Imperial College London

Lecture 3 Supplementary Notes

LM386 Explained

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This supplementary notes is provided for the die-hard enthusiasts on analogue integrated circuits. It is not examinable and is only provided for information.

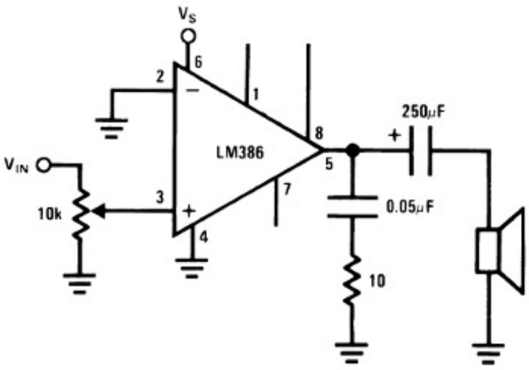
Here I explain exactly how LM386 works, but referring its internal circuits to the contents of Lecture 3 - The Anatomy of an Op-Amp.

Do not spend time on this unless you have mastered the main module lectures and labs.

Driving 8Ω speaker with LM386

LM386
Low Voltage Audio Power Amplifier

Amplifier with Gain = 20
Minimum Parts



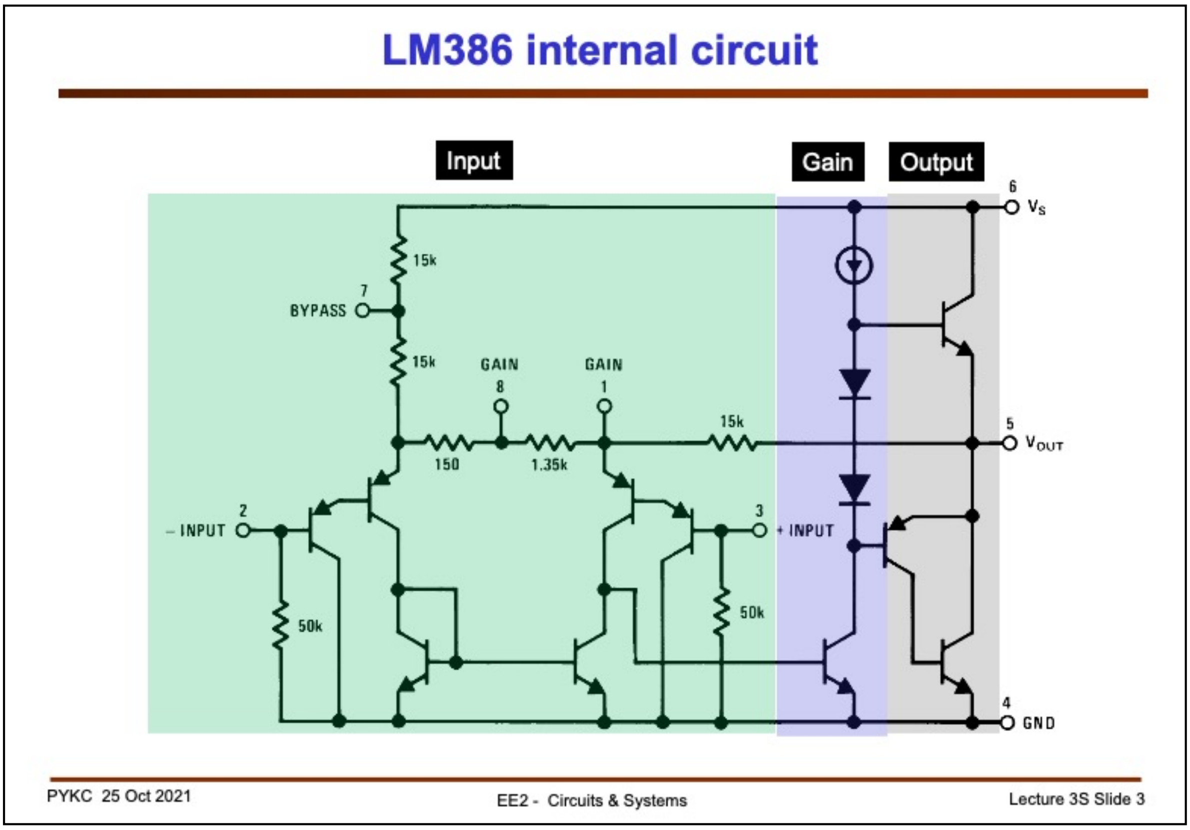
Features

- Battery operation
- Minimum external parts
- Wide supply voltage range: 4V–12V or 5V–18V
- Low quiescent current drain: 4mA
- Voltage gains from 20 to 200
- Ground referenced input
- Self-centering output quiescent voltage
- Low distortion: 0.2% (A_V = 20, V_S = 6V, R_L = 8Ω, P_O = 125mW, f = 1kHz)
- Available in 8 pin MSOP package

Now we are ready to examine exactly how LM386 works by studying the detail circuit inside the package.

This amplifier is NOT an op-amp because it cannot be connected in the usual way with an op-amp as you did with the MCP6002 from the previous lecture. Instead, this circuit contains its own internal feedback network such that it has an inherent voltage gain of around 20 (or 26dB).

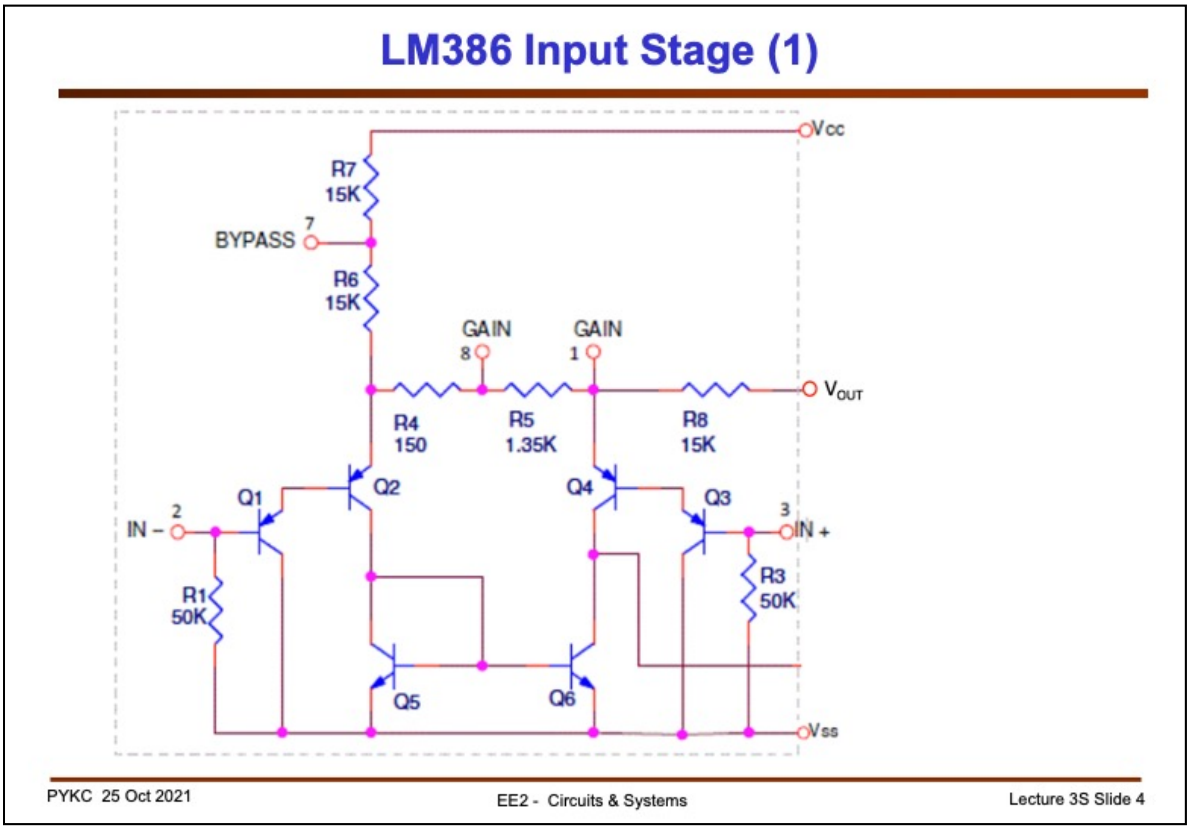
Shown here is the circuit from the datasheet showing the basic configuration of the LM386 as a x20 amplifier driving a speaker. It also provides a summary of its desirable features. Most notable are the first two: battery operation, meaning that it works with a single power supply, and minimum external parts.



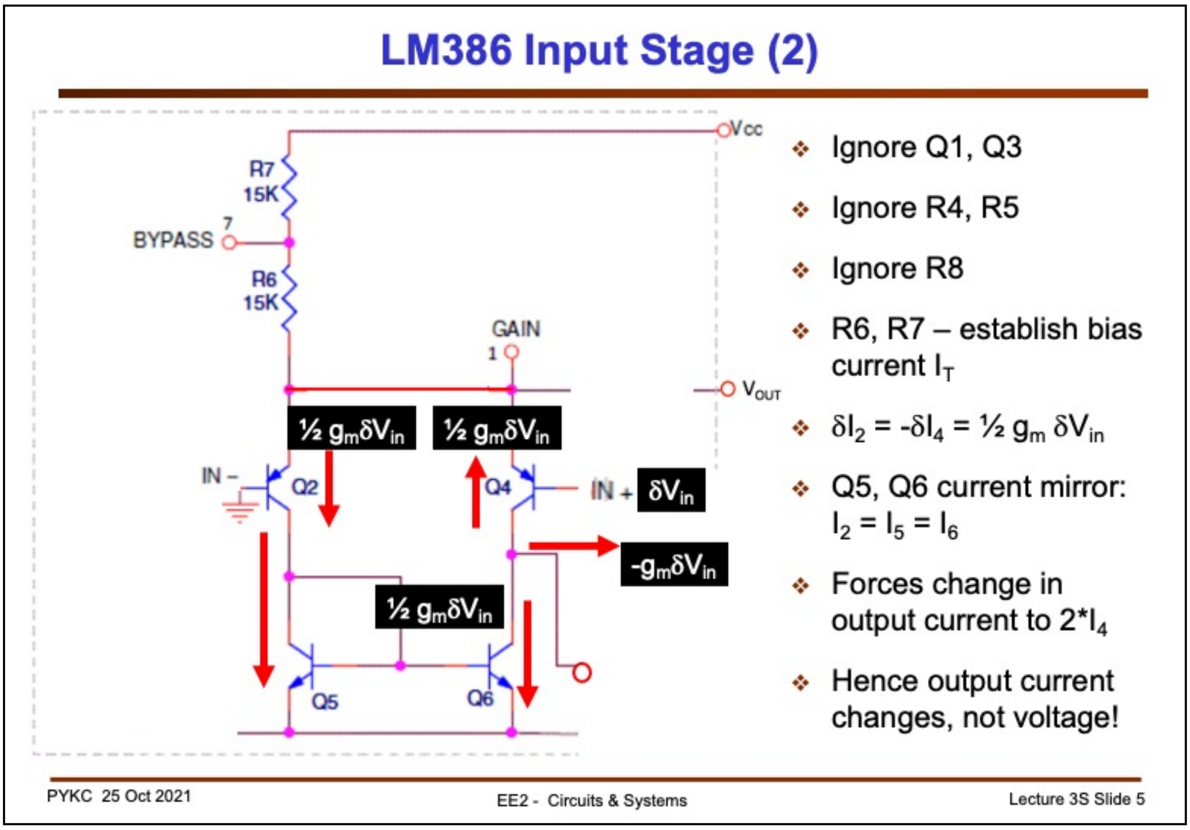
This shows the full internal circuit of LM386 at transistor level (except the current source in the 2nd stage).

This follows the classic three stage op-amp architecture with several refinements.

We will now consider each stage separately and discuss the design choices made and reasons why.



The input stage is a long-tail pair with additional input transistors Q1, Q3 and R1, R3. Here all components are labelled and numbered for ease of reference in the explanation. Otherwise, it is identical to the circuit you find in the datasheet.



Let us start by simplifying the circuit and ignore Q1 and Q3, the additional input stages. Further, let us remove R8, the feedback resistor from V_{out}. Since R4 and R5 also form part of the feedback network and is relatively small compared with other resistor values, let us assume them to be zero for now (i.e. short circuit).

Here we can see that this is a conventional long-tail pair except that the load resistor at the collector of Q4 is replaced by a circuit Q5 and Q6.

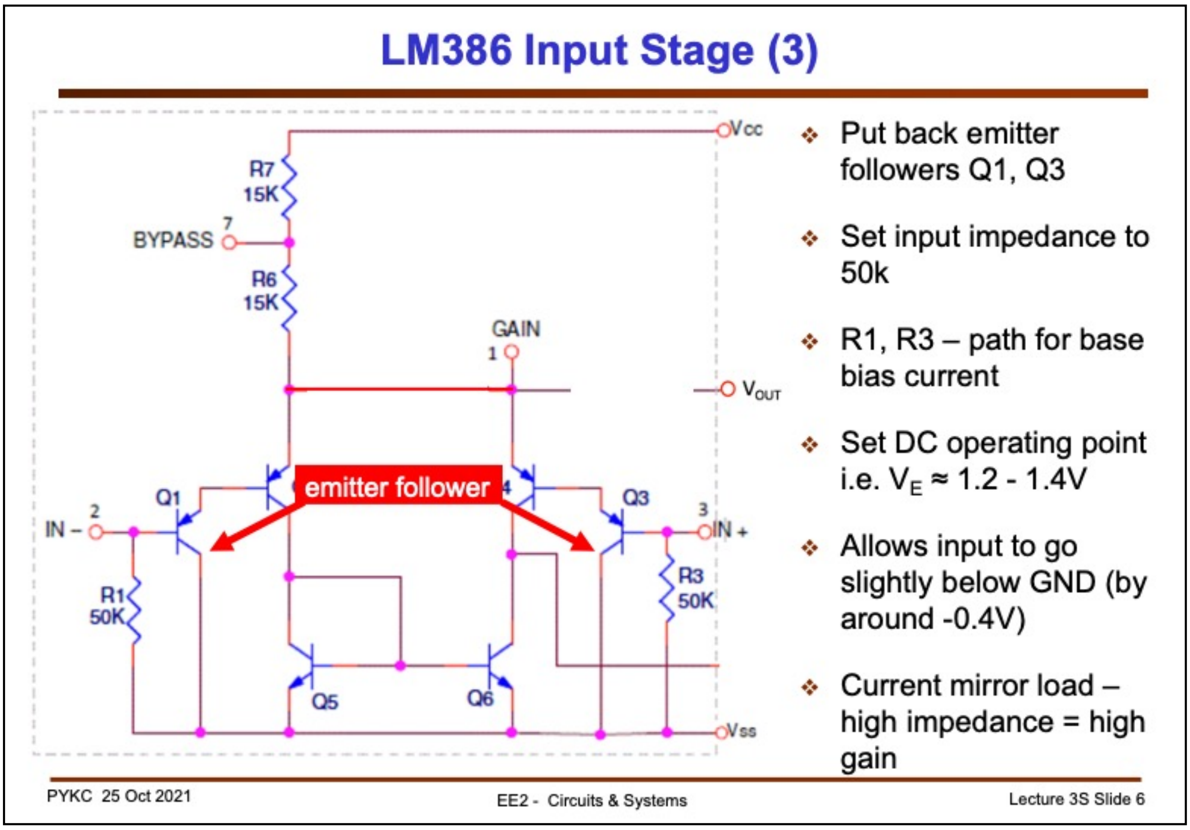
Consider IN+ goes up by δV_{in}. This increases V_{BE2} by ½ δV_{in} and decreases V_{BE4} by ½ δV_{in}. Therefore $\delta I_4 = - \delta I_2 = -$ ½ $g_m \delta V_{in}$.

However, Q2 and Q5 are in series and share the same current, i.e. $\delta I_5 = \delta I_2$. Therefore δI_2 is mirror by Q6 onto the right branch of differential pair as $\delta I_6 = \delta I_2$.

Since $\delta I_4 = - \delta I_2 = -$ ½ $g_m \delta V_{in}$, the change in output current is

$$\delta I_{out} = -\delta I_2 + \delta I_4 = -2\, \delta I_2 = - g_m \delta V_{in}$$

This design produces an output current gain, not voltage gain!

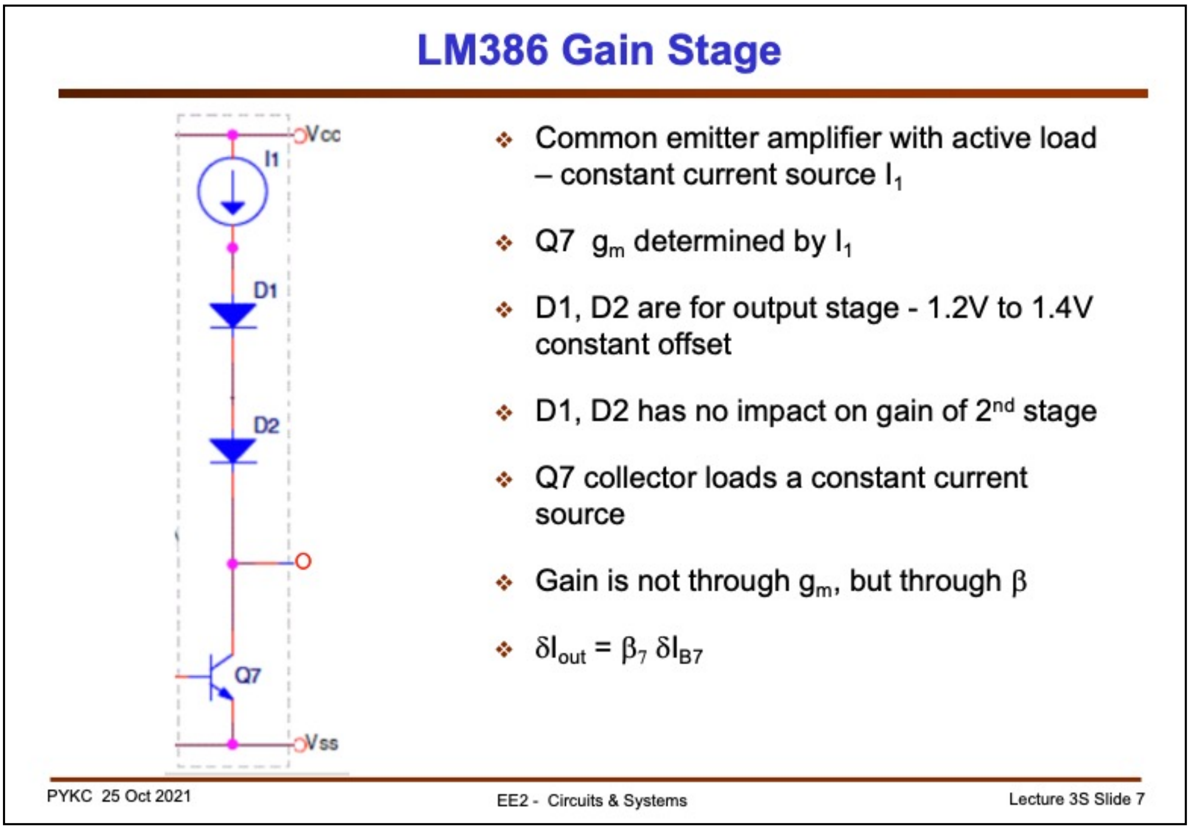


The long-tail pair inputs are "buffered" with two emitter follower type transistor Q1 and Q3. This additional circuit serves several purposes:

1. R1 and R2 fix the input resistances at 50k ohms and provide a DC path for the base current to follow, biasing the input stage. It avoids the inputs of the amplifier become floating, and therefore the amplifier output is also biased properly even the input terminals are open circuit.
2. It allows input to swing below V_{SS} (i.e. negative) and ensure that all transistors stay in the active region. Assuming that V_{SS} is GND, this allows inputs to swing between $\pm$0.4V.

Why is this the case? Let us assume IN+ is -0.4V, which is negative relative to V_{SS}. Since Q3 and Q5 are PNP transistors, their base-emitter junction diodes will be forward biased. For Q3 to work in the active region and thus behave like an emitter follower, the base-collector junction needs to remain reverse biased. Fortunately -0.4V is not sufficient to turn on the base-collector diode for Q3.

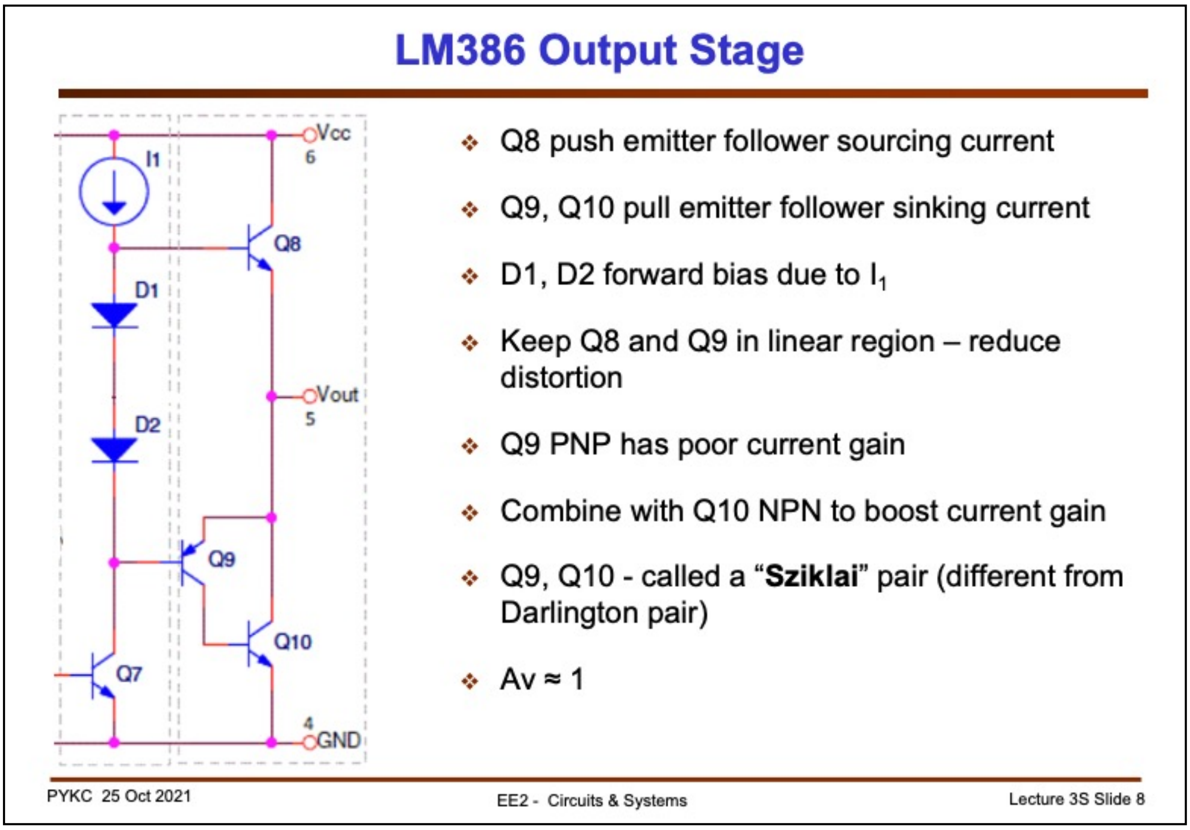
So far we have ignored R4, R5 and R8 because they are part of the feedback network, and they do not belong to the differential stage. We will come back to them later.



Unlike the classical 2nd voltage gain stage, the 2nd stage of the LM386 has a collector **current source** load instead of a **resistive load**. This is convenient because as seen in earlier slides, the differential stage provides an amplified current output, which feeds the base of Q7.

Since the load of the 2nd stage is the current source I_1, the output of this stage is again a current, $\delta I_{out} = \beta_7 \, \delta I_{B7}$.

The output current feeds the output stage.



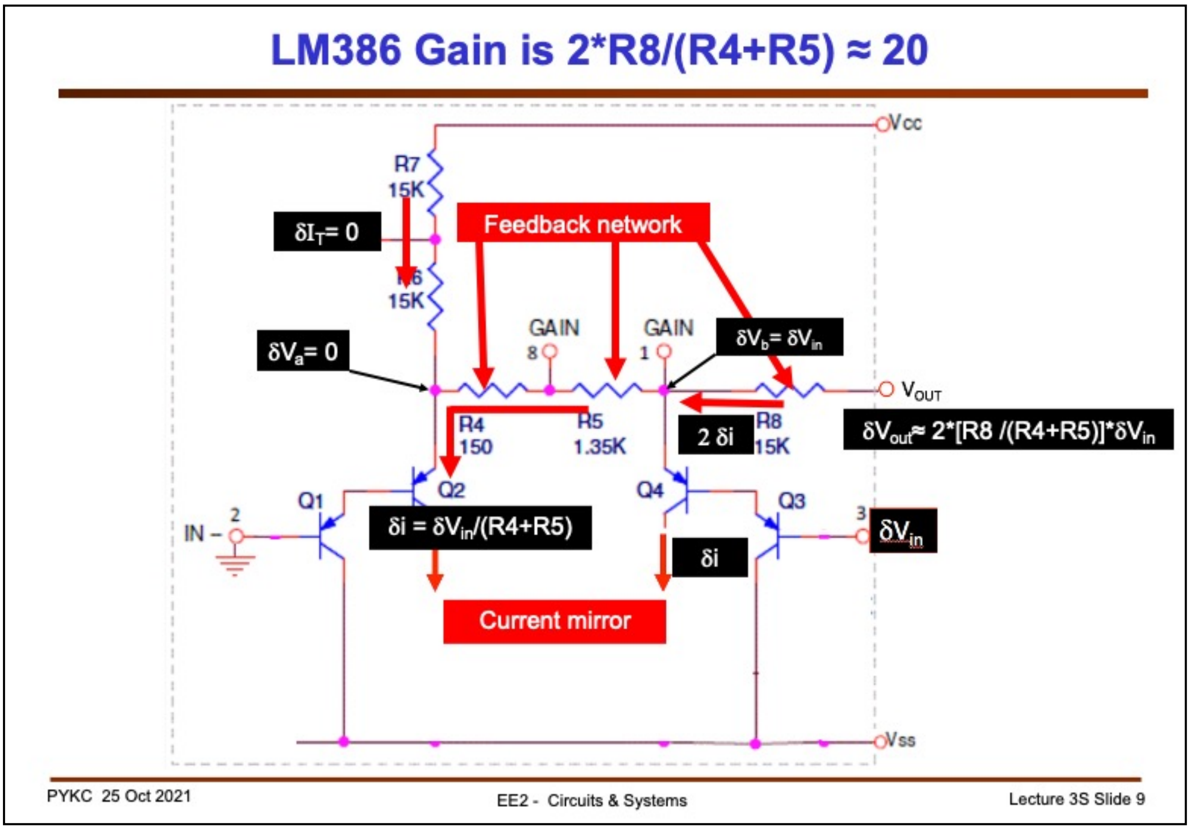
This output stage is very similar to what has been discussed before except for two features.

As discussed earlier in slide 10, the simple push-pull circuit exhibits severe distortion because the NPN and PNP transistors are not conducting whenever their base-emitter voltages are below 0.7V. This is mitigated by adding two diodes D1 and D2 as shown. These two diodes are forward biased via the constant current source I1, and they ensure that both Q8 and Q9 are always operating in the linear region (i.e. base-emitter forward biased). This eliminates much of the distortion.

The second feature is that the PNP transistor is enhanced with Q10, a NPN transistor. The reason is that PNP transistors typically have significantly lower current gain than NPN transistors.

By adding Q10, the combined current gain is boosted to: $\beta \approx \beta_9 \, \beta_{10}$. This configuration is known as a "**Sziklai** transistor pair". It is different from **Darlington pair** which consists of two transistors of the SAME TYPE connected in cascade.

Sziklai transistor pair, like a Darlington pair, provides the same improved current gain (product of the two transistors' current gains), but it requires only one V_{BE} to turn on, and not two as in a standard Darlington configuration.



Now let us put back the feedback resistors R4, R5 and R8, and establish why with these resistors in the circuit, LM386 provides a gain of approximately 20.

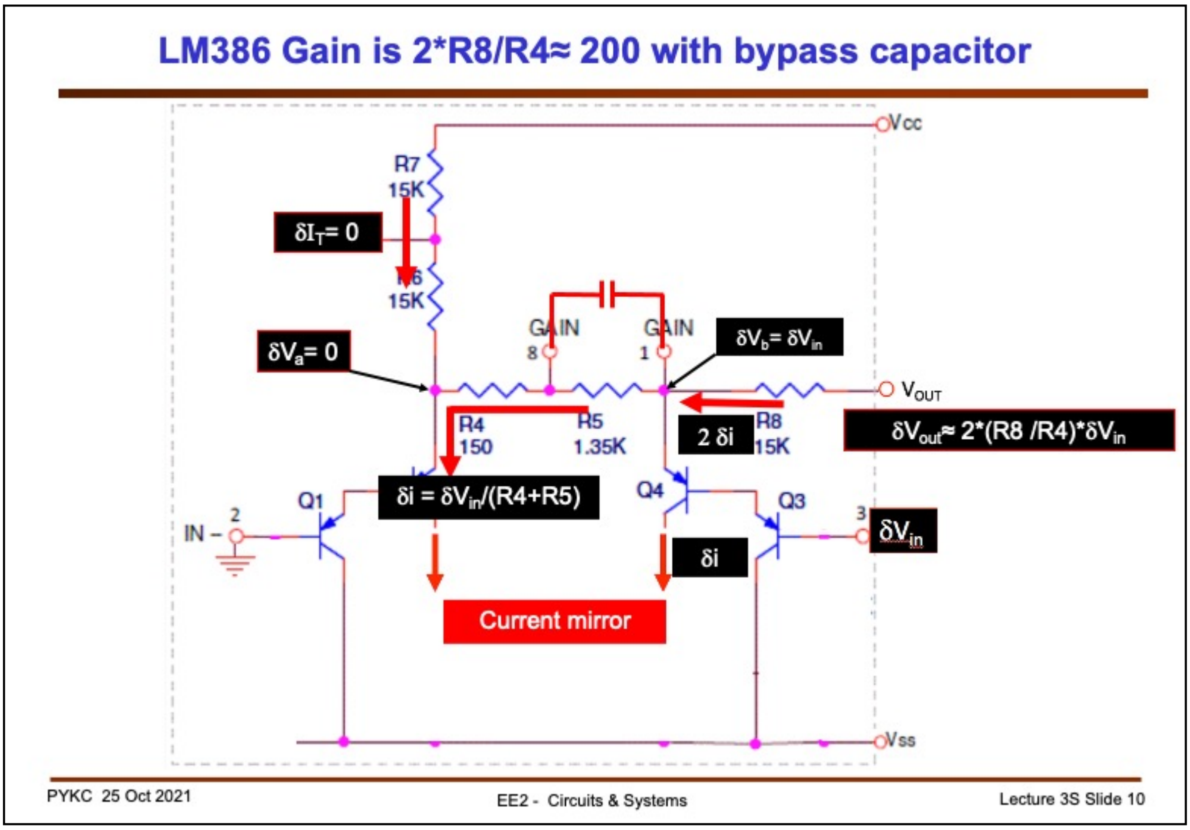
Here is a simplified version of the entire circuit schematic with stage 2 and 3 omitted. Let us assume that the input voltage at IN+ changes by δV_{in} . Due to the high gain of the circuit, V_{out} can drive the output load with small changes to V_{BE} of Q1-4. Therefore, the change in voltage at emitter of Q2 (node a) or δV_a can be assumed to be 0 because IN- is at 0V.

Similarly, δV_b at the emitter of Q4 (node b) can be assumed to be the same as δV_{in}. Hence the change in the current flowing from node b to a (i.e. through R4 and R5) is $\delta i = \delta V_{in}/(R4+R5)$. This change in current is mirrored on the right branch of the differential pair through Q4. This current cannot come from the tail current because Va has not changed and therefore $\delta I_T = 0$.

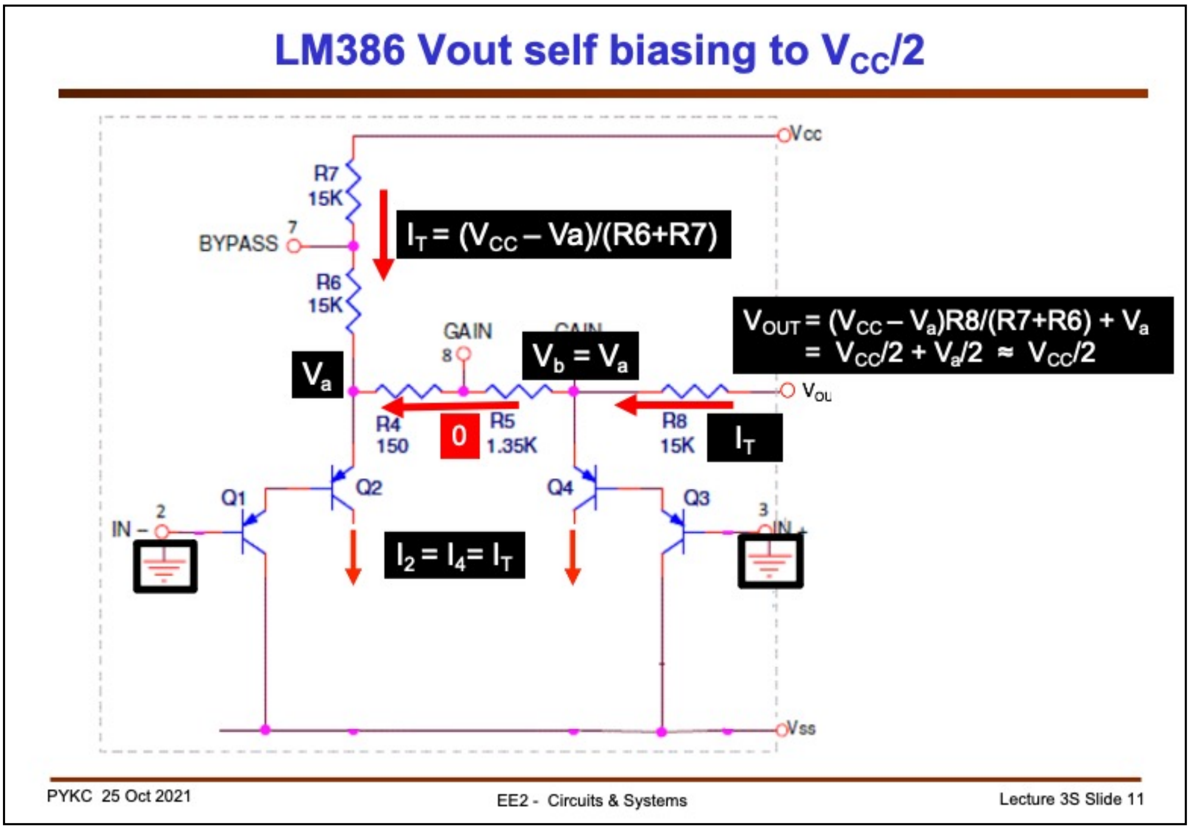
As a result, both δi through Q2 and Q4 must come from the R8 feedback resistor. Therefore δV_{in} results in $2\delta i$ flowing through R8.

Consequently, $\delta V_{out} = 2\delta i\ R8 + \delta V_{in} = 2 * \delta V_{in}\ R8/(R4+R5) + \delta V_{in}$.

Assuming $\delta V_{out} >> \delta V_{in}$, $\delta V_{out} / \delta V_{in} \approx 2\ R8/(R4+R5)$.



LM386 provides access to bypass R5 with a 10uF capacitor. Then the gain of the amplifier increases to x 200.



The LM385 with the feedback network R4, R5 and R8 is automatically biasing its output V_{out} to approximately VCC/2. This offset provides a maximum output voltage swing. This is how it works.

Assuming both inputs are zero (quiescent state). Va and Vb must the same because Q2 and Q4 are matched. No current flows through R4 and R5.

Therefore tail current I_T must flows through Q2. Current mirror reflects this current on Q4. Hence $I_2 = I_4 = I_T$. The same current I_T must flow from R8.

Hence, $V_{out} = I_T{*}R8 + V_a$.

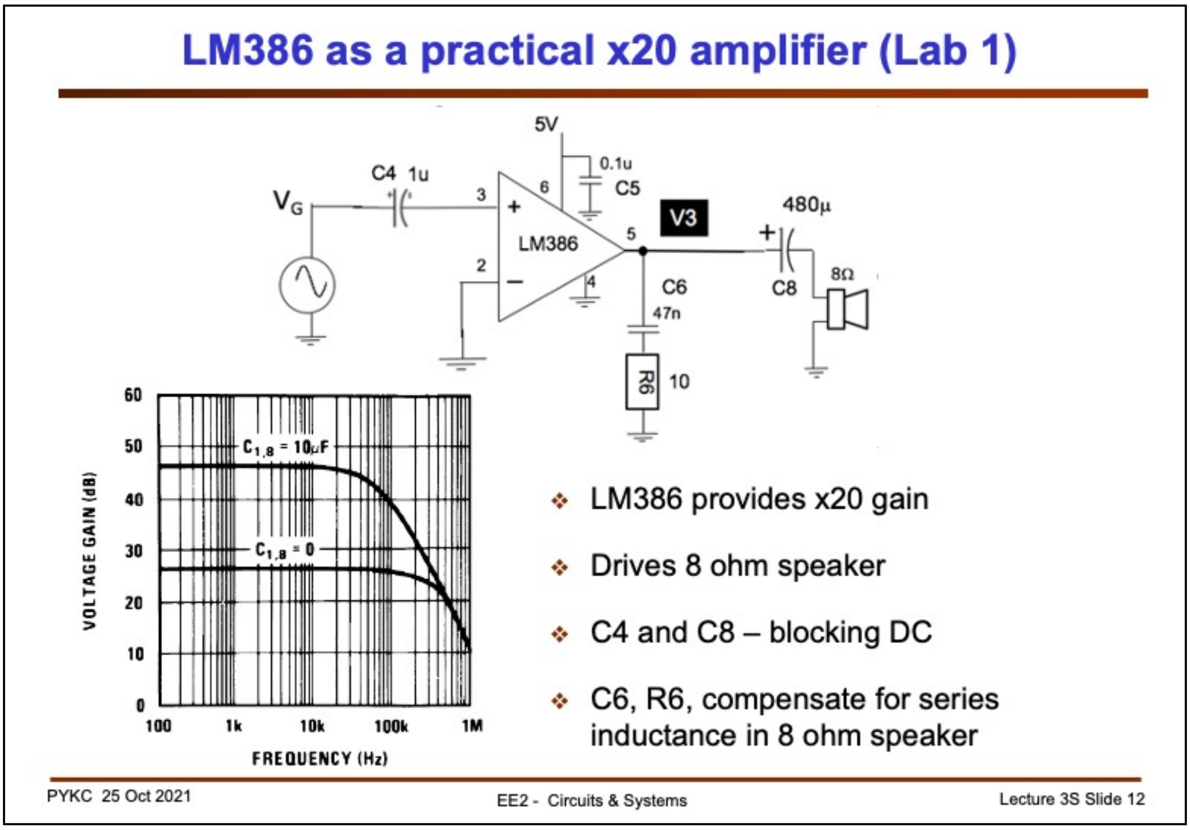
Since, $I_T = (V_{CC} - V_a)/(R6 + R7)$,

$$V_{out} = (V_{CC} - V_a)\ R8/(R6 + R7) + V_a$$

Assuming that $V_a << V_{out} << V_{CC}$,

$$V_{out} \approx V_{CC}/2.$$

This is particularly true when V_{CC} is, say, 10V.



In Lab 1, you will build a x20 amplifier driving an 8 Ω speaker.

C4 and C8 provide AC coupling for both input and output signals.

The input capacitor C4 prevents the signal source from disturbing the DC bias for the LM386.

The output capacitor C8 prevents the output offset of $V_{CC}/2$ being applied to the speaker, which may result in damage to the load.

The speaker is NOT equivalent to just an 8 Ω resistor. The voice coil of the speaker has an equivalent circuit of an inductor in series with a resistor. As a result, the load impedance changes with frequency, with the loading increases at higher frequencies. This can result in the phase of the output signal changes at higher frequencies in such a way that the internal feedback can cause oscillation to occur. C6 and R6, the series RC network at the output provides compensation and avoid instability.