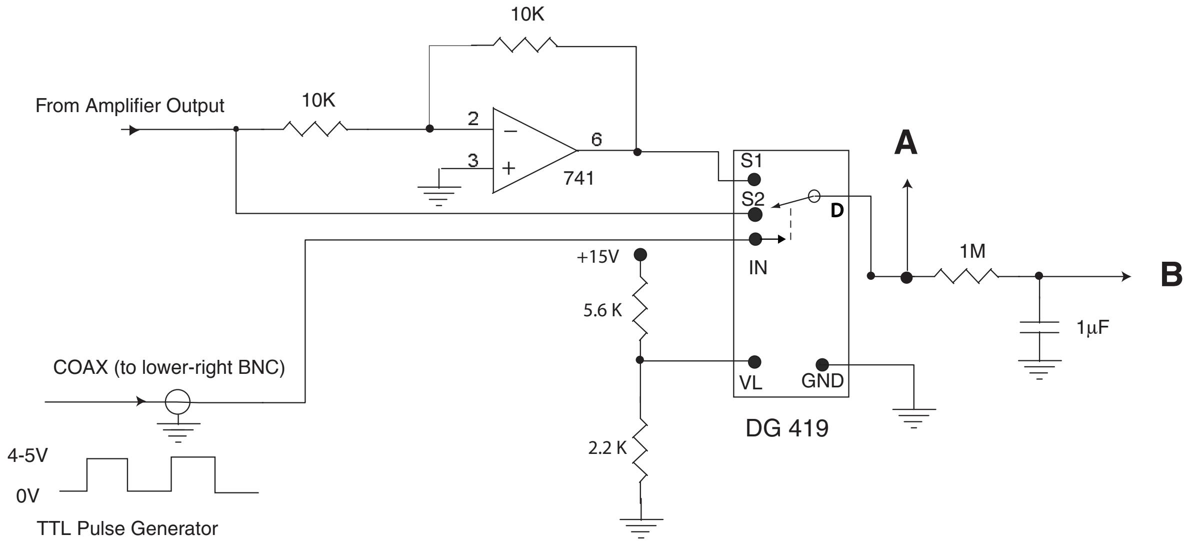
Physics 623
Phase Detector

November 14, 2017

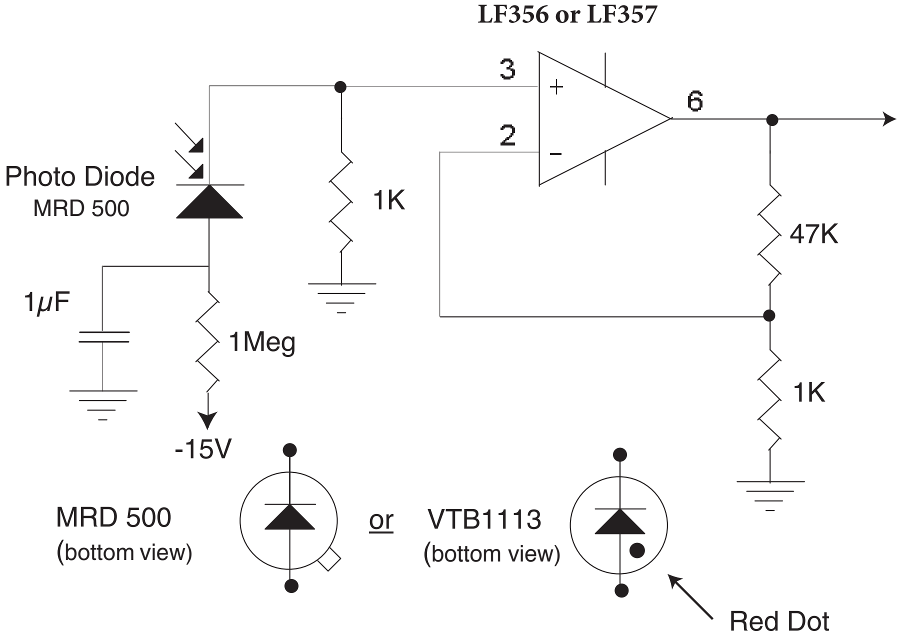
Reading: Section 8.14, pp 574-578 in *Horowitz-Hill*

Answer questions 1 and 2 in this writeup before coming to the lab. Read the referenced sections if you have not already done this.

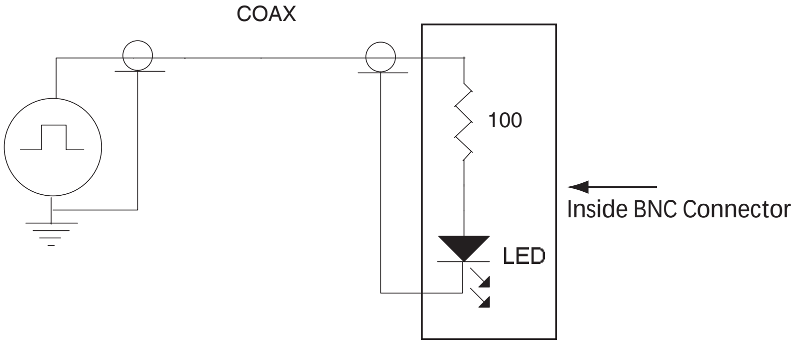
You will use your 3-stage tuned amplifier and low-noise input stage from the Johnson Noise lab. Construct the following circuit on the lower breadboard block as far to the right as possible (to keep it away from the 356 input).Be sure that the square wave comes in from the right side of the breadboard. Note that the DG-419 requires a ground connection for input control reference. Show the power supply and bypass connections for each type of chip in your notebook at the beginning of the lab. (See the device data sheets and note carefully that although the DG-419 uses the same power supply pins as the 741 — standard for 8 pin opamps — the +15 and −15 assignments are **reversed**.)



Set the pulse generator to give a 5 V square wave output at a frequency near f_0. Replace the 1 M resistor at the previous lab LF356/7 amplifier input with a 1 K and add a photodiode as shown below:



Put a $\sim$ 25 mm piece of black tubing over the end or your photodiode to limit the amount of background light. Bend the leads so it is aimed nearly horizontally at the left end of your breadboard, pointing it a part of the room that is not too bright (set up a dark screen, if necessary). Put a red LED in series with a 100 ohm resistor (available as a packaged unit in a BNC connector) and connect it to the pulse generator input as shown below.



- Look at the **amplifier** output on the scope. Push the LED into the end of the black tube on the photodiode and adjust the distance to give an output that is large, but not close to saturating (ie $\sim 4 - 18$ V p-p). If the amplitude is too large, reduce the light response by replacing the 1 K resistor on the amplifier input with a smaller value. Adjust the frequency for maximum amplitude (at f_0). The output will be a sine wave, even though you are driving the LED with a square wave.

Question 1 Why is the output sinusoidal? (Hint; think of the Fourier analysis of square waves!)

- Look at the signal on the output of the broadband 356 stage. Now look at the output of the phase detector switch at point A. Lock-in amplifiers usually have some provision for adjusting the phase of the reference relative to the signal. We will cheat and use the rapid change of phase with frequency of the signal while the reference (switching) phase remains constant. Try adjusting the frequency while watching point A. (Be sure the scope is DC coupled!) Sketch what you see. It works better to increase the frequency than to decrease it.

- Guess how the average voltage at A changes as you change the phase, then look at the output of the low-pass filter at point B. (Unfortunately, the amplitude also changes as you change the frequency and you will have to allow for this.) Use a 10× probe to look at point B. (Why?) Set the frequency back to f_0 to give zero phase shift.

- Now replace the 1K resistor with a 1M resistor and remove the LED. This will increase the light sensitivity by a factor of 1000. Looking at the amplifier output on the scope, you will see the Johnson noise of the 1M resistor, plus some 60 Hz hash from the room lights. If the output is saturating at any time due to pick-up, try placing a small piece (5 cm × 5 cm) of grounded Aluminum foil in such a way as to shield the input circuit. Check the output of the LF356 stage with the DC-coupled scope to be sure that it isn't saturating from ambient light. Set up shields or aim the tubing as necessary to keep the output of the amplifier last stage from saturating. Bring the LED near the end of the photodiode tube, while looking at the amplifier output (point A). Note the high sensitivity – but also the large amount of noise. Now look at the filter output (point B) on the other scope channel.

- Set the scope gain to 20 mV/cm. Note the noise level. Use a 10× scope probe (so that you do not overload the high impedance output), and DC coupling so you don't attenuate the very low frequencies of interest (AC coupling on the scope has a corner frequency of 3 Hz). Since the bandwidth is $\ll 1$ Hz, you will need to set the scope sweep to ~ 4 s/cm to see enough noise so that the rms amplitude can be estimated. You can use the scope's r.m.s. voltage calculator if you offset the DC component to zero.

Question 2 What *rms* fluctuation do you expect in the output of this filter due to the Johnson noise in the 1M resistor?

The output bandwidth is now set by the long time constant of the filter and as seen from the input side of the phase detector is almost a delta function at f_0. Thus the 3-stage amplifier gain is the peak gain (the gain evaluated at f_0). The effective width of the low-pass filter is <u>twice</u> the noise bandwidth of the low-pass filter because both positive and negative differences from f_0 are passed. The noise bandwidth is not the same as the conventional 3 db bandwidth ($\frac{1}{2\pi RC}$) for a single pole low-pass filter. The "noise bandwidth" is the width of a perfect "brick-wall" low pass filter that lets through the same noise voltage. It is not difficult to do the integral or you can look it up in Horowitz and Hill in the table for various filter configurations. The effective bandwidth is smaller than this result by 1/2, since noise components 90° out of phase with the reference don't give any output even though they are at the correct frequency. Note that the phase detector itself has an effective gain $< |\sin \omega t| >$. (Think of the output for a 1V p-p input at $f_0 + \delta$, where $0 < \delta \ll 1/\tau_{\text{filter}}$.)

- Try holding your thumb over the photodiode and then shining the LED through it.
- Can you see the shift at point B?
- Can you see the light through your hand?
- Can you see the signal at point A?