

Learning Objectives:

At the end of this topic you will be able to;

- ☑ recall the conditions for maximum voltage transfer between sub-systems;
- ☑ analyse a unity gain op-amp voltage follower, used in impedance matching;
- ☑ analyse and design a multi-stage voltage amplifier, incorporating decoupling capacitors, giving specific bandwidth and voltage gain;
- ☑ analyse and design a mixer circuit based on a summing amplifier;
- ☑ select/use the following formula to calculate a mixer's output voltage:

$$V_{OUT} = -R_F (V_1/R_1 + V_2/R_2 + V_3/R_3);$$

- ☑ define the break frequency for a filter;
- ☑ select/use the following formula to calculate a filter's break frequency :

$$f_b = 1 / (2 \pi R C);$$

- ☑ draw and interpret log gain / log frequency graphs for filters;
- ☑ analyse and design the following first order active filter circuits based on an op-amp inverting amplifier:

bass boost, treble boost, bass cut treble cut;

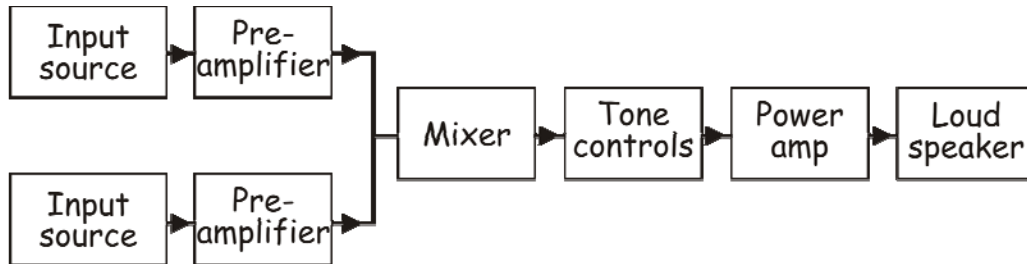
- ☑ recall and apply the maximum power transfer theorem;
- ☑ recall that an emitter follower can be used as a simple power amplifier, with the benefit of high input impedance and low output impedance;
- ☑ draw the circuit diagram for an emitter follower:
 - using resistor bias;
 - using a dual rail power supply;

- ☑ analyse and sketch waveform graphs for an emitter follower;
- ☑ draw circuit diagram for, and sketch waveform graphs in, a push-pull power amplifier, consisting of npn and pnp emitter followers;
- ☑ explain crossover distortion, and describe how it can be eliminated;
- ☑ select and use the following formula to calculate the maximum power dissipated in the load of a push-pull power amplifier:

$$P_{max} = V_S^2 / (8 R_L).$$

A typical audio system :

The specification for this part of the module focuses on an audio system like the one shown in the diagram. This is a monaural (mono) system.



Typical input sources are microphones, CD players, MP3 players and musical instruments such as keyboards. These generate alternating voltage signals, which are processed by the other sub-systems.

The pre-amplifiers are voltage amplifiers. Usually these are based on non-inverting voltage amplifiers, because these offer much higher input impedance than inverting amplifiers, and so draw less current from the signal source.

Mixing desks are at the heart of television, radio and recording studios. They are impressive pieces of kit, with expanses of slide controls and bar graph LED displays. They are used to combine input signals, from a number of microphones, from tape players, from keyboards and other musical instruments. They allow each to be 'faded' in or out. At their heart is a simple circuit which we will look at here, based on an op-amp summing amplifier.

Tone controls allow the user to emphasise high (treble) or low (bass) notes. This may be to compensate for factors that arose during recording or caused by the room the system is used in. It may be to suit the mood, or preferences of the listener!

The power amplifier has the job of producing both current and voltage signals to drive the loudspeaker. We will revisit the emitter follower as one way of doing this, and extend the idea to the push-pull power amplifier.

In this topic, we explore the electronics behind each of these sub-systems that make up a typical audio system.

Signal transfer:

In designing an audio system, it is important to consider how effectively the signal is transferred from one sub-system to the next. Through most of the system, we try to ensure that the voltage signal is passed on with as little loss as possible between stages, but pay no heed to current.

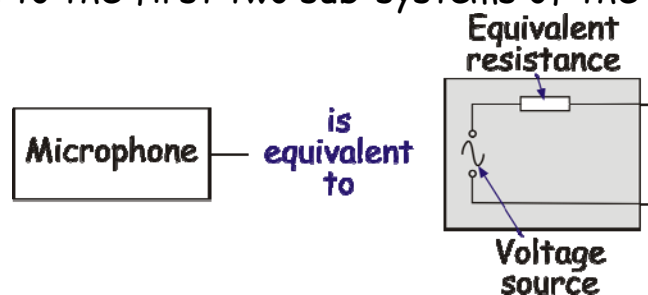
However, the final link between the power amplifier and the loudspeaker brings in a different requirement, that power is transferred effectively from one sub-system to the next.

Conditions for maximum voltage transfer between sub-systems:

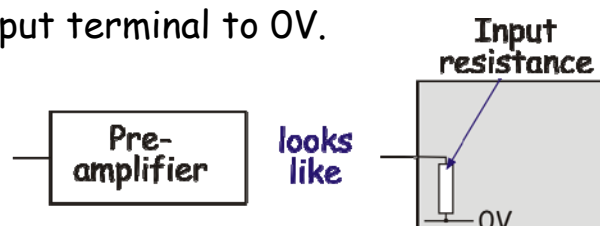
Why do cars rely on an expensive and very heavy 12V lead-acid batteries, when cheap batteries a few centimetres long, with a mass of only a few grams also output 12V? The reason is the low internal resistance of the lead-acid battery.

The output of the cheaper batteries may be 12V, but the current that they deliver is much smaller because of their higher internal resistance. If a device, like a starter motor, tried to draw a large current from them, the output voltage, seen by the motor, would drop substantially.

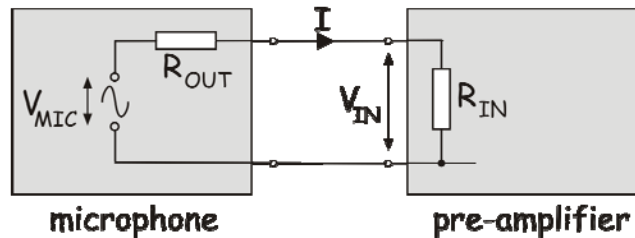
This effect was studied in ET2, when you looked at Thevenin's theorem, which says that the **output** of any sub-system can be considered as a voltage source in series with an internal equivalent resistance. The following diagrams show this principle applied to the first two sub-systems of the audio system:



On the other hand, the input of a subsystem looks like an input resistance connected from the input terminal to 0V.



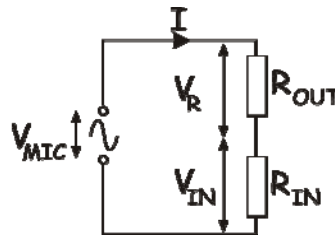
The next diagram combines both these ideas to represent a microphone connected to a pre-amplifier:



In the audio system, the first challenge is to design the system so that as much as possible of the voltage from each sub-system is passed on to the next sub-system. In other words, using the labels on the diagram above, we want:

$$V_{IN} \approx V_{MIC}$$

This arrangement is actually a voltage divider circuit, as shown in the next diagram.



Since:

$$V_{MIC} = V_{IN} + V_R$$

we need to make V_R , the voltage drop across R_{OUT} , much smaller than V_{IN} . To do this, we make R_{IN} much bigger than R_{OUT} .

So far we have referred to the input and output *resistance* of sub-systems. More generally, when AC signals are involved, we should talk about *impedance*, rather than resistance.

In general, to maximise voltage transfer from one sub-system to the next, the input impedance of the second sub-system should be much larger than the output impedance of the first one.

Exercise 1 (The solutions are given at the end of the topic.)

Calculate the voltage transferred from the microphone to the pre-amplifier in the following situation:

Output resistance of microphone = $100\text{k}\Omega$;

Input resistance of pre-amplifier = $800\text{k}\Omega$;

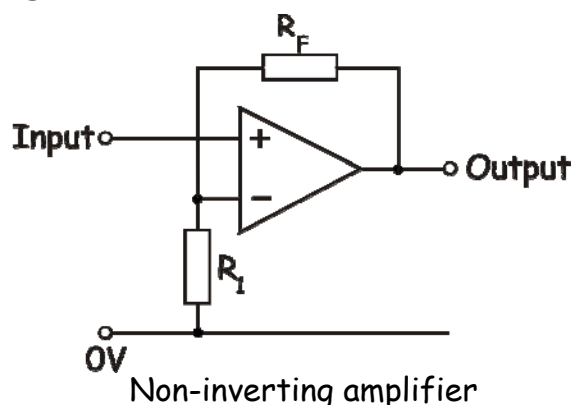
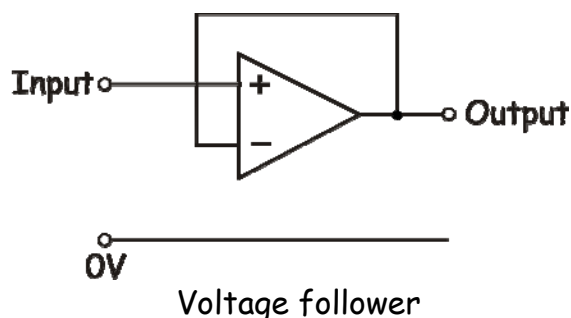
Voltage generated inside microphone = 1.8V .

Impedance matching:

In some situations, it is not possible to manipulate input and output impedance to ensure effective voltage transfer. It may then be worthwhile adding an extra sub-system to improve voltage transfer. This is known as impedance matching. One such sub-system is called a voltage follower.

Op amp voltage follower :

Compare the circuit diagram for the voltage follower with that for the non-inverting amplifier:



You can see that they are identical, when, for the voltage follower:

$$R_F = 0\Omega \text{ and } R_1 \text{ is infinite } (\infty).$$

Using the voltage gain formula for the non-inverting amplifier:

$$\text{voltage gain} = 1 + (R_F / R_1)$$

gives a voltage gain of unity (1) for the voltage follower.

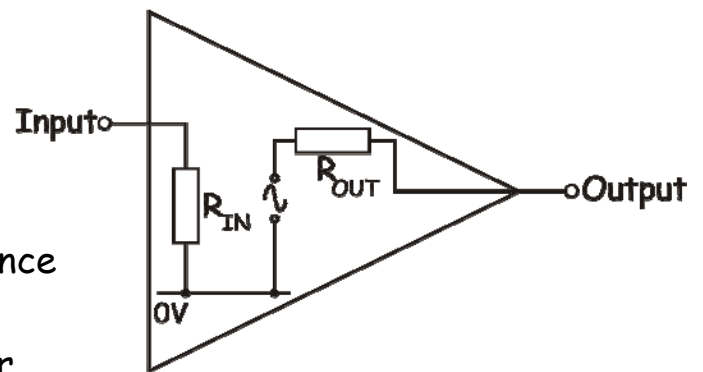
In other words, $V_{OUT} = V_{IN}$. The output 'follows' the input.

However, the important aspect of this circuit is impedance, not voltage. The diagram below shows the equivalent circuit for one input of the op-amp.

The input signal is connected directly (and only) to the non-inverting input of the op-amp. It therefore 'sees' the full input resistance, R_{IN} , of the op-amp, which is typically greater than $1M\Omega$.

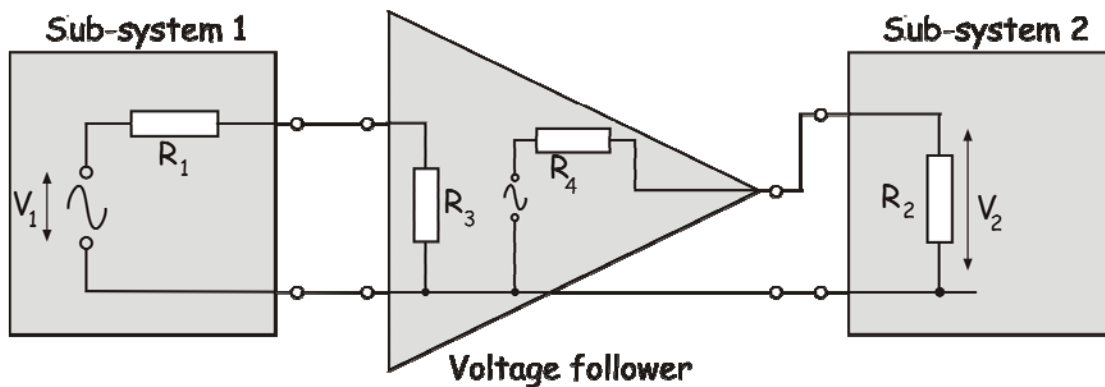
Similarly, the output resistance is very low, close to the output resistance, R_{OUT} , of the op-amp, typically $\sim 75\Omega$.

These two elements, a huge input resistance and a very low output resistance, make a significant difference to voltage transfer.



The next diagram illustrates a situation where a voltage follower is required.

The input resistance, R_2 , of sub-system 2 is not a lot bigger than the output resistance, R_1 , of sub-system 1. If they were connected together directly, the voltage, V_2 , seen by sub-system 2 would be much smaller than V_1 .



When a voltage follower is used, the input resistance, R_3 , of the voltage follower is much bigger than R_1 , and so the voltage transferred from sub-system 1 to the voltage follower is very close to V_1 .

The output resistance R_4 of the voltage follower is much smaller than R_2 , and so most of the output voltage of the voltage follower is passed on to sub-system 2.

As a result, then, V_2 is roughly equal to V_1 .

Multi-stage voltage amplifier:

In module ET1, you learned that one of the features of op-amps is a quantity called the 'gain-bandwidth product'. Essentially, there is a trade-off between voltage gain and bandwidth (range of frequencies that is amplified.)

The bigger the voltage gain, the smaller the bandwidth (and vice-versa.)

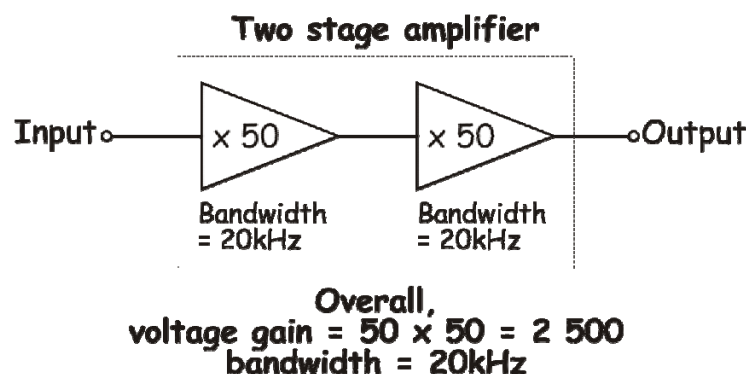
For example:

A 741 op-amp has a gain bandwidth product of 1MHz, (= 1 000 000 Hz).

The full audio frequency range runs from 20 Hz to 20 kHz, (a bandwidth of 20 kHz in other words.) With this bandwidth, an op-amp amplifier cannot have a voltage gain bigger than 50x, (as $50 \times 20\,000 = 1\,000\,000$.)

However, there is a way around this limitation - use a multi-stage amplifier.

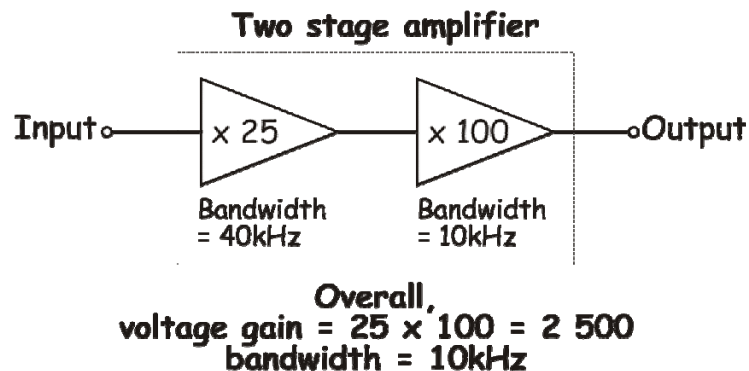
The next diagram shows a two-stage amplifier made from two voltage amplifiers, each with a bandwidth of 20 kHz, cascaded together, (the output of the first amplifier provides the input to the second.)



Assuming the two op-amps have a gain-bandwidth product of 1 MHz, each amplifier by itself has a gain of 50x. However, when they are cascaded, the overall gain is $50 \times 50 (= 2\,500)$. The first amplifier has a bandwidth of 20 kHz, and so amplifies successfully all frequencies in the audio range. So does the second amplifier. Overall, the system has a bandwidth of 20 kHz and a voltage gain of 2 500!

In this way we can have both bandwidth and voltage gain!

An important design point - we could get a voltage gain of 2 500 by cascading an amplifier with a voltage gain of 25 with a second one having a voltage gain of 100. However, the first would have a bandwidth of 40 kHz, but the second would have a bandwidth of only 10kHz. Although the first amplifier boosts signals with frequencies all the way up to 40kHz, the second one boosts only those with frequencies below 10kHz, and rejects all others. The high voltage gain of the first stage is wasted. The overall bandwidth of the cascaded amplifiers is 10kHz. This is shown in the next diagram.



The moral:

Use stages with identical voltage gains to maximise the bandwidth.

Exercise 2 (The solutions are given at the end of the topic.)

You have three identical op-amps, each having a gain-bandwidth product of 2MHz. You cascade them to give an overall bandwidth of 100kHz. What is the overall voltage gain of the multi-stage amplifier?

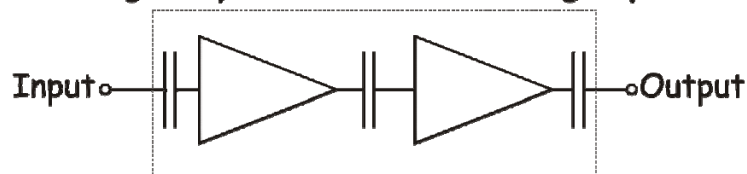
Use of decoupling capacitors:

Our treatment of multi-stage amplifiers overlooked an important aspect. Each amplifier stage offers voltage gain all the way down to 0Hz (i.e. DC). Audio signals are waves with frequencies above 20Hz. However, there are bound to be DC voltages lurking around in the system. If we are not careful, each stage of the amplifier will amplify these, and the output of a later stage may well be driven into saturation as a result of these DC voltages.

The solution is to block these DC signals - prevent them passing from one stage to the next. The component to do this - a capacitor! Used like this, they are known as **DC blocking capacitors**, (and also as **decoupling capacitors**, as they decouple each stage from any DC bias present in the previous stage.)

The next version of the multi-stage amplifier includes DC blocking capacitors:

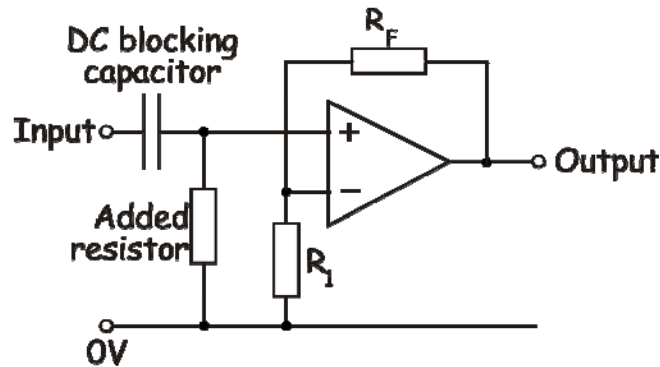
Two stage amplifier with DC blocking capacitors



The capacitors are chosen to have as little effect as possible on the audio signal. In other words, they should have a small reactance over the range of frequencies being amplified, the bandwidth of the amplifier. Since reactance decreases as the frequency increases, this requirement is most stringent for the lowest frequencies being amplified. A $10\mu\text{F}$ capacitor has a reactance of around 160Ω at a frequency of 100Hz, for example.

(In reality, the DC blocking capacitor and input resistance of the amplifier together form a high pass filter.)

When op-amp voltage amplifiers are cascaded together with DC blocking capacitors, a problem can arise. The op-amp inputs require a small DC current to allow them to operate. The DC blocking capacitor can prevent this. The solution is to add a high value resistor (typically $1\text{M}\Omega$) between the input and 0V. This is shown in the next circuit diagram:



Coupling together amplifier stages like this does not prevent noise signals from one stage being amplified by the next and subsequent stages. Noise is an AC signal occurring over a wide range of frequencies. As a result, it is not stopped by the DC blocking capacitors.

Exercise 3 (The solutions are given at the end of the topic.)

Design a two stage amplifier with an overall voltage gain of 900.

Your design should be based on non-inverting op-amps, in order to offer high input impedance, and should include a $10\mu\text{F}$ decoupling capacitor.

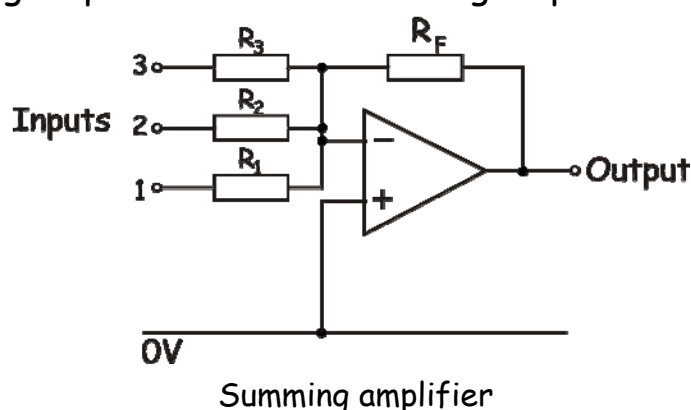
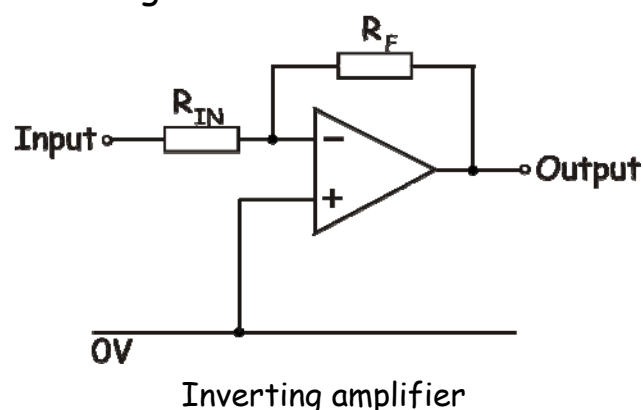
- (a) Draw the circuit diagram for your design.
- (b) Calculate the bandwidth of the multi-stage amplifier assuming that each op-amp has a gain-bandwidth product of 900 kHz.

The audio mixer

The design for the audio mixer is a development of the summing amplifier, which is itself developed from the inverting voltage amplifier, studied in ET1. First of all, we study the summing amplifier.

Summing amplifier:

The diagrams below show the inverting amplifier and the summing amplifier.



The voltage gain formula for the inverting amplifier is:

$$G = -(R_F / R_{IN})$$

so that the output voltage is:

$$V_{OUT} = -[(R_F / R_{IN}) \times V_{IN}]$$

Notice that the smaller the input resistor, the bigger the output voltage.

You can think of a summing amplifier as a combination of linked inverting amplifiers where the final output is the sum of the outputs of each inverting amplifier.

The output voltage for the summing amplifier is :

$$V_{OUT} = - \{ [(R_F / R_1) \times V_1] + [(R_F / R_2) \times V_2] + [(R_F / R_3) \times V_3] \}$$

where V_1 is the voltage applied to input 1, and so on.

This is sometimes written as:

$$V_{OUT} = - R_F [(V_1 / R_1) + (V_2 / R_2) + (V_3 / R_3)]$$

Using Ohm's law, we can introduce the following currents:

$$I_1 = V_1 / R_1, \quad I_2 = V_2 / R_2 \quad \text{and} \quad I_3 = V_3 / R_3$$

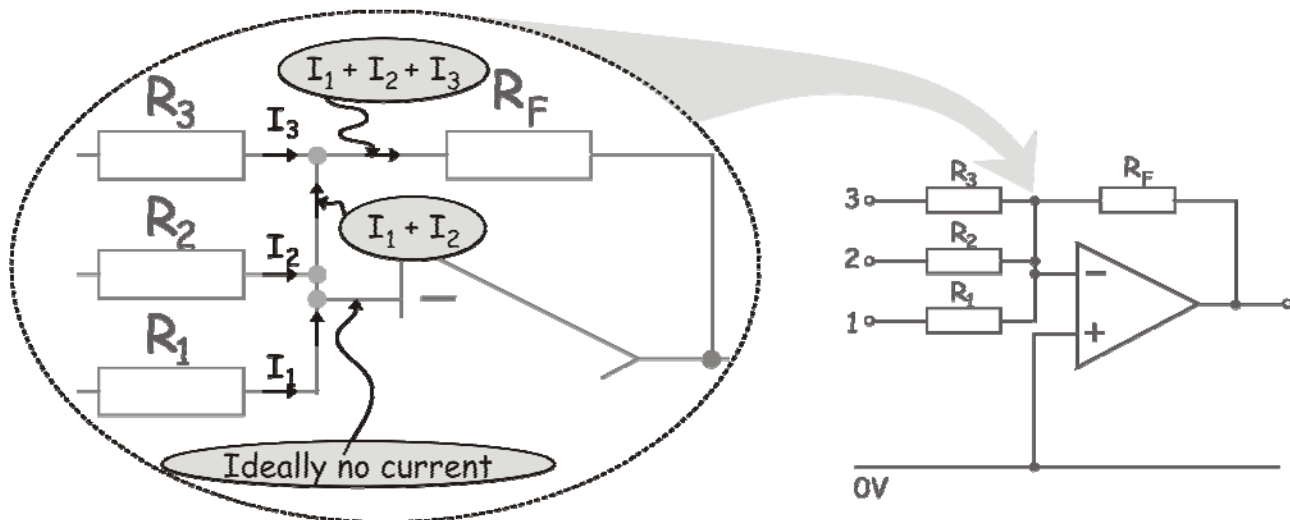
The formula then becomes:

$$V_{OUT} = - R_F [I_1 + I_2 + I_3]$$

which shows that the summing amplifier actually sums currents!

One of the assumptions we make about op-amps is that their inputs ideally have infinite resistance.

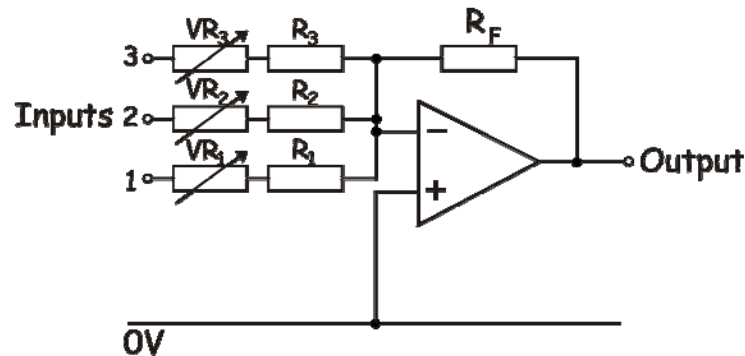
The next diagram shows that, with this assumption, and Kirchhoff's current law, it is obvious that the summing amplifier sums the input currents:



Next, we modify the circuit slightly and use it as an audio mixer.

The mixer:

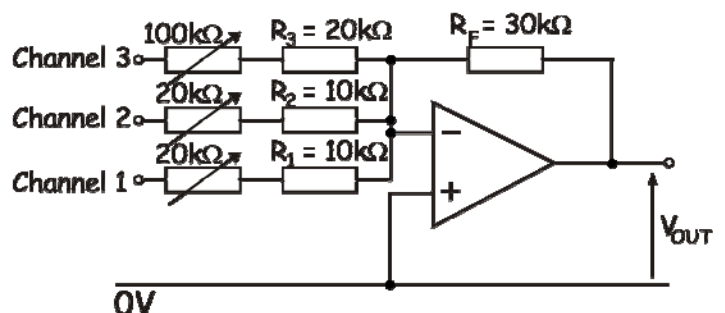
In a mixer, the input resistors have variable resistors added in series with them. The following diagram shows this:



The behaviour is exactly the same as for the summing amplifier, except that now the input resistance used in the output voltage formula is the sum of the fixed resistor and the variable resistor. As the variable resistor is adjusted to **bigger** resistance, the voltage gain on that input is **reduced** - that input is 'faded out'.

An example may make this clearer:

In the three channel mixer circuit shown here, channel 1 has an input resistance which can be varied from $10\text{k}\Omega$ to $30\text{k}\Omega$ by adjusting the variable resistor.



Treating this channel as an inverting amplifier, the voltage gain on channel 1 = $-(R_F / \text{input resistance})$.

Maximum voltage gain happens when the variable resistor is set to 0Ω . At that point, the input resistance = $10\text{k}\Omega$ (due entirely to the fixed resistor, R_1), and the voltage gain = $-(30 / 10) = -3$.

Minimum voltage gain happens when the variable resistor is set to maximum ($20\text{k}\Omega$.) At that point, the input resistance = $30\text{k}\Omega$ ($= 20\text{k}\Omega + 10\text{k}\Omega$) and the voltage gain = $-(30 / 30) = -1$.

Channel 2 is identical, and so its voltage gain can also be varied from -1 to -3.

The input resistance for channel 3 can be varied from 20kΩ to 120kΩ by adjusting the variable resistor. This means that the voltage gain can be varied from -1.5 (when the variable resistor is set to 0Ω,) to -0.25 (when the variable resistor is set to a maximum, 100kΩ.)

In reality, this mixer would be used to combine signals from microphones, musical instruments etc., but purely for illustration, suppose that the following input voltages occur:

Channel 1: 1V; Channel 2: 1.5V; Channel 3: 2V.

When all the variable resistors are set for maximum gain (set to minimum resistance,) the output voltage will be:

$$\begin{aligned} V_{OUT} &= -R_F [(V_1 / R_1) + (V_2 / R_2) + (V_3 / R_3)] \\ &= -30[(1 / 10) + (1.5 / 10) + (2 / 20)] \\ &= -10.5V \end{aligned}$$

Looking at it another way:

maximum gain on channel 1 = -3, so inputting 1V causes an output of -3V;

maximum gain on channel 2 = -3, so inputting 1.5V causes an output of -4.5V;

maximum gain on channel 3 = -0.5, so inputting 2V causes an output of -1V.

Adding all these together gives the mixer an output voltage of -10.5V.

A challenge: Prove to yourself that when all variable resistors are set for minimum gain, the mixer has an output voltage of -3V.

Exercise 4 (The solutions are given at the end of the topic.)

The mixer described on the previous page is adjusted so that the variable resistors on channels 1 and 2 are set to a resistance of 10kΩ, and that on channel 3 to 40kΩ. At some instant, the following voltages are applied to the channels:

Channel 1: 1.6V; Channel 2: 1.2V; Channel 3: 2.8V.

Calculate the resulting output voltage of the mixer.

Another design point:

A mixer sums input voltages. As a result, it is easy to drive the output into saturation. When designing a mixer, it is important to limit its voltage gain by keeping the value of the feedback resistor down.

Make sure that the output does not saturate when the input voltages have their maximum values.

If more voltage gain is needed, that can be provided by other components of the audio system.

Tone controls:

In module ET4, you were introduced to filters, specifically, low pass, high pass and band pass passive filters. These have some important limitations:

- They can only 'cut', they cannot 'boost'. In other words, they have a maximum gain of unity. For example, a low pass passive filter will reduce the amplitude of high frequency signals but it cannot increase the amplitude of low frequency signals.
- Their behaviour is modified substantially when they are connected to a load, unless that load has a very high impedance. In situations where they have to deliver a significant current to a load, they must be buffered by a suitable interface, such as an amplifier.

The active filter overcomes both of these limitations. They can have a voltage gain larger than unity for signals of a particular frequency. They include an amplifier which can deliver current to a load without affecting the frequency response of the system.

The circuits of active filters can be very complex. In this module, we introduce the topic by studying four types of filter, based on inverting voltage amplifiers using op amps, (the kind you studied in module ET1.) There are much better designs for active filters!

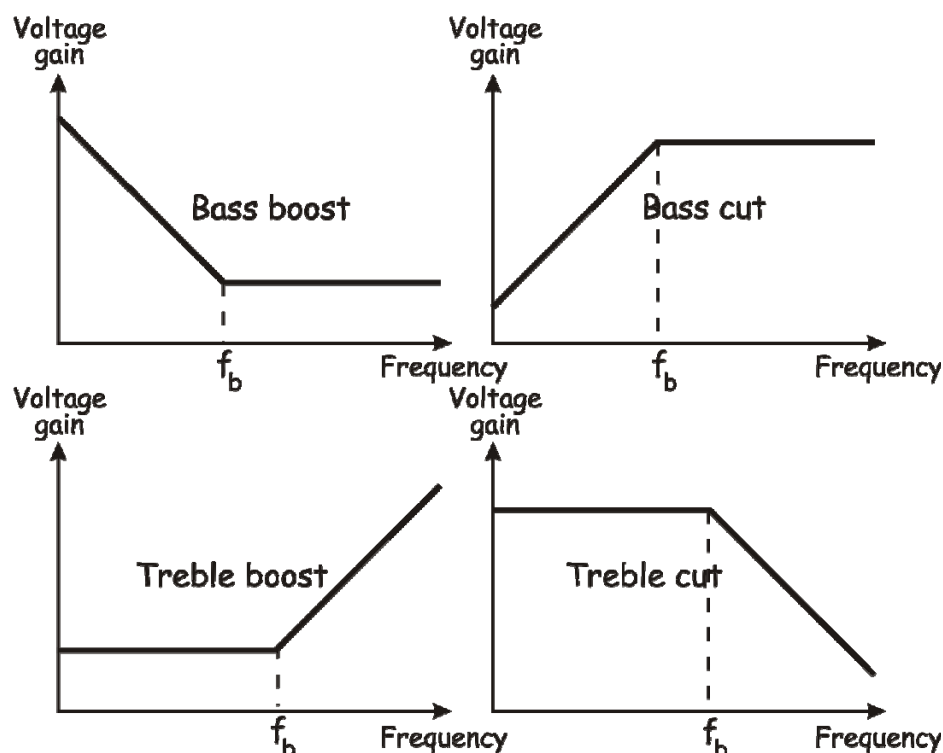
The behaviour of these filters is best studied using log-log graph paper. This is the same approach as that used in ET4. Again, we are going to rely on the 'two-straight-lines' approximation that was introduced there.

- One straight line is horizontal, and shows the gain due to the feedback and input resistors, as in the inverting amplifier itself. In other words, for this section of the frequency response:

$$\text{Voltage gain} = -R_F / R_{IN}$$

- The other straight line has a slope of 45° . The exact nature depends on which filter we are looking at. This is the part of the frequency spectrum where the resistor-capacitor (RC) network is controlling the behaviour.

Using log-log graph paper, the four types of filter have the following characteristics:



The break frequency f_b marks the boundary between the two types of behaviour.

It is defined as *the frequency at which the reactance of the capacitor is equal to the resistance of the resistor that is in the RC network.*

In other words, at the break frequency, f_b :

$$R = X_C$$

or

$$R = 1 / (2 \pi f_b C)$$

so that

$$f_b = 1 / (2 \pi R C)$$

The formula and definition are identical for all types of active filter. The only issue when applying this formula in an active filter circuit is to choose the right resistor, as there are two of them. Go for the resistor that is in the RC network, i.e. the one that is connected to the capacitor!

Here is a break frequency example:

The circuit for an active filter is shown opposite.

(It doesn't matter what kind it is.)

The RC network is made up of a 4.7nF capacitor and a 200kΩ resistor.

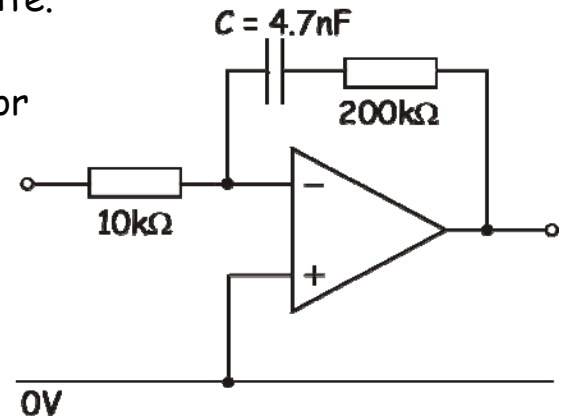
(Ignore the 10kΩ resistor for now - it will appear in a different calculation later!)

Using the break frequency formula:

$$f_b = 1 / (2 \pi R C)$$

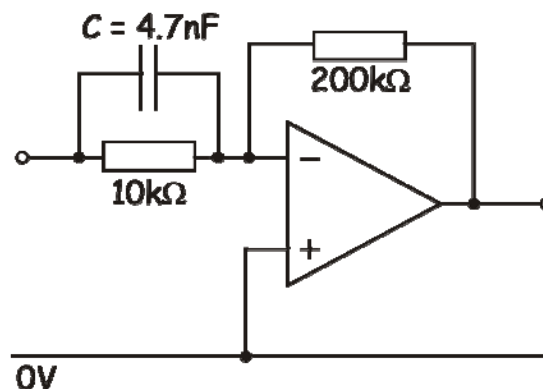
$$f_b = 1 / (2 \times \pi \times 200 \times 10^3 \times 4.7 \times 10^{-9})$$

$$= 169.3 \text{ Hz.}$$



Exercise 5 (The solutions are given at the end of the topic.)

Calculate the break frequency for the active filter circuit shown in the diagram.



Active filter design:

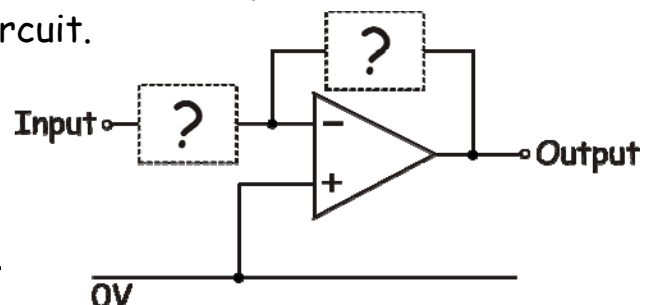
For all four filters, the basic circuit layout is that of the inverting amplifier.

- Something is connected in the negative feedback loop.
- Something is connected in the input circuit.

One of these 'something's is a RC network;
the other is a fixed resistor.

The voltage gain depends on

$$\frac{\text{Feedback ?}}{\text{Input ?}}$$



Active Bass Boost filter:

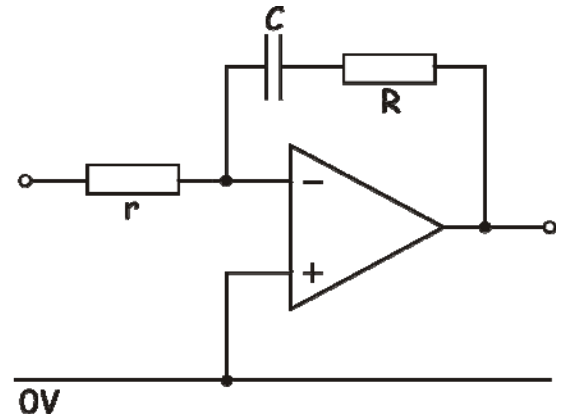
In this case, the feedback loop contains a series RC network and the input circuit contains the fixed resistor.

The break frequency is given by:

$$f_b = 1 / (2 \pi R C)$$

The voltage gain at **high** frequencies is:

$$G = - R / r$$



At frequencies **below** the break frequency, as the frequency **decreases**:

- the reactance of the capacitor increases, and so C behaves like a bigger and bigger resistor;
- this combines with R to give a value in the feedback loop that gets bigger;
- the voltage gain of the system **increases** as a result.

Active Bass Cut filter:

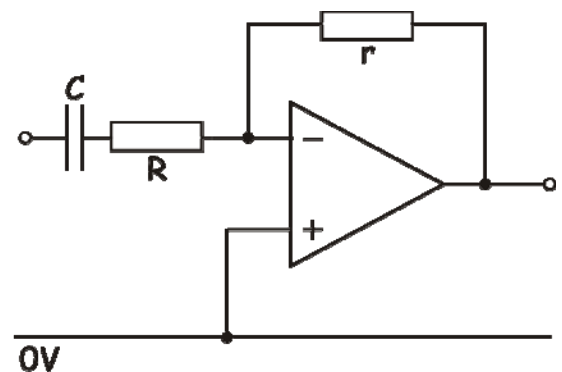
In this case, the input circuit contains a series RC network and the feedback loop contains the fixed resistor.

The break frequency is given by:

$$f_b = 1 / (2 \pi R C)$$

The voltage gain at **high** frequencies is:

$$G = - r / R$$



At frequencies **below** the break frequency, as the frequency **decreases**:

- the reactance of the capacitor increases, and so C behaves like a bigger and bigger resistor;
- this combines with R to give a value in the input circuit that gets bigger;
- the voltage gain of the system **decreases** as a result.

Active Treble Boost filter:

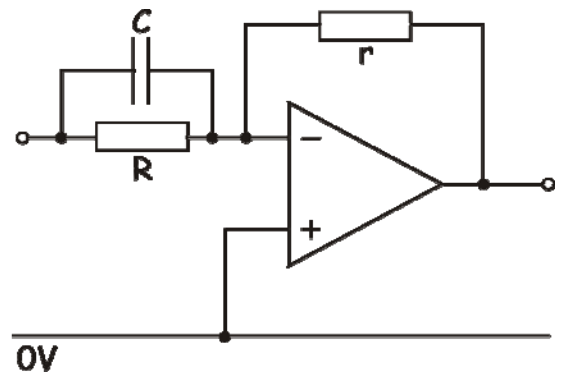
In this case, the input circuit contains a parallel RC network and the feedback loop contains the fixed resistor.

The break frequency is given by:

$$f_b = 1 / (2 \pi R C)$$

The voltage gain at **low** frequencies is:

$$G = - r / R$$



At frequencies **above** the break frequency, as the frequency **increases**:

- the reactance of the capacitor decreases, and so C behaves like a smaller and smaller resistor;
- this combines with R to give a value in the feedback loop that gets smaller;
- the voltage gain of the system **increases** as a result.

Active Treble Cut filter:

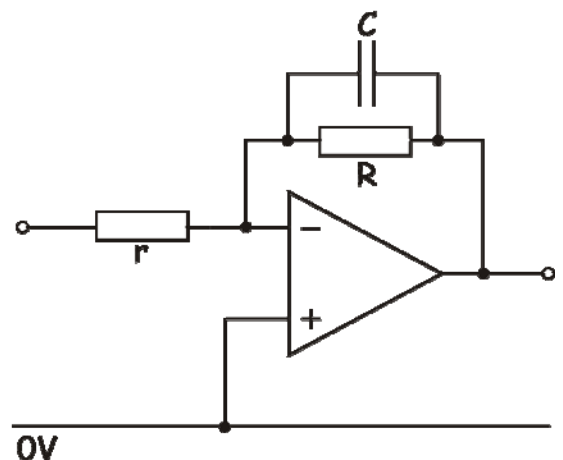
In this case, the feedback loop contains a parallel RC network and the input circuit contains the fixed resistor.

The break frequency is given by:

$$f_b = 1 / (2 \pi R C)$$

The voltage gain at **low** frequencies is:

$$G = - R / r$$

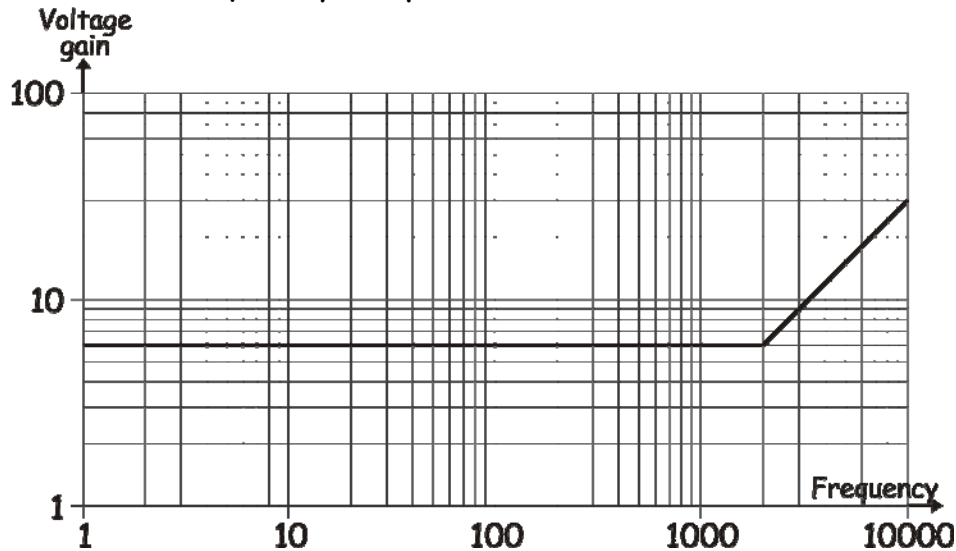


At frequencies **above** the break frequency, as the frequency **increases**:

- the reactance of the capacitor decreases, and so C behaves like a smaller and smaller resistor;
- this combines with R to give a value in the feedback loop that gets smaller;
- the voltage gain of the system **decreases** as a result.

Exercise 6 (The solutions are given at the end of the topic.)

The graph shows the frequency response needed for a filter:



Design a filter circuit which has this frequency response, using an op-amp, two resistors and a 3.3 nF capacitor. Draw the circuit diagram for your filter.

Calculate suitable values for the resistors, showing how you obtain your results.

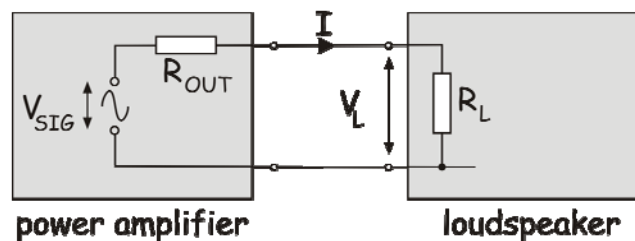
The power amplifier:

As pointed out in the introduction to this topic, the requirements for signal transfer change when we are looking at the final output, from the loudspeaker. Here we are concerned with transferring not only the voltage from the previous sub-system, but also as high a current as possible, to create enough power to drive the loudspeaker.

Conditions for maximum power transfer between sub-systems:

Since : power dissipated = current \times voltage,
for maximum power transfer, we need to maximise both current, I , and voltage, V_L , passed to the loudspeaker. These quantities are shown in the next diagram.

These are conflicting requirements. For maximum voltage transfer, the input resistance of the loudspeaker, R_L , should be as large as possible, compared with the output resistance, R_{OUT} , of the previous stage. However, to maximise current, all resistance needs to be kept as low as possible.



To explore this problem fully requires the use of calculus, and is beyond the scope of this course. However the result is the maximum power transfer theorem.

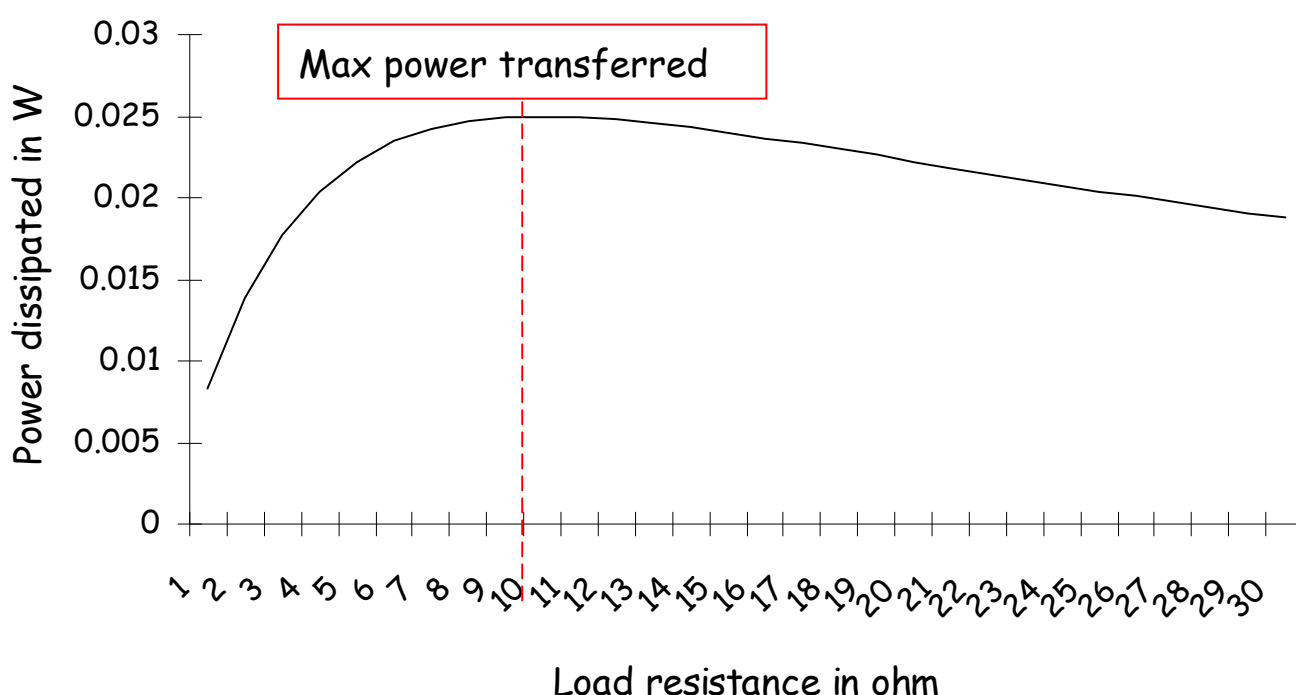
Maximum Power Transfer theorem:

The power transferred from one sub-system, **A**, to the next, sub-system **B**, is a maximum when the input resistance of **B** (R_L in this case,) is equal to the (Thevenin) output resistance (R_{OUT}) of **A**.

The graph below, generated using Microsoft Excel, shows the effect of a range of load resistances on the power transferred.

For this example:

- signal voltage = 1V;
- output resistance of power amplifier, $R_{OUT} = 10\Omega$;
- the current through the load, $I = V_{SIG} / (R_{OUT} + R_L)$;
- the voltage across the load, $V_L = I \times R_L$;
- the power transferred to the load, $P = I \times V_L$.



Notice that maximum power is transferred when the resistance of the load is equal to the output resistance of the power amplifier (10Ω).

Exercise 7 (The solutions are given at the end of the topic.)

The open-circuit output voltage of a power amplifier is 1.2V, and it has an output resistance of 12Ω .

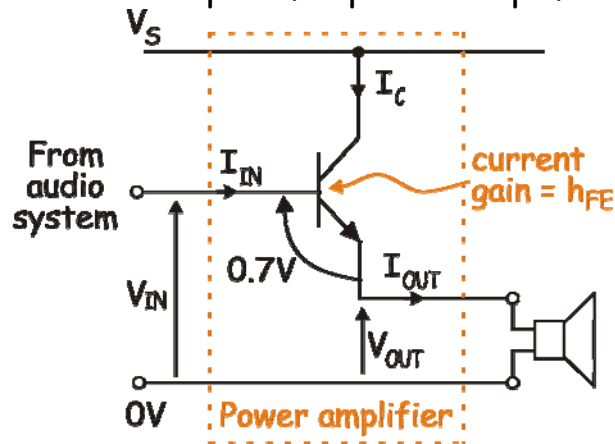
It is connected to each of the following loudspeakers in turn:

- (a) Loudspeaker A, which has an input resistance of 6Ω ;
- (b) Loudspeaker B, which has an input resistance of 12Ω ;
- (c) Loudspeaker C, which has an input resistance of 18Ω .

Calculate the power dissipated in each of these loudspeakers.

The emitter follower:

The emitter follower is one example of a power amplifier.



The output power, $P_{OUT} = I_{OUT} \times V_{OUT}$.

The input power, $P_{IN} = I_{IN} \times V_{IN}$.

The output voltage, V_{OUT} , is roughly equal to the input voltage, V_{IN} ($= V_{IN} - 0.7$).

The output current, I_{OUT} , is roughly equal to I_C and so $I_{OUT} \approx h_{FE} \times I_{IN}$

As a result, $P_{OUT} \approx h_{FE} \times P_{IN}$ and so the emitter follower is a power amplifier.

In the notes for section 5.3, on power supplies, it was pointed out that the emitter follower:

- is a voltage follower circuit - the output voltage V_{OUT} follows (tries to equal) the input voltage V_{IN} ;
- is a current buffer - the output current I_{OUT} is much greater than the current I_{IN} drawn from the signal source;
- is an example of a common-collector circuit;

and

- is often used as an impedance transformer, to interface a signal source having a high output impedance to a low impedance load.

It is this final aspect that is of use to us here. The emitter follower has a high input resistance ($\sim h_{FE} \times R_L$), and a low output resistance. It can therefore act as an interface between the loudspeaker (usually a low resistance) and the rest of the audio system. The circuit diagram for this arrangement is shown above.

A problem!

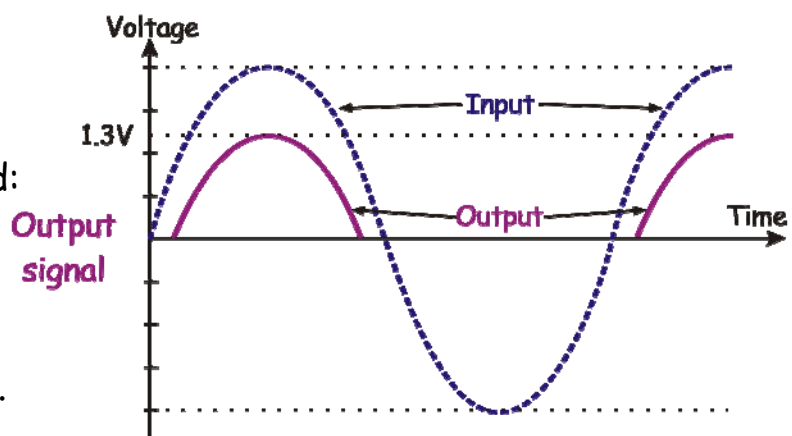
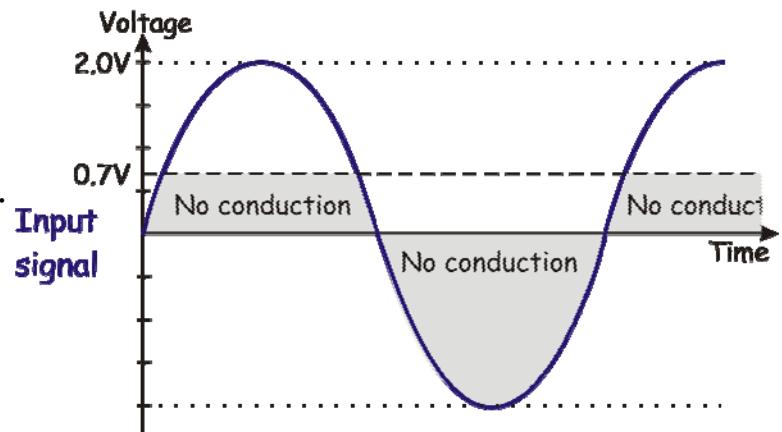
The emitter follower circuit shown earlier uses a npn transistor, and so does not respond to negative voltages. If the signal from the audio system contains a negative component, the emitter follower power amplifier will ignore it.

The result is shown in the graph, which assumes an amplitude of 2V for the input signal.

Notice that two things have happened:

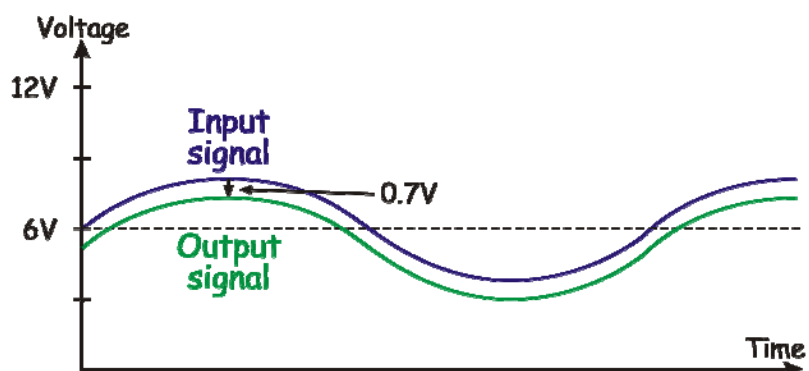
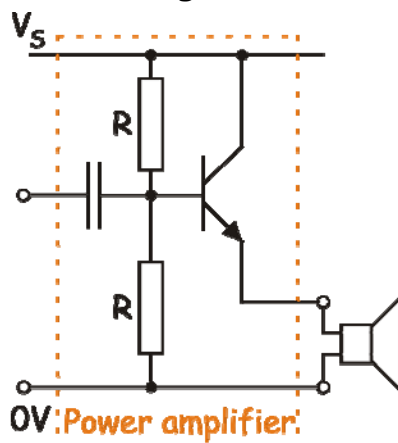
- the negative portion of the input signal is missing in the output;
- the transistor does not conduct until the input signal reaches 0.7V.

The amplitude of the output is 0.7V smaller than the amplitude of the input.



A solution:

One way forward is to add a DC voltage to the input signal to make sure that it is always positive, and greater than 0.7V. The way to do this is shown in the next circuit diagram. The resulting signals are shown in the graph.



The circuit diagram includes a decoupling capacitor to isolate the previous stage of the audio system from the DC voltage added by the power amplifier. This added DC voltage results from the two equal sized bias resistors, R .

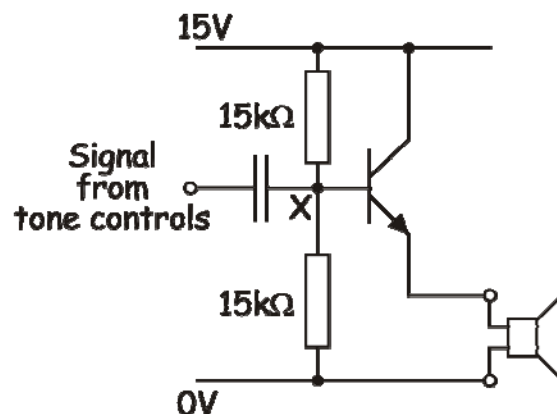
The graph assumes that the power supply voltage is 12V, and shows that the input signal now sits on a centre voltage of 6V, instead of 0V. As a result, the transistor is always conducting, even when the input signal is zero, and outputs an accurate copy of the input signal, but dropped by 0.7V.

The disadvantages of this arrangement are:

- the transistor is always conducting, even when there is no input signal, and so is always dissipating energy as heat;
- there is always a current flowing through the two biasing resistors, R , though these can have a large resistance to minimise this current.

Exercise 8 (The solutions are given at the end of the topic.)

The following emitter follower circuit is used as the power amplifier to drive the loudspeaker.



At one instant, the signal from the tone controls raises the voltage at point X to 7.9V.

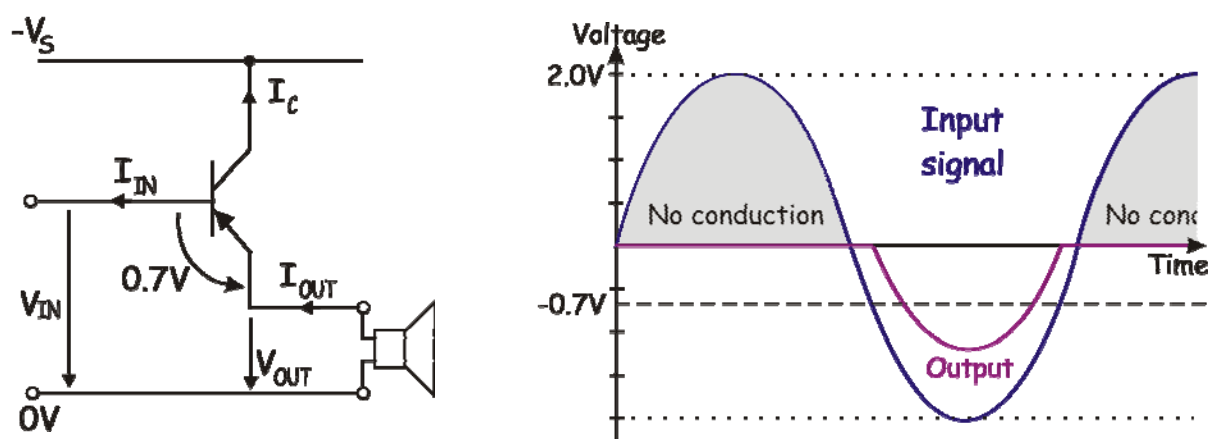
Calculate the resulting voltage across the loudspeaker.

An alternative:

If we replace the npn with a pnp transistor, the overall behaviour is unchanged except that the circuit now processes negative voltages.

Whereas the npn transistor conducts when the base is 0.7V higher than the emitter, the pnp conducts when the base is 0.7V lower than the emitter.

The circuit diagram and the resulting output signal graph are shown below.

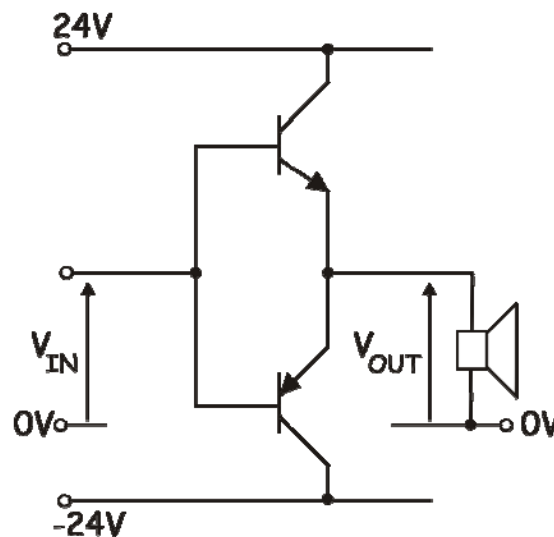


Notice that:

- the loudspeaker is still connected between the emitter and 0V;
- the collector is connected to $-V_S$ instead of $+V_S$;
- the arrows for V_{IN} and V_{OUT} point the other way, (as they point from low to high voltage;)
- all the currents flow in the opposite direction to those in the npn emitter follower, (as they flow from high voltage towards low;)
- in particular, the current through the loudspeaker now flows in the opposite direction.

The push-pull power amplifier:

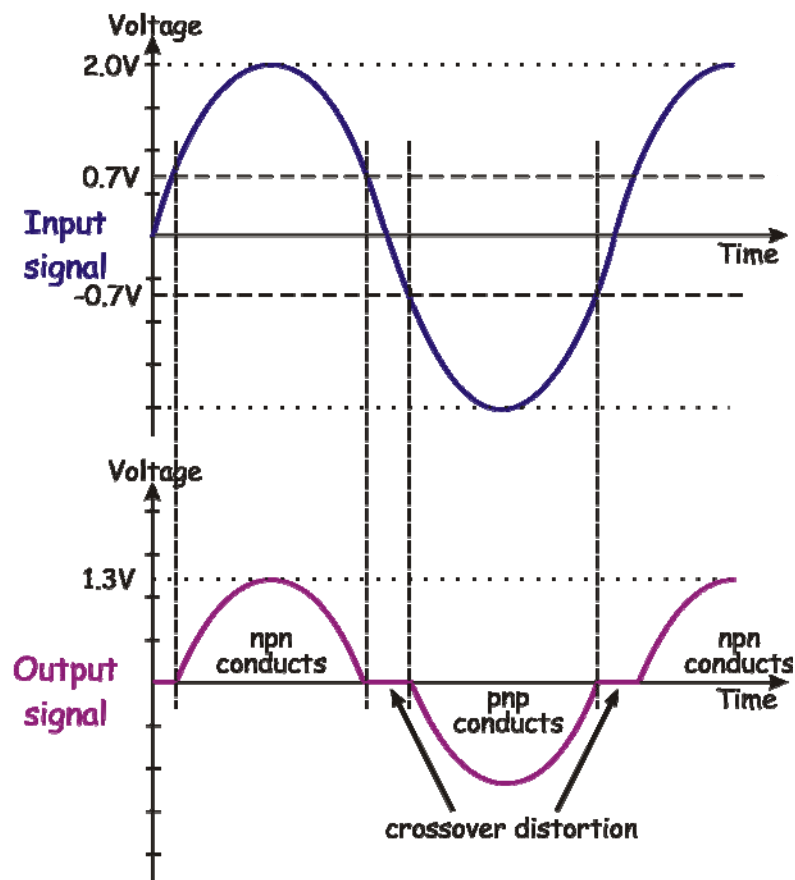
The alternative solution to the power amplifier problem, then, is to combine the npn and pnp emitter followers into what is known as a push-pull (or complementary pair) power amplifier. The circuit diagram for this is shown below.



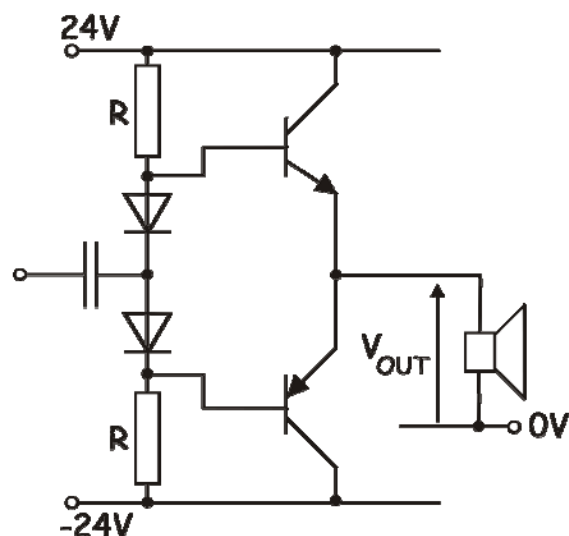
The circuit diagram assumes a power supply voltage of +24V/0V/-24V. However, any split power supply voltage can be used. The graph at the top of the next page shows the output signal produced by this arrangement. The loudspeaker passes a current during both the positive and negative half-cycles of the signal. During the negative half-cycles, the current flows in the opposite direction, making the cone of the loudspeaker move in the opposite direction. On both half-cycles, the amplitude of the signal is reduced by 0.7V, by the action of the emitter followers.

The graph shows up a disadvantage of the push-pull power amplifier - crossover distortion. When the input signal is between +0.7V and -0.7V, neither transistor conducts, and so the output voltage is zero. The output signal is not a copy of the input - it is distorted. This effect is known as crossover distortion. The result on the sound produced by the loudspeaker depends on the amplitude of the signal, but usually makes the sound produced rather harsh and 'tinny'.

Topic 5.6 - Audio Systems

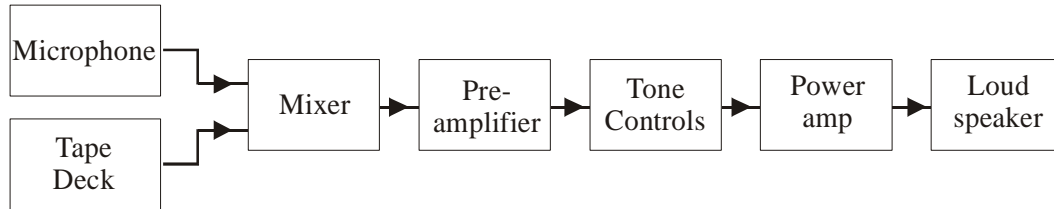


There is a solution to crossover distortion - add resistors and diodes to the input circuit, as shown. The resistors ensure that the two diodes are forward biased and conducting. As a result, the npn transistor base is always $0.7V$ higher than the input signal, and so is conducting even when the input signal is zero. The same, but opposite is true for the pnp transistor.



Practice Exam Questions:

1. Here is the block diagram for a public address system.

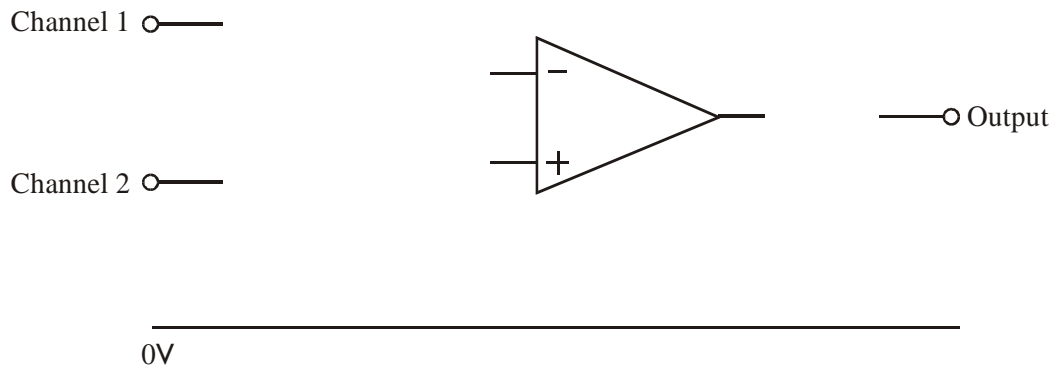


- (a) Part of the specification for the mixer is given below.

Description	Value
Number of input channels	2
Maximum voltage gain on input channel 1	10
Maximum voltage gain on channel 2	5
Minimum input impedance (either channel)	10k Ω
Bandwidth (either channel)	15kHz

- (i) Complete the following circuit diagram for the mixer.

[4]



- (ii) Calculate suitable values for the fixed resistors used in the circuit.

[3]

.....

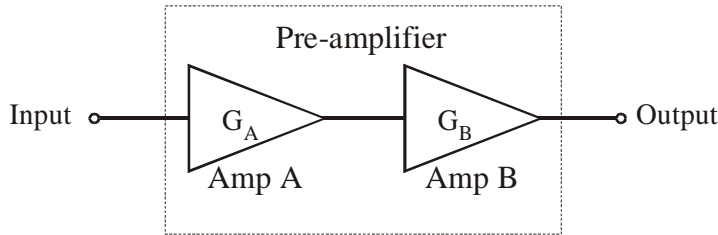
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Topic 5.6 – Audio Systems

(b) The pre-amplifier is a 2-stage non-inverting amplifier with a gain of 900.



(i) In order to optimise the bandwidth of the pre-amp, what is the gain of

Amplifier A, G_A ;

Amplifier B, G_B ; [2]

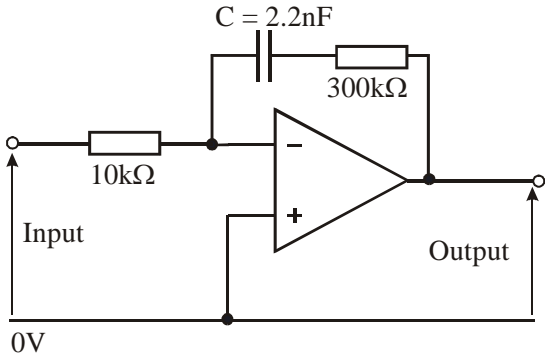
(ii) The table gives some data on the op-amps used in the circuits for amplifiers A and B.

Parameter	Typical Value
Open-loop voltage gain	10^5
Input resistance	$10^{12}\Omega$
Gain bandwidth product	1MHz
Slew-rate	$9V\ \mu s^{-1}$
Common mode rejection ratio	90dB

What is the resulting bandwidth of the pre-amplifier? [1]

.....

(c) Part of the tone control circuit is shown below.



(i) What type of filter is this – treble boost, treble cut, bass boost or bass cut? [1]

.....

(ii) Calculate the break frequency of this filter [3]

.....

- (iii) Calculate the voltage gain of the filter at frequencies well above the break frequency.

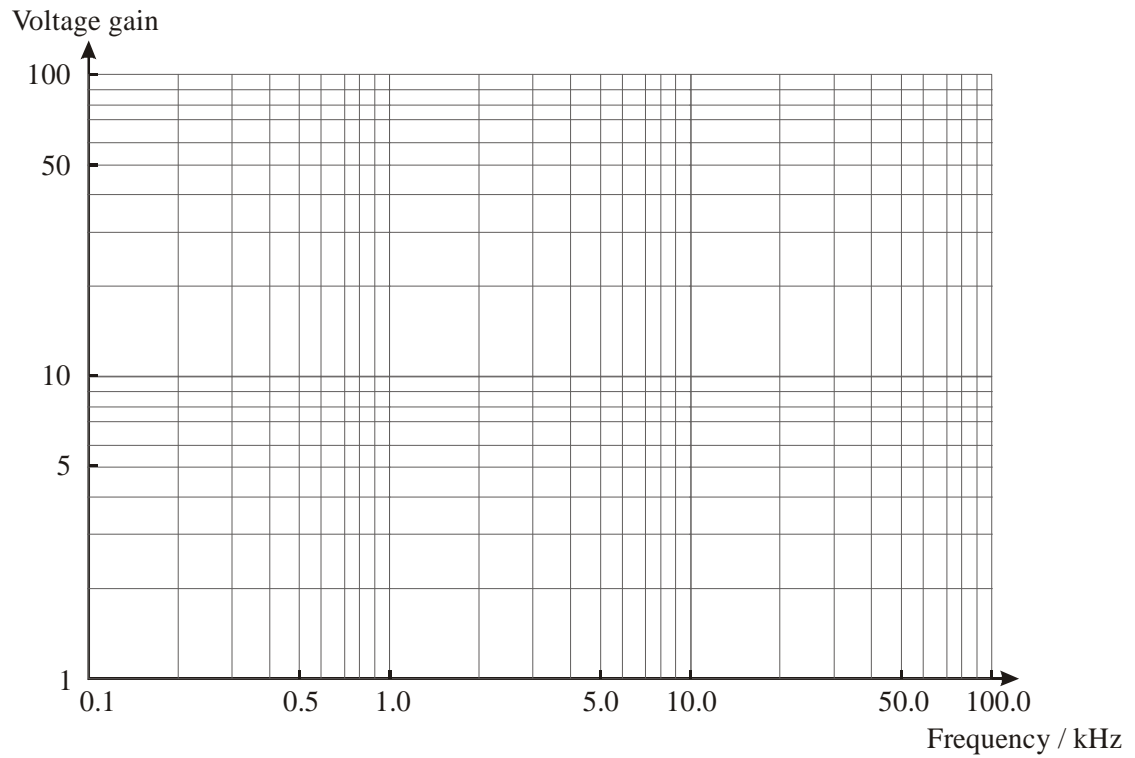
[1]

.....

.....

- (iv) Use the axes provided to sketch the frequency response of this filter.

[3]



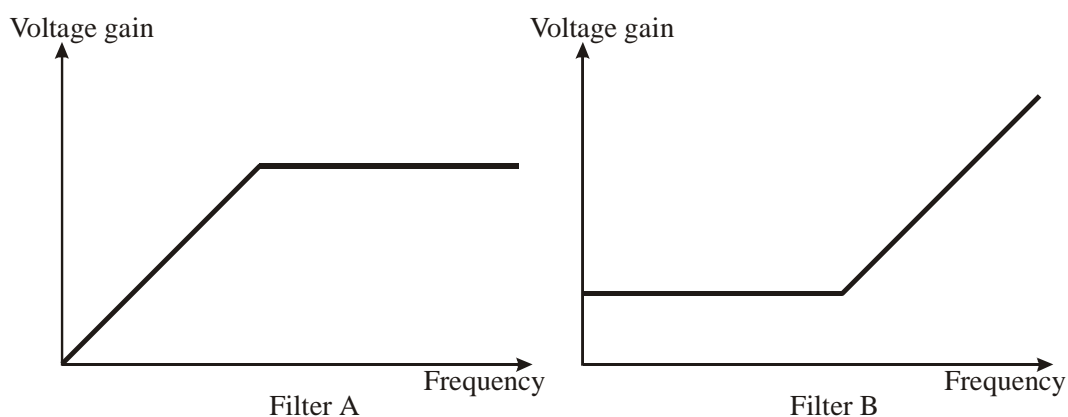
Topic 5.6 – Audio Systems

2. (a) In terms of voltage gain, what is the difference between the performance of an active filter and a passive filter? [1]

.....

.....

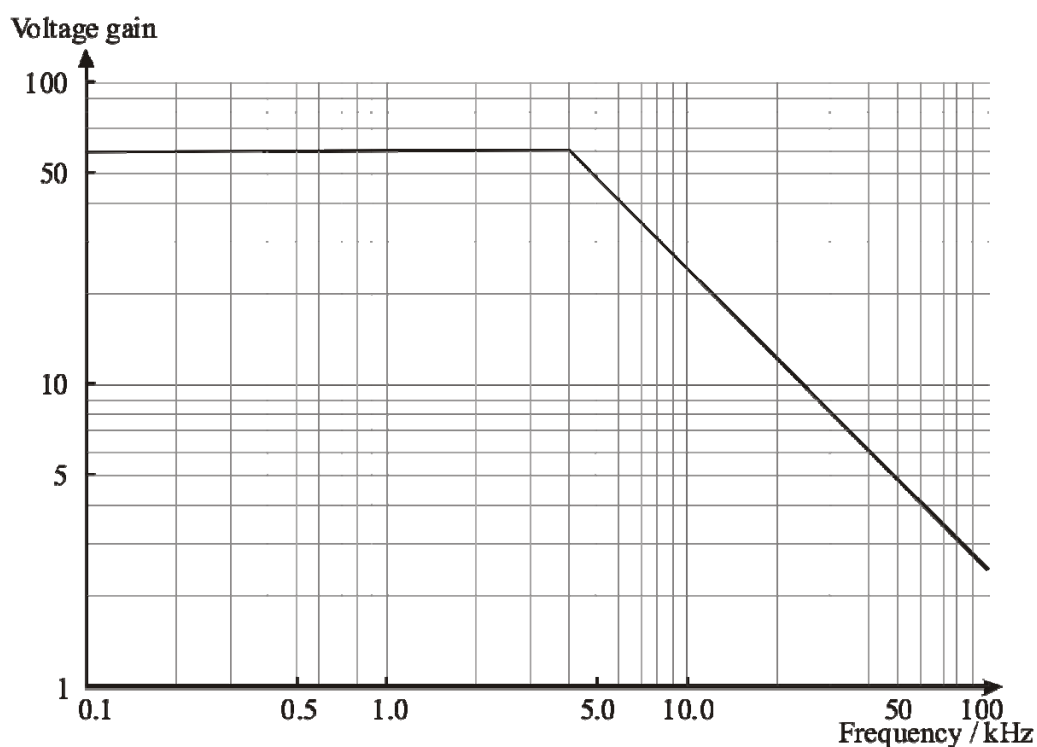
- (b) Identify the following types of active filter. [2]



Filter A =

Filter B =

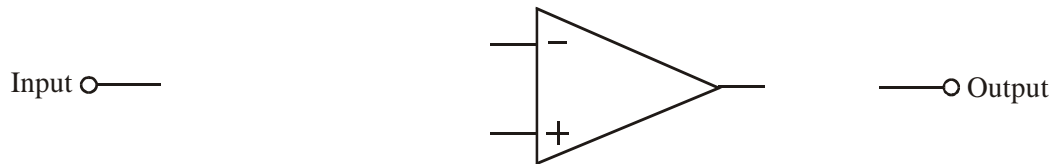
- (c) An audio communications system uses a low-pass filter with the following frequency response:



- (i) What is the break frequency for this filter? [1]

Break frequency =

- (ii) Draw the circuit diagram for a filter which has a frequency response of this type, based on a single op-amp. [3]



0V

- (d) Another low pass active filter has a voltage gain of 40 and a break frequency of 2kHz. [2]

The following resistors are available.

10Ω 50Ω 400Ω 2kΩ 10kΩ 80kΩ 4MΩ

- (i) Select the *one* pair of resistors that is most suitable to give the specified voltage gain. [2]

Resistor 1

Resistor 2

- (ii) Use the formula $C = 1 / 2 \pi f_B R$ to calculate the value of capacitor required. [2]

.....
.....
.....

Topic 5.6 – Audio Systems

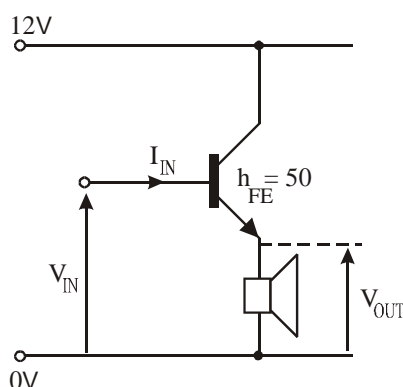
3. The block diagram for a simple public address system is shown below.



Extracts from the data sheets for the microphone and loudspeaker given in the table.

Microphone:.	
Impedance	50kΩ
Frequency response:	100Hz - 20kHz
Loudspeaker	
Power rating	10W
Impedance	8Ω
Frequency response	80Hz to 9kHz

- (a) (i) What is the ideal value of the input impedance of the preamplifier required to maximise transfer of the voltage signal from the microphone? [1]
-
- (ii) What is the ideal value of the output impedance of the power amplifier required to maximise power transfer of the signal from the output of the power amplifier to the loudspeaker? [1]
-
- (b) The power amplifier uses the emitter follower circuit shown below.



A student tests this by applying a DC input voltage, V_{IN} , of +3.0V.

- (i) Calculate the expected value of V_{OUT} ? [1]
-
- (ii) What is the voltage drop across the transistor? [1]
-

Module ET5

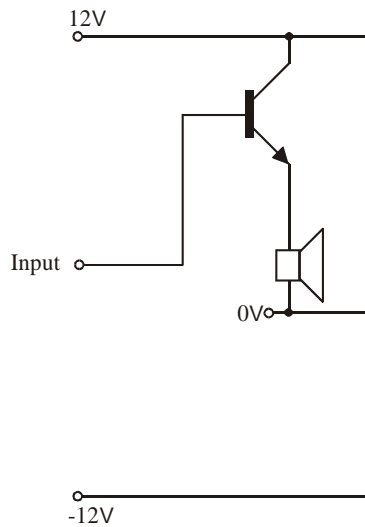
Electronic Systems Applications.

The student measures a DC current of 0.4A flows through the loudspeaker.

- (iii) What is the power dissipated in the transistor when $V_{IN} = +3.0V$? [1]
 (iv) Estimate the corresponding current I_{IN} , and show how you obtain your value. [2]

.....

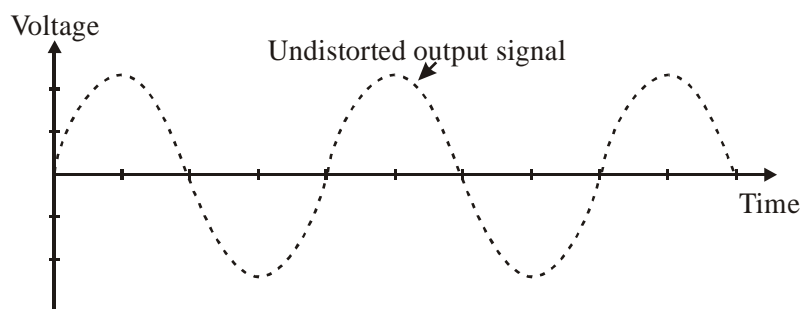
- (c) (i) An improved power amplifier uses a push-pull follower circuit. Complete the circuit diagram for the push-pull follower. [3]



- (ii) Give one advantage of the circuit over the emitter follower power amplifier. [1]

.....

- (d) (i) Push-pull followers can cause *crossover distortion*. Illustrate the meaning of cross-over distortion by drawing an output signal which exhibits it. An undistorted output signal is shown to assist you. [1]

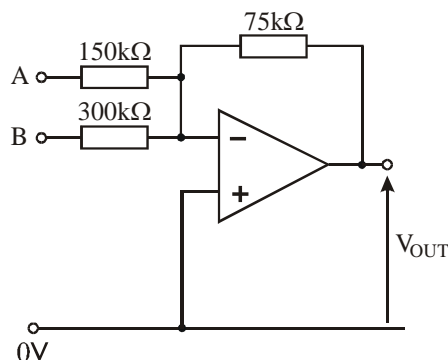


- (ii) Explain what causes crossover distortion in a push-pull amplifier. [1]

.....

Topic 5.6 - Audio Systems

4. (a) The circuit diagram shows a summing amplifier with two inputs, A, and B.



- (i) The following input voltages are applied:

$$V_A = 1.8V \quad V_B = 2.0V$$

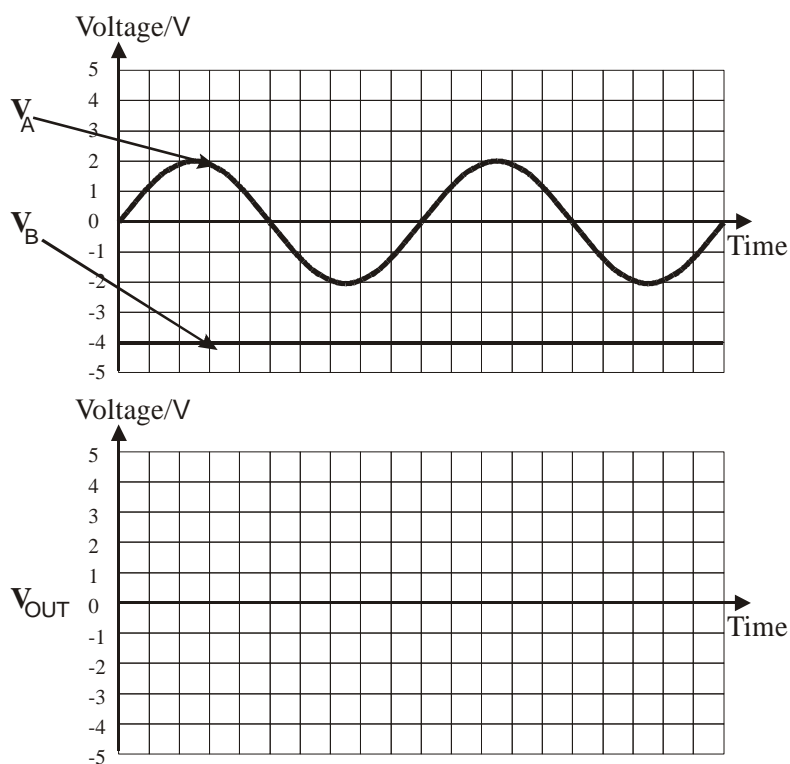
Calculate the output voltage V_{OUT} .

[2]

- (ii) The summing amplifier is now provided with new input signals. A sinusoidal input voltage is applied to input A and a steady negative voltage applied to input B. These signals are shown in the following graphs.

Use the axes provided to sketch the resulting output signal V_{OUT} .

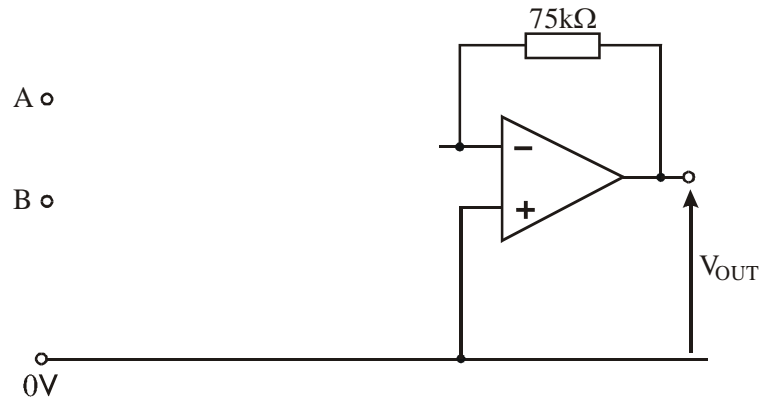
[3]



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Electronic Systems Applications.

- (b) The summing amplifier is modified to make a mixer for an audio system.
The $75k\Omega$ feedback resistor is retained.
 The specification for the system states that both inputs must have a voltage gain that is variable from a minimum of 0.1 to a maximum of 1.0.
 Complete the circuit diagram for the mixer, and calculate suitable **ideal** values for all components. [4]



.....

.....

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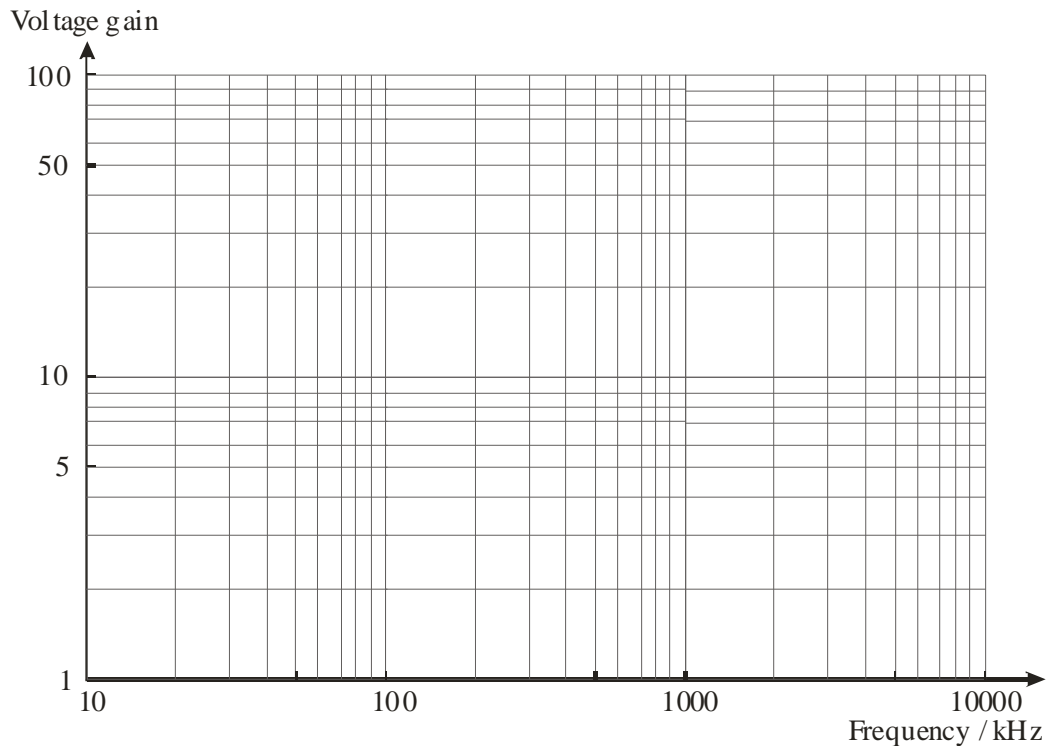
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Topic 5.6 - Audio Systems

5. An audio system requires a treble-cut filter, having a low frequency voltage gain of 20 and a break frequency of 800Hz.

(a) Sketch the frequency response of the filter using the axes provided.

[3]



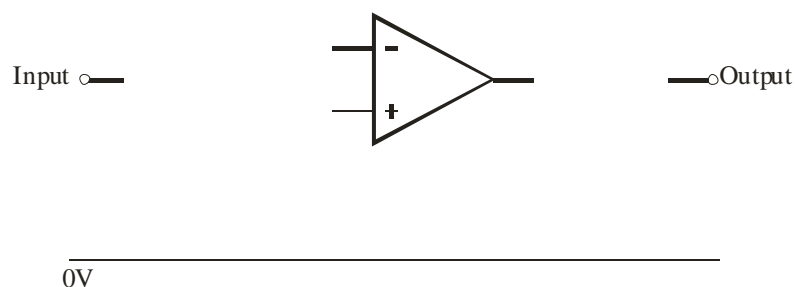
(b) A passive filter circuit would be unsuitable for this application. Why?

[1]

.....

(c) Draw the circuit diagram for an active treble-cut filter, based on an op-amp.

[3]



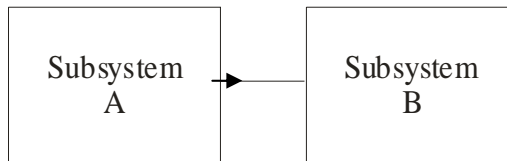
- (d) The circuit includes a 10 nF capacitor. Calculate the ideal values for any resistors used in the circuit. [2]

.....

.....

.....

6. (a) In the diagram, sub-system A sends a signal to sub-system B



Complete the following statements:

- (i) In order to maximise **voltage transfer** between the two sub-systems, the output impedance of sub-system A should be

.....

[1]

- (ii) In order to maximise **power transfer** between the two sub-systems, the output impedance of sub-system A should be

.....

[1]

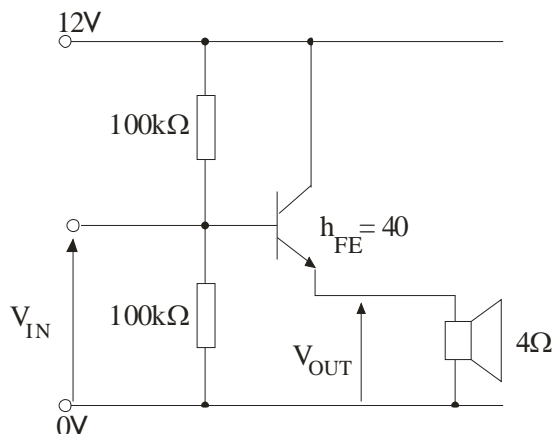
- (iii) A microphone is used for sub-system A, and a preamplifier for is used for sub-system B.

Is maximum voltage transfer, or maximum power transfer required?

[1]

.....

- (b) Here is the circuit diagram for a power amplifier, using an emitter follower.



- (i) Estimate the input impedance of the circuit.

[1]

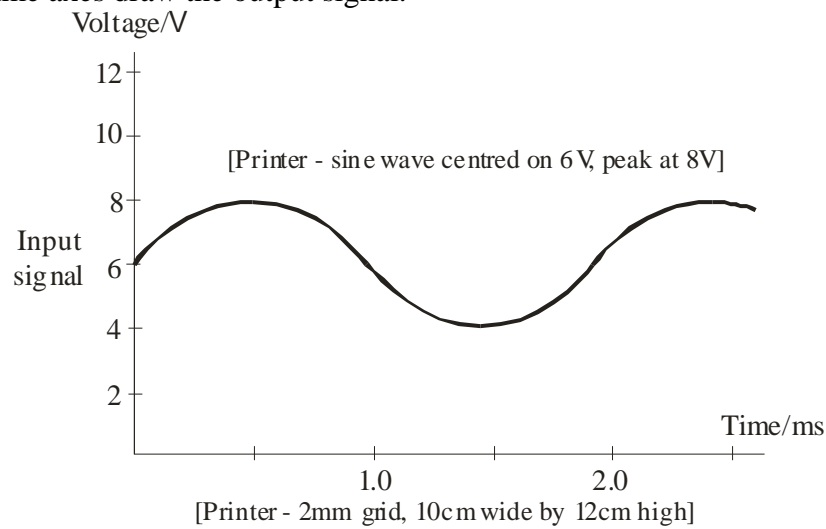
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Topic 5.6 - Audio Systems

- (ii) The signal shown below is applied to the input of the emitter follower.
On the same axes draw the output signal.

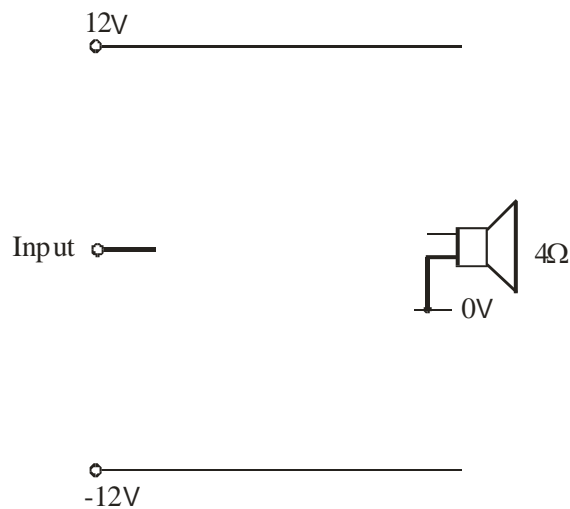
[2]



- (c) Power amplifiers often use push-pull circuits.

- (i) Complete the circuit diagram for a push-pull circuit used to deliver power to a 4Ω load.

[3]



- (ii) Calculate the maximum power dissipated in the 4Ω load.

[2]

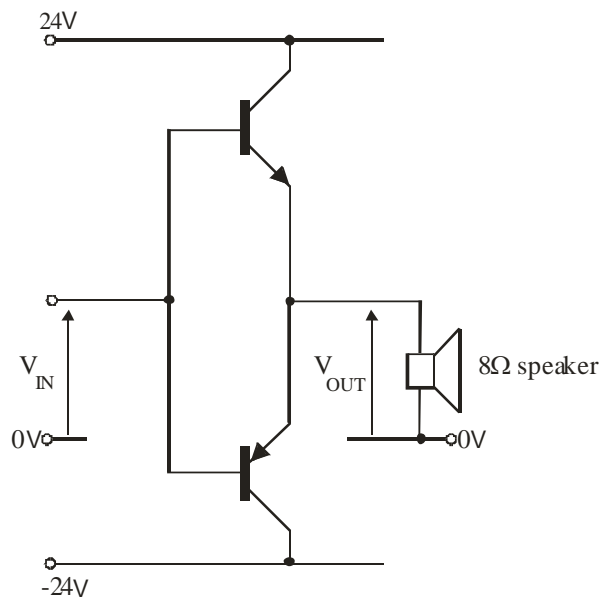
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Module ET5
Electronic Systems Applications.

7. The power amplifier shown in the following circuit diagram is used to drive a loudspeaker.



- (a) Complete the table to show the values of the output voltage V_{OUT} .

[3]

Input voltage V_{IN} /V	Output voltage V_{OUT} /V
+2.0	
+0.5	
-0.2	
-2.5	

- (b) Estimate the maximum power that can be dissipated in the 8Ω loudspeaker in this circuit.

[1]

.....

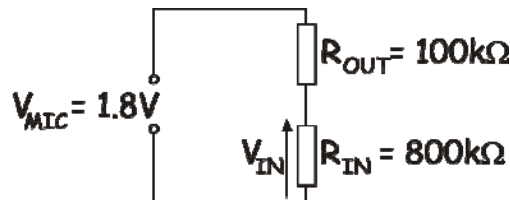
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Solutions to Exercises:

Exercise 1:

The situation can be represented by the following voltage divider:



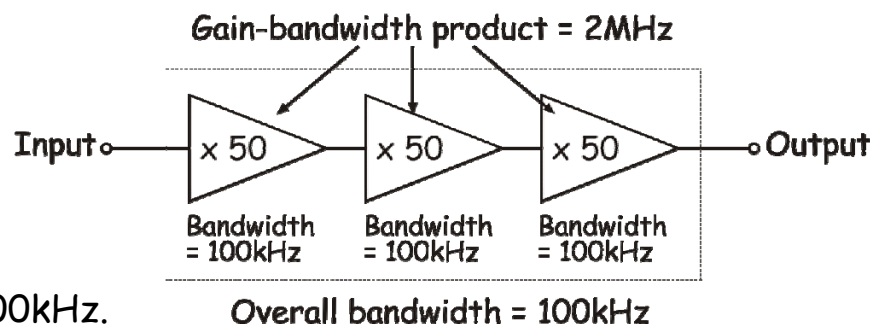
Using the voltage divider formula, the voltage transferred,

$$\begin{aligned} V_{IN} &= V_{MIC} \times \frac{R_{IN}}{R_{IN} + R_{OUT}} \\ &= 1.8 \times 800 / 900 \\ &= 1.6V \end{aligned}$$

Exercise 2:

The three-stage amplifier is shown in the diagram:

To give an overall bandwidth of 100kHz, the bandwidth of each stage must be at least 100kHz.



The best design uses the same bandwidths, and the same voltage gains, for each stage. This means giving each stage a bandwidth of 100kHz.

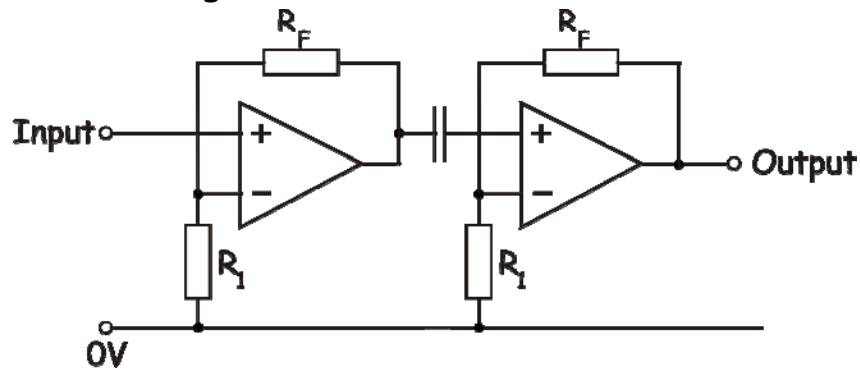
Since the gain-bandwidth product of the op-amps is 2MHz ($= 2 \times 10^6 \text{ Hz}$), each stage must have a voltage gain of:

$$\begin{aligned} G &= 2 \times 10^6 / 100 \times 10^3 \\ &= 20 \end{aligned}$$

The overall gain of the multi-stage amplifier is $20 \times 20 \times 20 = 8\,000$.

Exercise 3:

For best results, the two stages should have the same voltage gain, and same bandwidth. The circuit diagram for the solution is:



The overall voltage gain is 900, so each stage will have a voltage gain of 30.

The formula for the voltage gain of a non-inverting amplifier is:

$$G = 1 + R_F / R_1$$

To give a voltage gain of 30, R_F / R_1 must have a value of 29, so that:

$$R_F = 29 \times R_1$$

All resistor values should be greater than $1k\Omega$, to reduce power dissipation, so one solution is to use:

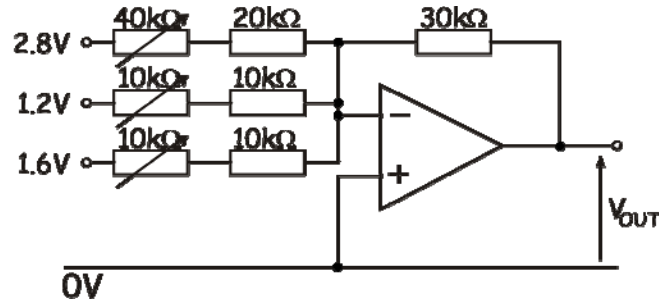
$$R_F = 290k\Omega \quad \text{and} \quad R_1 = 10k\Omega$$

(There is a wide range of possible answers. However, all resistors should be greater than $1k\Omega$, and the ratio $R_F : R_1$ should be 29 : 1.)

The gain-bandwidth product of the op-amps is 900kHz, so with a voltage gain of 30, each stage will have a bandwidth of 30kHz, giving an overall bandwidth of 30kHz.

Exercise 4:

The arrangement described in the question is shown in the following diagram:



The output voltage is calculated using the formula:

$$V_{OUT} = - R_F [(V_1 / R_1) + (V_2 / R_2) + (V_3 / R_3)]$$

The input resistances R_1 , R_2 and R_3 are found by adding together the resistances of the variable resistor and fixed resistor for each input channel.

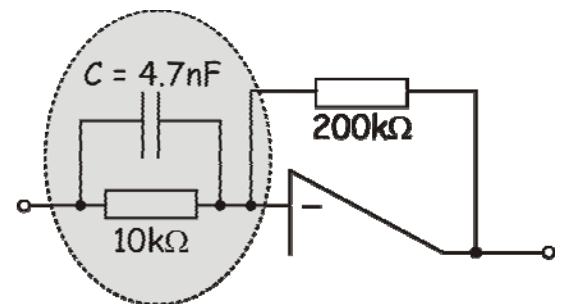
so:

$$\begin{aligned} V_{OUT} &= - 30[(1.6/(10+10)) + (1.2/(10+10)) + (2.8/(40+20))] \\ &= - 30 [(1.6/20) + (1.2/20) + 2.8/(60)] \\ &= - 5.6V \end{aligned}$$

Exercise 5:

The significant portion of the circuit diagram is shown opposite:

The break frequency is determined by the RC network. In this case, that is the 4.7nF capacitor and the 10kΩ resistor.



(The $200\text{k}\Omega$ resistor helps to determine the voltage gain in the horizontal section of the frequency response, as you will see shortly.)

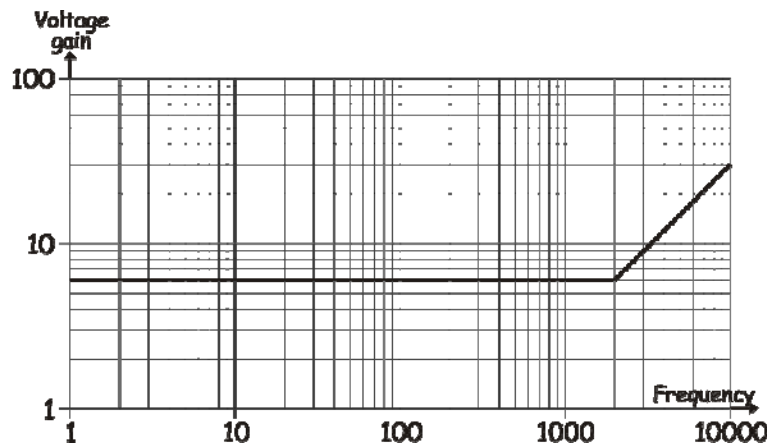
Using the break frequency formula:

$$f_b = 1 / (2 \pi R C)$$

gives a break frequency of $f_b = 1 / (2 \times \pi \times 10 \times 10^3 \times 4.7 \times 10^{-9})$
 $= 3.4\text{kHz}$

Exercise 6:

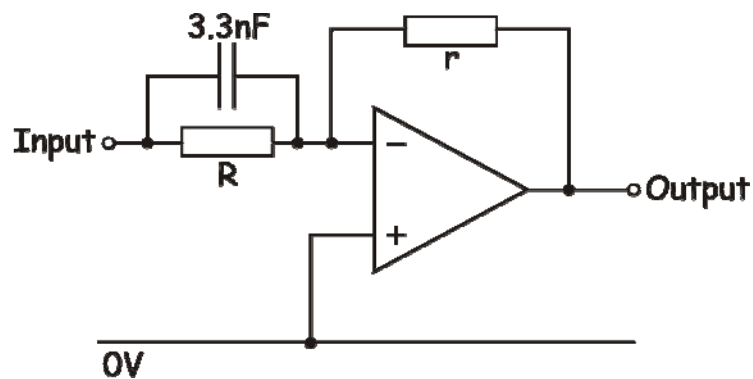
The frequency response for the filter is:



This has the following characteristics:

Type of filter	Treble boost
Low frequency voltage gain	6
Break frequency	2 000Hz

The circuit diagram for this filter, using a 3.3nF capacitor is given below:



Resistor R is chosen to give the required break frequency with the 3.3nF capacitor, i.e. using

$$\begin{aligned}
 f_b &= 1 / (2 \pi R C) \\
 R &= 1 / (2 \pi f_b C) \\
 &= 1 / (2 \times \pi \times 2\,000 \times 3.3 \times 10^{-9}) \\
 &= 24.1\text{k}\Omega
 \end{aligned}$$

Resistor r is then chosen to give the required low frequency voltage gain, i.e.

$$r / R = 6$$

Hence

$$r = 6 \times R$$

giving

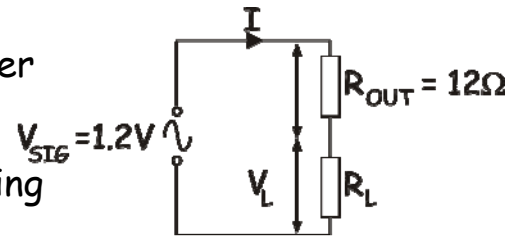
$$r = 144.7\text{k}\Omega$$

Using the E24 resistor series, the nearest values are $R = 24\text{k}\Omega$, $r = 150\text{k}\Omega$.

Exercise 7:

The arrangement of power amplifier and loudspeaker can be represented by the voltage divider circuit:

Answers to the exercise can be obtained by analysing this circuit.



Power transferred to the loudspeaker, $P = I \times V_L$

The current flowing through the loudspeaker, $I = V_{SIG} / (R_{OUT} + R_L)$

The voltage generated across the loudspeaker, $V_L = I \times R_L$.

The answers to the exercise are developed in the table:

Loudspeaker	$(R_{OUT} + R_L)$	I / A	V_L / V	P / W
A	18Ω	0.067	0.4	0.027
B	24Ω	0.05	0.6	0.03
C	30Ω	0.04	0.72	0.029

PS - The results support the maximum power transfer theorem!

Exercise 8:

The secret here is to see through the fog of unnecessary information.

This is an emitter follower, and it obeys the relationship:

$$V_{OUT} = V_{IN} - 0.7$$

The information given in the question says that the voltage at point = 7.9V.

This is actually V_{IN} .

Hence the answer:

the resulting voltage across the loudspeaker = $7.9 - 0.7 = 7.2V$.

(The $15k\Omega$ resistors play their part in setting up the 7.9V input. When the signal is zero, they maintain a voltage of 7.5V at point X. However, the question is answered without any reference to this.)