Experiment 4

Comparators, positive feedback, and relaxation oscillators

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This experiment will continue our investigations of nonlinear analog circuits. We consider first a simple op-amp application used to *interface* an analog signal to a digital device: the *Schmitt trigger*, a 1-bit *analog to digital converter* (in which the op-amp is used as a *comparator*). This circuit introduces us to the use of *positive feedback* in our op-amp designs, rather than the negative feedback we've used so far. In this case the positive feedback is used both to introduce *hysteresis* in the circuit's *state transition* trigger conditions and to speed up the op-amp's output state transitions.

Next we couple a Schmitt trigger with first an *RC* low-pass filter and then an op-amp integrator circuit to develop *relaxation oscillators*, simple signal generators which work much like a ticking clock to output a repetitive waveform. Spend some time studying this relaxation oscillator idea, because its feedback scheme is applicable to many types of simple analog signal generators, clocks, and timers (some of which could more correctly be considered to be simple digital circuits).

Finally, we introduce a special-purpose integrated circuit, the "555 timer," a versatile device we will use to build *astable* and *monostable multivibrator* circuits useful for a variety of applications. This device is our first true example of a *mixed-signal circuit* incorporating both analog and digital design concepts.

THE SCHMITT TRIGGER AND POSITIVE FEEDBACK

The op-amp as a "comparator"

Consider an op-amp used to amplify an input signal *without feedback* as shown in Figure 4-1. Because no feedback is used, the input signal is amplified by the op-amp's full open-loop gain, so even a tiny input voltage (on the order of a millivolt or less) will be enough to send the op-amp's output into saturation, as shown in the plots of v_{in} and v_{out}. Thus, in this case (since the op-amp's +*Input* is grounded), the output gives $-1 \times$ the sign of v_{in}, and the circuit is a one-bit *analog to digital converter* (*ADC*), also called a *comparator*.
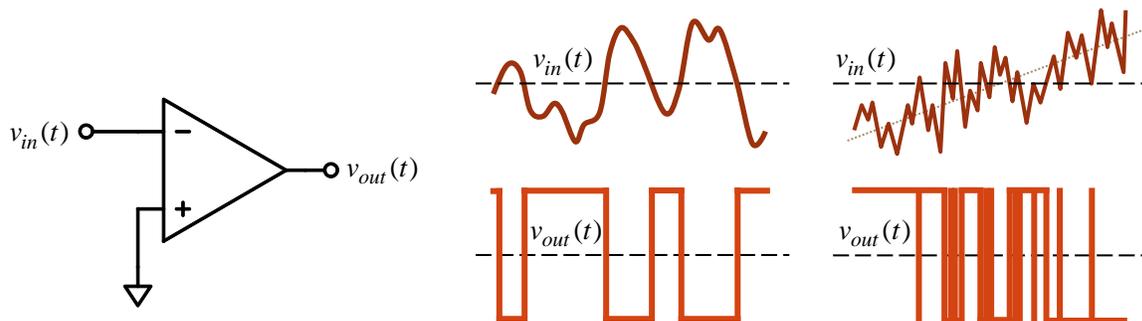
Figure 4-1: An op-amp used as a *comparator*. Whenever $v_{in} > 0$, the op-amp output v_{out} will go to its negative limit (saturation); when $v_{in} < 0$, v_{out} will go to its positive limit. This is an *inverting comparator*, since v_{in} is connected to the op-amp's –*Input*. One potential problem, however: a slowly rising, noisy input can cause many closely-spaced output transitions as it passes through 0, as shown by the right-hand graphs. This is undesirable if you need to use the circuit to accurately count 0-crossings of the underlying input signal.

Comparator-type circuits are useful in a variety of situations. For example, consider the circuit at right, where instead of grounding the +*Input*, it is connected to a constant *threshold* voltage source, V_{th} (shown here as a battery, but it could come from a user potentiometer setting or other voltage divider using the circuit power supplies, etc.). Whenever $v_{in} > V_{th}$, the op-amp output goes into negative saturation and the LED is illuminated; otherwise, the op-amp output is at positive saturation and the LED is off. Such a circuit could, for example, warn an operator of excessive temperature or pressure if v_{in} is generated by an appropriate sensor.
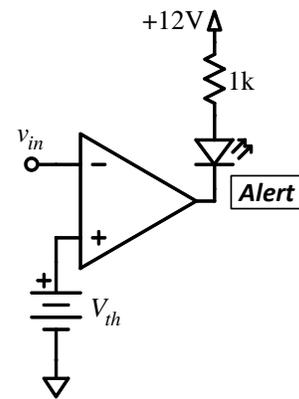
Figure 4-2: Inverting comparator used to illuminate a warning LED whenever $v_{in} > V_{th}$.

Another application could be to interface the comparator circuit output to a digital system in order to count zero crossings of the input signal to calculate its frequency or to count the number of events detected by a sensor. Unfortunately, if the input signal v_{in} rises through the threshold voltage slowly, but there is a significant amount of noise in the signal, many output transitions could

be generated by the noise while v_{in} is near V_{th}, as shown in the right-hand graphs in Figure 4-1. Such behavior would render the circuit useless for a counting application.

Using positive feedback to add hysteresis: *the Schmitt trigger*

A common solution to the problem just outlined is to add *noise immunity* to the comparator circuit by incorporating *hysteresis* into the transition threshold voltage V_{th}, as shown in Figure 4-3.
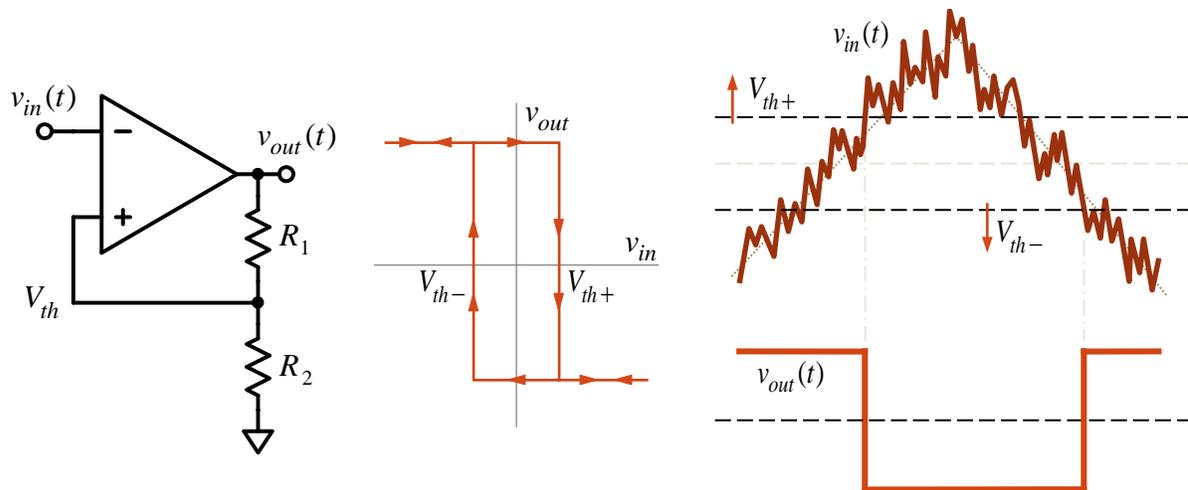
Figure 4-3: An inverting *Schmitt trigger* circuit. Positive feedback is used to add *hysteresis* to the transition threshold voltage. When the output is high the threshold voltage V_{th+} > 0, but when the output is low then V_{th-} < 0. If (V_{th+} − V_{th-}) > [noise peak-peak amplitude], then the noise cannot trigger unwanted transitions in the output as v_{in} slowly passes through 0. The center plot shows the *hysteresis loop* defined by V_{th+} and V_{th-}; the right-hand plot shows how these differing thresholds provide some level of *noise immunity*. Of course, the underlying input signal variations must cross the V_{th+} and V_{th-} thresholds in order to generate changes in the circuit output.

By "hysteresis" we mean that the threshold voltage is a function of the system's current *operating state*, which is defined for this circuit by its output voltage: positive or negative saturation. Because V_{th} is determined by the voltage divider constructed from resistors R_1 and R_2, it changes in response to a change in the output voltage: once the output has gone high in response to an input which has passed below the threshold voltage, the threshold voltage is changed to a higher value (V_{th+}); conversely, an input voltage climbing through V_{th+} will change the output to its low state and cause the threshold voltage to be set to a lower value (V_{th-}), as illustrated in Figure 4-3.

As shown in the right-hand graphs in the figure, this difference in V_{th+} and V_{th-} means that once a transition is triggered by a change in v_{in}, small noise excursions in the input will not cause v_{in} to reverse its course enough to cross the *hysteresis gap* ($V_{th+} - V_{th-}$) and cause an undesired reversal of the output state. If the hysteresis gap is made large enough, then the system can be made completely impervious to the noise in the input signal, eliminating the spurious output transitions suffered by the basic comparator circuit (Figure 4-1).

There is another important advantage to the use of positive feedback in the comparator circuit (Figure 4-3): as the output changes, the feedback increases the difference between the op-amp input voltages, accelerating the change in the output even if the op-amp open-loop gain is relatively modest. Thus, because of the positive feedback, *the output voltage will change at an exponentially increasing rate* until the op-amp slew rate limit is reached, even if the initial difference between v_{in} and V_{th} is very small, or v_{in} is changing very slowly. This "pulling oneself up by one's own bootstraps" effect is why positive feedback is also referred to as *regenerative feedback*. This idea of using regenerative feedback to incorporate noise immunity and to vastly increase output transition (*switching*) speed was first developed by Otto Schmitt at Washington University (St. Louis, Missouri) in 1934; a circuit incorporating these two features (threshold hysteresis and positive feedback) is called a *Schmitt trigger*.

Schmitt trigger circuit variations and trigger point calculations

Call the op-amp positive and negative output saturation voltages V_{sat+} and V_{sat-}; the resulting hysteresis gap for the circuit of Figure 4-3 is:

4.1 $$V_{th+} - V_{th-} = \frac{R_2}{R_1 + R_2}\left(V_{sat+} - V_{sat-}\right) \qquad \textbf{(inverting)}$$

For the TL082 with ±12V power supplies, $V_{sat+} - V_{sat-} \approx 21$–22V. Because the other end of the voltage divider (bottom of R_2) is connected to ground, the threshold voltages V_{th+} and V_{th-} will be centered around 0V (assuming that $V_{sat-} = -V_{sat+}$). Connecting the bottom of R_2 to a voltage reference source rather than to ground *will not affect the hysteresis gap*, but it will center that gap around a nonzero mean threshold proportional to the reference V_{ref} (see Figure 4-4 and equation 4.2 on page 4-5).
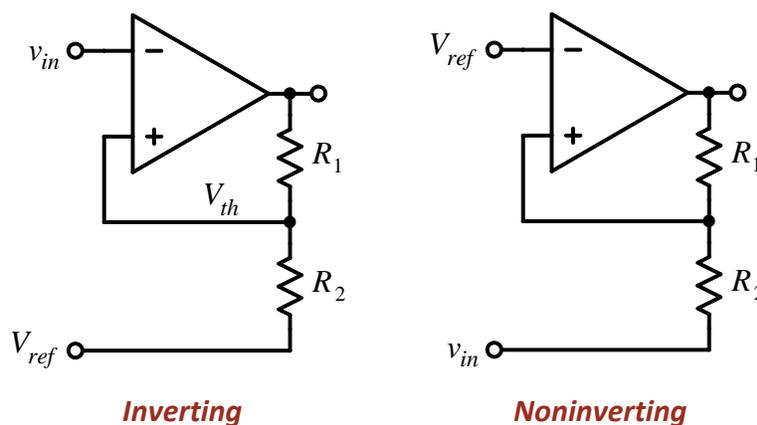
Figure 4-4: Inverting and noninverting Schmitt triggers with a supplied reference voltage V_{ref} used to set the trigger thresholds. Note that the voltage source connected to the bottom of R_2 in each circuit must have an output impedance «R_2 or the trigger points will be affected because of the current flowing between the op-amp's output and that source.

4.2
$$\overline{V_{th}} = \tfrac{1}{2}\left(V_{th+} + V_{th-}\right) = \frac{R_1}{R_1 + R_2}V_{ref} \qquad \textbf{(inverting)}$$

Note that a noninverting Schmitt trigger may be implemented by simply swapping the input and reference voltage connections, but now the trigger points are different from those for the inverting case, because now the voltage divider affects the input voltage rather than the reference.

4.3
$$V_{th+} - V_{th-} = \frac{R_2}{R_1}\left(V_{sat+} - V_{sat-}\right) \qquad \textbf{(noninverting)}$$

4.4
$$\overline{V_{th}} = \tfrac{1}{2}\left(V_{th+} + V_{th-}\right) = \frac{R_1 + R_2}{R_1}V_{ref} \qquad \textbf{(noninverting)}$$

Additional Schmitt trigger circuit design considerations

Note that equation 4.3 places an important restriction on the ratio R_2/R_1 for a noninverting Schmitt trigger: unless $R_2 < R_1$, the hysteresis gap ($V_{th+} - V_{th-}$) will exceed the output voltage swing range of the op-amp ($V_{sat+} - V_{sat-}$), and, depending on the reference voltage value V_{ref}, *one or both of the Schmitt trigger thresholds will be beyond the range of the op-amp output voltage*. Assuming the input signal voltage range is also limited to $V_{sat-} \leq V_{in} \leq V_{sat+}$, then the circuit's output could experience *lock-up* at V_{sat+} or V_{sat-}, rendering the circuit useless!

For either circuit in Figure 4-4, it is important to remember that the voltage source connected to R_2 must have a small output impedance, or its output impedance must be added to R_2 when calculating the trigger thresholds using equations 4.1 through 4.4. If necessary, use a voltage follower between the voltage input and R_2.

Another design consideration is the current required from the op-amp output to drive the voltage divider formed by resistors R_1 and R_2. If, say, both are chosen to be 1k, then their series resistance is 2k, and when the op-amp output is at saturation (approx. 11V), then over 5mA will flow through the resistors. This relatively large current draw will probably reduce the TL082 op-amp's saturation voltages. As the total resistance $R_2 + R_1$ is reduced, then the additional current drawn by them may cause significant changes in the op-amp's behavior, and the circuit will not work as you expect.

<div align="center">

THE RELAXATION OSCILLATOR

</div>

Simple, one op-amp oscillator

If you feed the output of a Schmitt trigger back to its inverting input through a *RC* low-pass filter, you get a circuit whose output switches back and forth between the op-amp's two saturation limits: you have made a simple *relaxation oscillator* (Figure 4-5).
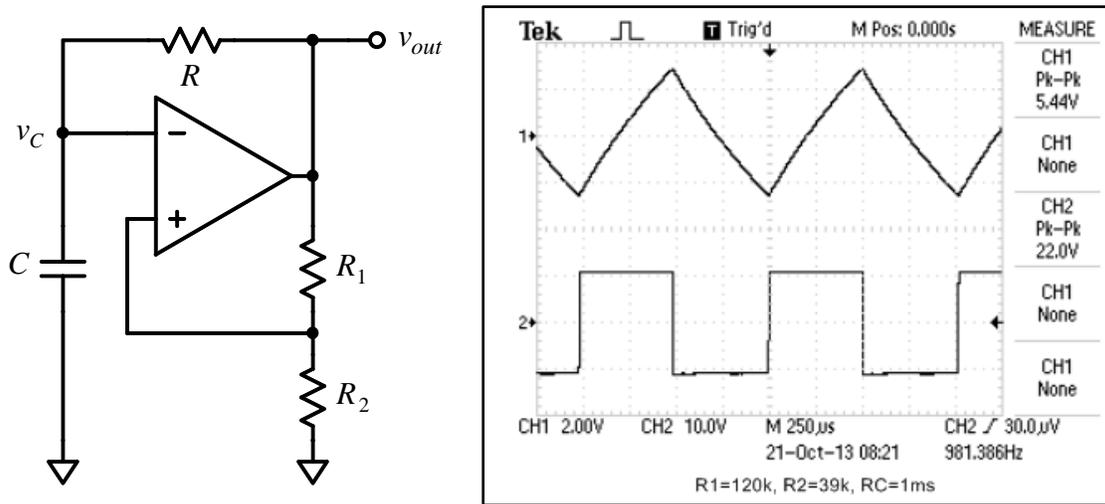

Figure 4-5: A simple *relaxation oscillator* using a Schmitt trigger to alternately charge and discharge the capacitor C through the resistor R. Whenever v_C, the voltage across C, reaches a trigger threshold, the op-amp output voltage reverses to its opposite saturation limit. Thus the current through R changes sign, and the capacitor voltage moves toward the opposite threshold. Consequently, v_C oscillates between the Schmitt trigger's two threshold voltages as the op-amp output switches back and forth between its two output saturation limits. The oscilloscope image shows v_C (CH1) and v_{out} (CH2) for trigger thresholds chosen so that $f = 1/RC$.

As should be clear from the figure, the op-amp's output charges the capacitor C via the resistor R. Because the capacitor's voltage is monitored by the op-amp's inverting input, every time it charges up to a trigger threshold, the op-amp output changes sign, and the capacitor voltage then begins to "relax" toward the opposite output saturation limit. The trigger threshold voltage at the op-amp's +*Input* has also changed sign, however, so that the op-amp output again changes state as the capacitor voltage reaches this opposite threshold; the process is then repeated.

The capacitor's voltage profile is an exponential *relaxation* toward an equilibrium voltage which will equal to the op-amp's output saturation voltage, V_{sat}, starting from the opposite trigger threshold voltage. If the + and – saturation voltages are assumed to be equal, then this exponential relaxation is described by:

4.5
$$v_C(t) \;=\; V_{sat} - (V_{sat} + V_{th})e^{-t/RC}$$

If the oscillation period is T, then after half a period the capacitor voltage reaches the next trigger threshold, so in equation 4.5 $v_C(T/2) = V_{th}$. With equation 4.1 relating V_{sat} and V_{th}, the relationship between the period T and the circuit's component values is:

4.6
$$\boxed{\frac{R_1}{R_2} = \coth\left(\frac{T}{4RC}\right) - 1}$$

where **coth** is the hyperbolic cotangent function. If you want the oscillator period to equal the filter's RC time constant $(T = RC)$, then

$$R_1 = 3.08 R_2$$

$R_1 = 120\text{k}\Omega$, $R_2 = 39\text{k}\Omega$ provide a pair of standard resistor values which closely matches this ratio (within 0.2%).

> Note that the current drawn by the RC feedback pair is as high as $(V_{sat} + V_{th})/R$ just after the op-amp output changes state — excessive current here will reduce V_{sat} as the op-amp tries to meet this output current requirement, distorting the output waveforms and lengthening T. Choosing $R \geq 10\text{k}\Omega$ should limit the capacitor charging current to a reasonable level.

Function generator

Using an op-amp integrator circuit rather than a simple RC pair would charge the capacitor as a constant rate, so the exponential relaxation in the last circuit would be replaced by a nice, linear ramp. The resulting circuit is shown in Figure 4-6; as mentioned in the caption, we must now use the noninverting form of the Schmitt trigger because the integrator is inverting.
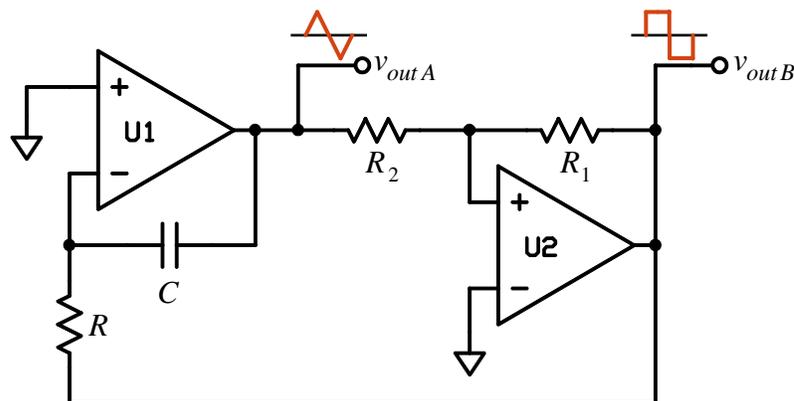

Figure 4-6: Integrator coupled to a Schmitt trigger to form a primitive *function generator*, outputting triangle and square waveforms. Since the integrator is inverting, its output must go to a noninverting Schmitt trigger, so that reaching a trigger point reverses the capacitor's charging current. This means that we must have $R_1 > R_2$, or the circuit won't work.

Since the input to the integrator is constant between triggers, its output will have a constant slope between triggers. For this reason the period of the output signals is much easier to calculate for this circuit; the formula is left to the exercises. To make the frequency variable, resistor R may be made variable; a switch could also be used to select one among a set of capacitors.

Below is a circuit which incorporates both variable frequency and symmetry adjustments of the output waveforms. Note how the diodes select which side of the symmetry potentiometer is used to set the current through the integrator's capacitor (depending on the sign of the voltage follower's output). The voltage follower (U3) isolates the Schmitt trigger's square wave output and the frequency adjust potentiometer from the current load required by the integrator, so changing the symmetry potentiometer setting will not affect the voltage divider ratio set by the frequency potentiometer or op-amp U2's output saturation voltages.
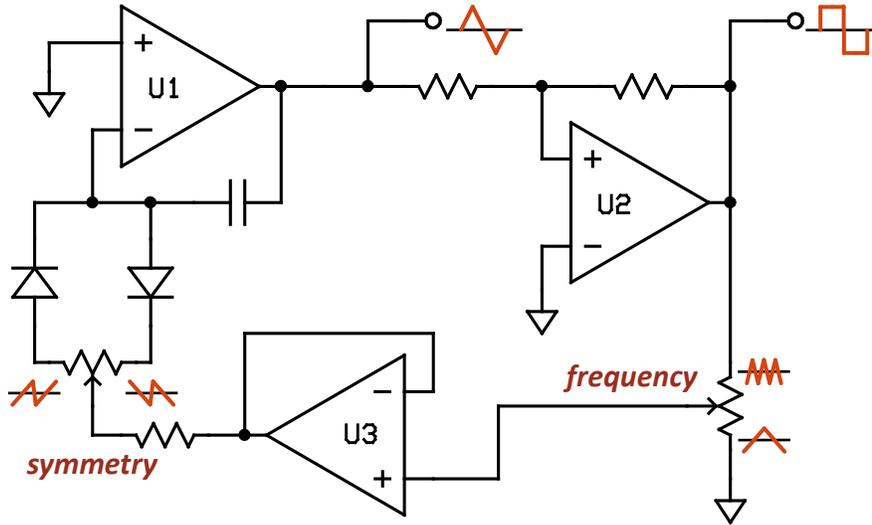
Figure 4-7: A function generator circuit with variable frequency and waveform symmetry. The voltage follower using op-amp U3 isolates the Schmitt trigger output and the frequency adjust potentiometer from the current load demands of the integrator, especially important when the symmetry potentiometer is set near one of its limits.

Figure 4-7 presents one of the most complicated circuits we've considered so far. You should spend some time studying this circuit so that you understand how it works and how you would select values for the components (the prelab exercises will help you focus on this task!). Why is the resistor in series with the output of op-amp U3 necessary?

Description

Next we consider a special integrated circuit designed specifically for timing and oscillator applications: the *555 timer IC*, originally invented in 1971 by engineers at *Signetics* (since absorbed into *NXP Semiconductors*). The version you will use for this experiment is the TLC555, an updated version manufactured by Texas Instruments. They and other companies also manufacture copies of the original version: for example, the LM555. This latter data sheet gives a few examples of the sorts of circuits you can build using this versatile device; a more thorough discussion of the device and its applications is provided in the original manufacturer's Application Note.

The 555 timer is an example of a *mixed signal* or *interface* IC, incorporating both analog and digital circuitry; we'll consider such circuits in more detail in a later experiment. Figure 4-8 shows the functional block diagram and the device *pinout* for the timer, which at first glance seems very complicated.
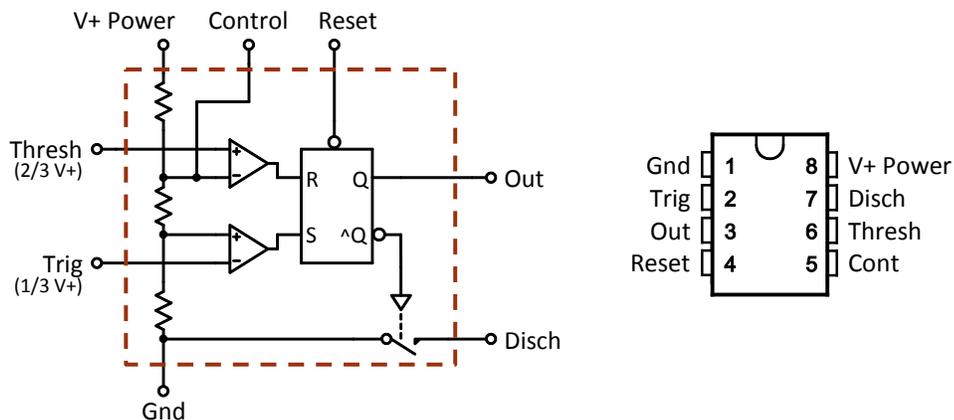
Figure 4-8: The *555 Timer* IC. Shown are its functional block diagram and the device *pinout*, or pin numbering scheme and identification. The heart of the circuit is an *RS flip-flop*; its operating state determines the outputs *Out* and *Disch*. The output (*Out*) is *LOW* and the discharge terminal (*Disch*) is shorted to ground (*Gnd*) whenever the flip-flop is in its *Reset* state; when the flip-flop is in its *Set* state, *Out* is *HIGH* and *Disch* is open (high impedance). The input voltages *Thresh* and *Trig* are used to trigger two analog comparators which control the flip-flop's state.

An *RS flip-flop* inside the 555 timer controls the device's two outputs: *Output* and *Discharge*. A *flip-flop* is the generic term for a two-state digital circuit which changes its operating state only when some particular sequence of its input signals is encountered; otherwise it remains in its current state — in other words, a flip-flop is an elementary, 1-bit *memory*. In this case, the flip-flop has two primary inputs: *Reset* (R) and *Set* (S). The inactive state for an input is *Low* (ground), whereas a *High* input (near the V+ power supply voltage) commands the flip-flop to its corresponding operating state: *Set* (Q = *High*; ^Q = *Low*) or *Reset* (Q = *Low*; ^Q = *High*). If both the R and S inputs are *High* concurrently, then the 555 gives priority to the S

input, driving the flip-flop to its *Set* state. The separate 555 *Reset* terminal input overrides any other command to its internal flip-flop and *clears* the flip-flop: drives it to the *Reset* state (the little circle on the wire from the *Reset* input at the top of the flip-flop means that it is active when *Low*: a 0V input on *Reset* commands the flip-flop to *clear*; otherwise the *Reset* pin should be connected to *V+ Power* to inactivate it.).

The operating state of the RS flip-flop determines the condition of the 555 terminals *Output* and *Discharge*. The *Output* terminal reflects the flip-flop's Q output: nearly equal to *V+ Power* when the flip-flop is *Set*, nearly equal to ground when the flip-flop is *Reset*. The *Discharge* terminal is connected via an *analog switch* to the ground terminal: When the flip-flop is *Set*, the switch is *open*, so the *Discharge* terminal is disconnected from ground; when the flip-flop is *Reset*, the switch closes, and the *Discharge* terminal is shorted to ground.

As shown in Figure 4-8 on page 4-9, the flip-flop R and S inputs are supplied by two comparators monitoring analog voltages on the 555's *Trigger* and *Threshold* inputs; the comparator reference voltages for these inputs are 1/3 and 2/3 of the power supply voltage applied to the *V+ Power* terminal. The following table itemizes the possible input combinations and how they affect the 555 output terminals.

Table 4-1
555 Timer State Table

Reset (pin 4)	Trigger (pin 2)	Threshold (pin 6)	Output (pin 3)	Discharge (pin 7)
LOW (< 0.4V)	-	-	Low (near Gnd)	Short to Gnd (on)
high	*LOW (< 1/3 V+)*	-	*HIGH (near V+)*	*OPEN (off)*
high	high	low	no change	no change
high	high	*HIGH (> 2/3 V+)*	Low (near Gnd)	Short to Gnd (on)

The **ACTIVE** state of each input is highlighted with italics, as shown. The *Reset* input (active when *Low*) overrides all other inputs; otherwise *Trigger* overrides *Threshold* when determining the flip-flop state. The active response state is *Output **HIGH**, Discharge **OPEN***. Connect *Reset* to *V+* if it is not used.

The normal sequence of events when using the 555 is as follows (the *Reset* pin is kept *high*): the *Trigger* pin is brought *low*, setting *Output* to *high* and *Discharge* to *open.* Next, with the *Threshold* pin *low*, the *Trigger* is brought back to *high*; the outputs remain unchanged. After some time, the *Threshold* is brought *high*, which resets the *Output* to *low* and shorts *Discharge* to ground. Finally, *Threshold* is brought back *low*, returning the system to its initial state. Let's now see how to use this event sequence to do something interesting…

Astable multivibrator (relaxation oscillator)

The first application of the 555 IC we consider, Figure 4-9 on page 4-11, is as an *astable multivibrator* (which is the name used for a relaxation oscillator by digital electronics
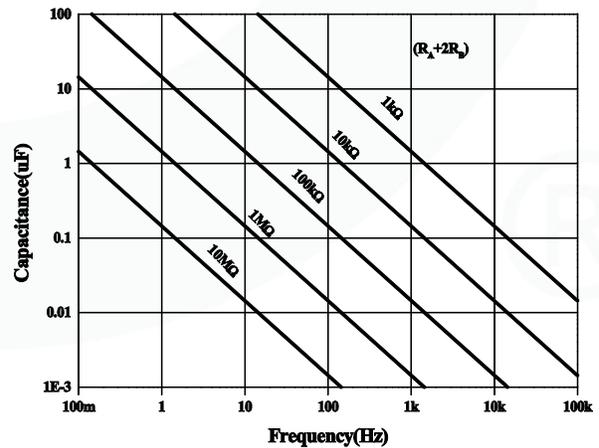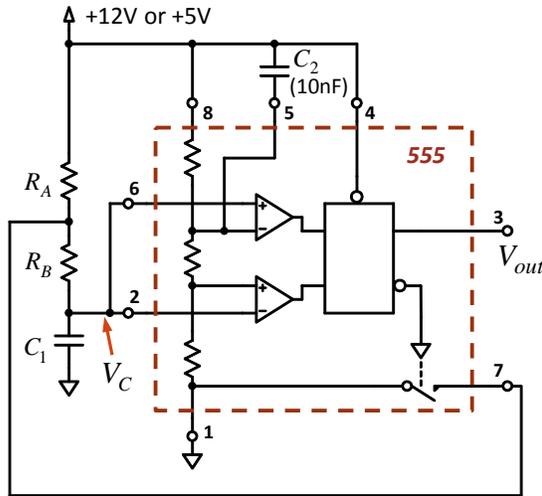
Figure 4-9: *Astable multivibrator* using the 555. The V_C and V_{out} waveforms are similar to those for the simple relaxation oscillator in Figure 4-5. Since the capacitor C_1 charges through R_A+R_B, but discharges through only R_B, the output waveform is not symmetrical. The graph at right is from the LM555 datasheet; it shows how resistor and capacitor selection affects the output frequency. IC pin numbers are shown next to the 555 terminals in the schematic.

engineers). The idea is to repeatedly charge and discharge a capacitor while monitoring its voltage using the 555's *Trigger* and *Threshold* inputs. The capacitor will be charged using the system power supply voltage (V_{supply}); when the capacitor voltage reaches $2/3\,V_{supply}$, the *Threshold* comparator will short the *Discharge* terminal to ground, and this can be used to discharge the capacitor. As it discharges to $1/3\,V_{supply}$, the 555's *Trigger* comparator opens the *Discharge* terminal connection, and the capacitor again starts to charge, repeating the process. Thus, the circuit's operation is similar to that of the simple Schmitt trigger relaxation oscillator (Figure 4-5).

Consider Figure 4-9; when the *Discharge* terminal is open (and the *Output* is high), the capacitor C_1 charges from the power supply through resistors R_A and R_B; Once V_C reaches $2/3\,V_{supply}$, the 555's flip-flop changes state, and the *Discharge* terminal is shorted to ground (and the *Output* goes low). Now C_1 discharges through R_B until V_C has dropped to 1/3 of the supply voltage. The flip-flop again changes state, the *Discharge* terminal is returned to its high impedance (open) state, and the capacitor again begins to charge.

Thus the capacitor voltage V_C relaxes back and forth between 1/3 and 2/3 of the supply voltage with time constants $(R_A + R_B)C_1$ and $R_B C_1$, so the oscillator period will be proportional to $(R_A + 2R_B)C_1$, as shown in the graph accompanying the schematic in Figure 4-9. Note that when the *Discharge* terminal is shorted to ground, the full supply voltage is applied across R_A, and this current will add to the capacitor discharge current flowing into the *Discharge* terminal. Clearly, the values of R_A and R_B should be large enough (at least a few kΩ) to keep these currents from becoming excessive.

> The TLC555 has very high impedance inputs for its *Trigger* and *Threshold* terminals, so large resistor values may be used to achieve very long oscillator periods; only about 10pA is drawn by either input terminal, and the leakage current into the *Discharge* terminal is only about 100pA when it is open. Oscillator periods of a few hours or longer are easily achievable.

The 555's *Reset* and *Control* terminals aren't needed for this application; the *Reset* pin should be tied to the 555's *V+ Power* (IC pin 8) so that noise will not cause spurious resets of the 555 state; similarly, the *Control* terminal should be connected through a small capacitor $C_2 \sim 10\text{nF}$ to either ground (IC pin 1) or *V+ Power* (IC pin 8) to keep noise from affecting the comparators' trigger points (as in Figure 4-9 and Figure 4-10).

Monostable Multivibrator (one-shot)
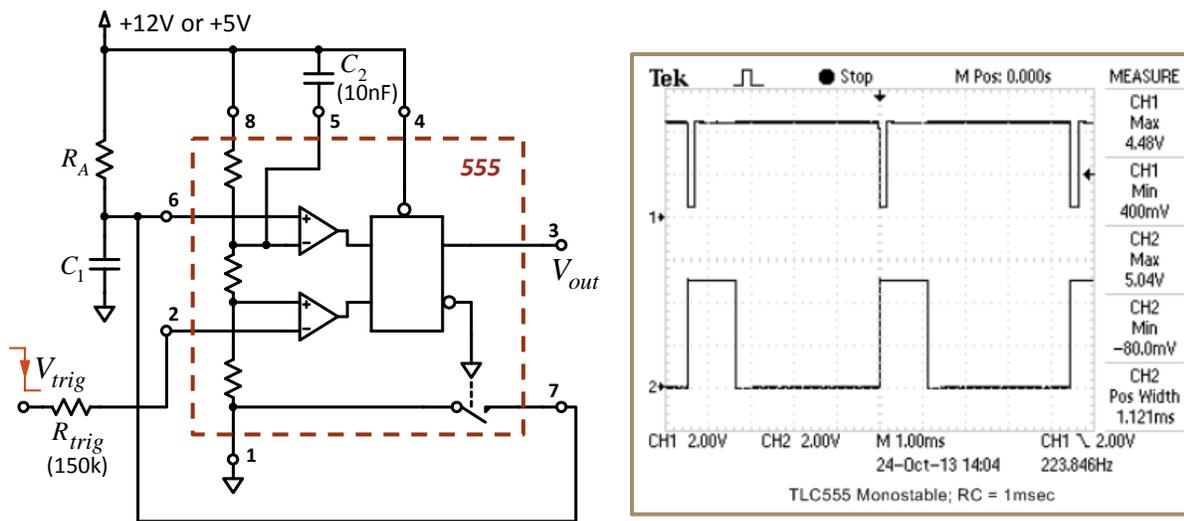
Figure 4-10: *Monostable multivibrator* using the 555. Whenever V_{trig} falls below 1/3 V_{supply} the output goes high and capacitor C_1 charges through resistor R_A. When the capacitor voltage reaches 2/3 V_{supply}, the output goes low, the *Discharge* terminal is shorted to ground, and C_1 is discharged back to 0. The oscilloscope shows trigger event inputs (CH1) and the resulting pulse outputs (CH2). Note that for proper operation, the trigger pulse input must be shorter than the output pulse.

Whereas neither the high nor the low output state of a relaxation oscillator is *stable* (because each state eventually changes to the other without any external input to the circuit), one of the states of a *monostable multivibrator* is stable — an external trigger input is needed to make the circuit transition to its other output state. The other state, however, is *unstable*: after some time the circuit will transition back to its stable state and remain there until another trigger event occurs. The idea is that a trigger event causes the circuit to emit a single pulse of a fixed width and then return to its original, quiescent state. For this reason the monostable multivibrator is also called a *one-shot*: one output pulse for each input trigger.

Figure 4-10 (on page 4-12) shows how to implement a simple one-shot using the 555 timer. Assume the capacitor C_1 is discharged and the 555's *Trigger* input voltage (V_{trig}) is greater than 1/3 of the power supply voltage (V_{supply}). Assume further that the 555 is in its *Reset* state ($V_{out} = 0$ and the *Discharge* terminal shorted to ground). This is the circuit's *stable* (quiescent) state.

A *trigger event* occurs when V_{trig} is momentarily taken well below $1/3 V_{supply}$. Now the 555 transitions to its active state: the *Discharge* terminal opens and V_{out} goes high. The capacitor charges through R_A toward V_{supply}; when its charge reaches $2/3 V_{supply}$, the 555 *Threshold* is triggered. If V_{trig} had returned to its quiescent state (well above $1/3 V_{supply}$) before this happens, then the 555 will return to its *Reset* state, lowering V_{out} and discharging the capacitor back to ground. The time it takes the capacitor voltage to relax from 0V to 2/3 V_{supply} is just over one time constant, i.e. $\approx 1.1 R_A C_1$.

Note that if the trigger input voltage remains below $1/3 V_{supply}$, then the 555 will remain in its active state (V_{out} high), since the *Trigger* comparator overrides the *Threshold* comparator (see Table 4-1 on page 4-10). If the capacitor voltage has exceeded $2/3 V_{supply}$, then as soon as V_{trig} goes back above $1/3 V_{supply}$ the 555 will change state, and its output will immediately return to 0.

The IC's *Trigger* input (pin 2) is protected against excessively low or high V_{trig} voltages ($V_{trig} < 0$ or $V_{trig} > V_{supply}$) by the resistor $R_{trig} = 150\text{k}\Omega$. This resistor limits the current flow within the 555 IC during these V_{trig} excursions so that the 555 isn't permanently damaged.

As with the astable multivibrator circuit, input signals to the 555's Reset and Control pins aren't required for this application, so properly connect them as described before (as in Figure 4-9 and Figure 4-10).

Additional 555 applications

So far we have just scratched the surface of the many applications of the 555 IC. Many more are described in the LM555 datasheet and the 555 Application Note. The web, of course, has sites with myriads of circuits; check out http://www.555-timer-circuits.com.

PRELAB EXERCISES

1. Consider the function generator circuit in Figure 4-6 on page 4-7. Sketch the waveform at the +*Input* of the Schmitt trigger op-amp (U2).

2. Use equation 4.3 on page 4-5 and the first of equations 2.16 on page 2-22 of <u>Experiment 2</u> to show that the oscillation period *T* of the simple function generator circuit in Figure 4-6 is given by:

4.7
$$T = 4RC\left(R_2/R_1\right)$$

   Will the circuit work if $R_2 > R_1$ (consider equation 4.3)? What should the generator frequency f be if $R = 10\text{k}\Omega$, $C = 0.1\mu\text{F}$, $R_1 = 10\text{k}\Omega$, and $R_2 = 1\text{k}\Omega$? What is the output amplitude (peak-to-peak) of the triangle wave if the square wave amplitude is 22V peak-to-peak?

3. How does the symmetry control potentiometer in Figure 4-7 on page 4-8 affect the output waveform symmetry (how does this part of the circuit work)? Does it change the output frequency by any significant amount when it is adjusted? If the magnitude of the maximum output current available from an op-amp is 10mA and the magnitude of its saturation voltage is 11V, then what is the minimum allowable value for the resistor in series with the output of op-amp U3 for the circuit to work properly? How does the frequency control potentiometer affect the output frequency? Does it affect the waveform symmetry to any significant degree when it is adjusted?

4. Consider the monostable multivibrator circuit in Figure 4-10 on page 4-12. Sketch the voltage waveform at the 555 IC pin 6 (the *Threshold* terminal) to accompany the trigger voltage and output voltage waveforms shown in the oscilloscope screen shot.

5. Again consider the simple function generator circuit in Figure 4-6 on page 4-7. How could you add a multiplier (using the MPY634) to that circuit to provide an input so that an applied voltage will determine the function generator's frequency? Such a circuit is called a *VCO* for *voltage-controlled oscillator*.

   Design a circuit which will output a frequency proportional to the input control voltage applied to the circuit such that ½ the original circuit frequency ($1/T$, where *T* comes from equation 4.7 above) will be generated when the control voltage is ≈ 5V (it's ok if the circuit cannot quite generate a frequency as high as $1/T$, since the multiplier output will be < 10V). Provide a complete schematic of your circuit using the component values supplied in problem 2 above and assigning values to the additional components you add.

   Are there limits to the input control voltage beyond which the circuit stops working?

LAB PROCEDURE

Overview

During lab you will investigate the behavior of a Schmitt trigger circuit and measure its hysteresis. You will then look at a couple of relaxation oscillator circuits, including the circuit you designed in response to Prelab exercise problem 5.

Next you will build astable and monostable multivibrator circuits using the TLC555 timer IC. To accomplish this task you will need to construct the circuit in the breadboard area of the analog circuit trainer, including installing the integrated circuit and correctly wiring to its pins. This will help prepare you for your upcoming project work, which will be built completely on such a breadboard. ***Make sure you pay attention to the clock during lab and budget enough time to complete this work!***

The Schmitt trigger

Build an inverting Schmitt trigger (Figure 4-3 on page 4-3) using one of the op-amps on the analog trainer which have installed resistors available on its *+Input*. Using a triangle wave input signal, measure its trigger thresholds V_{th+} and V_{th-}. Note how these thresholds change when you change the feedback resistor values. See if you can use the **XY** display mode of the oscilloscope to generate a hysteresis plot like the center image in Figure 4-3.

Reconfigure the input and ground connections to convert your circuit to a noninverting Schmitt trigger (right-hand circuit in Figure 4-4 on page 4-4); use ground (0V) for V_{ref}. Again take an oscilloscope screen shot identifying the trigger thresholds using a triangle wave input for a least one combination of resistor values.

Simple relaxation oscillator

Use the installed components available on the op-amp's *–Input* to reconfigure your circuit into the simple relaxation oscillator shown in Figure 4-5 on page 4-6. Use the 10k and 2.2k resistors on the *+Input* for resistors R_1 and R_2, and choose some R and C pair from those components available on the *–Input*. Take an oscilloscope screen shot similar to that in Figure 4-5; does the formula given in equation 4.6 correctly relate your oscillator's period T to your component values?

Function generator

Construct the simple function generator circuit in Figure 4-6 on page 4-7. Using installed resistor and capacitors available on the trainer, use the component values listed in Prelab exercise problem 2. Take an oscilloscope screen shot showing the both the triangle and square waveform outputs. Does your oscillator's frequency f and the triangle wave amplitude agree with your solution to problem 2?

Voltage-controlled oscillator (VCO)

Using your solution to Prelab problem 5, add a multiplier to your function generator circuit to convert it to a *VCO*. Test its performance using the signal generator to input a constant DC voltage to your circuit's frequency control input.

Use a low-frequency sine wave signal generator output (with an appropriate amplitude and DC offset) to modulate the output frequency of your VCO. Trigger the oscilloscope from the signal generator's voltage to your VCO and take a screen shot showing this control voltage along with your VCO output. This sort of modulation is called *frequency modulation* (FM).

Building a TLC555 timer circuit

Warning

Do not connect the breadboard circuit to the analog trainer power supply until either your TA or the course instructor has looked over your circuit. Wiring the power supply incorrectly into an integrated circuit will often leave it fatally damaged.

Construct the astable multivibrator circuit (Figure 4-9 on page 4-11) in the breadboard area of the trainer. Your TA or the course instructor will give you a TLC555 IC and show you how to determine its pin numbers. Make sure you understand how the various contacts of the breadboard are interconnected and pay attention to the advice your TA and the course instructor give you regarding the layout and wiring of your circuitry on the breadboard.

Caution
555 Timer Voltage Limits

The maximum allowable voltage difference between the *V+ Power* and *Ground* terminals is **less than 16V** or so (depending on the specific IC version). Always connect the *Ground* terminal to the breadboard ground; you may then use +12V or +5V for *V+ Power*.

Never let a terminal voltage exceed the limits set by *Ground* and *V+ Power*! In particular, **never let an input signal go < 0V (Ground)**. Violating this rule means nearly instant destruction of the IC. For the TLC555, putting a 150kΩ resistor in series with an input should protect the IC from inadvertent inputs between +12V and −12V, regardless of its power supply voltage values.

Pick component values which will give an output frequency of a couple of kilohertz. Use at least 10kΩ for resistor R_A to avoid excessive current draw when the capacitor C_1 is being discharged. Using the +12V power supply for V_{supply}, observe the capacitor voltage V_C and

the output voltage V_{out} . Does the output change state when $V_C = 4V$ and 8V ? Take a screen shot; compare your circuit's output frequency to the chart included with Figure 4-9.

Now use +5V as the power supply voltage. Does the output frequency change by very much?

Additional 555 circuits

If you have time, reconfigure your 555 circuit as a monostable multivibrator (Figure 4-10 on page 4-12). Don't forget the 150k resistor R_{trig} to protect the IC's *Trigger* input from errant trigger voltage inputs!

You can use the pulse output of the signal generator as a trigger source: set the pulse **HiLevel** to about 2/3 V_{supply} and its **LoLevel** to 0V. Set the **Dty Cyc** to ≈ 90% or more to generate a narrow, negative-going pulse as in the oscilloscope image in Figure 4-10. Try to capture a result similar to the result in that figure.

If you have time for more circuits, look through those in the 555 Application Note.

Lab results write-up

As always, include a sketch of the schematic with component values for each circuit you investigate, along with appropriate oscilloscope screen shots. Make sure you've answered each of the questions posed in the previous sections.