Chemistry 628
University of Wisconsin-Madison

Lab Unit 4: Oscillators, Timing and the Phase Locked Loop[*]

Oscillators and timing circuits are very widely used in electronic measurement instrumentation. In this lab you will look at several types of oscillators and timing devices. The first, using a precision time base (quartz clock oscillator) combined with digital counters, provides the highest resolution and stability and is widely used in scientific instruments. However, in most cases it is necessary to use a significant number of integrated circuits, such as cascade counters, logic gates, etc. The relaxation oscillator and one-shot are hybrid analog-digital devices that incorporate charging circuits combined with comparators and logic gates to perform specific functions; they are less accurate and less reproducible than a purely digital timing circuit, but they are very useful in a large number of applications. In a couple of weeks you will be building a lock-in amplifier, one of the most useful instruments for extracting small signals from high levels of noise. As a prelude to that lab, you will be looking at a voltage controlled oscillator and a phase locked loop. In addition to being very useful on their own, these are two of the components that are used in the lock-in amplifier.

I. Quartz clock with digital counter (Modulo-N counter) One common way of controlling the timing in instrumentation is to use a fast clock, and to use digital counters to create pulses separated by some precise time. For example, starting with a 1 MHz clock and a digital counter, it is very easy to create pulses separated by 1 μs, 2 μs, 3μs, or any other integral multiple of the clock period. This is done by creating something called a "modulo-N divider". In the modulo-N divider, you use a divider that can be preset to some particular value. The input clock causes the counter to count down from the preset value. When it gets to zero, instead of wrapping around to 15 again, you use a special output, usually called the "terminal count-down" or sometimes called the "borrow" pin, to cause original number to be preset again. The net result is that the terminal count-down (borrow) pulse will be generated only after every 5th clock pulse. When the modulo-N divider is combined with a flip-flop, you can make a digital delay generator in which a particular trigger signal makes the counter start counting down from some preset-value, and when it is done it generates an output pulse. Inexpensive (a few dollars each) quartz oscillators have frequency stability on the order of 10 parts per million. By adding an oven to control the temperature, small oven-controlled crystal oscillators (OCXO's) are available for ~$200. that are stable to ~ 1 part in 10^{11} ! Of all the possible things that one can measure (voltage, current, etc.), time and frequency are can be measured more accurately than *any* other physical quantity. So, converting analytical signals to the time/frequency domain often leads to the highest precision.

Procedure:

You will use the 74193 (or 74LS193) counter. This particular counter is a 4-bit counter, so that it can count from 0 to 15. It can also count either up or down, depending on which input you apply the clock pulse. We will be counting DOWN.

A) Begin by wiring up the quartz oscillator, which is the four-pin device. Note that the quartz clock has a black dot and one pointed corner to denote the orientation. When powered with + 5V and ground, the quartz oscillator will produce a square wave output at a specific frequency (usually stamped on the front of the oscillator). Look at the output of the oscillator (also called a "clock") on the oscilloscope. The pulse may look somewhat ugly, with ringing, unless your scope is terminated with 50-ohm impedance, but you should see a square wave at the appropriate frequency.

B) Now construct the rest of the circuit. The output of the clock is connected to the DOWN (clock-pulse down) input at pin 4 of the 74193. The UP (clock pulse up) is pulled to +5V through a pull-up resistor. In the modulo-N counter, we control the "preset" of the counter by connecting the four data inputs (A,B,C, and D) to a DIP-switch (**D**ual-**I**nline-**P**ackage switch). In order to make it easy to switch any individual line between low and high, we pull each of the four data inputs to +5 V through individual resistors. The far side of the switch is connected to ground for each of the inputs. For each of the data lines, if the switch is open, then that data line is pulled high. If the switch is closed, then the data line is pulled low by the direct connection to ground.

To make the modulo-N divider, the terminal count-down output ($\overline{BO}$ pin 13) is connected to the programmable $\overline{LOAD}$ input (pin 11). As the counter is counting down, the $\overline{BO}$ output is normally high. However, when the counter gets to zero, the $\overline{BO}$ goes low. When the programmable load pin goes low, it forces the counter to go back to the value D, C, B, A (where D, C, B, A (LSB) are the binary representation of the values set by the four switches). If all four switches are "open", then D, B, C, and A are all high and the counter resets to 15. If C, B, and A are high and D is low, then the counter resets to 0111 (binary) = 7 (decimal). So, in this case the counter would
Count 7, 6, 5, 4, 3, 2, 1, 0→7, 6, 5, 4, 3, 2, 1, 0→7, 6, 5,
The terminal-count-down $\overline{BO}$ pin goes "low" for a brief time after every 7th clock pulse. So, the output at the $\overline{BO}$ pin is our original input frequency divided by the binary value of D C B A. Refer to the 74193 data sheet to help with your understanding of this chip.

Start by leaving the connection between pins 11 and 13 DISCONNECTED, and look at the output of pin 13. You should see a signal that is mostly high, but that momentarily goes low. Trigger the scope from pin 13 and look at the clock pulse (pin 4); count how many clock pulses you see on pin 4 before the pin 13 is triggered. Also, look very carefully at the timing of the clock pulse and the output of pin 13; does pin 13 go "low" on the upward-going or downward-going clock pulse? How long is the pulse on pin 13?

Looking at the various binary outputs (Q_A, Q_B, Q_C, and Q_D), you should see values of the individual "bits" changing; the lengths of the four bits should be different from one another by a factor of 2.
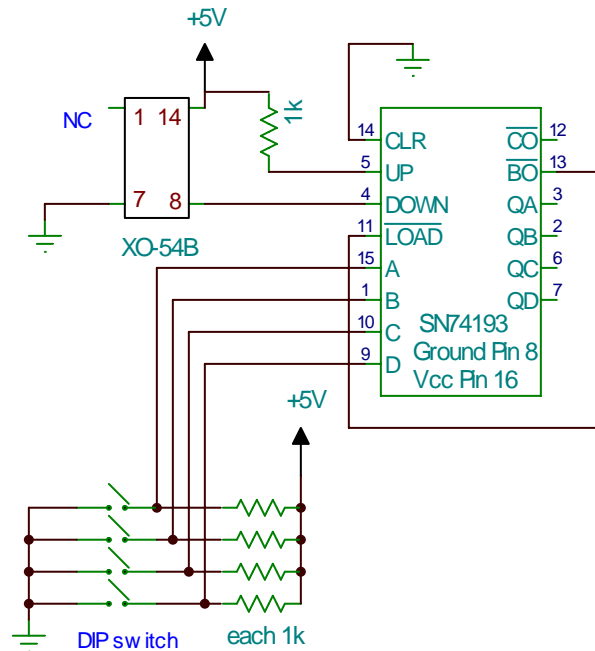

Now, connect pin 13 to pin 11. Again, set up the oscilloscope to trigger from this signal. On the other channel of your scope, hook up the clock input (i.e, pin 4). Chances are good that the pulse on pin 11/13 will now occur more frequently. On the dipswitch, it might not be obvious which direction of each switch corresponds to being "closed". To figure this out, set A,B,C,D to be all in the same direction; then the binary number DBCA is either 0 or 15. Now, change the switches A, B, C, and D to represent some other binary number. Does the output change as you expect? Look carefully at the output of pin 13 – is the duration the same as it was before? In many applications you would need to cascade multiple counters together in order to divide by a larger number. However, from this experiment you can see the basic idea of how to use a counter.

II. Relaxation Oscillators Many oscillator circuits are based on the time response of charging a capacitor, and using a comparator to detect when the capacitor has charged up to a value sufficient to trip the comparator. One common comparator is the LM311. Unlike an op-amp, with a comparator you usually have direct access to the collector and emitter of the output stage. This is done to make it easier to work with various voltage levels on the output. In this activity you will be using an LM311 chip. The functional diagram for the chip is:
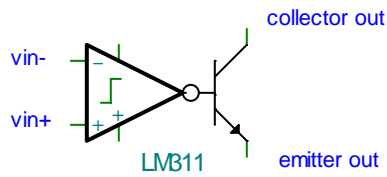
This circuit chip is an example of an "open collector" output, so you must provide the collector load resistor used in the comparator circuits. Also note that the sign of the operational amplifier is inverted, denoted by the small circle on the output. This way, if $v_+ > v_-$ the output of the operational amplifier will go to the negative supply voltage and turn off the transistor because the BE junction will not be forward biased. Hook up the LM311 in the following circuit: Note that the emitter must be made negative, -5 V, in order for the circuit to oscillate.
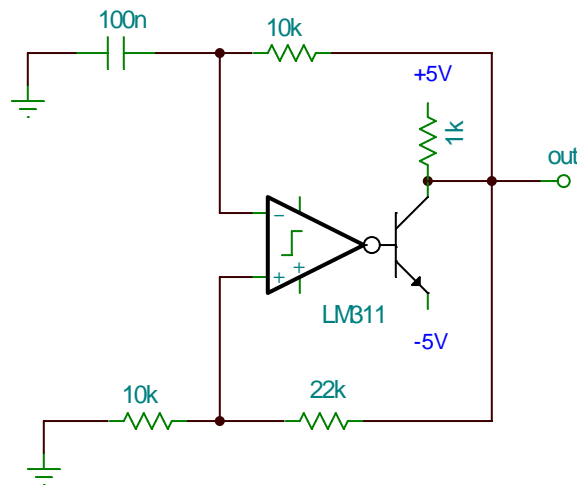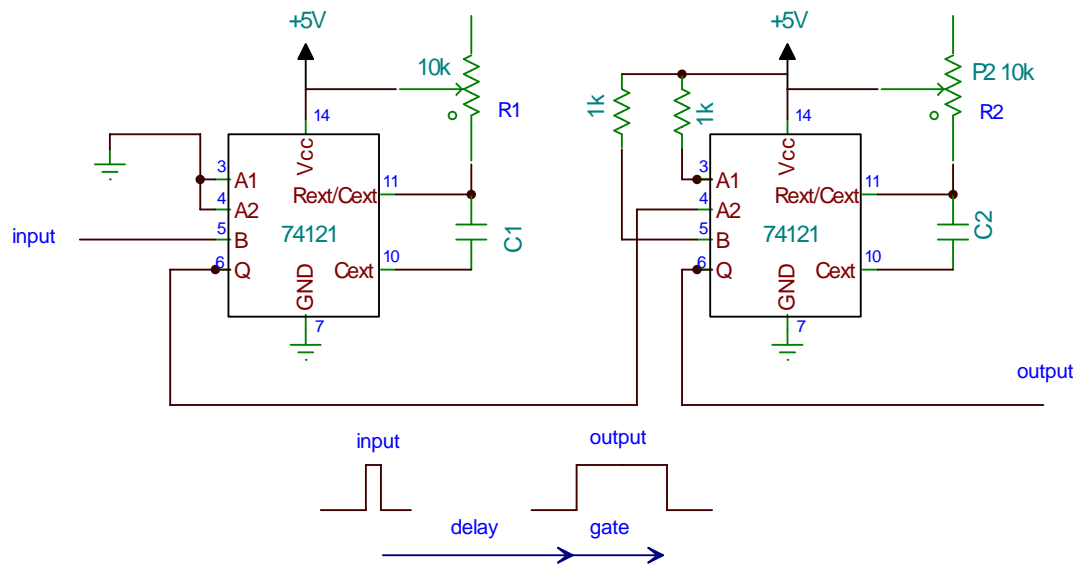

Make sure you understand how this circuit works. Is the period of oscillation what you expect based on your component values? Explain. Now, change the value of the capacitor from 0.1 μ to some other value. Does the period of oscillation change as you would expect? The above circuit essentially converts the value of capacitance to a frequency. Certain types of measurement transducers (such as Baratron capacitance manometers) are based upon changes in capacitance; by incorporating these capacitors into an oscillator, the value of capacitance is encoded in the frequency of the oscillator. Since time and frequency can be measured very accurately, these schemes provide very high sensitivity. Leave you oscillator hooked up for the next section of the lab.

III. Monostable Multivibrator, or "One-shot" The monostable multivibrator, or one-shot, is a common circuit for applications where precise timing is not needed. The 74121 uses an integration scheme combined with a comparator (similar to the relaxation oscillator), but also includes a flip-flop and some additional circuitry so that instead of oscillating continuously, the "one-shot" can be driven to one particular state by an applied trigger pulse, and then after some controlled time the output will revert back to its original state. One use of a single 74121 is to act as a "pulse-stretcher"; you will use it in this way in the voltage controlled oscillator.
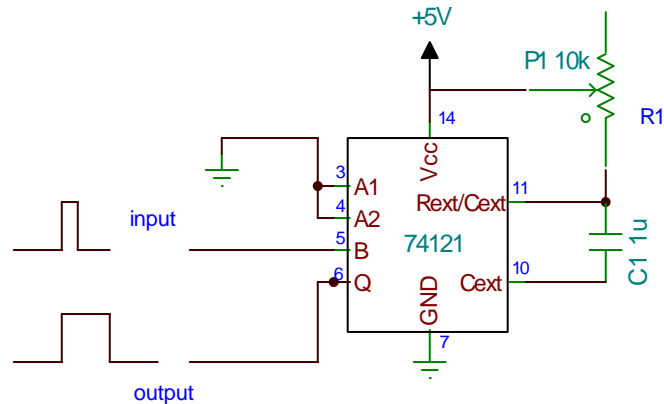

Hook up the circuit shown above. Start with C=1.0 microfarad and use a 10 K potentiometer for P1. Use the square-wave output from your relaxation oscillator to trigger the one-shot. Trigger the oscilloscope from the input trigger, and look at the output of the one-shot on the scope. Vary the value of R1 by turning the knob on the potentiometer, and you should see the "stretched" output pulse vary in duration.

Combining two 74121's can create gate-and-delay generator. Set up a second 74121, using the output of the first 74121 to trigger the second 74121.   In this case you create a variable delay (controlled by R1 and C1) and a "gate" (controlled by R2 and C2). Use a 10 K potentiometer for R2 and a 0.1 μF capacitor for C2. This circuit is widely used in experimental measurements where you want to define a precise window during which you do an experimental measurement. An example would be a laser spectroscopy experiment using a pulsed laser to generate fluorescence, where the laser pulse provides the trigger signal, and the gate-and-delay generator is used in conjunction with a sample-and-hold amplifier and/or a "boxcar averager" to control when you actually measure the fluorescence signal.   Adjust R1 and R2 to change the gate and the delay.

+5V

10k

R1

14

A1

A2

B

Q

3

4

5

6

Vcc

Rext/Cext

Cext

GND

74121

11

10

7

C1

input

1k

1k

+5V

P2 10k

R2

14

A1

A2

B

Q

3

4

5

6

Vcc

Rext/Cext

Cext

GND

74121

11

10

7

C2

output

input

output

delay

gate

IV. Voltage Controlled Oscillator One of the most important types of oscillator is one where the frequency of oscillation can be controlled by an input signal. Such an oscillator is called a voltage controlled oscillator (VCO). VCOs can be purchased as single chips or as part of a phase lock loop (PLL) chip. Note that in a VCO it is the *frequency* of oscillation that is "controlled" and not necessarily the amplitude of oscillation. In order to better understand how a VCO operates, you are going to construct your own VCO as shown here:
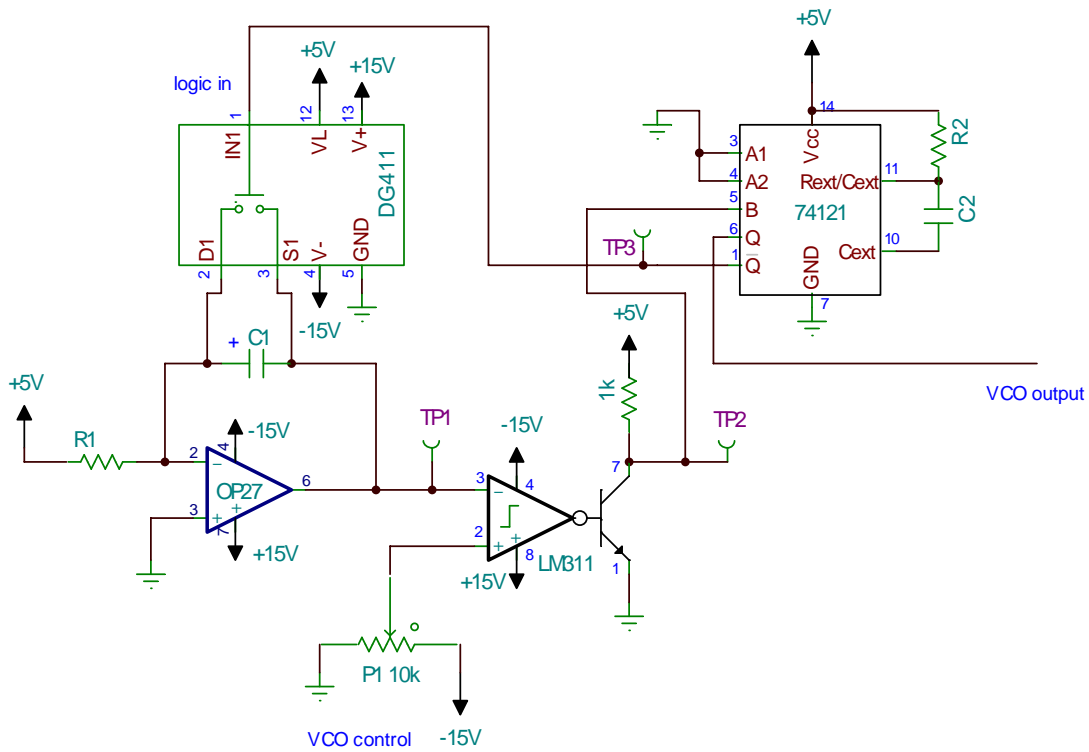

You will construct and test this circuit in sections in order to minimize mistakes and see the functionality of each section. Start by building the integrator. Use a 1 MΩ resistor and a 10 μF capacitor. This will provide a long enough time constant so you can easily see the charging with the scope or DVM.
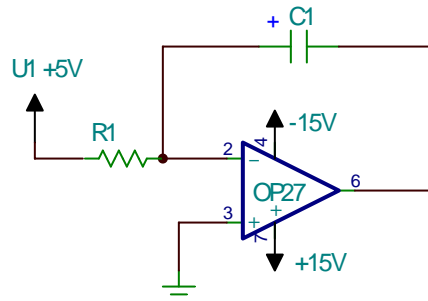
Look at the charging cycle by shorting the capacitor and then removing the short. Is the circuit behaving as you expect?

You will now add an FET analog switch to provide the short. The switch is part of the DG411 package. For now, use the output of one of the logic switches on the IDL-800 to control the analog switch. The pins needed for the DG411 are shown:
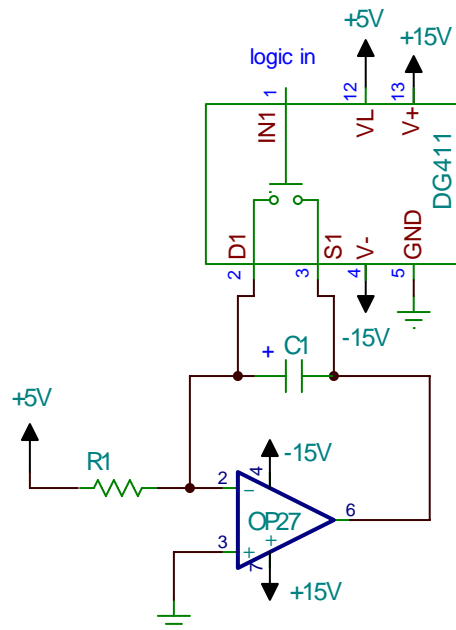

Test the reset of your integrator. What input is required at IN1 to "integrate" and what input is required to "reset"?

Now add the comparator. Use the LM311 with the emitter grounded and a 1 K resistor at the collector. Use a 10 K variable resistor to control the voltage at v_+. This is the threshold voltage.
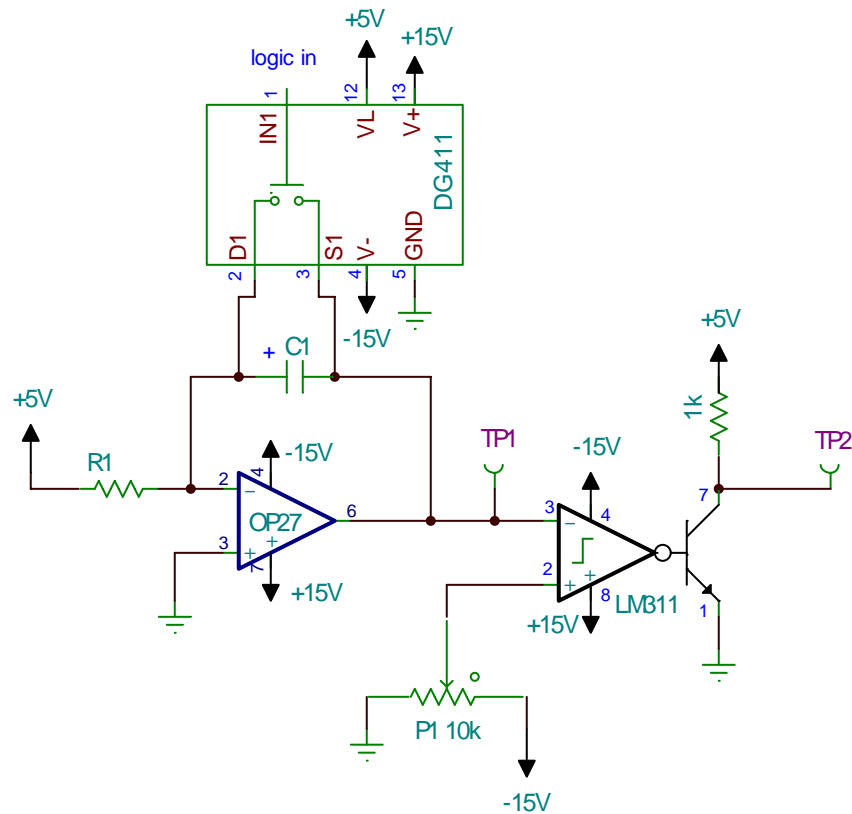
Set the threshold at – 5V. Monitor test point 1 and 2 simultaneously so you can look at the response of the comparator as the integrator is working. You still have control of the reset with the switch. Change the threshold to –10 V. Be sure you understand how your circuit is working at this point. When you are convinced that your circuit is working properly, speed up the integration by replacing the 10 μF capacitor with a 0.1 μF capacitor.

Now set up the monostable multivibrator (one shot). Build this circuit independent of the other components first, test it, and then combine it with the rest of the system. Again use a switch to test the operation.   The pulse length of the one shot is determined by the value of the resistor and capacitor that you use. Start with a 10 μF electrolytic capacitor (positive side goes to pin 10 of the 74121) and a 220 K resistor.
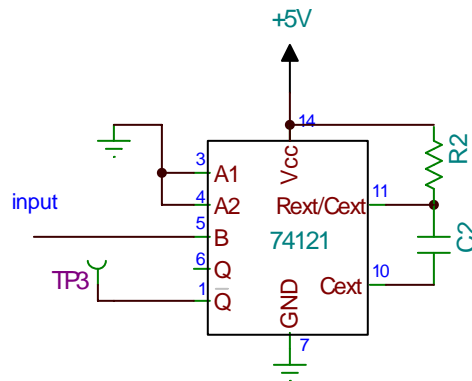
Confirm that the one shot fires on the rising edge of the input pulse. Change the capacitor to 1 μF and the resistor to 10 K to shorten the pulse. Add the one shot to your circuit so that the comparator controls the one shot and the one shot resets the integrator. Look at the output on pin 6 of the one shot. You should now have a working VCO.

At TP3, measure the time that the output is high and the time that the output is low. Also measure the threshold voltage with the DVM. What does the waveform look like at TP1? TP2? and V_o?
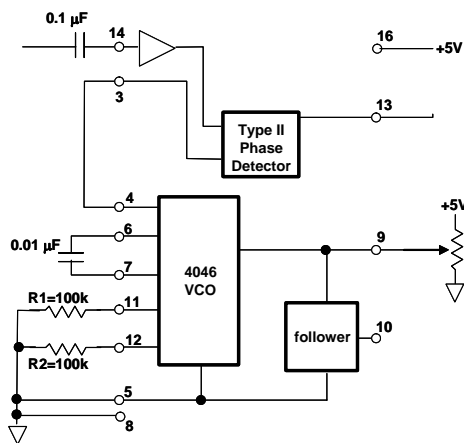
Let's play with the timing of the circuit. Reduce the resistor on the integrator to 100K. How does this affect the waveform at V_o? Now reduce R on the one shot to 1 K. How does this affect the waveform? Adjust the threshold and watch how the waveform changes. Do you understand the operation of the VCO?

Now, instead of connecting the non-inverting input of the LM311 to the potentiometer, connect this input directly to your function generator. Set up your oscilloscope so that one channel is your function generator and the other channel is the output of your VCO. Set your function generator so that its average voltage is about -2.5V and the amplitude of the input is approximately 2 V peak, so that the input signal goes from approximately -0.5 to -4.5 V; now look at the output of the VCO. The type of signal you are seeing is called "frequency modulation". The "average" frequency of oscillator is called the carrier frequency; the instantaneous frequency ranges over some smaller range of values that is controlled by the amplitude of your input signal. This is how information is encoded in FM radio and in television. In both case, the frequency of a carrier (for FM, 88 MHz – 108 MHz, depending on the station) is modulated by an input audio signal (0 – 20 kHz).

V. Phase-locked Loop (Do this only if you have time) The phase-locked loop has many similarities to an op-amp: it has two inputs, a high-gain section, and a set of resistors and capacitors that filter the output signal and couple it back to the input.   Like an op-amp, one of the critical features of the phase-locked loop is to have enough feedback that it keeps the inputs to the phase comparator equal, while also making sure that the magnitude and phase shifts caused by the filter do not cause the PLL to oscillate.

The major parts of the PLL are the voltage-controlled oscillator, the phase detector (or phase comparator), and the loop filter.

We'll start with the VCO. In a PLL, the oscillator will operate over some limited range. The center and width of the range are controlled by the resistors R1 and R2 and by the capacitor between pins 7 and 8. Hook up the PLL c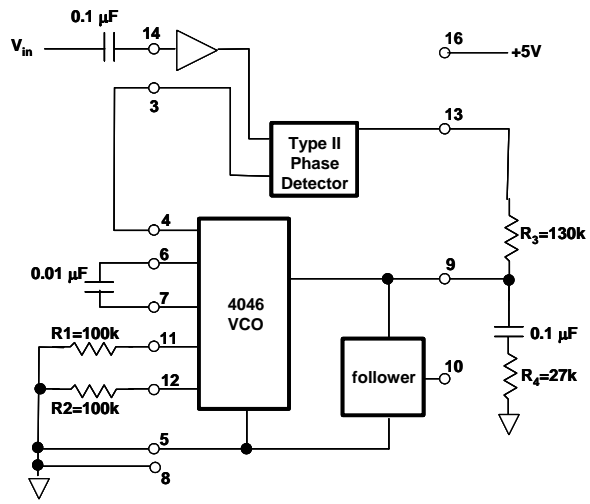hip as shown below. To control the VCO, use an external potentiometer between +5 V and ground, and connect the wiper to pin 9 of the VCO. Look at the output of the VCO at pin 4. As you vary the input to pin 9 over a range from 0 to + 5 V, you should see the output frequency of the PLL change. Be sure to write down what frequency range your oscillator range covers.

In the PLL, the input signal is applied to one input of the phase detector at pin 14. The output of the VCO is applied to the other leg of the phase detector at pin 3. The phase comparator compares these inputs, and creates output pulses at pin 13. These pulses are filtered by the lead-lag filter (the 0.1 µF capacitor along with the 27k and 130 resistors) and applied back to the VCO as shown below. The 130k resistor and 0.1 microfarad capacitor form a low-pass filter and the additional 27k resistor makes it so that at high frequencies the phase shift from pin 13 back to pin 9 does not get too big, which would cause oscillation. (The phase shift of the lead-lag filter approaches zero at very high and very low frequencies).

Put your signal generator on square wave mode, look at it on the oscilloscope, and adjust its output to go from 0 to + 5 V; then connect it through a 0.1 microfarad capacitor to pin 14. Now, connect your oscilloscope up so that one channel is connected to your input signal, and the other channel is connected to pin 4, which is the output of the VCO. Adjust the frequency of your signal source; at some point you should see the output of the VCO "lock" to the input signal. You may see some "jitter" on the VCO output.

0.1 µF

V_{in}

14

3

16 +5V

Type II Phase Detector

13

4

6

0.01 µF

7

4046 VCO

R1=100k 11

12

R2=100k

5

8

9

R_3=130k

follower 10

0.1 µF

R_4=27k