Experiment 392: Active Pulse Circuits

Aim

The aim of this experiment is to show how linear and non-linear active circuits may be used to process and generate waveforms.

Introduction

In general terms, “active” circuits are those which require a source of electrical power in order to perform their specified functions. Active circuits can be further classified into linear and non-linear configurations, where the term “linear” signifies that the output is linearly dependent upon the excitation. This experiment illustrates how high-gain amplifier circuits may be used in conjunction with passive components to implement both these circuit types.

This experiment is set out in sections, each of which is divided into one or more subsections. In each subsection involving experimental work, students should familiarise themselves with the theory presented before proceeding with the experimental work.

Experimental Set-up

The components required are mounted on a breadboard and the various circuits are implemented by connecting wire links between appropriate components. **Please do not remove, or move,** any of the components on the breadboard.

The power supply should be switched off each time circuit changes are made. In some circuits, power supply rails are omitted for clarity. The signal from the function generator should be connected or disconnected only while power is applied to the integrated circuits.

In order to plot your data points it will be necessary to use the Cleverscope digital oscilloscope installed on the computers in the laboratory. This oscilloscope is the small white box underneath the bench with the two leads attached to the front. To use this go to the start menu and open the Cleverscope application from the physics folder. This works in a similar manner to a normal oscilloscope and many of the buttons and functions should already be familiar, even if the layout is not. It is possible to change the scale on the scope graph by clicking on the square wave buttons — the larger one to increase the scale and the smaller one to decrease it. The arrows may be used to move the axes in relation to each other. A graph with an XY view can be opened by going `View > Display XY Graph`. It may be necessary to spend a few minutes familiarising yourself with its operation before you begin. A manual is available in the lab.

Suitable settings for this experiment are for the coupling to be set to **AC** and the acquire mode set to Triggered. Set the level of Trigger 1 to 0 V. In order to obtain a clean waveform on the screen it may be necessary to turn on the averaging function of the scope which is found at the bottom of the control panel or to reduce the analysis bandwidth by setting **BW** to 25.

To save your data go to `file > Save Graph as Text`. This `.txt` file contains three columns of data representing the time axis and the two oscilloscope traces, which can then be imported directly into PYTHON and plotted from there.

The Comparator

Comparator Characteristics

The fundamental non-linear circuit to be considered in this experiment is the comparator. It is a device having two inputs, labelled + and −, and an output which is in one of two states depending on whether V_+ is greater or less than V_-. Fig. 1 summarises the essential characteristics of an ideal comparator.

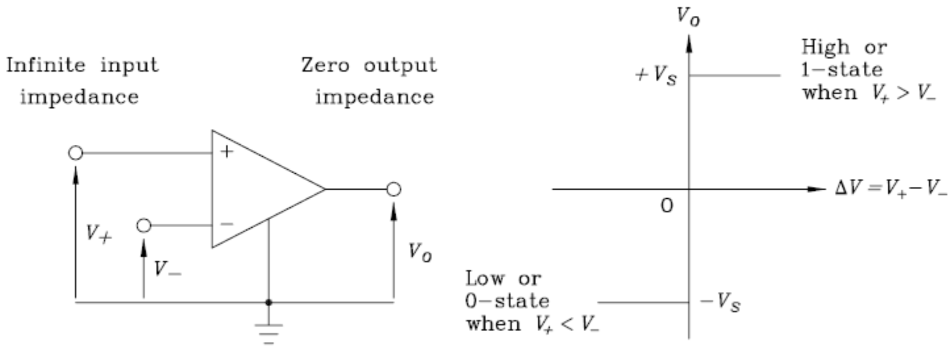

Figure 1: Ideal comparator

A high-gain difference amplifier can be used as a comparator under suitable conditions. The transfer function is:

$$V_\mathrm{o} = A_d\,\Delta V = A_d\,(V_+ - V_-)$$

where A_d is the differential-mode gain and ΔV is the differential input voltage. These characteristics are shown dotted in Fig. 2. In practice, since the output voltage is constrained to lie between the supply rails, the actual characteristics are as shown by the solid line in Fig. 2.

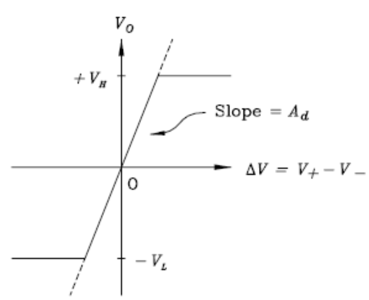

Figure 2: Difference amplifier characteristics

Usually, $+V_H$ and $-V_L$ are approximately equal to the supply rail voltages. These characteristics approach those of an ideal comparator if:

(i) $V_\mathrm{H} = V_\mathrm{L} = V_\mathrm{supply}$

(ii) $A_d \to \infty$

(iii) input impedance $\to \infty$

(iv) output impedance $\to 0$

Devices with characteristics which satisfy nearly all of these conditions are commercially available as operational amplifiers. Devices specially optimised to operate as comparators are also available. The latter often have output voltage levels compatible with those of logic circuits or have uncommitted open-collector outputs which require external pull-up resistors to provide a voltage output.

In practice, high-gain amplifiers also exhibit various forms of non-ideal behaviour. It is found that V_o is non-zero even when $V_+ = V_-$ so that a better approximation to the transfer function is:

$$V_{\mathrm{o}} = A_d\,(V_+ - V_- + V_{\mathrm{io}})$$

where V_{io} is called the (input) **offset voltage**. Furthermore, the output voltage of an amplifier cannot change immediately in response to the input. The maximum rate at which the output voltage can change is called the (maximum) **slew-rate** of the device. The effect of slew-rate limiting is to introduce a delay between the time the comparator output should change state and the time that the input voltage passes through zero volts (see Fig. 3). The slew-rate is primarily determined by the speed at which compensation and stray capacitances can be charged and discharged. These capacitances also cause a phase shift between the input and the output for small signals — this effect is important when the amplifier is used in linear applications or when the input signal is sufficiently small that the difference amplifier spends a considerable time in the linear region of its characteristics.

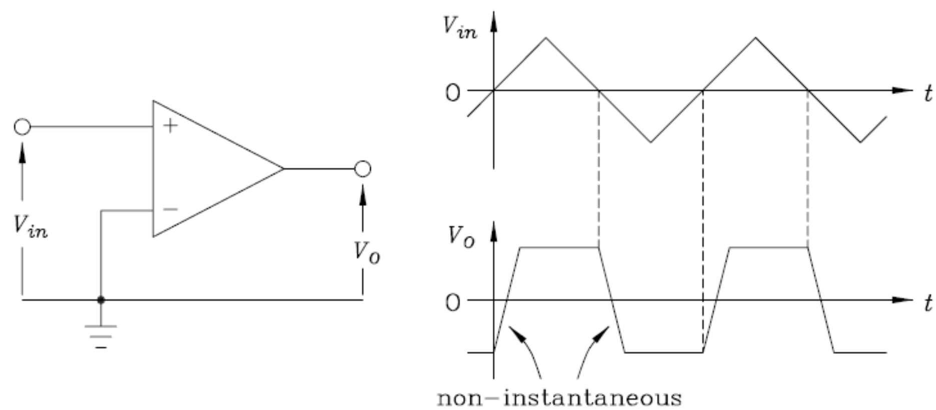

Figure 3: Effect of slew-rate limitation.

Two commercial high-gain difference amplifiers will be examined in terms of their use as voltage comparators. They are:

(i) LM741 which is an internally compensated general purpose operational amplifier, and

(ii) LM339 which contains four voltage comparators with open-collector outputs.

Data sheets for these devices are provided with the experiment and students should refer to them in the course of the experiment.

(1) Using the circuit of Fig. 4, plot V_{o}-vs-V_{in} for the LM741 using the oscilloscope in the XY mode with DC-coupled inputs. A suitable input signal is a 20 V p-p triangle waveform at 50 Hz.

(2) Observe V_{o} and V_{in} in time sychronization as the frequency of the input triangular waveform is gradually increased (see Fig. 3). Measure the maximum slew-rate of the device.

(3) Repeat procedures (1) and (2) for one of the comparators of the LM339. The LM339 comparator requires a pull-up resistor for its operation. Use the circuit of Fig. 5 for the LM339.

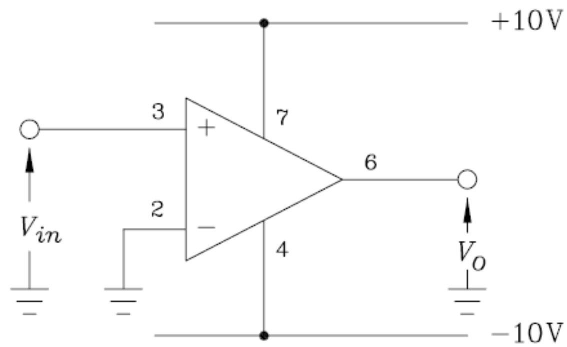

Figure 4: Set-up for LM741.

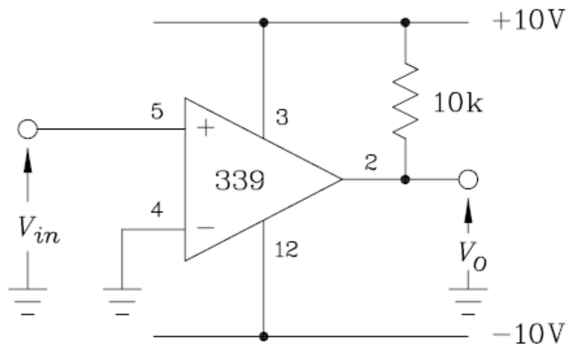

Figure 5: Set-up for LM339.

Comparator-based circuits

In all the circuits in this section, the ideal comparator model can be used to explain their operation.

The Window Comparator

The outputs of two comparators may be wired together so that the common output is in the LOW ($V_o = -V_s$) state when one or both of the comparators is in the LOW state. The circuit of Fig. 6(a) may then be used to give an indication of when an input voltage lies between two preset levels [see Fig. 6(b)]. Such an arrangement is called a window comparator.

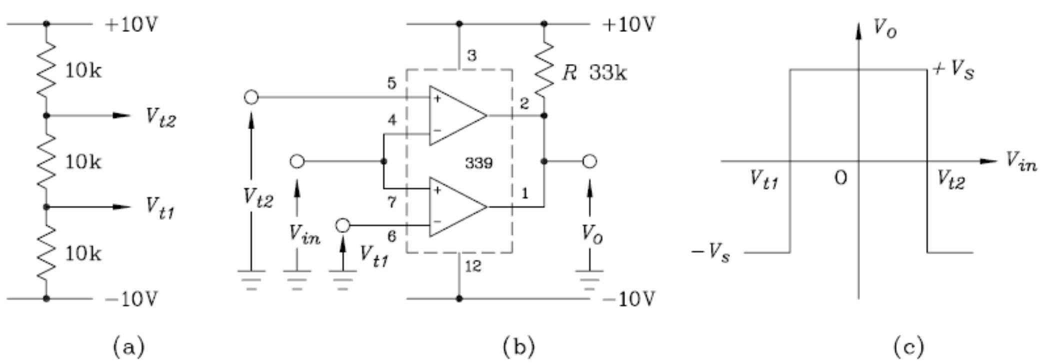

Figure 6: Window comparator

(4) Set up the circuit of Fig. 6(b) using the LM339 with $R = 33$ kΩ, $V_{t1} = -3.33$ V and $V_{t2} = +3.33$ V. Derive V_{t1} and V_{t2} from a simple potential divider using three 10 kΩ resistors across the +10 V and -10 V power supply rails (see Fig. 6(a)). Plot V_{o}-vs-V_{in} using the oscilloscope in the XY mode with a 20 V p-p triangular input waveform of sufficiently low frequency to avoid non-ideal behaviour.

(5) Repeat procedure (4) with $V_{t1} = 0$ V and $V_{t2} = +3.33$ V.

The Current-Mode Comparator

By combining a potential divider and a simple comparator (see Fig. 7) voltages of opposite polarity may be compared. This circuit, which is known as a current-mode comparator, suffers from the disadvantage that the current flowing through the inputs is non-zero so that the voltages must be supplied by low-impedance sources.

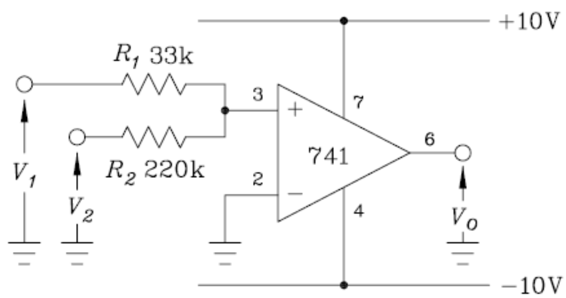

Figure 7: Window comparator

Exercise

Show that:

$$V_{\text{o}} = -V_{\text{s}} \qquad \text{when} \qquad V_1 < -\frac{R_1}{R_2} V_2$$

$$V_{\text{o}} = +V_{\text{s}} \qquad \text{when} \qquad V_1 > -\frac{R_1}{R_2} V_2$$

(6) Implement the circuit of Fig. 7 with the LM741. Use $V_2 = +10$ V, $R_1 = 33$ kΩ and $R_2 = 200$ kΩ. Plot V_{o}-vs-V_{in} using the oscilloscope in XY mode with a 20 V p-p triangular input waveform of sufficient low frequency to avoid non-ideal behaviour. Compare the theoretical and experimental values of the threshold voltages at which the output changes state.

The Schmitt Trigger

This is a circuit which uses regenerative (positive) feedback. It is useful for converting slowly varying waveforms into rectangular pulses (e.g. for triggering digital logic from an analogue input) where the simple comparator is inadequate as the presence of noise on the inputs causes multiple output transitions.

Fig. 8 shows a general Schmitt trigger. Note that feedback through R_2 and R_1 is applied to the + or non-inverting input to give the necessary regenerative feedback. If the amplifier inputs are reversed, a linear circuit with gain equal $-R_2/R_1$ is the result.

If we consider V_1 to be a fixed voltage and plot V_{o} against V_2, we see that the output will change from a HIGH ($V_{\text{o}} = +V_{\text{s}}$) state to a LOW ($V_{\text{o}} = -V_{\text{s}}$) state when V_2 is increased beyond a HIGH threshold voltage V_{tH}. The output will change from a LOW state to a HIGH state when V_2 decreases below a LOW threshold voltage V_{tL}.

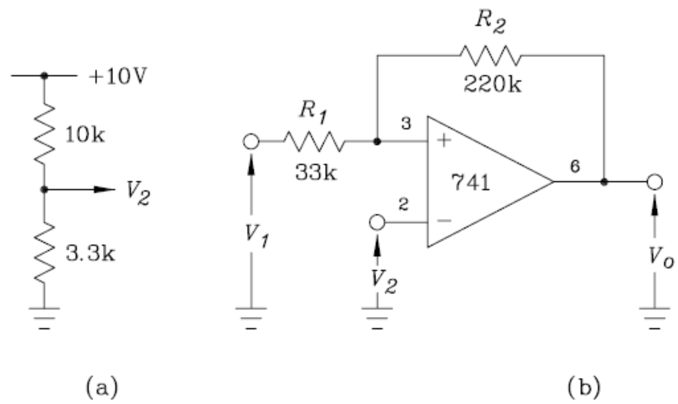

Figure 8: Basic Schmitt trigger

Exercise

Show that:

$$V_{tH} = \frac{R_2 V_1 + R_1 V_s}{R_1 + R_2} \qquad \text{and} \qquad V_{tL} = \frac{R_2 V_1 - R_1 V_s}{R_1 + R_2}$$

and verify that the characteristics are consistent with those of Fig. 9(a). Show also that if V_2 is held constant and V_o is plotted against V_1 the characteristics of Fig. 9(b) are obtained. Determine V'_{tH} and V'_{tL} in terms of R_1, R_2, V_2 and V_s. Verify further that the difference between the threshold voltages is $(2R_1/R_2)V_s$.

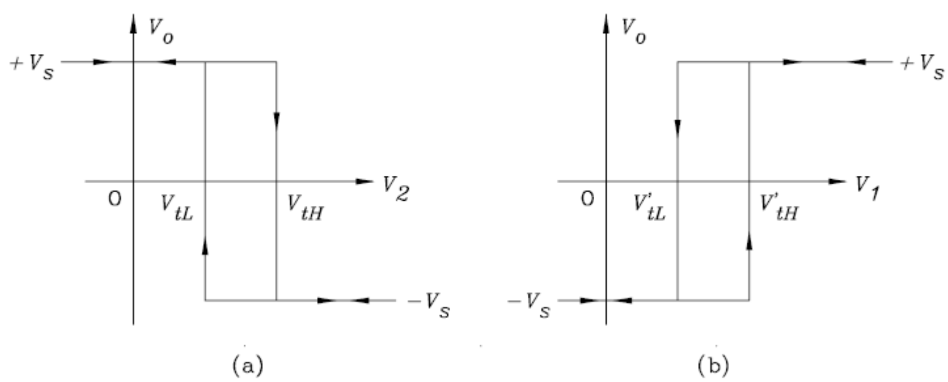

Figure 9: Schmitt trigger characteristics

(7) Use the LM741 to implement the circuit of Fig. 8(b) with $R_1 = 33$ kΩ and $R_2 = 200$ kΩ. Let V_1 be fixed at 0 V and plot V_o-vs-V_2 using the oscilloscope in the XY mode (DC-coupled) with a 20 V p-p triangular waveform of sufficiently low frequency as the input. Verify that the threshold voltages are as expected. It is also instructive to observe the transfer characteristics being plotted out with a very low input frequency (e.g. 0.2 Hz).

(8) Using the same configuration as in procedure (7), supply V_2 with +2.48 V from a potential divider using a 10 kΩ and a 3.3 kΩ resistor across the +10 V and ground power supply rails (see Fig. 8(a)). Measure the actual voltage V_2. Plot V_o-vs-V_1 as above and compare the results with those expected.

Linear use of Operational Amplifiers

In general, an operational amplifier is in the linear region when its output voltage lies strictly between $+V_s$ and $-V_s$ rather than being clamped at one or other of these levels. Analyses of these circuits can be performed by applying the following rules:

(a) Negligible current flows into the amplifier inputs since the input impedance is very high.

(b) The differential voltage $(V_+ - V_-)$ is essentially zero for linear operation since the gain is very high.

The Integrator

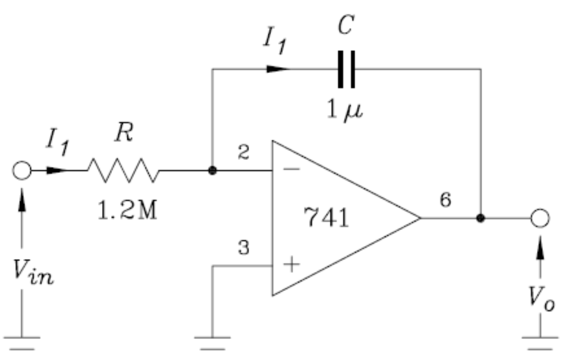

Figure 10: Integrator circuit.

The circuit of the integrator is shown in Fig. 10. The potential at the inverting input is approximately 0 V since the non-inverting input is connected to ground. Remembering that negligible current flows into the amplifier:

$$\frac{V_{\text{in}}}{R} = I_1 = -C\frac{dV_{\text{o}}}{dt}$$

Therefore

$$V_{\text{o}} = -\frac{1}{RC}\int_0^t V_{\text{in}}\,dt + V_c$$

where V_c is the initial voltage on the capacitor at time $t = 0$. Hence the output voltage is equal to $-(1/RC)$ times the integral of the input voltage. In particular, the output is a triangular waveform if the input is a rectangular waveform.

Drift in the integrator can be caused by a non-zero offset voltage. This has the effect of introducing to the integrator input a constant voltage which adds to the applied voltage V_{in}. When integrated, this gives rise to a drifting mean DC level which ultimately drives the amplifier out of the linear region. This problem can be avoided by using the circuit of Fig. 11(a).

The transient response of this circuit is mainly determined by R_1 and C since the capacitive reactance to high frequency components is much less than the value of R_2. Hence, for small values of t, the circuit behaves like a true integrator.

The output V_{o} will be given by:

$$V_{\text{o}} \approx -\frac{1}{R_1 C}\int_0^t V_{\text{in}}\,dt$$

In the steady state, no current flows through C as all the input current I_1 flows through R_2. Hence:

$$V_{\text{o}} \approx -\frac{R_2}{R_1}V_p$$

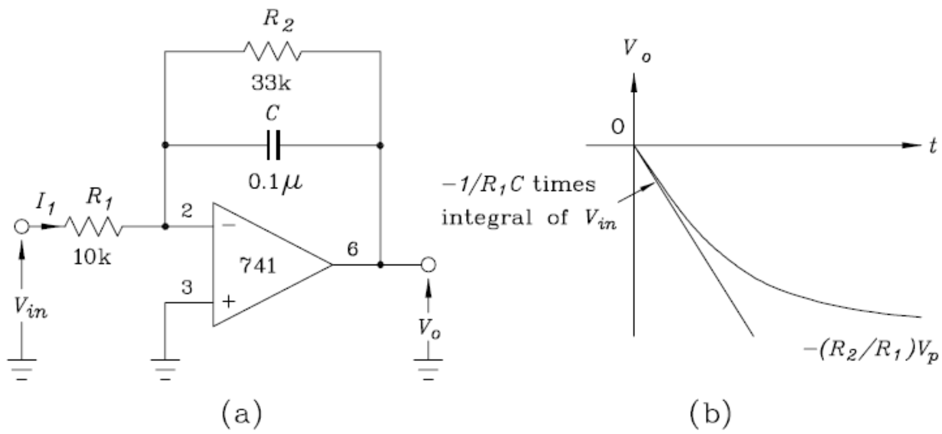

Figure 11: Quasi-integrator.

The response to a step input $V_p\,u\,(t)$ is hence shown in Fig. 11(b). A more rigorous treatment involving Laplace transforms shows that, for a step input, the output voltage is given by:

$$V_o = -\frac{R_2}{R_1}V_p\left[1-\exp\left(\frac{-t}{R_2C}\right)\right]\,u\,(t)$$

The linear term of the Taylor series expansion of the above expression is indeed $-\left(1/R_1C\right)V_p\,t$ and the value of the expression tends to $-\left(R_2/R_1\right)V_p$ as $t\to\infty$.

If the input frequency is sufficiently high, the output will be very similar to that of the ideal integrator. The offset voltage, which is a steady-state phenomenon only, causes the output DC level to be slightly different from zero and no longer introduces a drift as before.

(9) Set up the integrator of Fig. 10 using the LM741 with $R = 1.2$ MΩ and $C = 1$ μF. Connect V_{in} to zero volts and monitor V_o on the oscilloscope with a vertical sensitivity of 1 V/div. Momentarily short-circuit C to reduce the output voltage to zero, and observe the voltage drift when the shot-circuit is removed.

(10) With the circuit of procedure (9), set the oscilloscope sensitivity to 5 V/div and short circuit the capacitor momentarily to return the output to zero volts. Connect V_{in} to +10 V and observe the result.

(11) Repeat procedure (10) with V_{in} connected to −10 V.

(12) Set up the quasi-integrator of Fig 11(a) using the LM741 with $R_1 = 10$ kΩ, $R_2 = 33$ kΩ and $C = 0.1$ μF. Observe V_{in} and V_{out} in time synchronization with a 100 Hz square-wave input. Ensure that the input amplitude is such that the amplifier remains in the linear mode at all times. Comment on the results and verify that the measured slopes and levels are as expected.

The Differentiator

The circuit of Fig 12 illustrates the differentiator. Again, since the potential at the inverting input is approximately zero volts, we get:

$$V_o = -I_1R = -R\,C\frac{dV_{in}}{dt}$$

The output for a triangular input waveform is a square wave. The circuit is prone to high frequency instability and noise due to its high gain at high frequencies and is seldom used in practice.

(13) Set up the circuit of Fig. 12 using the LM741 with $R = 10$ kΩ and $C = 0.1$ μF. Apply a 100 Hz triangular input waveform. Monitor V_{in} and V_o in synchronization and verify that the slopes and levels of the observed waveforms conform to those expected. Notice the high-frequency instability as evidenced by ringing on the output waveform.

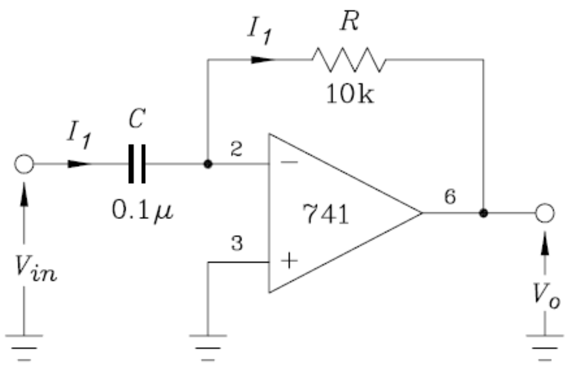

Figure 12: Differentiator circuit.

Waveform Generation

The circuits described in this section are sometimes called function generators and are commonly used for generating waveforms over a wide frequency range such as in the Wavetek generator provided. These circuits use difference amplifiers in both their linear and non-linear models.

Triangular and Rectangular Waveform Generator

The triangular and rectangular waveform generator consists of an integrator connected to a Schmitt trigger as shown in Fig. 13(b). Assume that the output of the Schmitt trigger is in the LOW state ($V_1 = -V_s$). Then V_2 will be linearly increasing with time until it reaches the higher threshold voltage V_{tH} of the Schmitt trigger. At this time the output of the Schmitt trigger switches to the HIGH state ($V_1 = +V_s$) which in turn causes V_2 to fall linearly until it reaches the lower threshold voltage V_{tL}. The Schmitt trigger then switches to the LOW state repeating the cycle. The voltage-vs-time curves for this circuit are shown in Fig. 14.

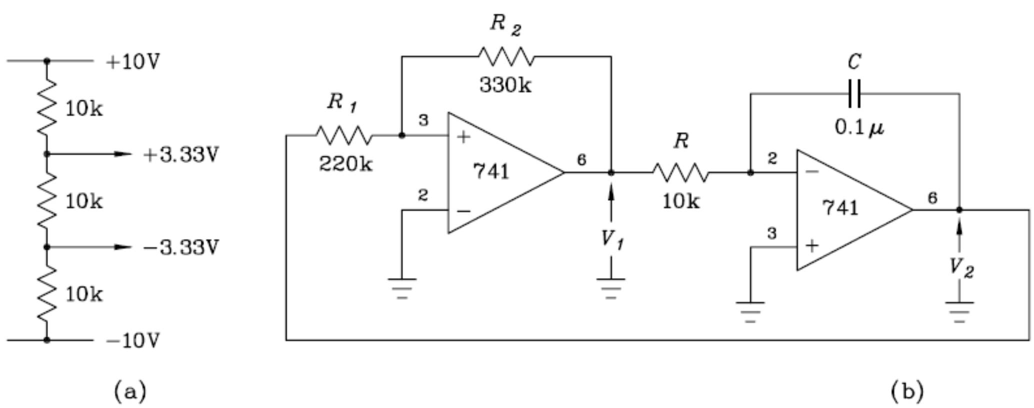

Figure 13: Triangular and rectangular waveform generator.

Exercise: Show that the frequency of oscillation is given by:

$$f = \frac{R_2}{4R_1RC}.$$

Explain the effect of integrator offset voltage on the output waveform. Note:

(i) The oscillation frequency is independent of $+V_s$.

(ii) The frequency can be changed without altering the output amplitudes by varying R.

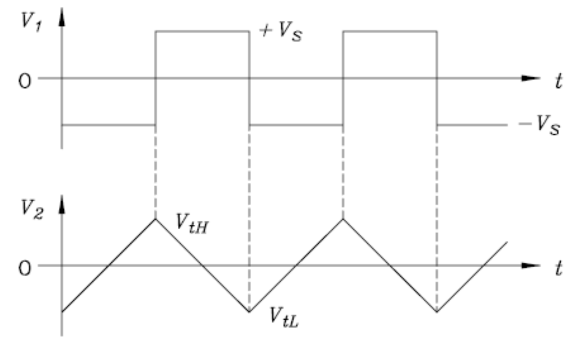

Figure 14: Output voltage waveforms.

(iii) The integrator gives a very linear rise and fall for the triangular output waveforms.

(iv) The triangular output waveform may be shaped by diodes to obtain a sine wave.

(14) Implement the circuit of Fig. 13(b) using LM741s for the integrator and the Schmitt trigger. Use $R = 10$ kΩ, $R_1 = 220$ kΩ, $R_2 = 330$ kΩ and $C = 0.1$ μF and observe V_1 and V_2 in time synchronisation. Compare the measured slopes, levels and periods with the calculated values.

(15) Replace R by a 33 kΩ resistor and verify that the output frequency changes and the amplitudes of both waveforms are unaltered.

(16) Connect the non-inverting input of the integrator to −3.33 V and then to +3.33 V derived from a potential divider using three 10 kΩ resistors across the +10 V and −10 V power supply rails (see Fig. 13(a)). Observe and explain the effect of altering the voltage at the non-inverting input on both the rectangular and triangular output waveforms.

The Multivibrator

The circuit in 15(a) is similar to that considered in the previous subsection except that an RC quasi-integrator is used instead of a true integrator. It is used when only a rectangular output waveform is required. The output and input waveforms of the Schmitt trigger are shown in Fig 15 (b).

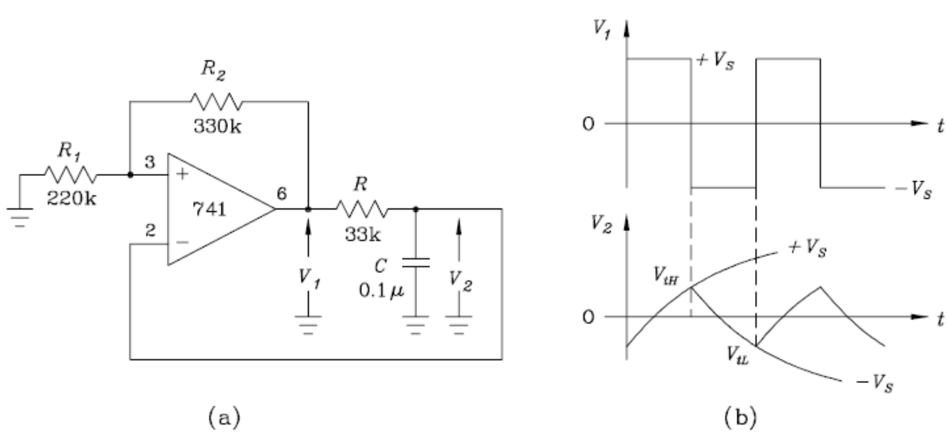

Figure 15: Multivibrator and waveforms.

Exercise: Show that the oscillation period is given by:

$$T = 2RC \ln\left(\frac{2R_1 + R_2}{R_2}\right).$$

(17) Set up the circuit of Fig 15(a) using the LM741. Let $R_1 = 220$ kΩ, $R_2 = 330$ kΩ, R=33 kΩ and $C = 0.1$ μF. Observe V_1 and V_2 in time synchronisation and compare waveform levels and period with those expected.

CMOS Gates as Comparators

CMOS Transfer Characteristics

Although CMOS gates are primarily designed for logic applications, the transfer characteristics of CMOS gates are such that they can be used as comparators. The output voltage swings between 0 V and $+V_{\rm DD}$ rather than between $-V_{\rm S}$ and $+V_{\rm s}$, but the response is otherwise similar to that of a comparator whose non-inverting input is held at a fixed threshold voltage V_t which is typically approximately $\frac{1}{2}V_{\rm DD}$.

The advantages of using CMOS logic gates as comparators include:

(i) Relatively large voltage swing for a given supply voltage as there is essentially no voltage drop across the conducting MOSFET.

(ii) Ease of interface with subsequent logic.

(iii) Reasonably high speed operation.

The disadvantages include:

(i) Threshold voltage V_t is not variable.

(ii) The gain of a single stage is not high.

In practice, CMOS gates are often used as comparators in the design of multivibrators.

(18) Wire up the CD4001 to a +5 V supply. Using the oscilloscope in the XY mode, plot $V_{\rm o}$-vs-$V_{\rm in}$ for one of the NOR gates with its inputs tied together. Ensure that the inputs to all the unused gates are earthed.

(19) Verify that the characteristic curve resembles that of the comparator. Determine its threshold voltage.

CMOS Monostable Multivibrator

This is a multivibrator with only one stable state. It produces an output pulse of fixed duration on application of a trigger pulse. It is often used for timing purposes and for stretching narrow pulses. The circuit for the monostable multivibrator is shown in Fig 16(a). Referring to the waveforms shown in Fig. 16(b), suppose $V_{\rm in}$ goes from LOW to HIGH due to a trigger pulse. This forces V_1 LOW, causing V_2 also to go LOW. There is negligible voltage drop across R_2 when V_2 lies between 0 V and $V_{\rm DD}$ as the input protection diodes of the NOR gate functioning as the comparator are not conducting and hence V_3 follows V_2 and V_4 goes HIGH. Tis in turn holds V_1 LOW even when $V_{\rm in}$ returns to the LOW level.

The capacitor charges through R_1 causing V_2 and hence V_3 to rise until they reach the threshold voltage of the comparator. When this occurs, V_4 goes LOW forcing V_1 HIGH and V_2 to $V_t + V_{\rm DD}$, the protection diodes of the comparator, however, ensure that V_3 does not rise above $V_{\rm DD}$. The circuit then returns to the standby mode once C has discharged through R_1 to give $V_2 = V_{\rm DD}$.

Exercise: Show that:

$$\tau = R_1 C \ln\left(\frac{V_{\rm DD}}{V_{\rm DD} - V_t}\right) \approx R_1 C \ln(2) \approx 0.69 R_1 C$$

as $V_t \approx V_{\rm DD}/2$.

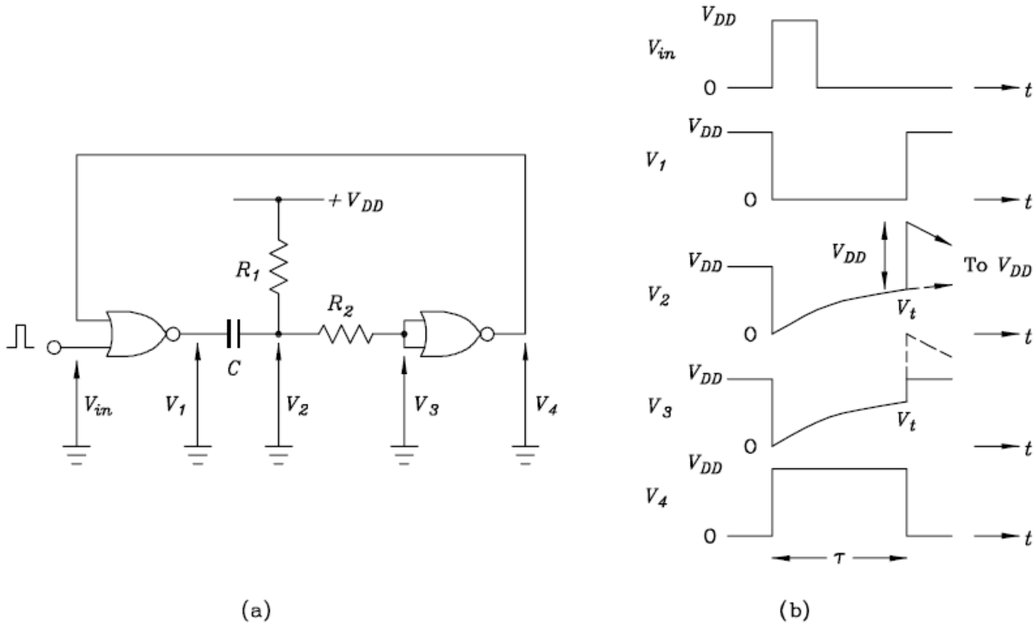

Figure 16: Monostable multivibrator and waveforms.

(20) Set up the circuit of Fig. 17 using two of the gates in the CD4001. The quasi-differentiator is used to provide trigger pulses for the monstable multivibrator circuit from the square wave output of the signal generator. The negative spikes occurring in synchronisation with the falling edge of the square wave are clipped by the internal protection diodes of the CMOS gate. The 10 kΩ series resistor limits current flow through these protection diodes to a safe value. The amplitude of the square wave should be sufficient to produce a positive going spike of amplitude ∼ 5 V.

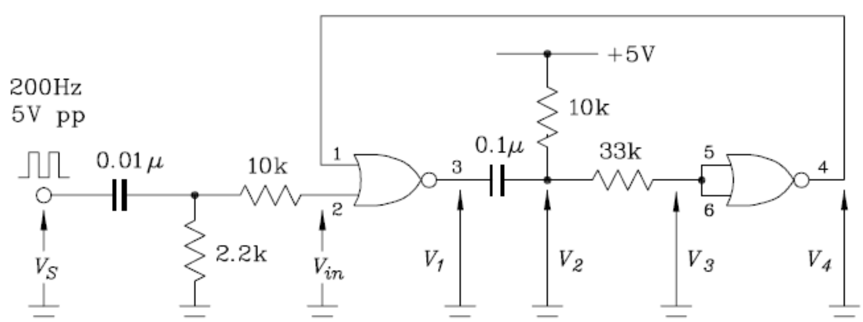

Figure 17: Experimental layout for the monostable multivibrator.

(21) Observe the waveforms at various points in the circuit to confirm that the graphs sketched in Fig. 16(b) represent the actual waveforms present.

(22) Measure the threshold voltage of the comparator from the V_3 voltage curve. Calculate τ from the expression above and compare this with the measured value.

CMOS Astable Multivibrator

This multivibrator (Fib. 18(a)) has no stable states but oscillates freely between two quasi-stable states. It operates in a similar manner to the monostable multivibrator of Fig. 16 (a).

Exercise: Show that:

$$\tau_1 = R_1 C \ln\left(\frac{V_{\rm DD} + V_t}{V_t}\right)$$
$$\tau_2 = R_1 C \ln\left(\frac{2V_{\rm DD} - V_t}{V_{\rm DD} - V_t}\right)$$

In practice, $V_t \approx V_{\rm DD}/2$. Then:

$$\tau_1 = \tau_2 \approx R_1 C \ln(3) \approx 1.1\, R_1 C.$$

The period of oscillation of the multivibrator will then be approximately $2.2\, R_1 C$. Note that the multivibrator will function if R_2 is absent, but values of τ_1 and τ_2 will differ from those given above. The resistor R_2 minimises the effects of variations in conduction characteristics of the protection diodes from one chip to another.

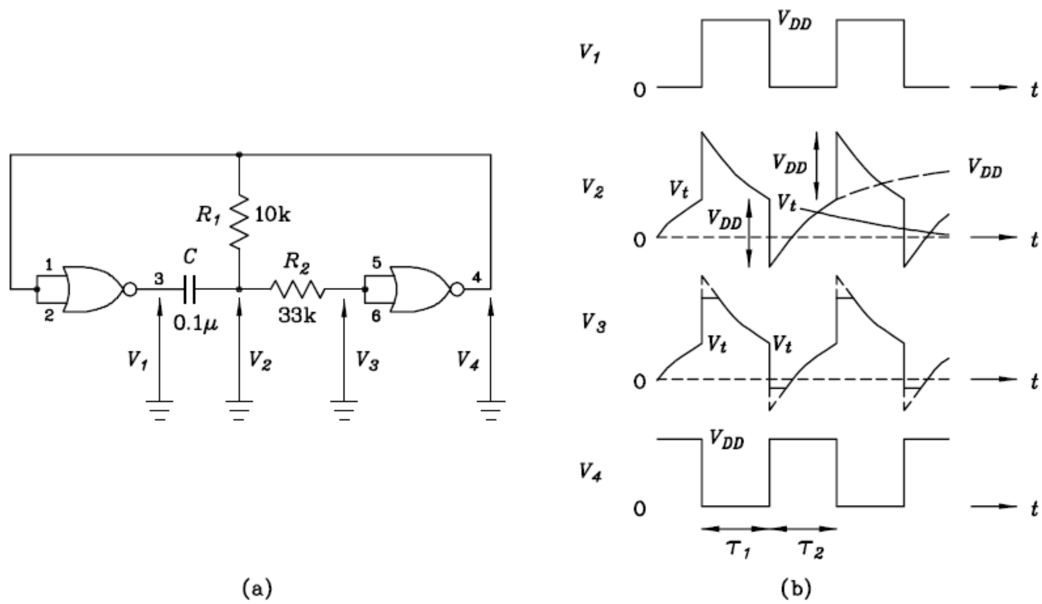

Figure 18: Astable multivibrator circuit and waveforms.

(23) Set up the circuit of Fig. 18(a) using two gates of the CD4001 with $R_1 = 10$ kΩ, $R_2 = 10$ kΩ and $C = 1$ μF. Ensure that all unused inputs are earthed.

(24) Observe the waveforms at various points in the circuit to confirm that Fig. 18(b) accurately represents conditions in the circuit.

(25) Measure the threshold voltage of the comparator from the V_3 waveform and calculate $\tau_1$and τ_2. Compare these with the measured values.

List of Equipment

1. Noy-Tronix 300 MSTPC/02 Function generator
2. Cleverscope CS328 Digital Oscilloscope and PC
3. Topward 630D Dual power supply
4. Circuit Board housing
5. Circuit breadboard containing:

2 x LM741 op amp	33 kΩ resistor
LM339 comparator	220 kΩ resistor
CD4001 CMOS NOR	330 kΩ resistor
3 x 10 kΩ resistors	1.2 MΩ resistor
2.2 kΩ resistor	0.01 μF capacitor
3.3 kΩ resistor	0.1 μF capacitor
	1 μF capacitor

S.M. Tan and L.R. Watkins: 24 August, 2003.

Updated by W. Parker and S. Coen: Aug 2008

Revised for Python: 24 November 2014.