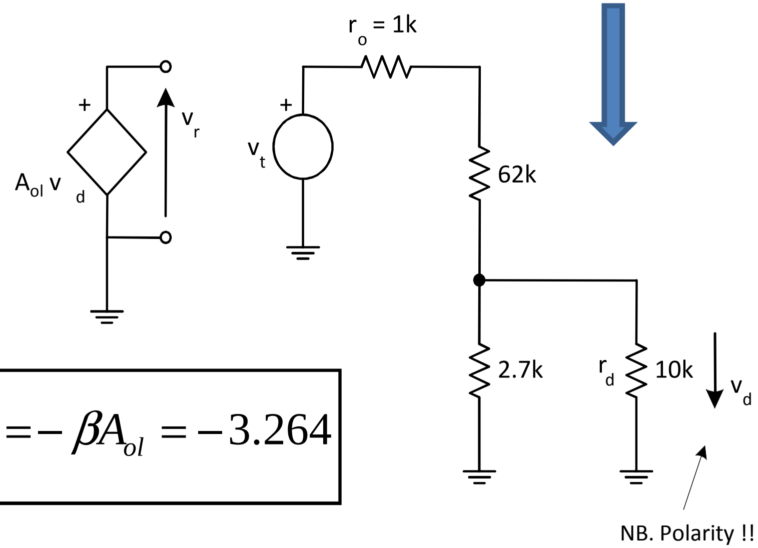

Then, calculate the loop gain:

$$v_d = -\frac{(2.7k \parallel 10k)}{2.7k \parallel 10k + 62k + 1k} \times v_t$$

$$= -\frac{2.126k}{65.126k} \times v_t = -\frac{1}{30.63} v_t$$

$$\therefore v_r = A_{ol}\, v_d = -\left(10^2 \times \frac{1}{30.63}\right) v_t$$

$$\boxed{\frac{v_r}{v_t} = -\beta A_{ol} = -3.264}$$



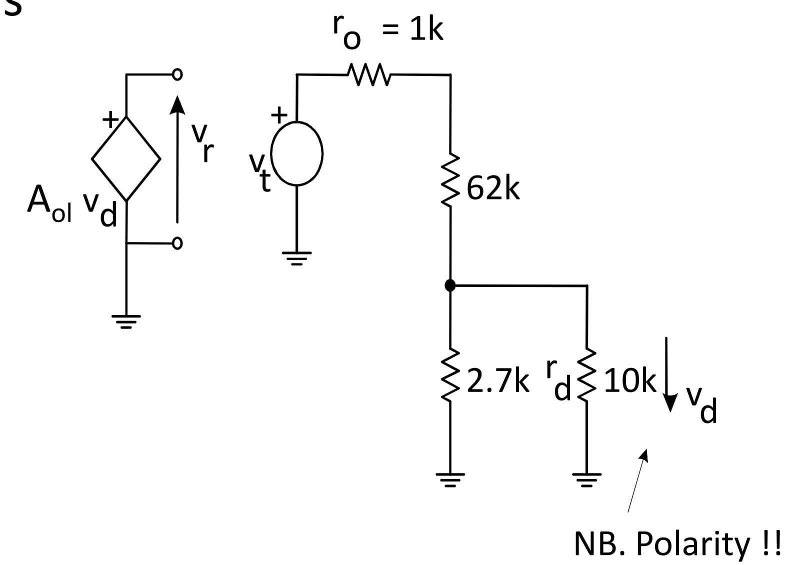

{Note that had an **ideal amplifier** been assumed, $A_{ol}\beta = -100 \times \left(\frac{2.7k}{2.7k + 62k}\right) = -4.17$}

**Also, 1/β approx would give a gain of 24 (1 + 62/2.7)**

# Calculation of loop gain (contd.)

A better estimate of gain of **this** circuit however, is

$$A_f = A_\infty \frac{T}{1+T} = 24\frac{3.264}{1+3.264} = 18.37$$




**Compared to the approx. Value: 1/β = 24!**

Also can get good estimates for:

$$R_{in} \cong r_d\left(1+\beta A_{ol}\right) = 10k \times \left(1+3.264\right) = 42.64k$$

and $$R_o \cong \frac{r_o}{1+\beta A_{ol}} = \frac{1k}{4.264} = 234.5\,\Omega$$

**Conclude: our calculation of gain using 1/β only valid if T>>1**

Note that if the gain had been $A_{ol} = 2 \times 10^5$ , $r_d = 2$ MΩ, $r_o = 75$ Ω, (typical values for 741 op-amp) then **repeating the analysis** gives

$\beta A_{ol} = 8.35 \times 10^3$ and $R_{in} = r_d\left(1+\beta A_{ol}\right) = 2\text{M}\Omega \times \left(1+8.35\times 10^3\right)$

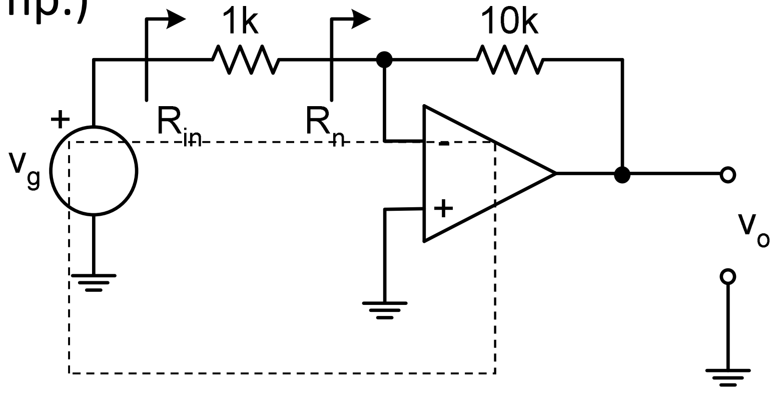
$= 16.7 \times 10^9\,\Omega$ - big! (as required for a V-amp)

$$\left\{ R_o = \frac{r_o}{1+\beta A_{ol}} = \frac{75\Omega}{1+8.34\times 10^3} = 9.00\times 10^{-3}\,\Omega \quad \text{- small! (as required for a V-amp)} \right\}$$

# Estimate of loop gain, Example 2

**Inverting amplifier** (recall it's a trans-resistance amp.)

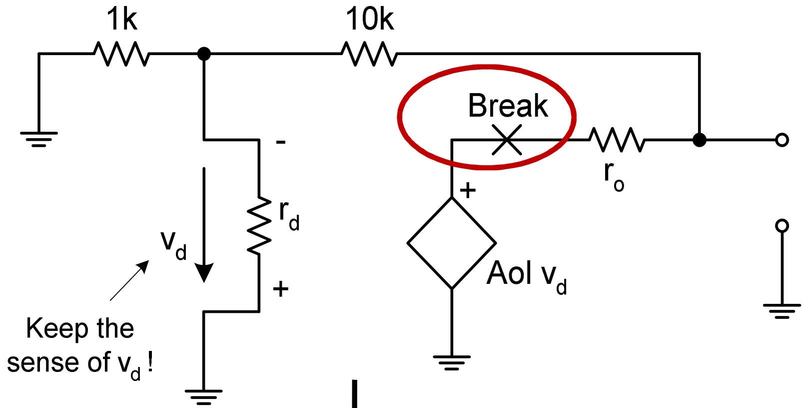
Virtual short principle gives a gain of –10



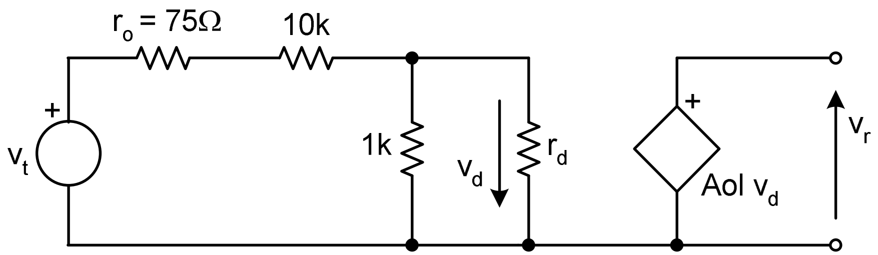

(Take values for 741

$A_{ol} = 2\times10^5 \quad r_d = 2\,\mathrm{M\Omega}$

$r_o = 75\ \Omega$




Re-draw




$$v_d \approx -\frac{1k}{1k+10k+75}v_t = -\frac{1}{11.075}v_t$$

(because $1k \| r_d = 1k \,//\, 2M \cong 1k$ )

$$\therefore \frac{v_r}{v_t} = -2\times10^5 \times \frac{1}{11.075} = -1.806\times10^4$$

**So feedback is negative and loop gain is** $\beta A_{ol} = 1.806\times10^4$

# Loop gain of inverting op-amp. (contd.): $R_o$ and $R_n$

$$R_o = \frac{r_o}{1+\beta A_{ol}} = \frac{75}{1+1.806\times10^{4}} = 4.15\times10^{-3}\Omega$$

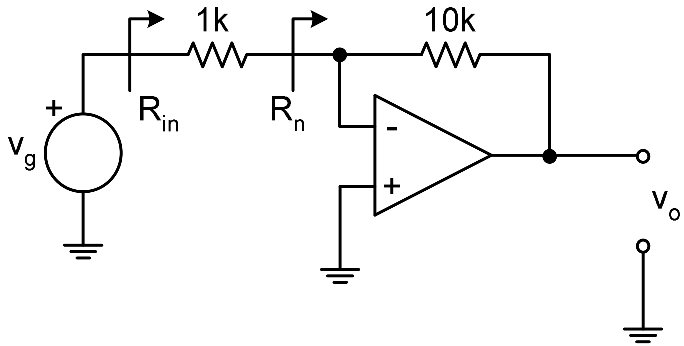
- Small - as expected

$$R_n \sim \frac{R_f}{1+A_{ol}} = \frac{10k}{1+2\times10^{5}} = 0.05\Omega$$

- Small - as expected (because the feedback makes it an ‘ideal’ trans-resistance amplifier)

$$R_{in} = 1k + R_n \approx 1k$$

i.e. $R_{in}$ is set by the external resistor!



# Advantages of Negative Feedback

1. Negative feedback reduces the **sensitivity** of the gain on parameters of amplifier such as transistor current gain.
2. Negative feedback allows us to set gain to any value we want.
3. Negative feedback allows us to adjust the **input** and **output** impedances of an amplifier.
4. ***Negative feedback increases the bandwidth of the amplifier.***
5. Negative feedback reduces **distortion**

BUT these advantages **<u>do not</u> come FREE**!

1. Negative feedback **always** reduces the gain of an amplifier.

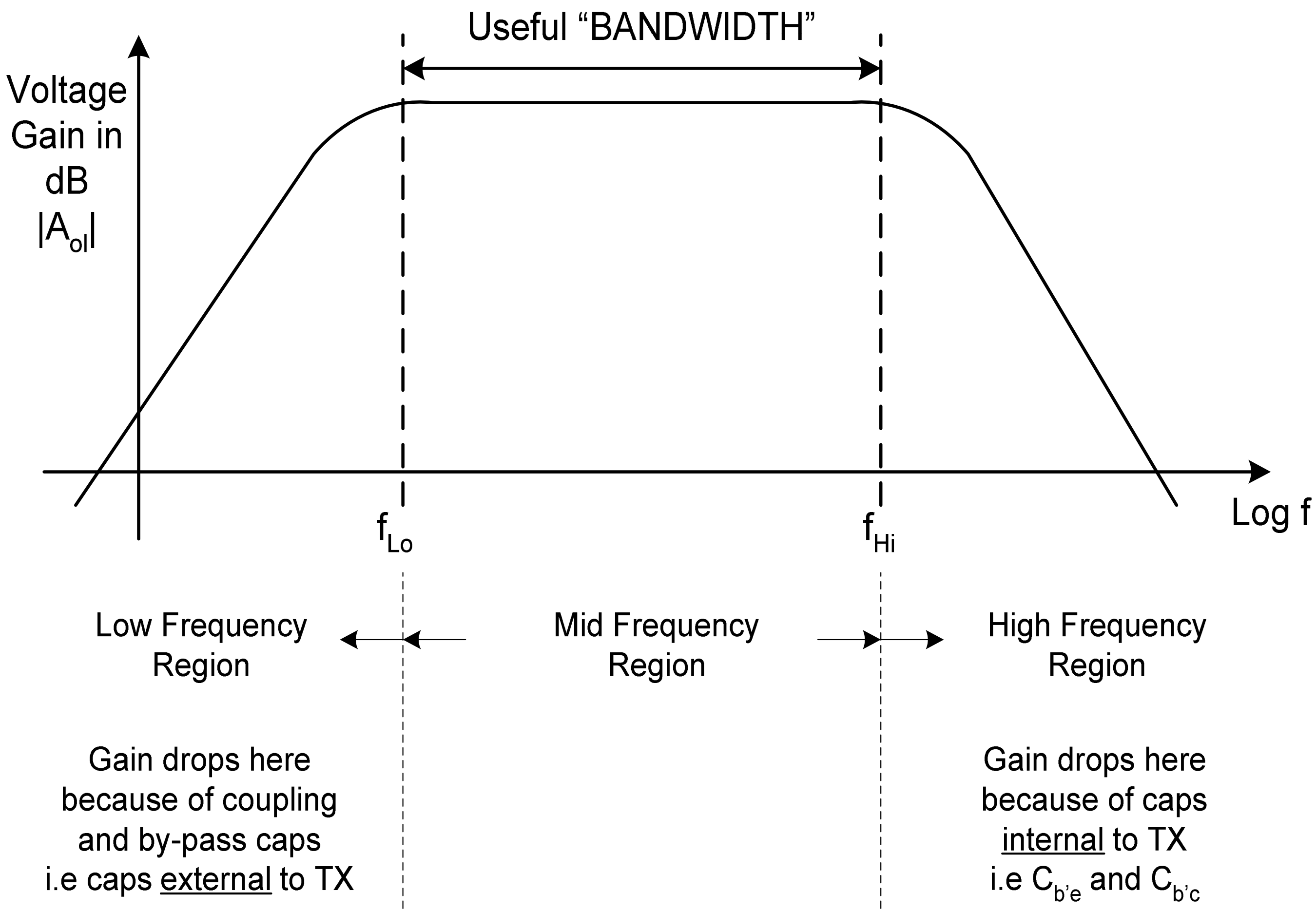
2. Over certain frequency ranges, it can be that negative feedback changes from **negative** to **positive** with catastrophic results. Positive feedback <u>increases</u> gain of the amplifier and amplifier may be converted to an <u>oscillator</u> – no longer any use as an amplifier

# Electronic circuits and systems
# ELEC271

## Part 19: Effect of Feedback on Bandwidth

# Effect of Negative Feedback on Amplifier Bandwidth

Bandwidth of transistor amplifiers is determined by CAPACITORS:




Note that this is a log – log graph (the vertical axis is plotted in dB)

## Q: What happens when we apply feedback? How is bandwidth affected?

**A: The bandwidth is effectively increased by the feedback factor $(1 + \beta A_{ol})$**

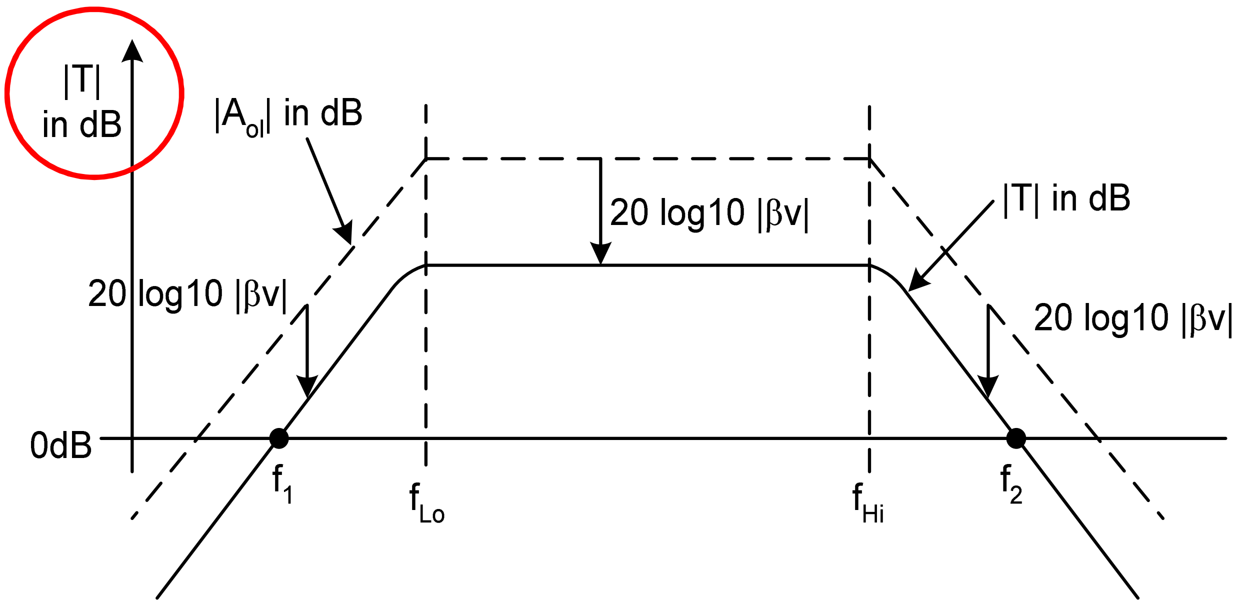
To explain this, consider first the loop gain of a voltage amp. ($A_{ol}\beta_v$).

When expressed in dB this becomes: $20\log_{10}(A_{ol}\,\beta_v) = 20\log_{10}(A_{ol}) + 20\log_{10}(\beta_v)$

Note that $\beta_v < 1$ so $20\log_{10}\beta_v$ will be a negative quantity

eg. if $\beta_v = 0.1$, then $20\log_{10}\beta_v = -20dB$

**So the plot for $A_{ol}\beta_v$ vs. frequency is simply the curve for $A_{ol}$ shifted down by an amount equal to $\log_{10}\beta_v$**

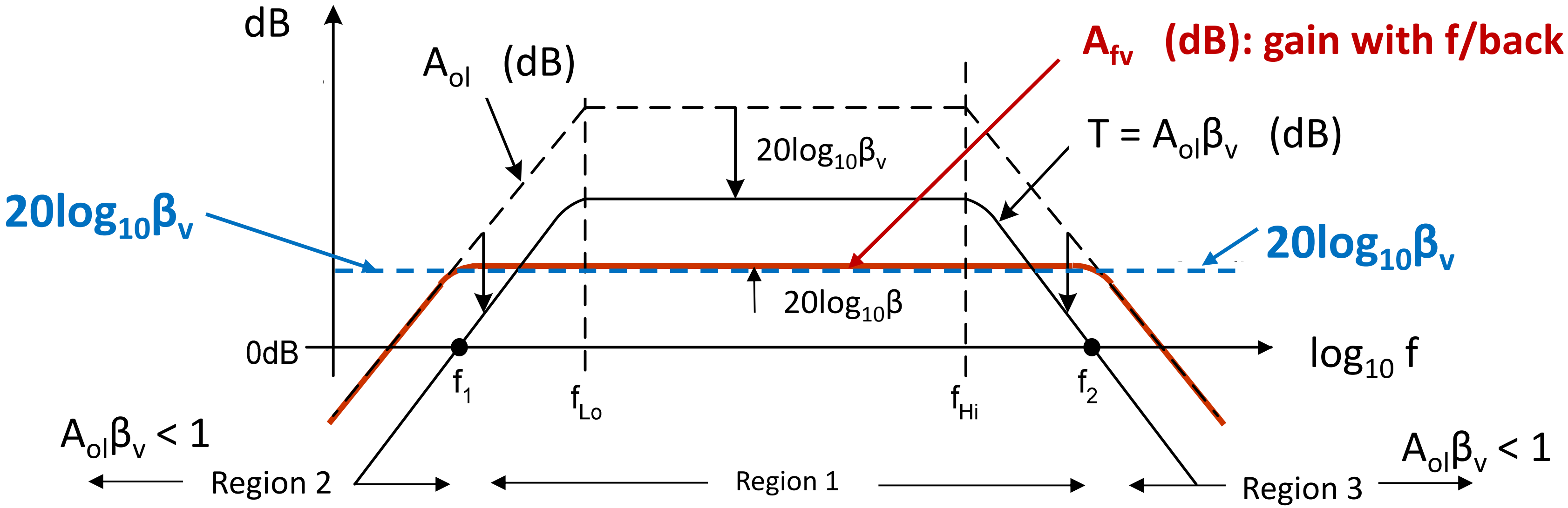



**Note points where**

$$|T| = 0dB \rightarrow f_1, f_2$$

The amplifier with feedback has a closed loop gain $A_{fv} = \frac{1}{\beta_v}\frac{T}{1+T}$

And if $T \gg 0dB$, $A_{fv} \sim 1/\beta_v$ independent of $A_{ol}$!




*Region 1* $A_{ol}\beta_v > 1$ between $f_1$ and $f_2$

In this region,

$$A_{fv} = \frac{A_{ol}}{1+\beta_v A_{ol}} \approx \frac{1}{\beta_v} = \text{constant}$$

*Region 2 & 3* $A_{ol}\beta_v < 1$ up to $f_1$ and beyond $f_2$

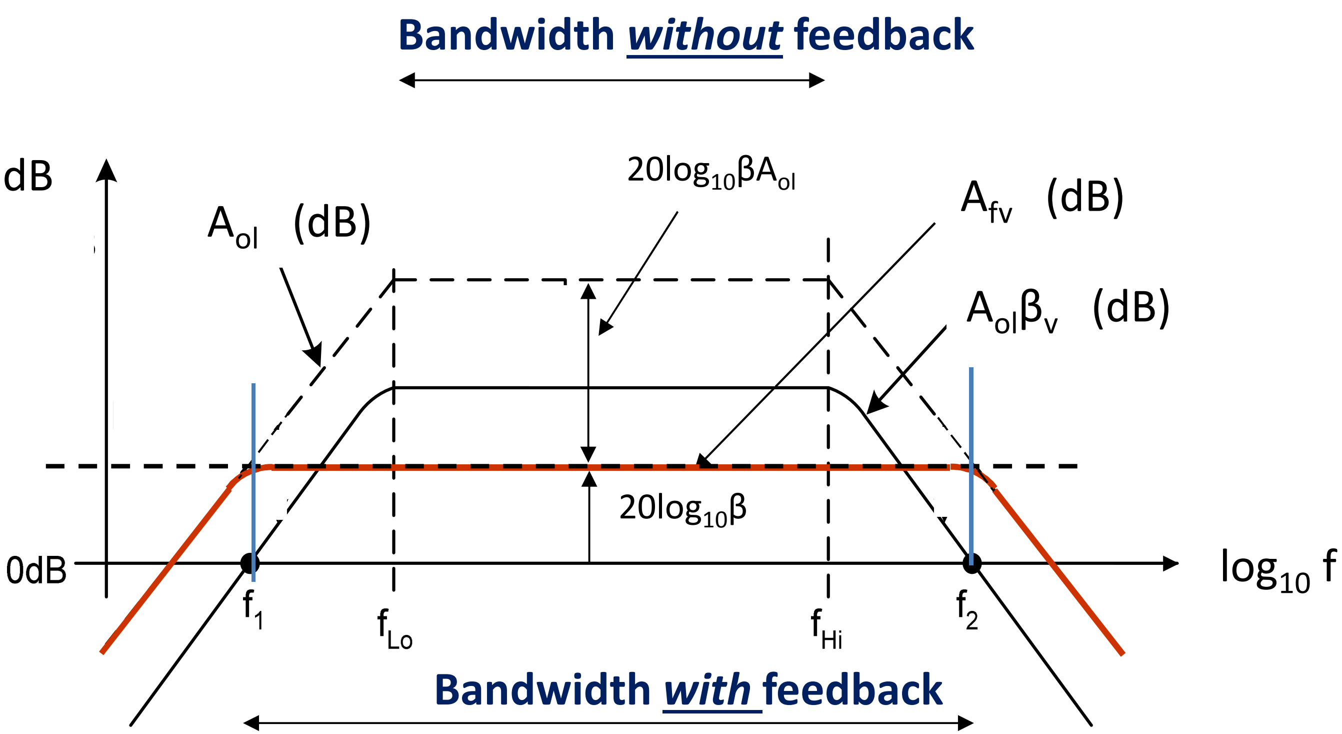
In both these regions,

$$A_{fv} = \frac{A_{ol}}{1+\beta_v A_{ol}} \approx A_{ol}$$

**So the curve for $A_f$ follows $1/\beta_v$ in region 1 and $A_{ol}$ in regions 2 and 3.**

**The NEW Bandwidth has been increased by the feedback to $(f_2 - f_1)$**

# Look at curves again...




Note that the separation between the open loop (- - -$A_{ol}$) and closed loop (---$A_{fv}$)

curves on this log-log plot is approximately $T = A_{ol}\beta_v$

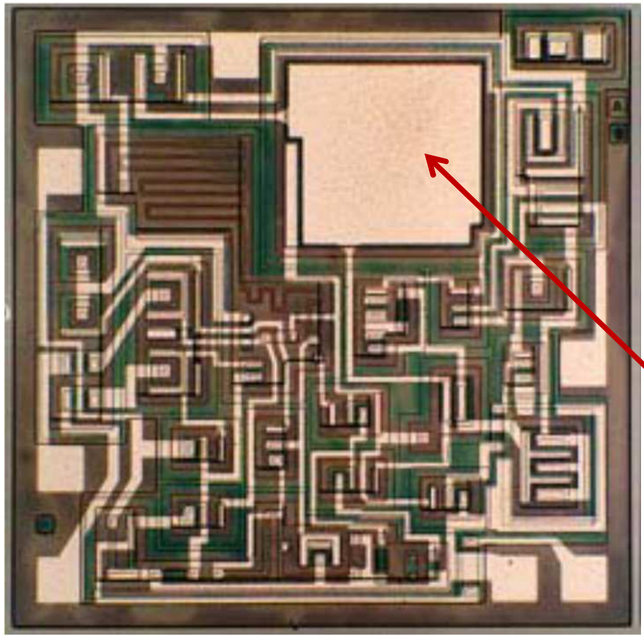
**Let's prove this:** $$\log(A_{ol}) - \log(A_{fv}) = \log(A_{ol}) - \log\left(\frac{A_{ol}}{1+\beta_v A_{ol}}\right)$$

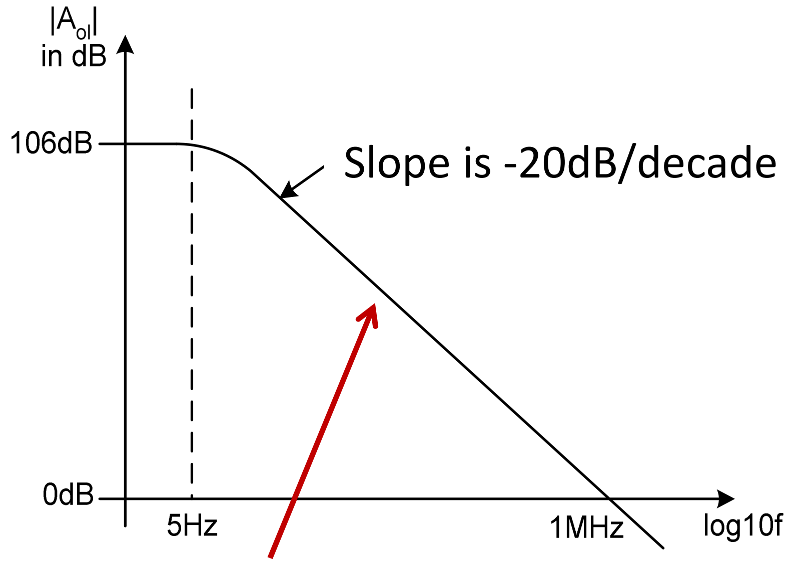
$$= \log(1+\beta_v A_{ol}) \quad \boxed{\approx \log \beta_v A_{ol} \quad \text{if } \beta_v A_{ol} >> 1}$$

log(A/B)
= log(A) –log(B)

**How much bigger is bandwidth? Let's look at a real op-amp: 741**

# 741 Bode plot: open loop gain versus frequency (log-log plot)






A very big on-chip capacitor (30pF)
Is responsible for this roll-off

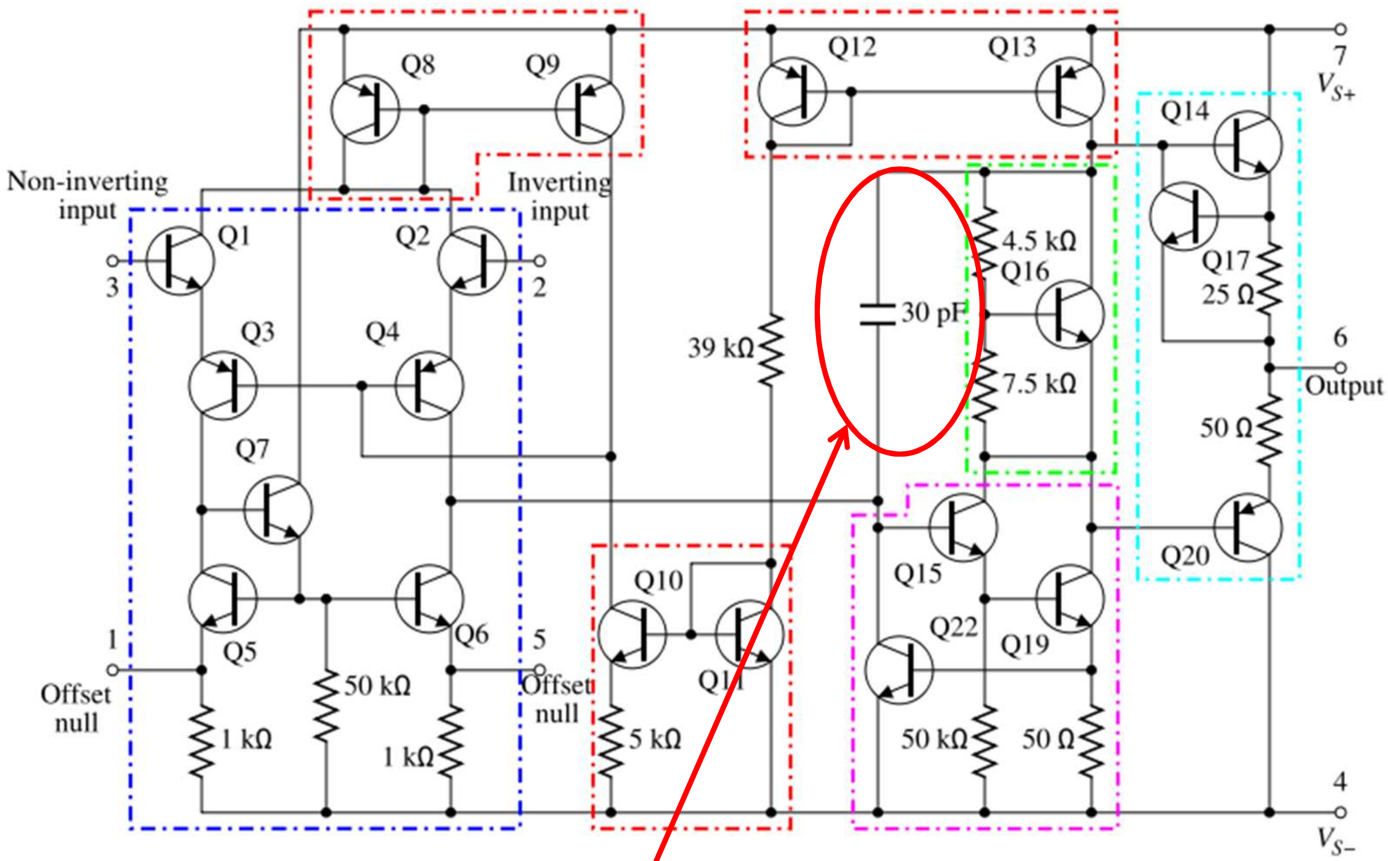
The 741 is designed to prevent users operating the amplifier at high frequencies with high gain - the amplifier can become very unstable!

'Uncompensated' op-amps are available where you can add your own 'compensating' capacitor externally – but you need to know what you are doing!

Note $A_{ol} = 106\ \text{dB} = 2 \times 10^5$ Open loop Bandwidth = 5 Hz only!

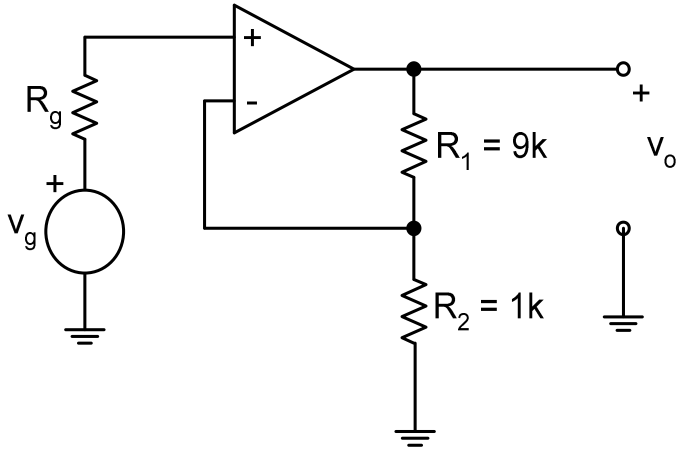
– gain down to DC (0Hz)

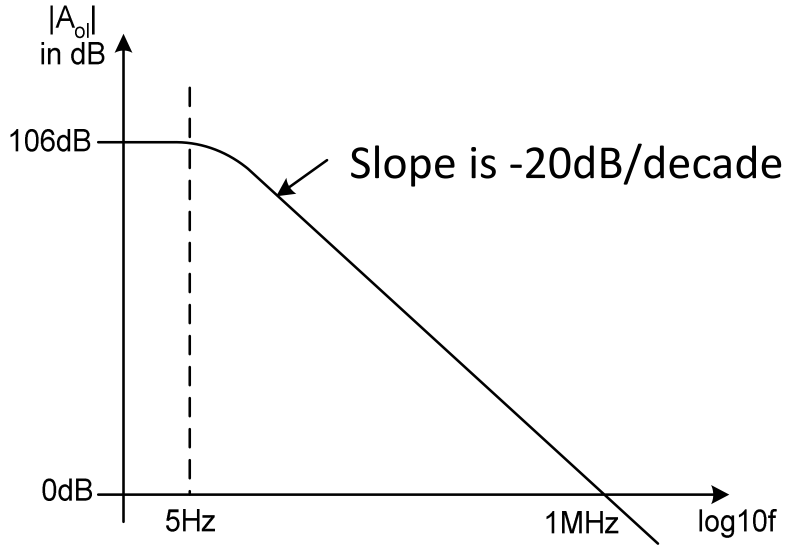
# Where is the compensating capacitor?




Provides INTERNAL feedback of this stage of the amplifier

# Example: 741 circuit (non-inv. Amp again)




The 741 data sheet shows the above open loop / frequency dependence

**$A_{ol}$ = 106 dB = 2 × $10^5$**  **Bandwidth = 5Hz!**

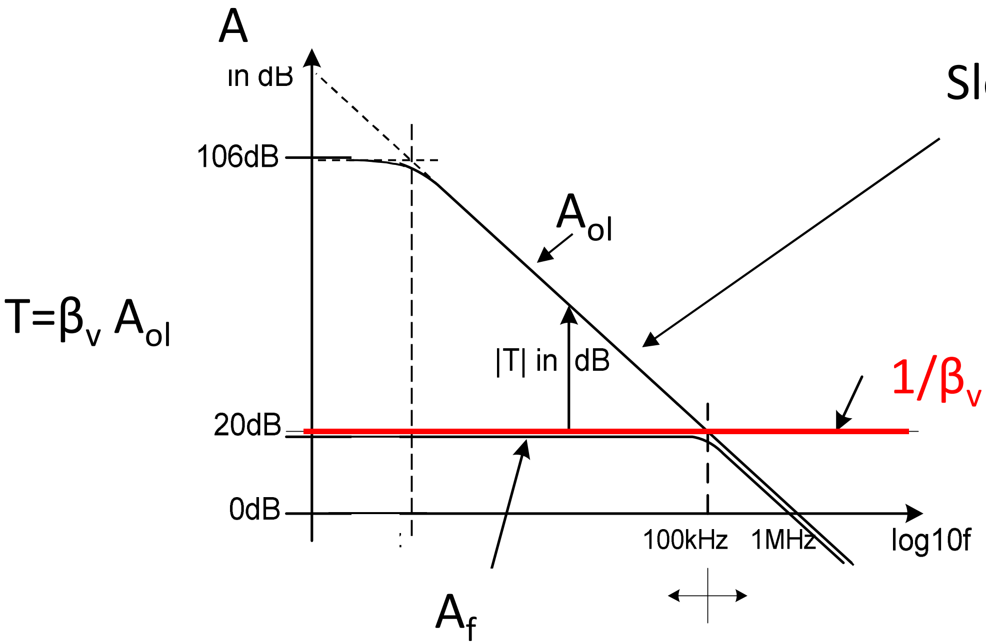
Note that $\beta = \frac{R_2}{R_1 + R_2} = \frac{1k}{1k + 9k} = \frac{1}{10}$ and $\beta_v A_{ol} = \frac{1}{10} \times 2 \times 10^5 = 2 \times 10^4 >> 1$

So for this non-inverting amplifier, the closed loop gain at low frequencies, (when $\beta_v A_{ol} >> 1$)

$$A_{fv} = \frac{A_{ol}}{1 + \beta_v A_{ol}} \sim \frac{1}{\beta_v} = \frac{R_1 + R_2}{R_2}$$ **= 10 = 20 dB**

# Example 741 (contd)

Adding the closed loop gain onto the plot of the open loop gain gives




Slope of this line is -20dB per decade,

$$-20dB/\text{decade slope MEANS } A_{ol}\ \alpha \frac{1}{f}$$

$$\text{so } A_{ol}\times f = \text{constant on this slope}$$

Open loop gain = $2\times10^5$, bandwidth is 5 Hz : **Gain × bandwidth product = $10^6$**

Closed loop gain = 10, bandwidth = 100 kHz : **Gain × bandwidth product = $10^6$**

Gain ***reduction*** is by the feedback factor $(1+\beta_v A_{ol}) \approx \beta_v A_{ol} = 0.1\times2\times10^5 = 2\times10^4$

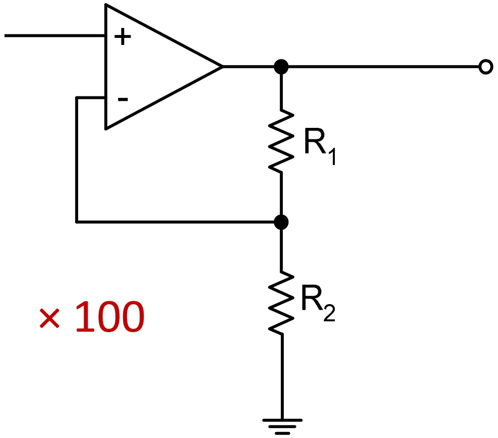
Bandwidth *increase* is by the feedback factor $(1+\beta_v A_{ol}) \approx \beta_v A_{ol} = 0.1\times2\times10^5 = 2\times10^4$

**So the Gain × bandwidth is a constant!**

# Improve bandwidth by cascading stages

GBWP = 1 MHz (741)

1-stage



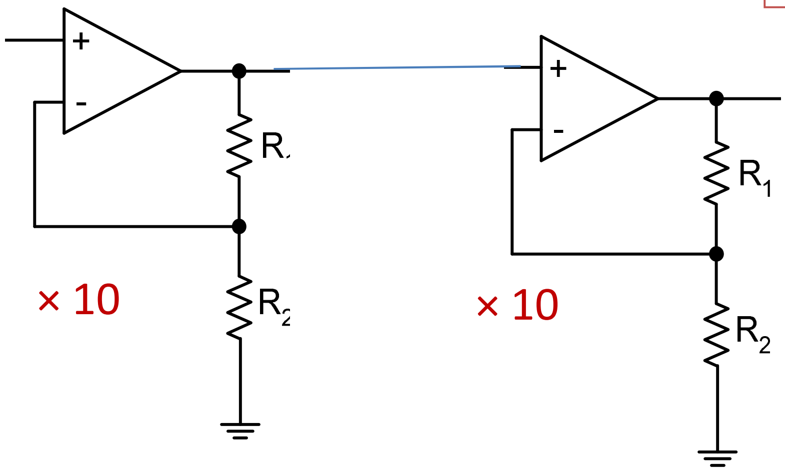

× 100

$$BW = \frac{1MHz}{100}$$ **= 10 kHz**

If Gains are same and identical op-amps:

$$\boxed{BW_{Total} = BW(1stage) \times \sqrt{2^{1/N} - 1}}$$

2-stages




× 10

× 10

BW$_2$ = 64.4 kHz

$$100k \times \sqrt{2^{\frac{1}{2}} - 1}$$

Note BW of 1 stage is 100 kHz because the gain is now 10

3-stages

× 4.6916

× 4.6916

BW$_3$ = 109.8 kHz

4-stages

Not advised as difficult to set gains

BW$_4$ = 138 kHz

# Advantages of Negative Feedback

1. Negative feedback reduces the **sensitivity** of the gain on parameters of amplifier such as transistor current gain.
2. Negative feedback allows us to set gain to any value we want.
3. Negative feedback allows us to adjust the **input** and **output** impedances of an amplifier.
4. Negative feedback increases the bandwidth of the amplifier.
5. ***Negative feedback reduces distortion***

BUT these advantages **do not come FREE**!

1. Negative feedback **always** reduces the gain of an amplifier.

2. Over certain frequency ranges, it can be that negative feedback changes from **negative** to **positive** with catastrophic results. Positive feedback increases gain of the amplifier and amplifier may be converted to an oscillator – no longer any use as an amplifier

# Electronic circuits and systems
# ELEC271

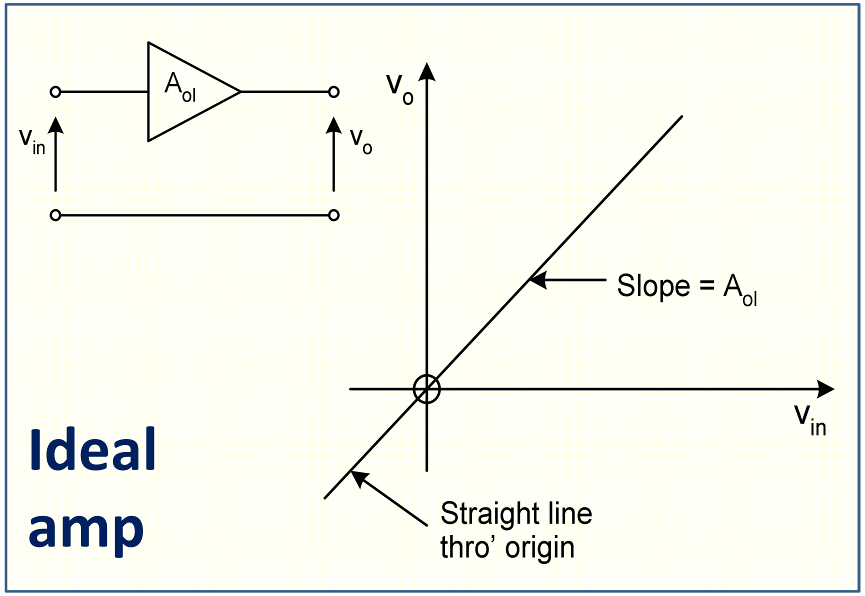
## Part 20
## Effect of feedback on distortion

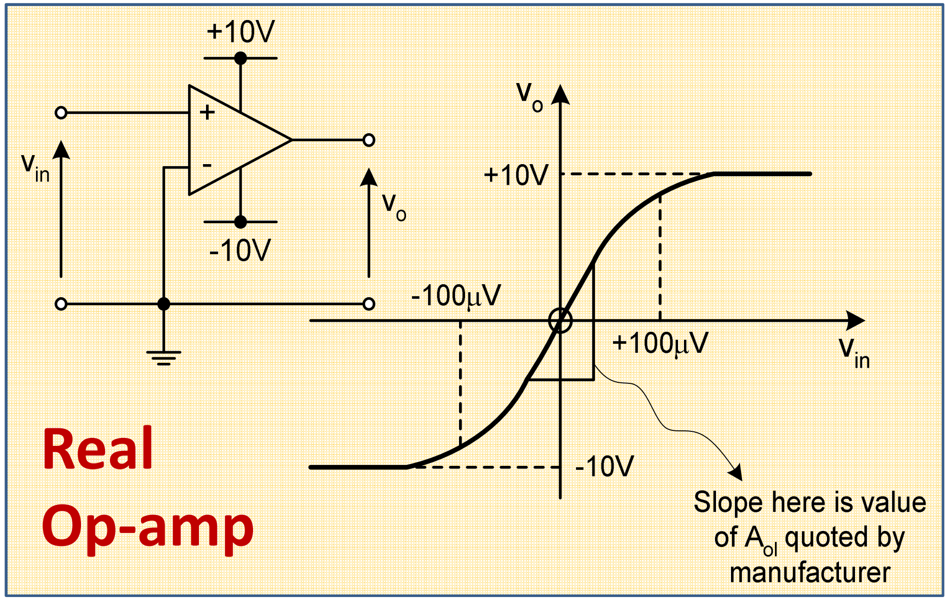
What do we mean by ‘distortion’?
How does feedback help reduce it?

# Effect of feedback on distortion

Negative feedback can reduce the amount of distortion produced by an amplifier.
Distortion occurs when the output is **not** a magnified but otherwise **exact copy** of input.
Why does negative feedback affect distortion?

- First, look at the **Voltage Transfer Curve** (VTC) of an amplifier.




Real amplifiers are only approximately linear because:

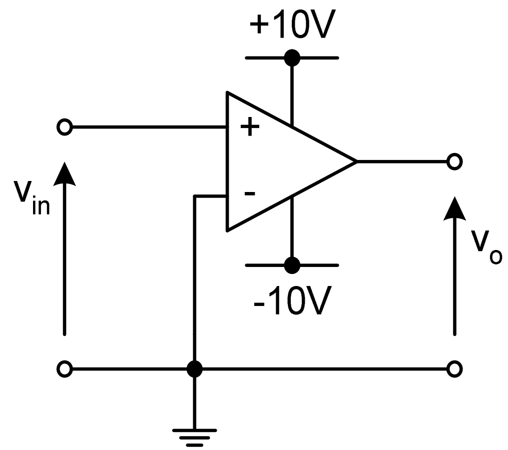
1) Transistors are **not** very linear devices

2) Output voltage swing is limited by **supply rails (-10 and 10V above)**

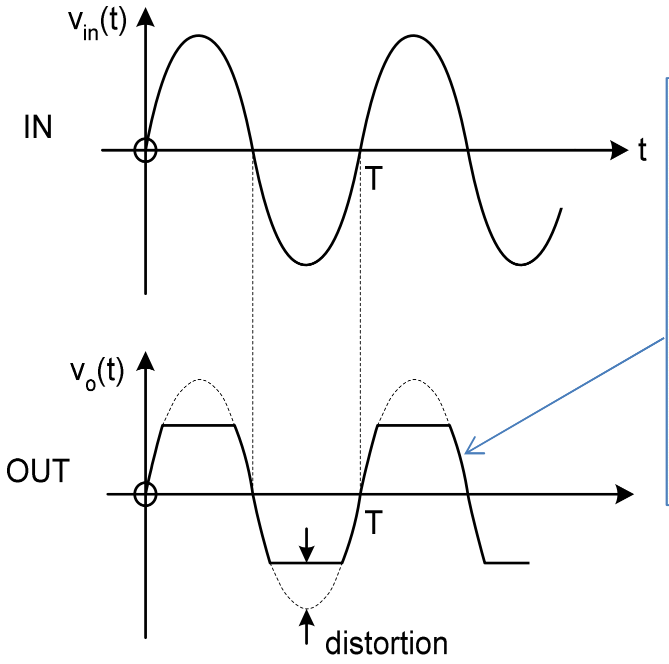
**(Q: what kind of distortion does (2) give??)**

**Note that the VTC was simulated in the assignment!**

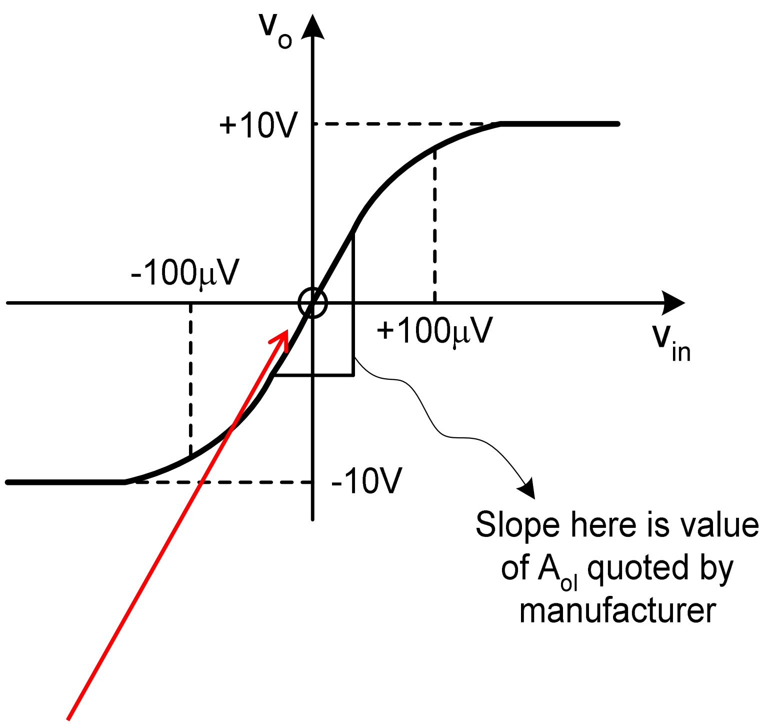
# Distortion




For this op-amp, if $v_{in}$ is a sinewave,
the output will be distorted - have flattened peaks



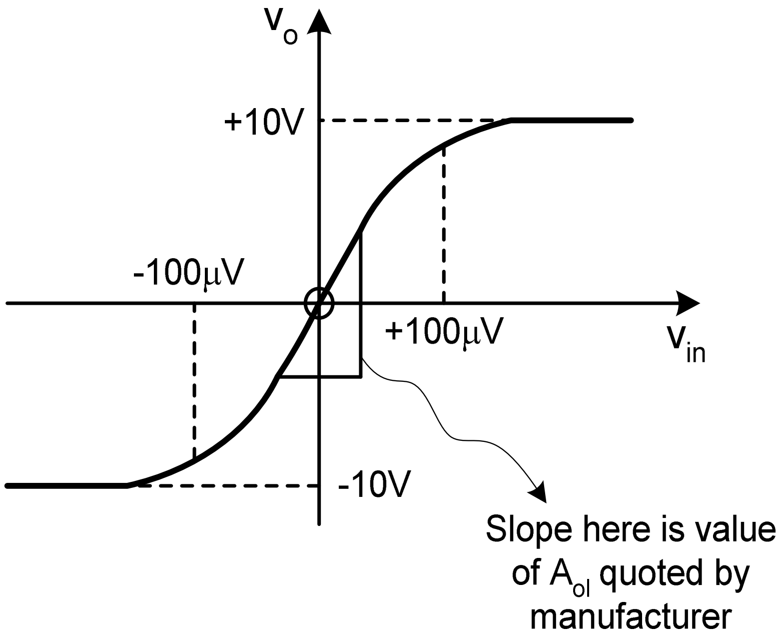

The sine wave also suffers distortion here because Gain is not constant



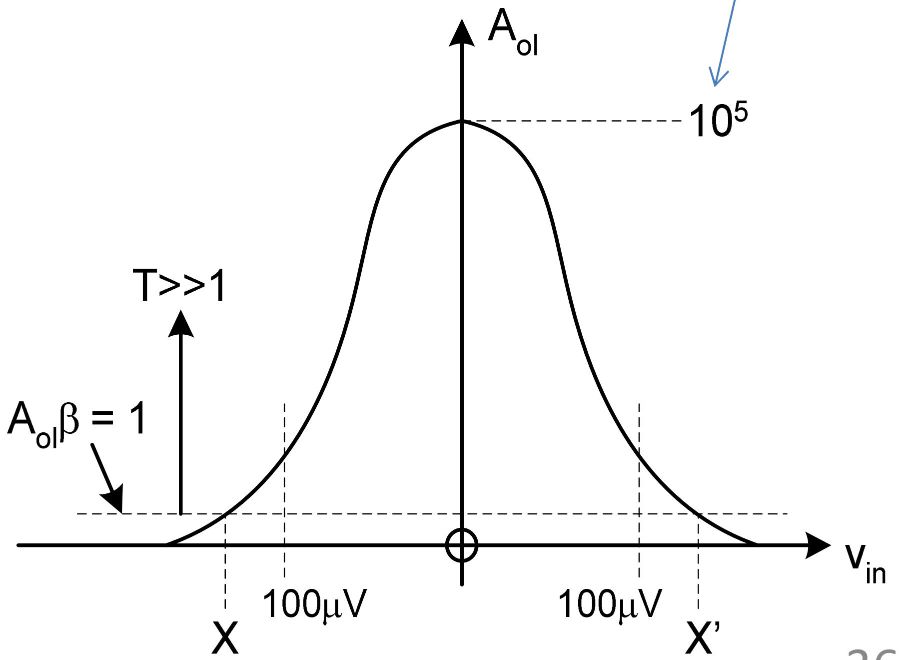

We should now define gain as $\dfrac{dv_o}{dv_{in}}$ i.e. as slope of curve $v_o$ vs $v_{in}$

# Distortion (contd)

So $A_{ol}$ varies with ***the amplitude of the input signal*** as slope of curve varies!

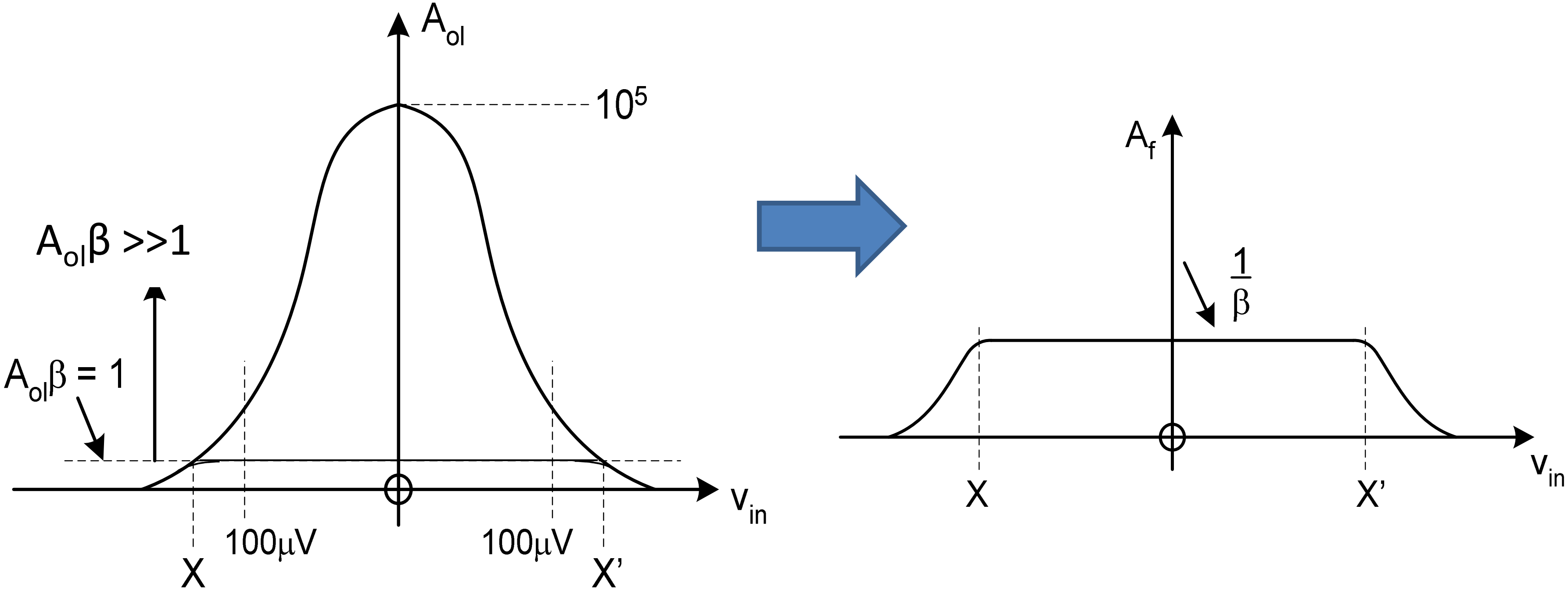



( This is the open loop gain published by the manufacturer )



# Distortion (contd)

$A_{ol}$ varies with **the *amplitude of the input signal***

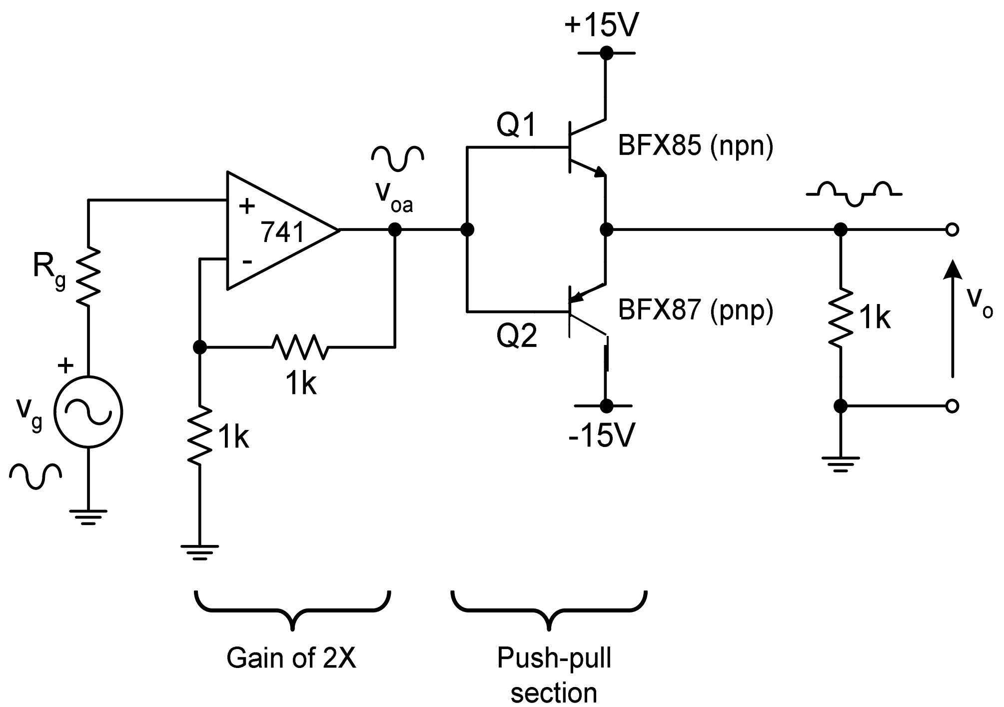



If we use this op-amp with **feedback** then $A_{fv} \approx 1/\beta_v$ over the range $A_{ol}\beta_v >> 1$

Over this range, the gain is then is determined by $1/\beta_v$ and is independent of $A_{ol}$ away from origin – so distortion is reduced (by the feedback factor)!

# Another example: cross-over distortion

Consider the very common 'push-pull' circuit shown below



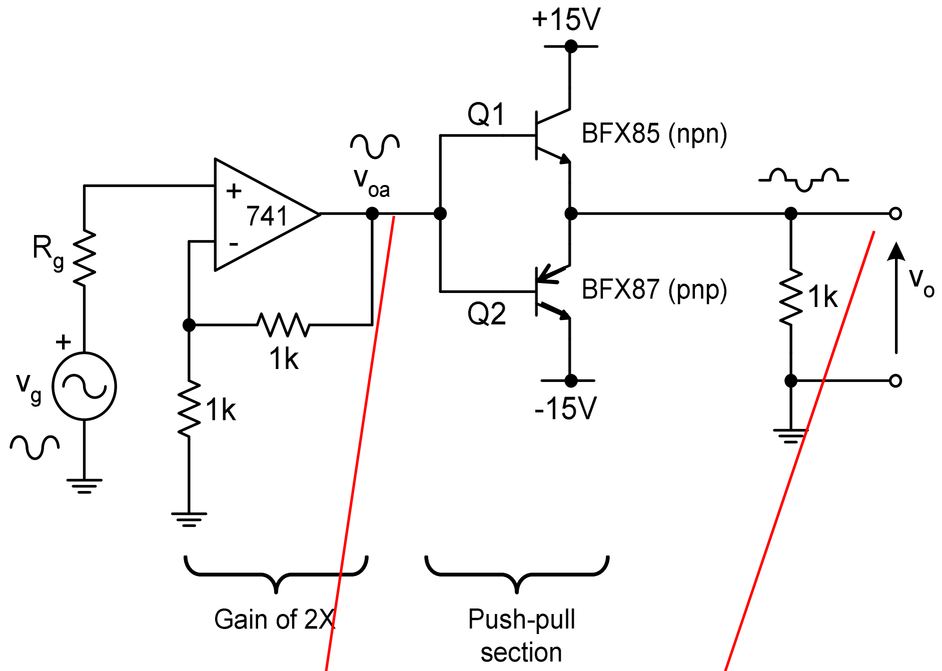

The circuit comprises of a small signal amplifier (the op-amp stage) followed by a 'push-pull' output stage that is two common collector stages in series connection across the power supply.

It is a **power amplifier** stage(known as CLASS B); can provide high power to the load (e.g. a loudspeaker)

# Cross-over distortion

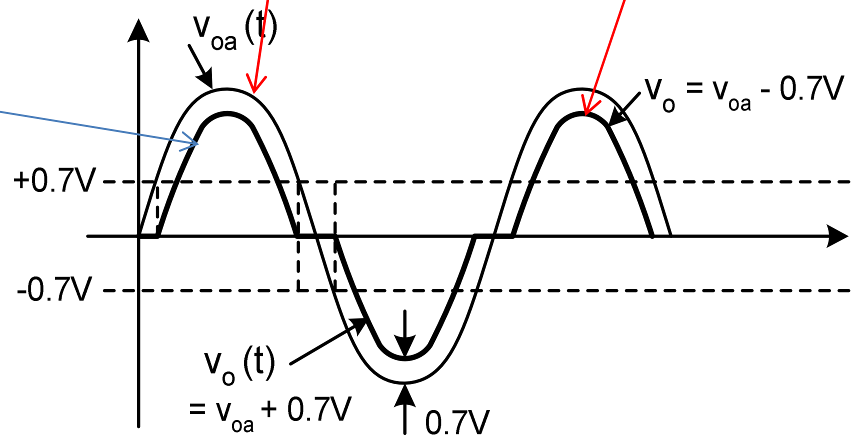
During one half cycle
Q1 is OFF and Q2 is ON

During the following half cycle
Q1 is ON and Q2 is OFF
etc




During the period of ‘cross-over’ between these two transistors conducting, there will be a short period when ***neither*** transistor conducts, which occurs whilst the input voltage to the base of the transistors changes from -0.7 to + 0.7 volts.

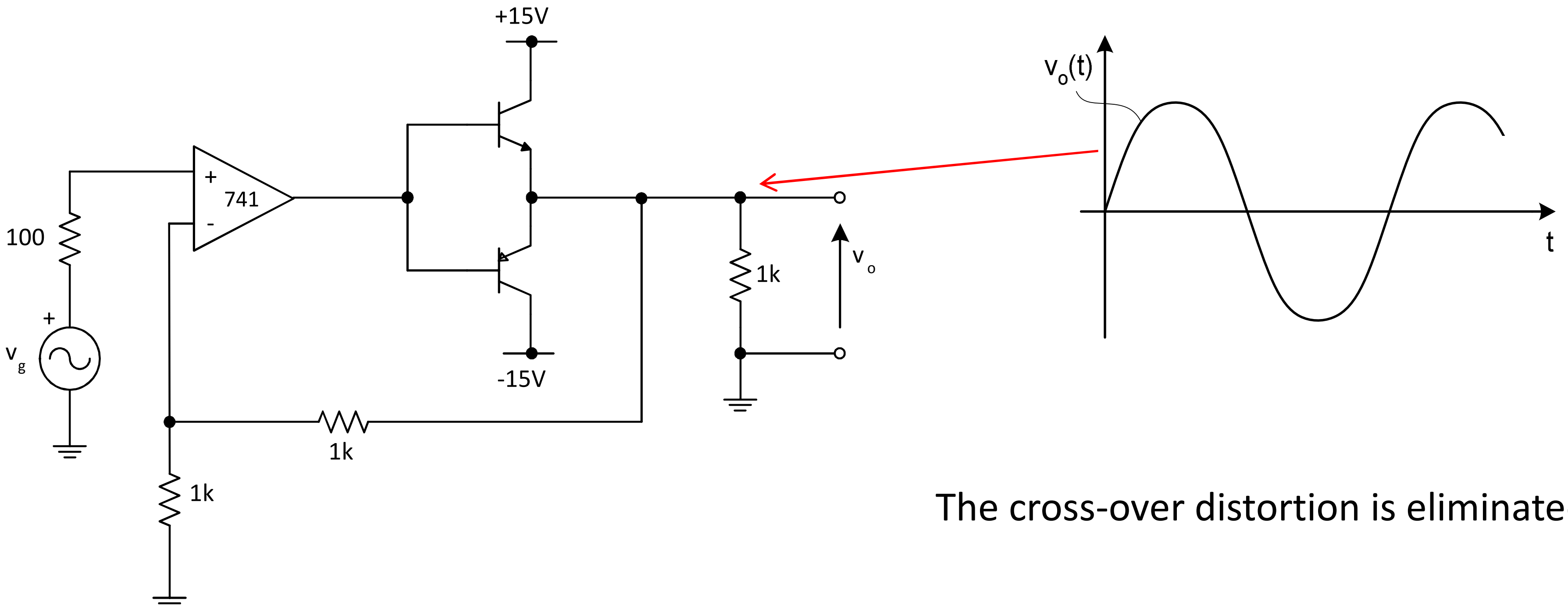
This causes ‘Cross-over Distortion’
So the output waveform becomes



# Solutions to cross-over distortion

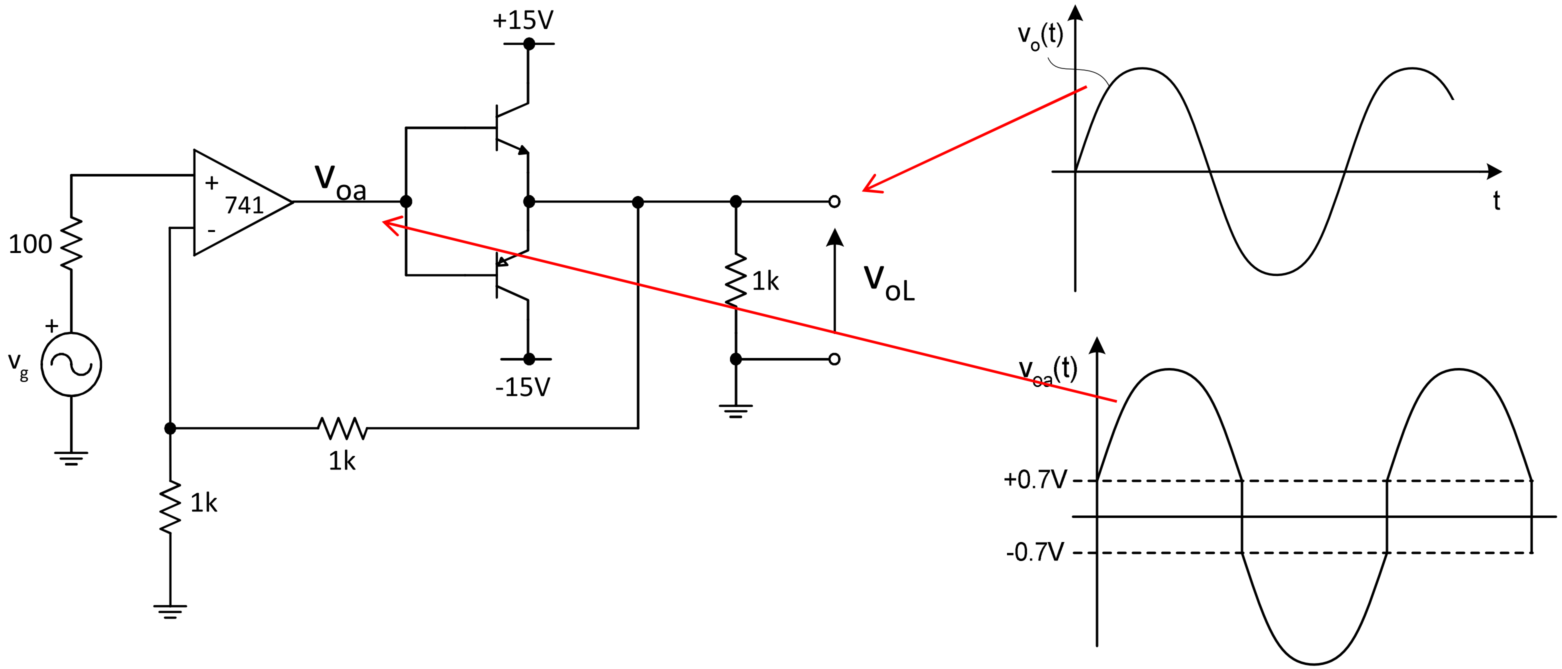
• One solution is to (carefully) bias both the transistors slightly ON so that there is only a very small voltage change required on the base of the transistors to make them start conducting significantly (called CLASS AB).

• BUT an alternative and highly effective method is to include the push-pull circuit **within** the feedback loop, giving :




The cross-over distortion is eliminated!

# How does it work

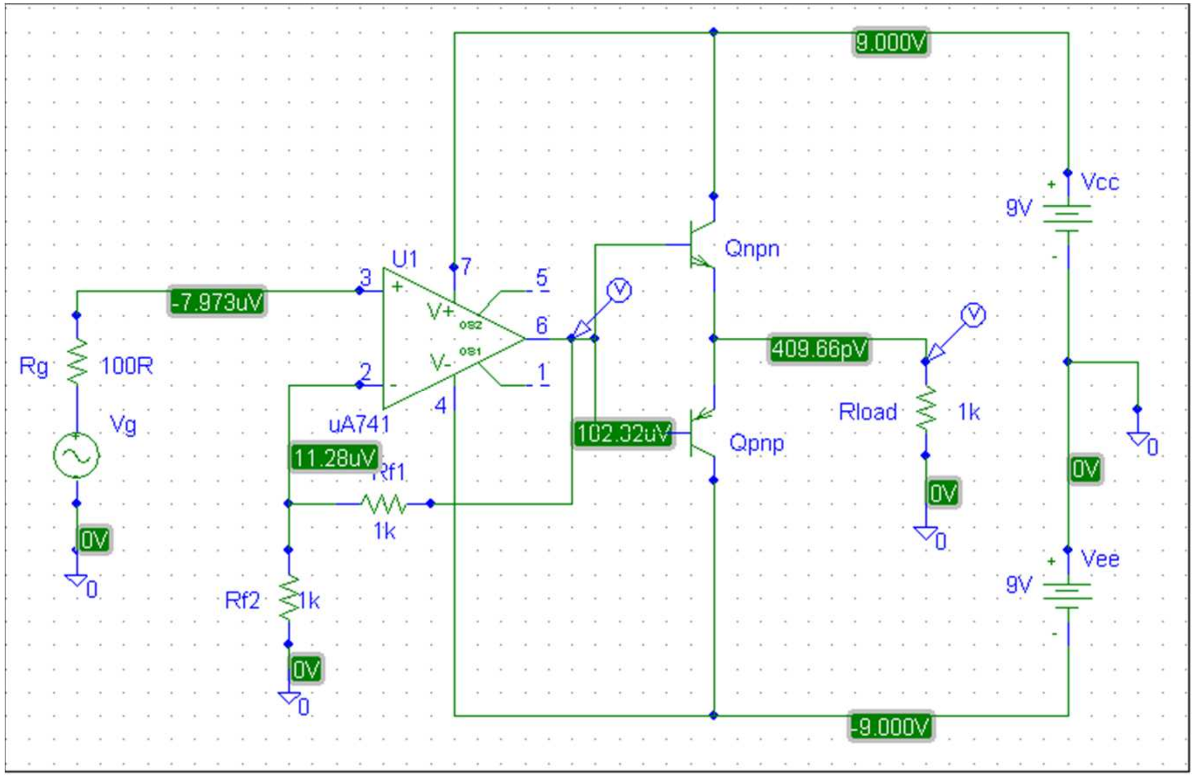


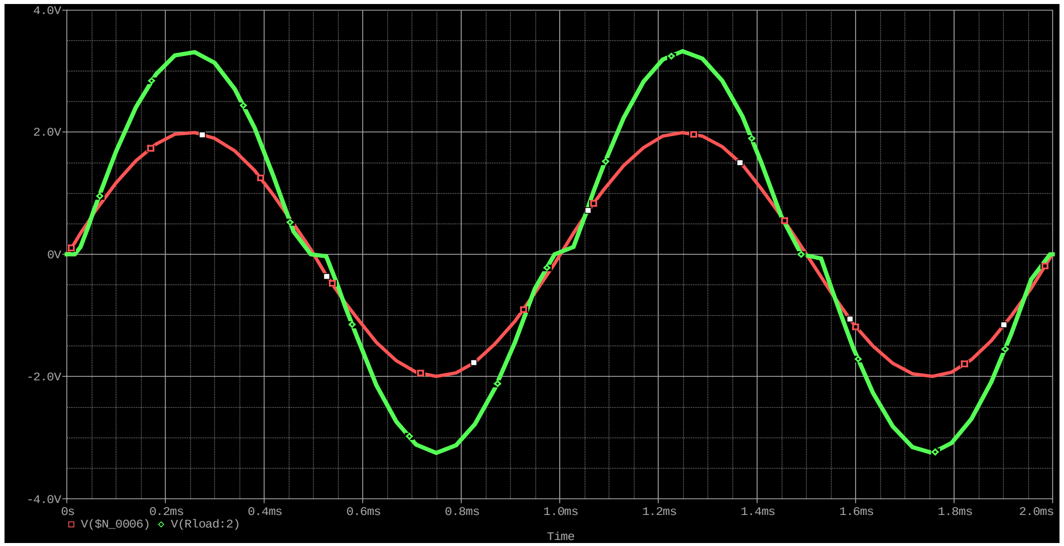

- The output of the op-amp jumps between levels -0.7V to +0.7V to force the push-pull amplifier through its "dead band" quickly.

- In effect, the input to the push-pull is **pre-distorted** by the op-amp in order to compensate for the distortion produced by the push-pull.

The feedback is monitoring the output voltage ***at the load*** **NOT** the output of the op-amp itself - so the amplifier maintains $1/\beta_v = v_{oL}/v_g$ rather than $v_{oa}/v_g$

# Demonstration: SPICE Simulation



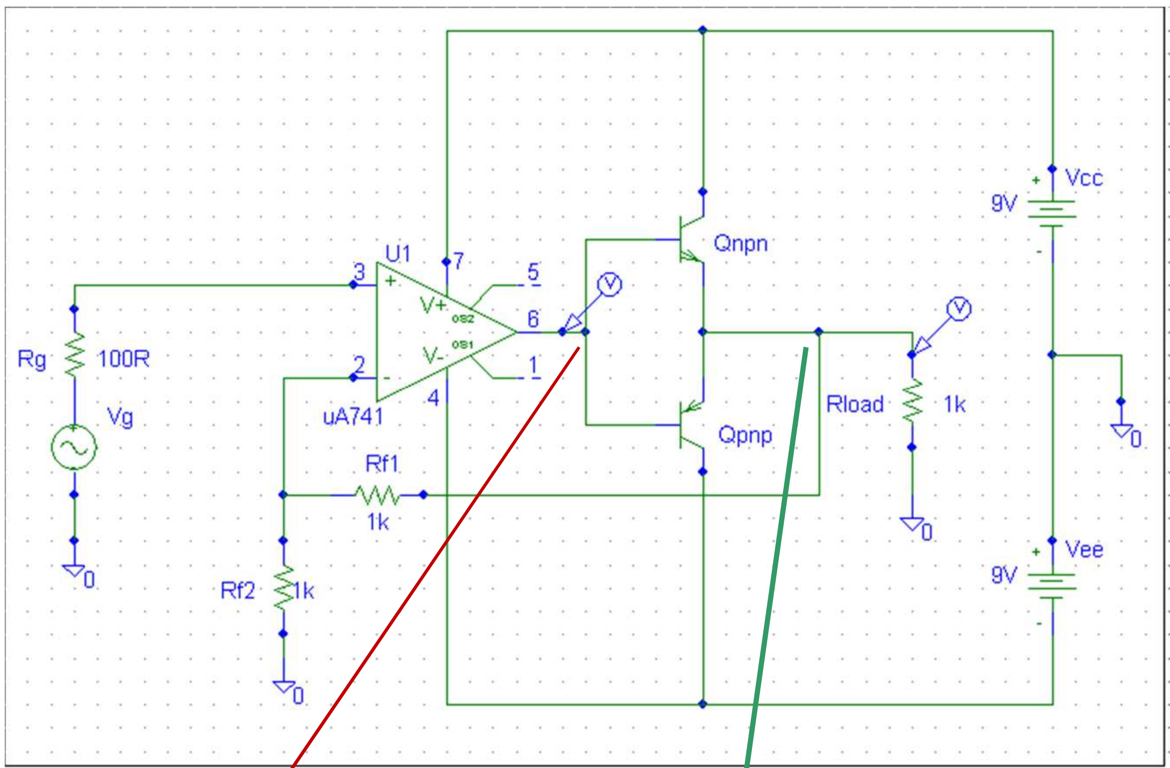



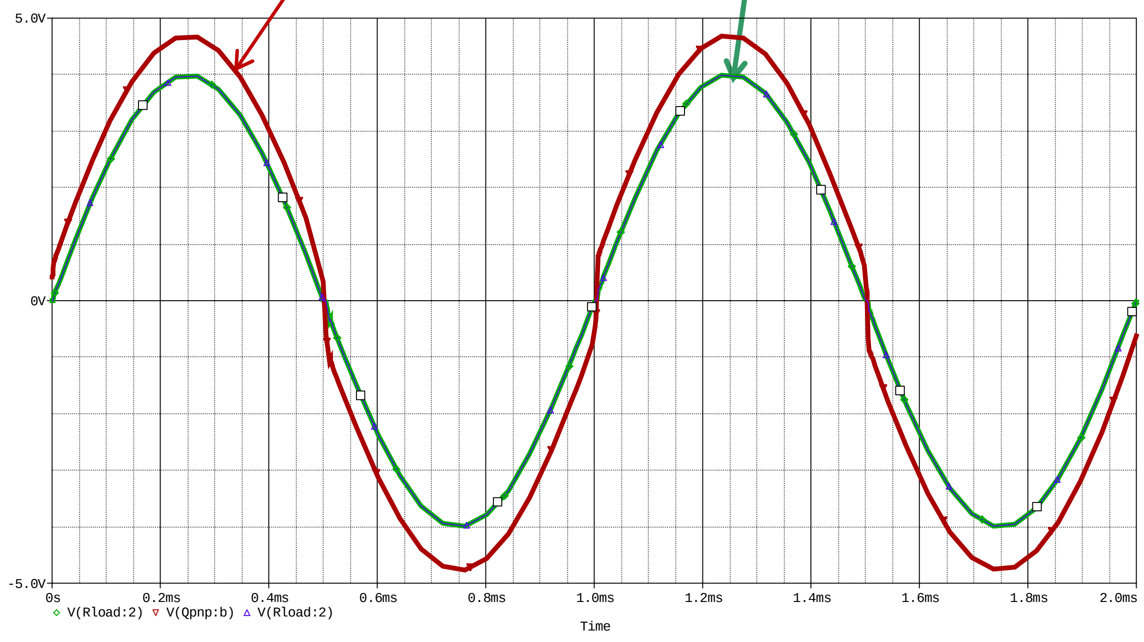

**Green line** is output voltage
Indicating
'Cross-over distortion'

**Red-line** is signal at output of op-amp

**TRY changing feedback**

# Sample at output




**Green line** is output voltage
Cross-over distortion has gone!

**Red-line** is signal at output of op-amp

**Look at shape of waveform!**

- End of part 20....

# Electronic circuits and systems
# ELEC271

## Part 21
## Op-amp limitations

**So far have assumed an ideal op-amp:**

Input draws no current

Zero output voltage for zero input voltages

**Not in fact true!** Although OK for doing simple design

**Now the truth!** ....... And what can be done

# Slew-rate limit to bandwidth

SR relates to the ability of the op-amp to respond to a signal;
that is, it relates to the **transient response** of the op-amp.

**Part 9:** the response, $t_{rise}$ of an ac coupled amplifier is an **exponential rise** with a time constant related to the upper cut-off frequency, $f_H$ of the amplifier:

$$f_H \approx 2.2\frac{1}{2\pi\tau_r} = \frac{0.35}{\tau_r}$$

**Op-amps also have a limit on how rapidly the output voltage can change**

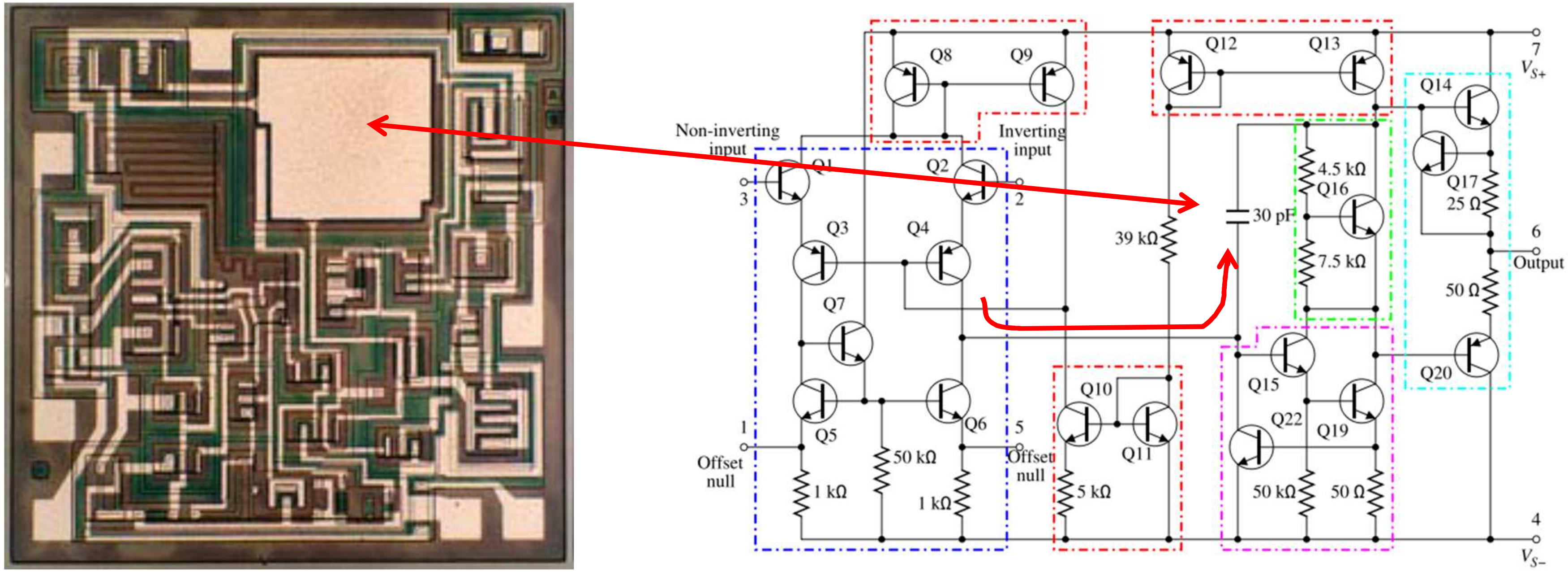
- Transient response of an **op-amp** is **linear -** gradient is referred to as the **slew rate**.
- such a response is obtained when a capacitor is charged by a constant current.
- The capacitor in this case is the large compensation one (C) – see the 741 schematic circuit - the constant current (I) is provided by the current mirror bias circuit at the saturated input stage. So....

$$SR \equiv \frac{dV_o}{dt} = \frac{I}{C}$$

For the op-amp

**If the applied signal amplitude exceeds the slew rate limit at some frequency below $f_H$, then an incorrect estimate of the true bandwidth will be obtained.**

# Charging of Compensation capacitor




30pF Compensation capacitor charges via a constant current source (current mirror)

# Slew rate (contd.)

$$SR \equiv \frac{dV_o}{dt} = \frac{I}{C}$$

For the 741 op-amp C = 30 pF and I ~ 19 μA giving a SR value of about 0.6 V/μs.

**Consider a sine-wave input to an op-amp circuit:** $V_i = V_m \sin(\omega t)$

Then $\frac{dV_i}{dt} = \omega V_m \cos(\omega t)$ and $\left.\frac{dV_i}{dt}\right|_{\max} = \omega V_m = 2\pi f V_m$

If value of ($2\pi f V_m$) is **less than** the **SR limit (0.6 V/μs)**, output can follow the input!

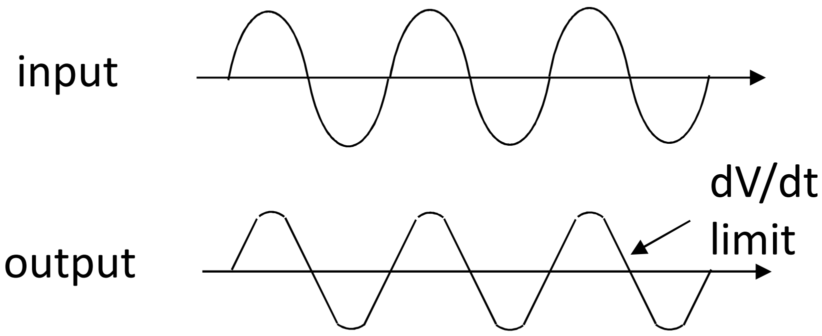
**Example:** Assume input signal amplitude same as power supply value (10 V say),

then $V_m$ = 10 V. $SR = \omega V_m = 0.6V/\mu s$

that is, $f = \frac{0.6}{2\pi . 10^{-6}} \frac{1}{10}$ = 9.6 kHz for the slew rate limited frequency of a 10 V amplitude signal

**Higher frequency signals would be limited and distorted.**

**A slew rate limited output will be apparent from the shape of the output waveform**




**Unlike the upper bandwidth limit**, the frequency at which the slew rate limit is reached depends on the **amplitude of the output signal as well as its frequency.**

**Exercise:** An operation amplifier with a slew-rate limit of 1V/us is required to amplify a sinusoidal 100 kHz signal. Calculate the maximum amplitude of the output voltage that can be achieved without distortion.

**Solution**

**Slew rate = $dv_o/dt$ = 1V/us**

For a sinusoidal signal, $v(t) = V_o \sin(\omega t)$; $dv_o/dt = V_o \omega \cos(\omega t) = V_o \omega$ (maximum)

$$SR = V_o 2\pi f$$

for a signal frequency of 100 kHz, then: $10^6 = V_o \times (2 \times \pi) \times 10^5$

So $\mathbf{V_o = 1.6\ V}$