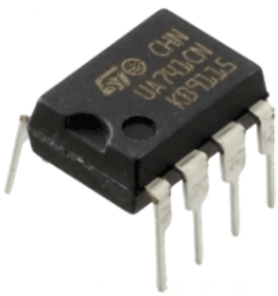
Physics 364, Fall 2014, Lab #8 **Name:** ____________________

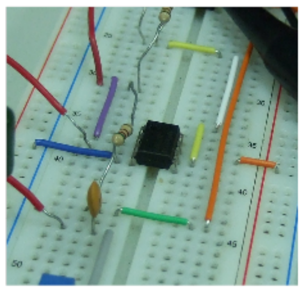
(opamps II)

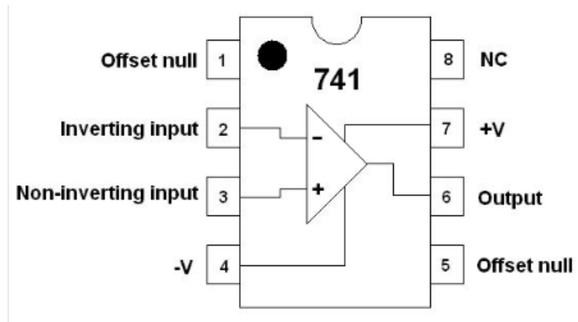
Wednesday, September 24 (section 401); Thursday, September 25 (section 402)

Course materials and schedule are at `positron.hep.upenn.edu/p364`

Today we continue to work with opamp circuits that can be understood by application of the Golden Rules.







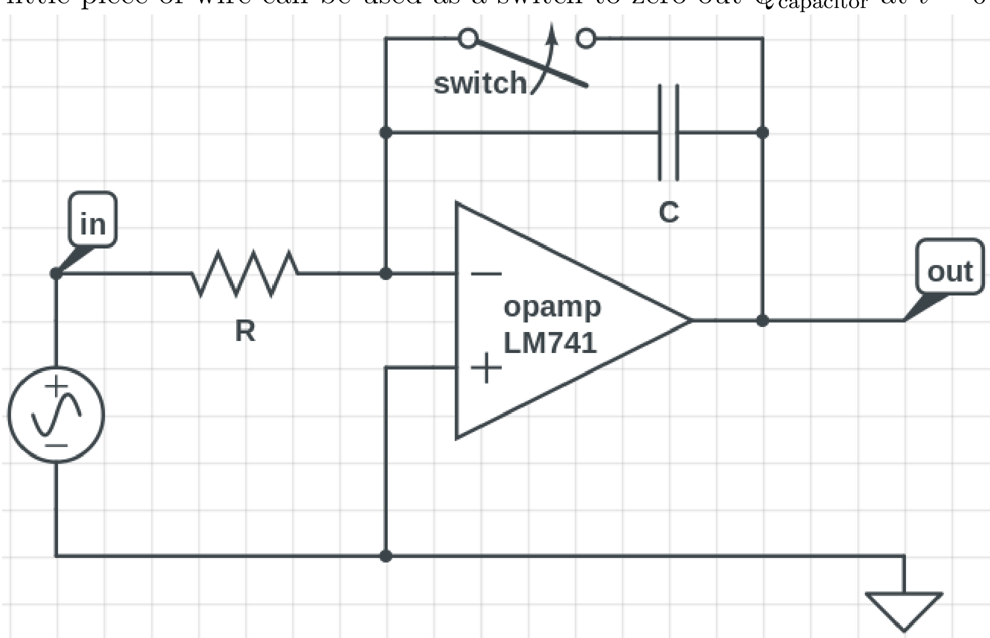
Part 1 **Start Time:** ____________

opamp integrator (time estimate: 45 minutes)

Let's start with the opamp *integrator*. Ideally, the integrator looks like the circuit drawn below (which you don't need to build just yet), and has output

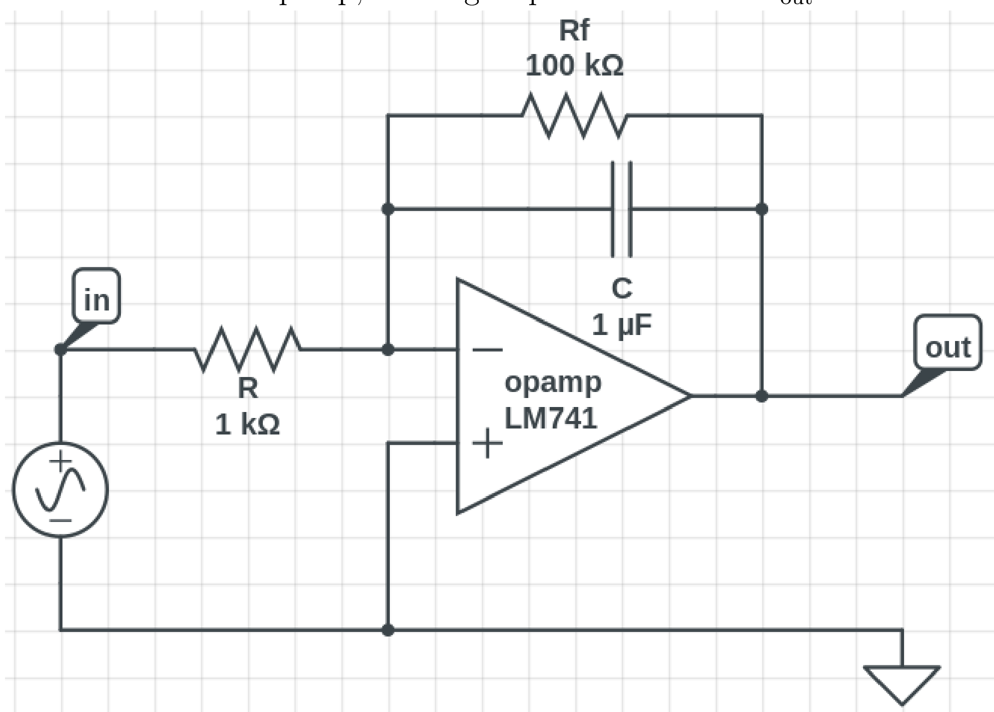
$$V_{\text{out}}(t) = -\frac{1}{RC}\int_{t'=0}^{t} V_{\text{in}}(t')\ \mathrm{d}t'.$$

The purpose of the switch is to zero the charge on the capacitor for $t < 0$. Opening the switch at $t = 0$ ensures that the integral starts from $V_{\text{out}}(t = 0) = 0$. On a simple breadboard set-up, a little piece of wire can be used as a switch to zero out $Q_{\text{capacitor}}$ at $t = 0$.



1.1 (Nothing to build here.) Assuming that the switch is closed for $t < 0$ and open for $t \geq 0$, use the Golden Rules and your knowledge of capacitors to show that $V_{\mathrm{out}}(t)$ has the form of the above equation.

1.2 The reason why the switch is important in the above circuit is that without the switch, the integral will eventually become large enough to saturate V_{out} near $\pm V_{\text{supply}}$. Even if the average value of $V_{\text{in}}(t)$ is only a few millivolts, the time integral of this tiny average will be large enough to saturate V_{out}, after thousands of RC times have elapsed. (If you use $\pm V_{\text{supply}} = \pm 15$ V for a 741 opamp, the largest possible value of V_{out} is about ± 13 V.)



A common alternative to using a switch is to drain the capacitor continuously through a large feedback resistor. Let's take that approach. Build the integrator shown above, with a 100 kΩ "bleeder" resistor.

What is the time constant for draining the capacitor?

Try your integrator out with a number of different input waveforms. Does it integrate?

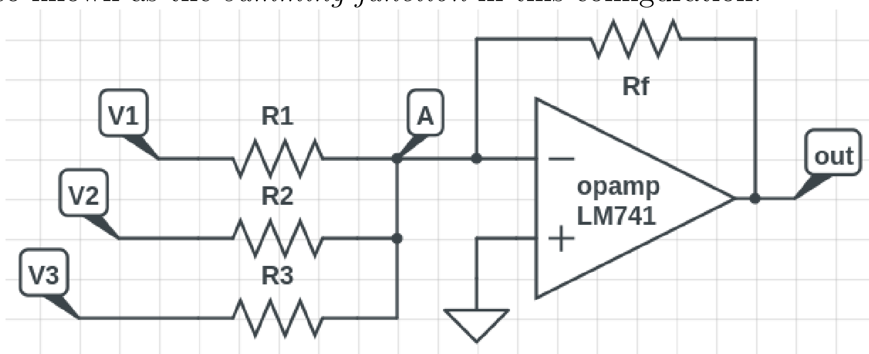
1.3 Question (nothing to build here): Can you look at the integrator circuit (leaving out R_F, to simplify the math) as a special case of the inverting amplifier, with impedances replacing the resistors in the gain expression? If you do so, what is $V_{\text{out}}/V_{\text{in}}$ for a sine wave? Is this expression equivalent to integrating the sine wave? (You can answer this question with a hand-waving argument — no need for elaborate math.)

1.4 If you wanted to make a differentiator instead of an integrator, how would you change this circuit? You don't need to do the math to prove that it works, but if you're so inclined, it can be fun to do so. Optional: if you have time, try building your differentiator and see if it works as expected. If it misbehaves (e.g. oscillates?), call one of us over to suggest a fix to improve its stability.

Part 2 **Start Time:** ______________

summing amplifier (time estimate: 30 minutes)

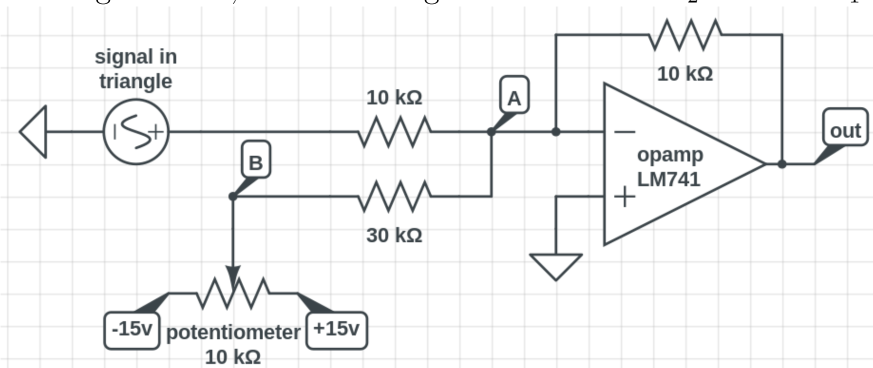
The circuit shown below is called the opamp *summing amplifier,* since it produces an output V_{out} that is a (weighted) sum of its several input voltages V_i. It's yet another variant of the inverting-amplifier configuration that we studied in the previous lab. The virtual ground at point **A** is also known as the *summing junction* in this configuration.



2.1 (Nothing to build yet!) Use the opamp Golden Rules to derive an expression for V_{out}, for the above circuit, in terms of V_1, V_2, V_3, and the four resistor values. The key here is to make use of the fact that point **A** is a *virtual ground,* which makes it easy for you to calculate the current through each resistor. You might want to check that in the limiting case in which $R_2 = R_3 = \infty$, i.e. inputs 2 and 3 are disconnected, your V_{out} expression reduces to the familiar expression for the inverting amplifier's V_{out}.

2.2 Now let's use the opamp summing amplifier to add an adjustable DC offset to the signal coming out of your function generator.[1] (Turn off the FG's own DC offset, and pretend that your friend's FG is missing this handy feature and needs your opamp know-how to come to the rescue.) This is an opportunity for you to meet a useful three-terminal device called a *potentiometer,* which we're embarrassed not to have shown you sooner.

A potentiometer of resistance R ($R = 10$ kΩ in this case) has three terminals, which we'll call $1, 2, 3$. The resistance R_{13} between the two outer terminals is R. If you turn the knob a fraction α of the way from end to end, you get $R_{12} = \alpha R$ and $R_{23} = (1-\alpha)R$ between terminal 2 (the middle terminal, a.k.a. the "wiper") and the outer terminals. The potentiometer is often used as a voltage divider, where turning the knob varies V_2 between V_1 and V_3.



Build the opamp summing circuit shown above, and show that by turning the potentiometer knob, you can add a DC offset to V_{out}. Check that the voltage at point **B** varies between ±15 V as you turn the knob on the potentiometer. What is the range of DC offsets at V_{out}? Is it what you expect?

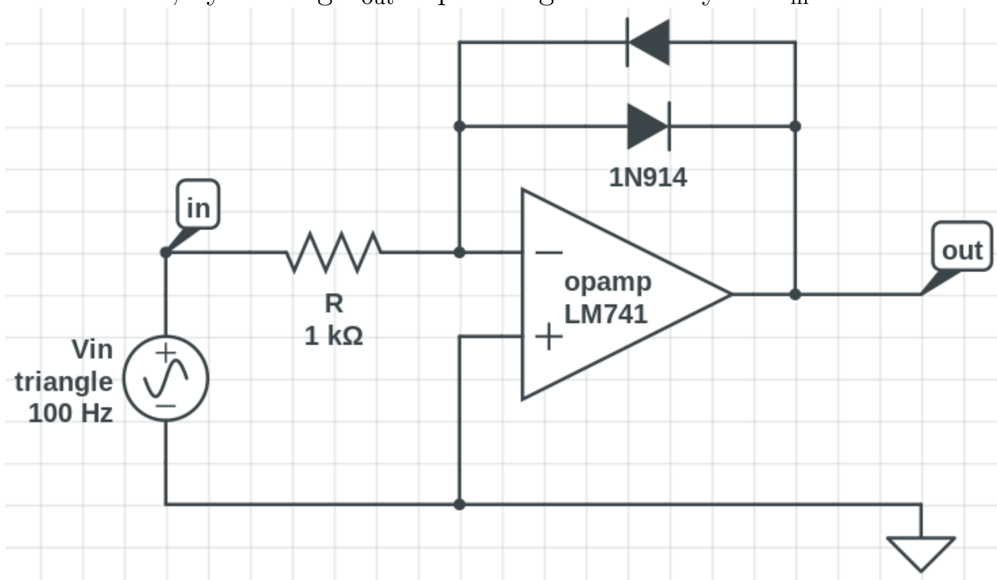
[1]Part 2.2 is adapted from Tom Hayes's Lab 6L.6.

2.3 With what value would you replace the 30 kΩ resistor if you wanted the offset range at V_{out} to be ±10 V instead? Give it a try! We don't have the exact resistor you need, so you'll need to improvise by combining two resistors that we do have.

Part 3 **Start Time:** ______________

logarithmic amplifier (time estimate: 30 minutes)

The idea here is to put something unusual (and nonlinear!) into the feedback loop, to illustrate the generality of feedback. It seems remarkable that for such a wide range of operations that you can "do" in the feedback path, the opamp's output somehow finds a way to "undo" these operations. In this case, the opamp will magically "undo" the exponential behavior of the diode, by making V_{out} depend logarithmically on V_{in}.



3.1 Try the circuit shown above, using an input waveform that is DC biased, so that it is always positive (or always negative) — for example a 4 V_{pp} **triangle** wave with a 2 V DC offset. See if V_{out} appears to respond logarithmically. (We expect the top of the triangle to be squashed a bit, like a barn roof, while the bottom of the triangle has its slope exaggerated.) **If you didn't manage to try CircuitLab last week, feel free to do Part 3 in CircuitLab instead of on the breadboard.**

3.2 See if you can derive an expression for $V_{\rm out}(t)$ using the Golden Rules and the Shockley diode equation,

$$I = I_{\rm sat} e^{qV/kT}$$

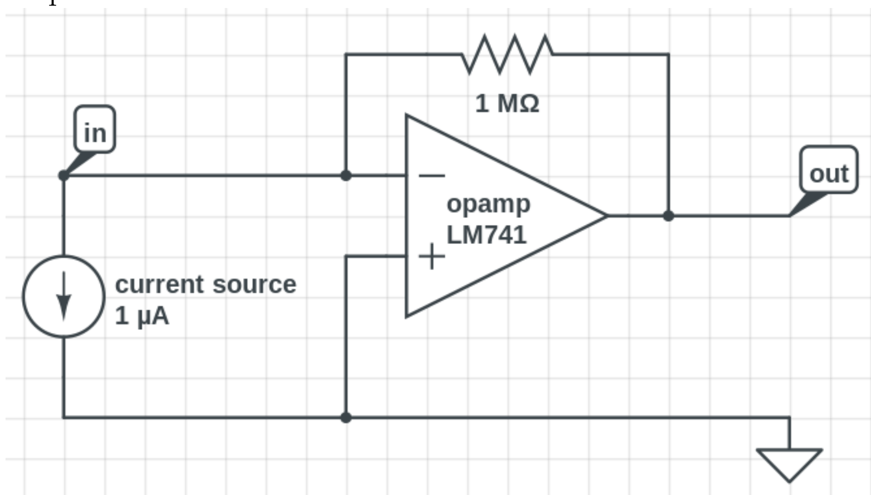
where $kT/q \approx 25$ mV at room temperature, and $I_{\rm sat}$ is a constant that depends on the diode design. (To be precise, the diode equation is $I = I_{\rm sat}(e^{qV/kT} - 1)$, but $I_{\rm sat}$ is so small that this difference is seldom important.) Assume that $V_{\rm in}(t) > 0$ so that the upper of the two diodes can be ignored.

3.3 If you have time, repeat part 3.1 without the DC offset, and see if you can qualitatively make sense of the shape of $V_{\rm out}(t)$, for a triangle-wave input. We put the second diode into the feedback path so that the output would be sensible for either sign of $V_{\rm in}(t)$.

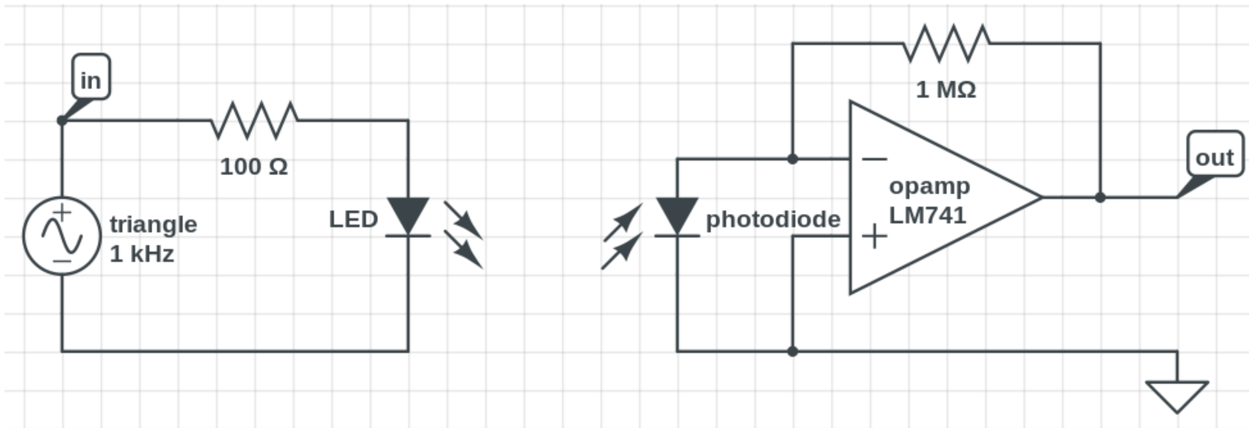
Part 4 **Start Time:** ______________

current-to-voltage amplifier (time estimate: 45 minutes)

When struck by incoming light, a photodiode should look like a very weak current source, emitting current in proportion to detected light. The amplifier drawn below is basically the inverting configuration with $R_{\text{in}} = 0\ \Omega$, i.e. with the resistor at the input replaced by a wire. The current source looks right into a virtual ground, with $\approx$ zero input resistance. Remember that the output of a weak voltage source is preserved by a load having a very large input resistance; conversely, the output of a weak current source is preserved by a load having a very small input resistance. A voltage source prefers to drive an open circuit, while a current source prefers to drive a short circuit.



4.1 Using the enormous 1 MΩ resistor shown in the above schematic, what is the output of this amplifier for an input current of 1 μA?



4.2 What you want to do next (though some improvisation may be needed to make this work) is to drive an LED (protected by a resistor) with the function generator. The signal from the LED travels (optically!) to the photodiode, whose signal you will amplify and display on the scope. Look around the room to compare notes with people who have got something working here.

(blank page)