PHYS20181E Amplifiers and Feedback

A 3-day laboratory course

Contents

Sections in bold are experimental and are described in this script as well as being covered in the lectures. Others are covered in the lectures and provide the theory for the experimental sections.

Prerequisites for This Course

PHYS10182C (1st year Circuits), PHYS10180E (1st year Digital Electronics) and PHYS10302 (Vibrations and Waves) are prerequisite.
Please bring notes from these courses if possible.

Aims

To understand how analogue signals may be amplified, manipulated and generated in a controlled manner, and how they may be interfaced to digital systems for subsequent processing.

Objectives

- To understand the behaviour of an ideal amplifier under negative and positive feedback.
- To be able to apply this to simple amplifiers, summers, integrators and phase shifters.
- To understand the limitations of a real amplifier in terms of its gain bandwidth, and impedance.
- To understand basic methods of analogue-to-digital conversion (ADC).
- **To be able to use lecture notes and handouts in combination with an experimental script**.

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0 Preamble

0.1 Preamble

This script covers only the parts of the course that are in bold in the contents on page 1. The remaining, theory, sections will have been covered in the lectures. Sections marked with an asterisk are optional.

Please write up your lab notebook as you go along. It is the basis of the assessment of your work. Assessment will take place during a short interview in which you should be able to reconstruct exactly what you did using your notebook—including problems, circuits that didn't work (and what you did about it), and the principles on which circuits did work.

0.2 Practical Details: Read This First!

The 741 is provided for you on a chip, and its pin connections are shown in Figure 1. One end of the chip has a notch, a dot, or both, depending on the manufacturer. If the chip is placed with the notch at the top, pin 1 is in the upper-left corner; if a dot is present, it identifies the position of pin 1. Pins are numbered anti-clockwise, starting from pin 1.

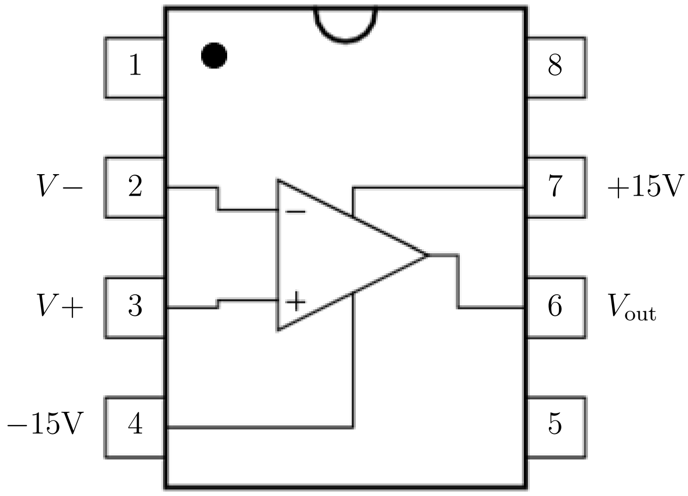

Figure 1. Pin connections of the 741 chip.

You should also have a board into which to plug your components. The connectors on the board are arranged as follows:

- **Any horizontal group of five holes is electrically connected.**
- **In a vertical line of holes *outside the groups of five*, the whole line is connected.**
- **If in doubt consult your demonstrator.**

The board also provides +5 V, ±15 V, and two 0 V lines (which must be connected together when both supplies are in use). **Note that whenever you are wiring up a circuit you need a 0 V common ground line.** All other components that you use—oscilloscopes, etc.—also need to be connected to this ground line (using the black cables).

In every circuit you build **you need the +15 V and −15 V power supplies connected to the chip (pins 7 and 4). You also need connections to the two inputs, V+ and V−, for the chip to operate.** Please always check that you have done this if a circuit does not initially work.

Leave pins 1, 5 and 8 unconnected.

0.3 Management (Safe and Good Experiment)

In electronic circuits many components are vulnerable. With a few good tips, you can perform your experiments both successfully and safely.

The chip is more delicate than the digital chips you used last year. A guaranteed way to break the chip is to draw large currents out of the output (pin 6) by connecting something of low resistance (e.g. a wire) between it and any DC voltage (0 V, +15 V or whatever). The low-current requirement in combination with Ohm's law requires that **anything connected to the output should have a reasonable resistance**. This means a resistor of some kind, a component with a high resistance such as a logic gate, or your oscilloscope that typically has a resistance of a few MΩ.

How to test a chip A tester is available. The two lights will alternate on and off if the chip is working.

Never connect the oscillator output to any power line, for example the ±15 V and +5 V lines: this can damage the output circuitry of the oscillator. If in doubt, contact your demonstrator.

Exercise with demonstrator Your demonstrator will build a non-inverting amplifier. Discuss and note the following:

1. How to avoid damaging circuit components (chip, oscillator, and oscilloscopes etc.).
2. How to build a safe circuit design.
3. What to check if it fails to work.

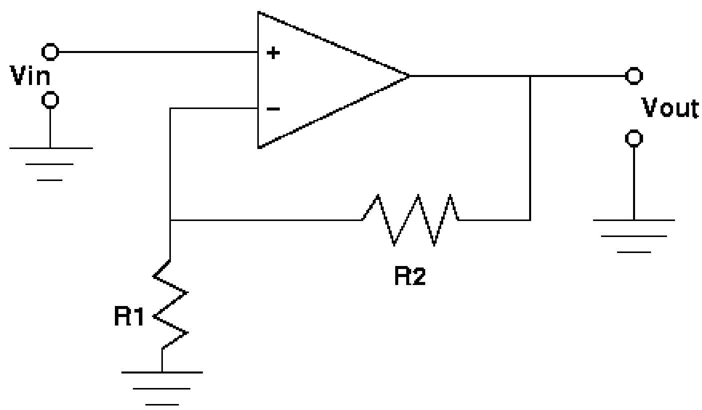

Figure 2. Non-inverting amplifier.

2 Amplifiers

2.3 Two Further Circuits: Inverting Amplifier and Summer

Build the inverting amplifier and summer circuits as shown in Figure 3 and Figure 4.

2.3.1 Experiment: Inverting Amplifier

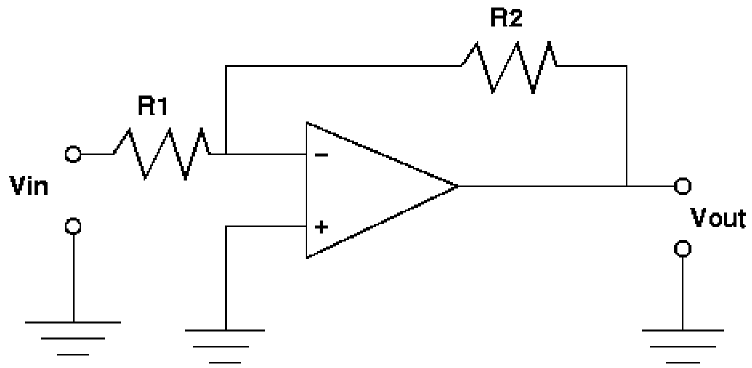

Figure 3. Inverting amplifier.

2.3.2 Experiment: Summer

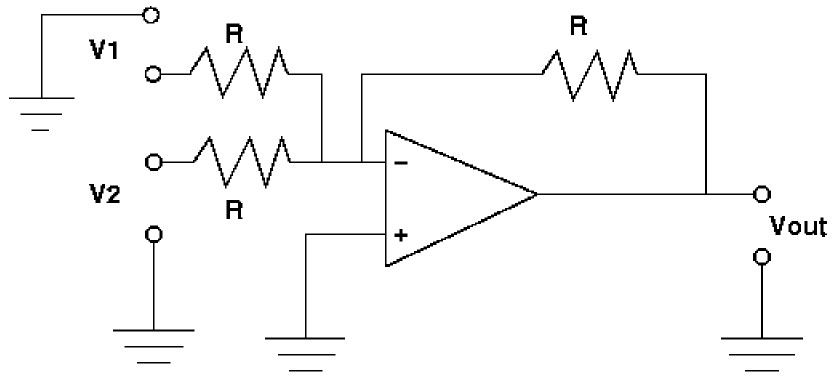

Figure 4. Summer.

Measure V_{out} at low frequency (say 100 Hz) in both cases using two different pairs of resistors. Verify that your theoretical expectations are correct. Use a second waveform generator and the oscillator to drive the two inputs of the summer.

Check 1 Investigate the $V-$ terminal of the chip to check that you really do have a virtual earth at this point.

Check 2 For the inverting amplifier, check gains ($V_{\mathrm{out}}/V_{\mathrm{in}}$) at high frequency (say 100 kHz) to see if the gain or signal is changed.

2.4 Experiment: Integrator

Design a circuit for which the output signal is the integral of the input signal.

Hint 1 Remember the simple RC integrating circuit from section 1.7 in the small-signal approximation.

Hint 2 You will need a virtual earth somewhere to remove the need for the small-signal approximation.

When you are content with the basic design, check with a demonstrator, and then construct the circuit.

Check Look at the output signal using at least two different input waves.

2.5 Experiment: Phase Shifter

The circuit in Figure 5 introduces a phase shift, θ, between V_{in} and V_{out}. Calculate θ in terms of the circuit components, and determine the values that will provide $\theta \sim 60^\circ$ at 1 kHz. Build and test the circuit.

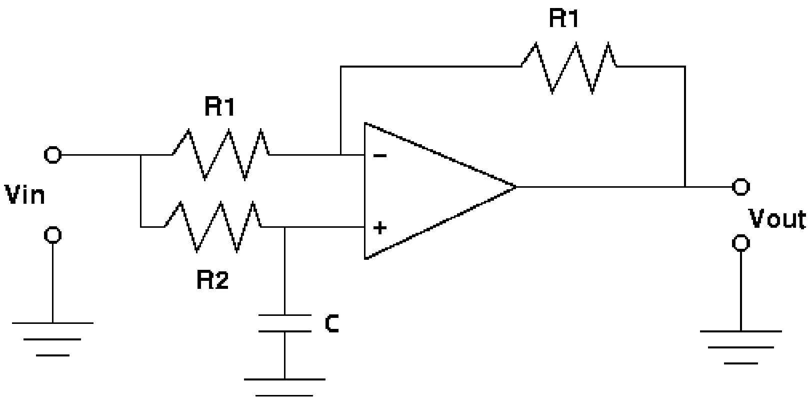

Figure 5. Phase shifter.

Hints First evaluate the voltage at the non-inverting input (you will need complex RC circuit analysis). Then use this in a potential divider along the line between V_{in} and V_{out}, to get $V+$ and $V-$. Then use one of the golden rules for ideal amplifiers to get the phase.

2.6 Bonus* Experiment: In the Real World: Gain Limitation

In the real world, there are several problems with the simplest theory:

- The gain is not infinite. This limitation becomes important at high frequencies where the gain decreases rapidly.
- The output cannot change instantaneously.
- The input impedance is not infinite, so a small amount of current does enter the inputs.
- The output impedance is not zero. This will be discussed further later.

Use the inverting amplifier circuit, with $R_1 = 1\,\mathrm{k\Omega}$, and two values of R_2, $100\,\mathrm{k\Omega}$ and $10\,\mathrm{k\Omega}$.

Check 1 Check the output response time at high frequency using a square wave input and determine the maximum slope (in V/s) that the output can provide.

Check 2 For two different gain settings, plot a graph of gain ($V_{\mathrm{out}}/V_{\mathrm{in}}$) against frequency from about 100 Hz–1 MHz. Use log-log graph paper or computer graphic package.

Check 3 Find the $-3\,\mathrm{dB}$ points. Is your bandwidth larger with lower gain?

Check 4 Check whether there are any phase shifts at very low or very high frequencies.

Hint You may need a very small voltage at the input in order not to saturate or exceed the maximum slope at the output.

2.7 Bonus* Experiment: Output Impedance

Another possible departure from ideal operation arises from the *output impedance*. To explore this you can treat the amplifier as a "black box" which delivers a certain voltage at its terminals and which then has a certain amount of internal impedance R at its output terminal. This means that when you connect a load resistor r across it, the voltage will fall by a factor $r/(R + r)$ (see Figure 6).

Check 1 Measure the output impedance of the non-inverting amplifier using small resistor r at high frequency. Why do we need to go to the high frequency region?

Check 2 Can you detect the output impedance using a $10\,\mathrm{k\Omega}$ resistor? If not, why?

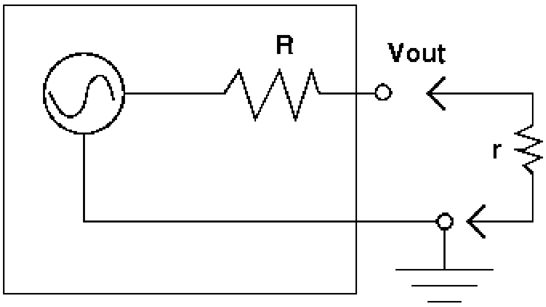

Figure 6

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3 Positive Feedback and Oscillators

3.2 Experiment: Schmitt Trigger

Build the Schmitt trigger shown in Figure 7 using $R_1 = 4.7\,\mathrm{k\Omega}$ and $R_2 = 47\,\mathrm{k\Omega}$.

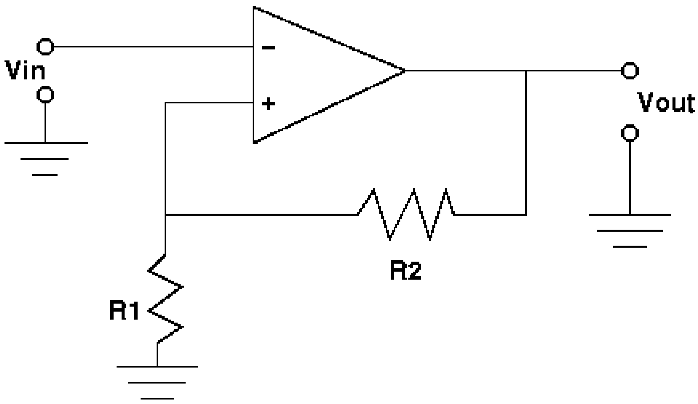

Figure 7. Schmitt trigger.

Check Verify the behaviour of the Schmitt trigger with a sine or triangular wave of amplitude 5 V and frequency $\sim$ 100 Hz at the input. The point on the input at which the output switches from +15 V to −15 V is not the same as that at which the output switches the other way: why?

3.3 Experiment: Astable Multivibrator

Remove the input in the Schmitt trigger and connect a third resistor and capacitor as shown in Figure 8. The circuit is called an *astable multivibrator*.

Check What kind of output wave do you get, and at what frequency? Check with your prediction.

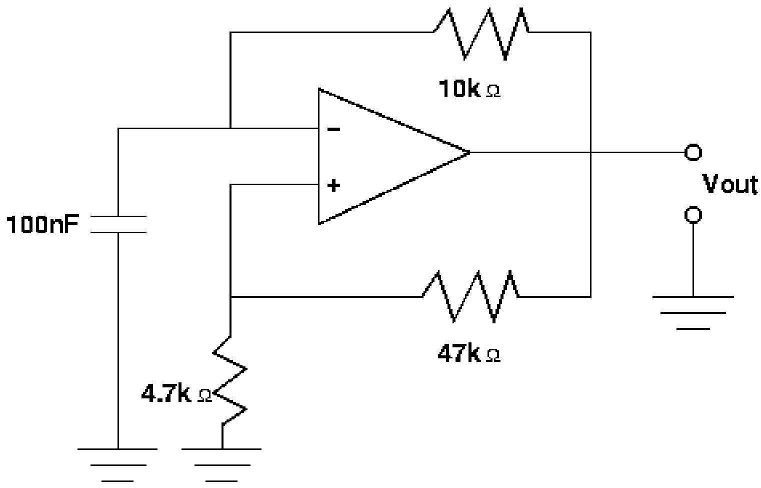

Figure 8. Astable multivibrator.

Hint Suppose V_{out} starts at $+15\,\text{V}$; what happens in the $10\,\text{k}\Omega$ resistor and the capacitor? Will this go on happening indefinitely?

3.4 Bonus* Experiment: Wien Bridge Oscillator

Complete the theory for the Wien bridge oscillator discussed in the lecture; build the circuit.

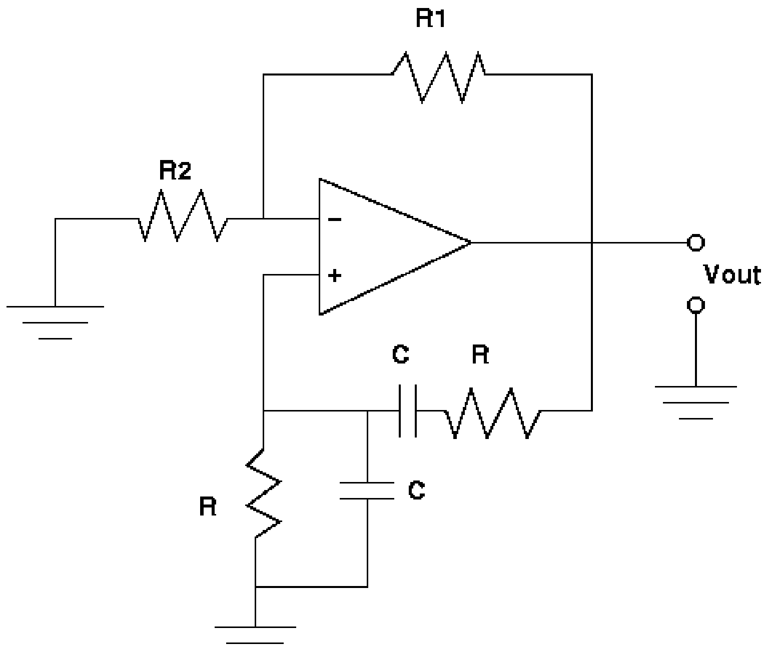

Figure 9. Wien bridge oscillator.

Use a light bulb for R_2 (think why this stabilizes V_{out}, given that the resistance of the bulb increases with current), $68\,\Omega$ for R_1, $10\,\text{nF}$ for both capacitors and $10\,\text{k}\Omega$

for the two other resistors.

Check 1 Check whether $V+$ is same as $V-$.

Check 2 Measure the frequency at V_{out} terminal, and then check whether it agrees with your calculation.

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4 Analogue-to-Digital (ADC) Conversion

Analogue circuits often provide the first stage of a system that ultimately involves digital signal processing. Typically a signal is detected, amplified and then routed to an analogue-to-digital converter (ADC) for computer processing. A simple converter is illustrated in the next experiment.

4.3 Experiment: Flash ADC

Throughout this section you should use an LM311 chip instead of the 741 chip that you have been using so far. Its pin connections are shown in Figure 10.

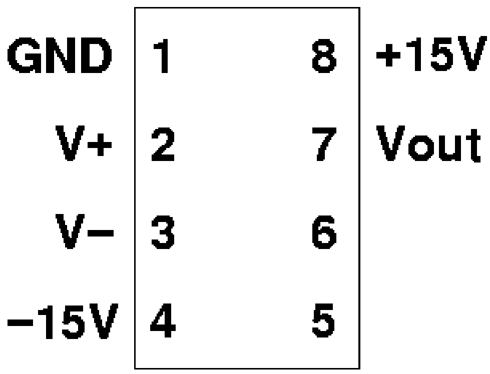

Figure 10. Pin connections of the LM311 chip.

The LM311 has an "open collector" output in which a transistor acts as a switch connected to pins 1 and 7. When the switch is closed, pin 7 (V_{out}) is connected to pin 1 (ground). When the switch is open, V_{out} is disconnected and has virtually no effect on the circuit. The "pull-up" resistor shown in Figure 11 takes over, pulling the output up to the +5 V level. The LM311s can then drive TTL logic gates and other devices used in typical digital electronic applications (without complicated circuits to convert their output voltages).

4.3.1 Comparator

Design a comparator as shown in Figure 11. Use a 100 Ω pull-up resistor and connect a light bulb to the output, then change the resistor to 1 kΩ and the bulb to an LED.

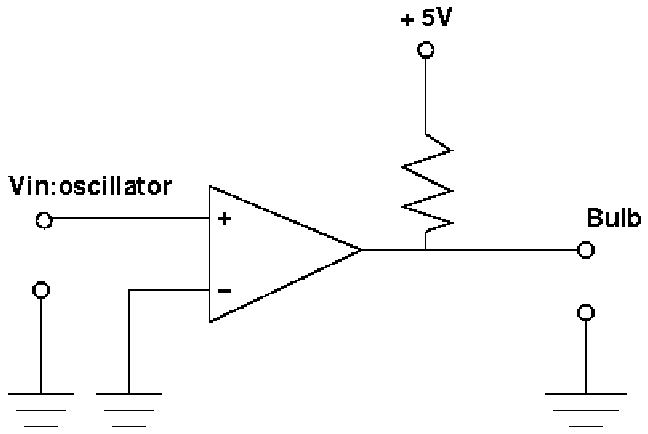

Figure 11. Comparator circuit diagram.

Check Confirm that your comparator works using a low frequency input triangular or sine wave.

4.3.2 2-Bit ADC

Once you verify your 1-bit converter works, design a flash ADC (2 bits) which will light two LEDs A, B as follows:

- Both off, if $V_{\text{in}} < 1\,\text{V}$
- A off and B on, if $1\,\text{V} < V_{\text{in}} < 2\,\text{V}$
- A on and B off, if $2\,\text{V} < V_{\text{in}} < 3\,\text{V}$
- Both on, if $V_{\text{in}} > 3\,\text{V}$

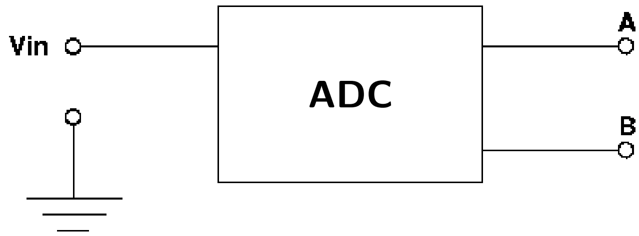

Figure 12. ADC block diagram.

To build this circuit, you need to set up three comparators and then combine the output signals using logic gates, to produce outputs A and B. See the procedure below:

Step 1 You need to build three comparators with different comparison voltages.

Step 2 Think how you are going to provide the different comparison voltages you need using a +5 V input voltage. You will need voltage dividers to get the correct comparison voltages.

Step 3 Work out how the output signals from the comparators are going to be linked to LEDs A and B. You will need at least two logic gates.

Check Test it with a very low frequency triangular or sine wave of a suitable amplitude, so that you can see the lights flashing in the expected order. You can also confirm your outputs using the oscilloscope. Once it works, get confirmation from your demonstrator.

Created by Dr Neal Jackson in the mid-1990s.

Converted from TeX to MS Word by Dr Un-ki Yang.

Revised by Dr Paul Campbell, 2010: R_1 of Wien bridge oscillator reduced to suit the type of bulb available in the lab.

Revised by Dr Paul Campbell, 2011: Waveform generator button description removed, as it doesn't apply to built-in waveform generator of Agilent/Keysight oscilloscope. Amplitude reduced from > 5 V to 5 V, to suit max. output of generator. "50 Hz" removed from 2nd gen. description, as apparatus changed from fixed- to variable-freq. gen. Flash ADC now includes LEDs.

Revised by Dr Cinzia Da Vià, *circa* 2014: TTL chips no longer described as being used in Digital Electronics course.

Converted from Word to LaTeX, and corrected, by Peter Cunane in Dec. 2017.