We begin with a project that combines our previous experiences with both op-amps and transistors, and build a circuit (much like those in audio amplifiers and motor controllers) that can drive significant current. We use this to demonstrate the importance of feedback across the entire circuit, as opposed to just the op-amp sub-circuit.

### 9.1 Push-pull amplifier and system-wide negative feedback

The transistors can be connected in series that, properly biased, can function as a linear amplifier over a range of voltages (Figure 9.1) As we shall see, the tricky part is the crossing near zero volts where one transistor is turning off as the other has not yet turned on.

**Figure 9.1:** NPN and PNP transistors together span positive and negative $V_{CE}$, except for $|V_{CE}| < |V_{CE(sat)}|$. 

**Op-amp feedback only**

**Figure 9.2:** Amplifier with push-pull buffer.

Build the push-pull amplifier circuit shown in Figure 9.2. Drive it first with a sine wave between 100 - 500 Hz ($V_{in}$). Use scope probes to simultaneously look at the output of the op-amp (point "A") and the output of the push-pull stage ($V_{out}$); make sure you have at least a few volts of output and that the function generator is set for zero DC offset. You should see classic cross-over distortion; highlight this on SCREENSHOTs with different output amplitudes (2 pts) and describe why this occurs (2 pt).

*Listen* to this waveform on a small speaker. But before you drive the speaker you should determine the maximum safe amplitude given the following power ratings:

- transistors: 350 mW
- speaker: 250 mW
With system-wide feedback

Now reconnect the right side of the 100 kΩ feedback resistor across the full amplifier, \textit{i.e.}, to \( V_{\text{out}} \) rather than the output the op-amp ("A" in Figure 9.2), and once again look at the push-pull output. The crossover distortion should be \textit{almost} eliminated. What does the signal at the output of the transistors look like? Document your observations with \textsc{screenshots} for two different amplitude inputs (2 pts), choosing one amplitude to highlight any residual distortion.

Try listening with the speaker again. Better?

System-wide feedback and feed-through connectivity

The near complete elimination of crossover distortion makes use of a linear feed-through so that the op-amp can directly drive the load when the currents required are very small. Add the 100 Ω resistor as shown below. Is the distortion gone (1 pt)? Document your observation with \textsc{screenshots} for two different amplitude inputs (1 pt).

![Amplifier with system-wide feedback and feed-through resistor.](image)

\textbf{Extra credit}

A complementary means to minimize cross-over distortion is to ensure that the transistors never turn off. This can be accomplished by the use of diodes to boost the input to the PNP and NPN transistors (Figure 9.4). Revise your previous circuit. What value can you choose for \( R \) (1 pt)? Is the distortion gone? Document your observation with \textsc{screenshots} for different amplitude inputs (2 pts).

![Amplifier with system-wide feedback and diode bias to the transistor inputs.](image)

\textbf{9.2 Combined circuits}

Hook up the output of the modulation circuit that you built for exercise 6.2 - \textit{hopefully saved and still operative!} - as the input to the push-pull amplifier with full feedback (Figure 9.3 or 9.4).
Does the 10 kΩ input resistance of the push-pull amplifier load the output of the modulator circuit (hint: do a simple calculation; see http://en.wikipedia.org/wiki/Electrical_load)? By how much (1 pt)? Document your observed output with SCREENSHOTS for different amplitude inputs (2 pt) and describe what you hear (1 pt).

**Fun**

Try to make your combined device sound like a few bars from the late keyboardist Keith Emerson, shown above in his musical prime next to his Moog synthesizer. Be careful, too high a gain and you will blow out the transistors and/or the speaker!

### 9.3 Three Comparators and positive feedback

Comparators work best with positive feedback. But before we show you these good circuits, let’s look at two poor comparator circuits: one using an op amp, the other using a special-purpose comparator chip. These circuits will perform poorly; they will help you to see what’s good about the improved comparator that does use positive feedback.

**Open-loop op amp as comparator**

![Op amp as simple comparator](image)

Figure 9.5: Op amp as simple comparator.

You will recognize this (Figure 9.5) as the very first op amp circuit you wired (exercise 4.1), where the point was to highlight the high gain of the device. In that exercise the excessive gain was factored out of the circuit equations and the input/output was linear. Here we view the circuit as a comparator and the very high gain and the “pinned” output are desired.

Drive the circuit with a sine wave with a 100 mV (or less) amplitude at around 100 Hz and notice that the output is close to a "square wave"; document with a SCREENSHOT (1 pt). Now drive the circuit at 100 kHz, and document with a SCREENSHOT (1 pt) that the “square wave” output is not as square as it was for 100 Hz. Why not (1 pts)?

**Special-purpose comparator IC**

Now substitute a 311 comparator for the 411; the pin-outs are not the same (Figure 9.6). You will notice that the output stage looks funny: it is not like an op amp’s, which is always a push-pull; instead, two pins are brought out, and these are connected to the collector (pin 7) and emitter (pin 1)
of the output transistor, respectively (Figure 9.6). These pins let the user determine both the top and bottom of the output swing (e.g., one can use +5 V and ground to make the output compatible with standard digital logic).

![Figure 9.6: 311 comparator and no feedback.]

Here, you will keep the top of the swing at +15 V and set the bottom of the swing to ground. Does the 311 perform better than the 411 (1 pt)? How so (1 pt)? Document the improvement in gain(s) with a SCREENSHOT (1 pt), including a zoomed in picture of the rapid transitions near the threshold (1 pt). A side-effect of the 311’s fast response is its readiness to oscillate when given a small voltage difference between its inputs; show this and document with a SCREENSHOT (1 pt).

**Special-Purpose Comparator IC configured with positive feedback as a Schmitt Trigger**

The positive feedback used in the circuit of Figure 9.7 provides hysteresis that will eliminate potential harmful oscillations by shifting the threshold immediately after a transition. Predict the thresholds of the circuit above (see class handout as a guide but derive the expression for this simplified case) (2 pts); then try it out and document your a functioning circuit with a SCREENSHOT (1 pt).

![Figure 9.7: Schmitt trigger: comparator with positive feedback]

Notice that triggering stops for sine waves smaller than some critical amplitude. Explain this (1 pt). Measure and report the hysteresis (1 pt). Observe the rapid transitions at the output, independent of the input waveform or frequency. Look at both the "-" and "+" comparator terminals and document with a SCREENSHOT of the V− and V+ inputs and the output (1 pt).

Reconnect the so-called “Ground” pin of the 311 to -15 V; this pin is not necessarily ground, rather it is the emitter of the output transistor. Can you explain why the chip’s designers brought out this pin, as well as why they provided an open-collector output (1 pt)

**9.4 Relaxation oscillator**
A comparator is used with positive feedback to construct a free-running oscillator. Build the circuit of Figure 9.8 and show, with a SCREENSHOT (1 pt), that $V_{out}$ oscillates. What are the expected (1 pt), and measured (1 pt), frequencies (see, e.g., class notes)? Record from both the output and point "X" and explain, documenting with a SCREENSHOT (1 pt), what you see. Repeat, including SCREENSHOT (1 pt), with the 10 kΩ resistor replaced with 1 MΩ.

9-4 7555 IC oscillator (square wave)

The 555 and its derivatives have made the design of moderate-frequency oscillators easy through the use of a monolith device. The 7555 runs up to 500 kHz and its very high input impedances and rail-to-rail output swings can simplify designs.

![Figure 9.8: RC relaxation oscillator](image)

**Figure 9.8: RC relaxation oscillator**

Connect a 7555 in the classic relaxation oscillator configuration, as shown above. Look at the output and document with a SCREENSHOT (1 pt), The frequency is given by:

$$f_{oscillation} = \frac{1.4}{(R_A + 2R_B)C}$$

Look at the waveform on the capacitor (C). What voltage levels does it run between? Document with a SCREENSHOT (1 pt). Does this make sense (1 pt)?

Replace $R_B$ with a short circuit. What do you expect to see at the capacitor? At the output (1 pt)? Document your conclusions with a SCREENSHOT (1 pt).

36 points total

3 points extra credit