Physics 364, Fall 2014, reading due 2014-10-05.

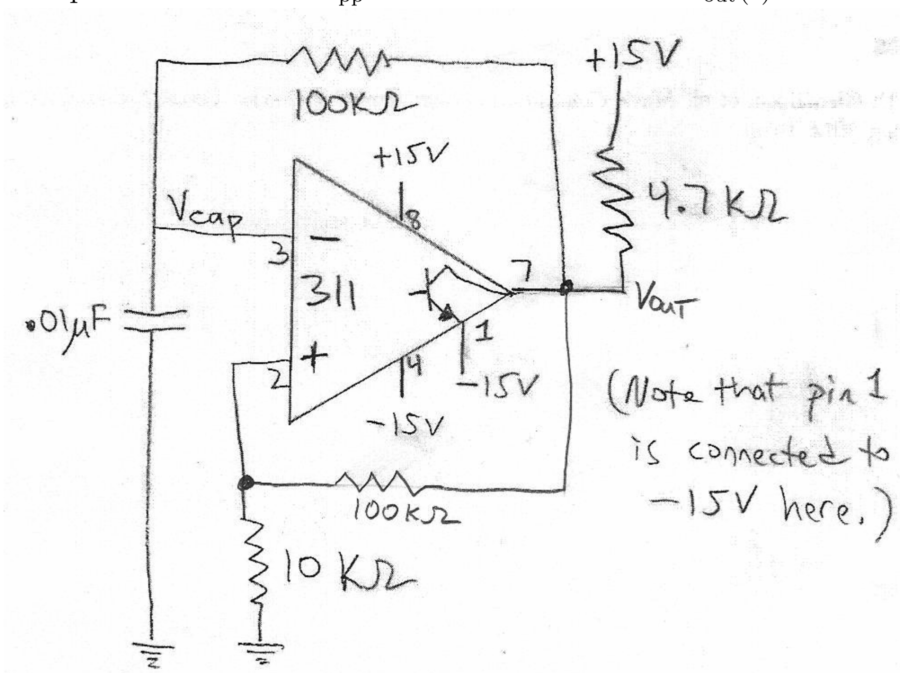
Email your answers to ashmansk@hep.upenn.edu by 11pm on Sunday

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

Assignment: (a) First read through my notes, which are very short this time! (b) Then read Eggleston's absurdly short §6.2 (pp 153–154) and his also quite short §6.5 (pp 165–167). (c) Then email me your answers to the questions below.

1. Why would a bit of hysteresis be useful in a thermostat? What is a comparator? What is a Schmitt trigger?

2. Briefly describe why V_{cap} in the circuit shown below oscillates back and forth between about ± 1.3 V. The capacitor voltage $V_{\text{cap}}(t)$ looks like a ≈ 3 kHz triangle wave with amplitude about 2.7 V_{pp}. What waveform does $V_{\text{out}}(t)$ look like?

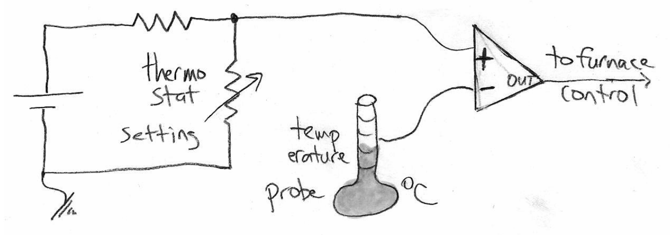


3. Is there anything from this reading assignment that you found confusing and would like me to try to clarify? If you didn't find anything confusing, what topic did you find most interesting?

4. How much time did it take you to complete this assignment?

So far we have used opamps mainly in their linear mode of operation (where V_{out} is linearly related to the inputs, rather than being saturated near $\pm V_S$), and we have used them always with *negative feedback*. Now let's look at **comparators**, which are like opamps that are optimized for non-linear use, where V_{out} is intended to be saturated at its maximum or minimum value, rather than having V_{out} linearly related to the inputs. In this context, we will also see a case in which **positive feedback** will be useful.

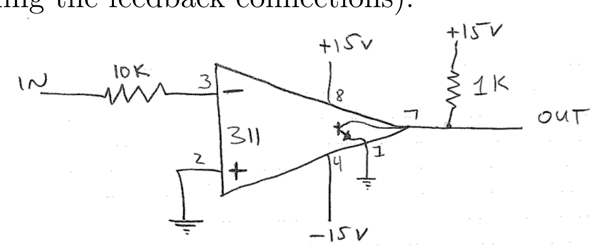
Suppose you just want to compare two signals: for instance, you might want to compare the temperature of your room to a thermostat setting. When $V_{\text{probe}} < V_{\text{setting}}$ in the figure below, the furnace control is driven to V_{S+} (e.g. +15 V), and when $V_{\text{probe}} > V_{\text{setting}}$, the furnace control is driven to V_{S-} (e.g. −15 V).



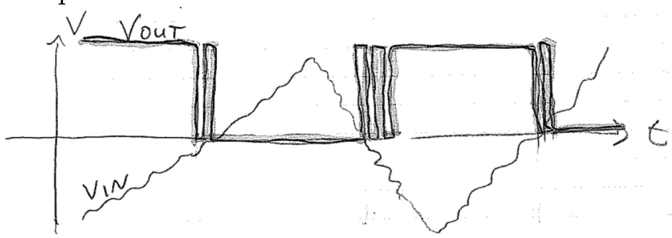
We could do this with an opamp. But ...

- Opamps don't like to be (i.e. their design is not optimized for being) slammed from one power-supply rail to the other, and they can take some time to recover from each transition.
- We may want to slew from OFF to ON and back faster than the limited opamp slew rate will allow.
- The opamp's $V_{S\pm}$ may not be what we want for the two possible output states (e.g. for the ON and OFF voltages to send to the furnace control). We may want more flexibility in choice of output voltages for the ON and OFF states.

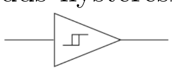
For these reasons, the **comparator** exists. The figure below shows an LM311 comparator (before adding the feedback connections).



The problem with this circuit is that the presence of any noise at all in the input signal makes it very indecisive about which value its output should take. Instead of turning the furnace on or off just once when the temperature is close to the thermostat setting, it turns it on and off many times before finally making up its mind, as illustrated below. We'll fix that problem in a moment.

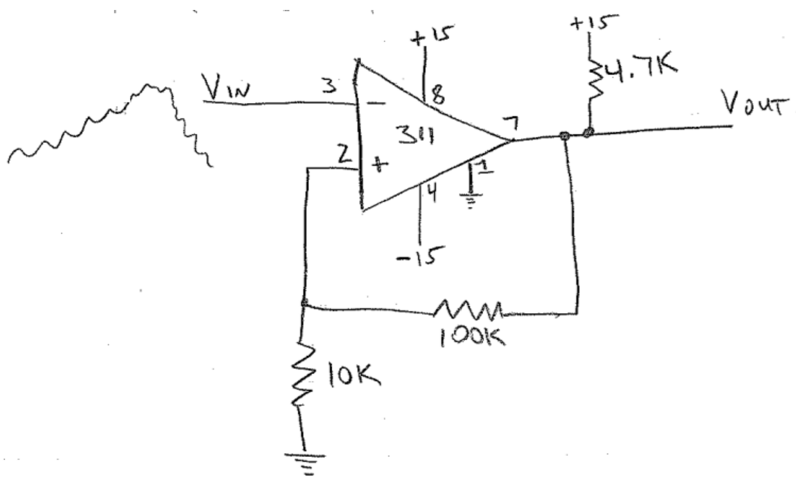


By the way, the mysterious-looking output is called an *open-collector* output. When the output is in the LOW state, it looks like a short circuit to ground (or more precisely, a short circuit to whatever is connected at pin 1, which in this case is ground). When the output is in the HIGH state, it looks like an open circuit. This gives you considerable flexibility in using the output. An open-collector output requires a *pullup resistor* to reach the proper HIGH voltage. This nomenclature and the way it is drawn on the diagram will make much more sense to you after next week, when we study transistors.

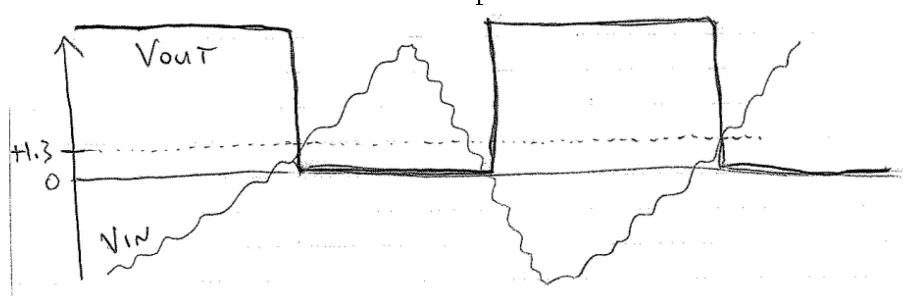
The solution to the open-loop comparator's indecisiveness is called a **Schmitt trigger**. It adds hysteresis to the circuit. In fact, the schematic symbol for a Schmitt trigger is  which resembles the M vs. H curve for a ferromagnet (drawn on the inside of an opamp-like symbol).

It would be helpful to define hysteresis here.

The figure below uses a '311 comparator to implement a Schmitt trigger. When V_{out} is driven to ground by the comparator (in the LOW state), we have $V_+ = 0$, so the low-to-high threshold is at 0 V. When V_{out} is pulled up to +15 V (in the HIGH state), we have $V_{\text{out}} = (15\text{ V})\frac{110\text{ k}\Omega}{110\text{ k}\Omega+4.7\text{ k}\Omega} \approx 14.4$ V, so then $V_+ = (14.4\text{ V})\frac{10\text{ k}\Omega}{10\text{ k}\Omega+100\text{ k}\Omega} \approx 1.3$ V. So the high-to-low threshold is at +1.3 V. (This sounds backward, but note that V_{in} is at the inverting (−) input in this example.



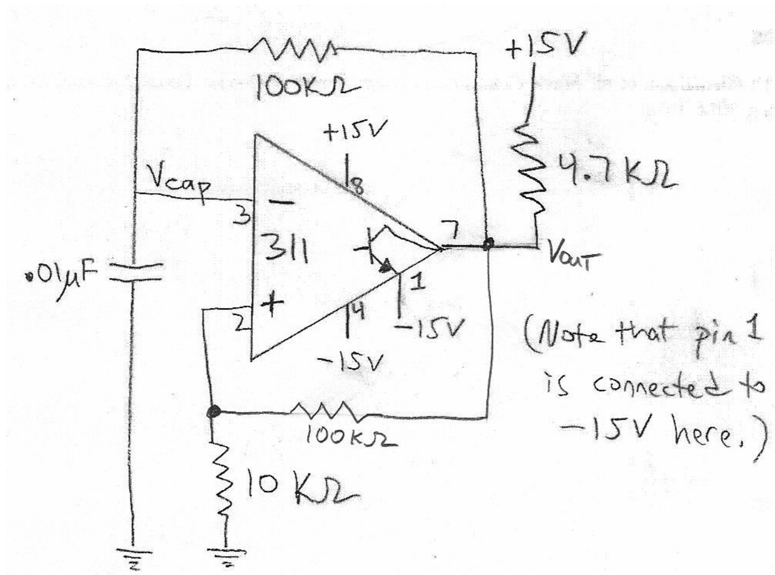
Note that the feedback connection from V_{out} goes to the **non-inverting** (+) input of the comparator. The resulting **hysteresis** looks like the figure below. The key idea is that the low-to-high threshold is different from the high-to-low threshold, because of the feedback connection. This cures the previous circuit's indecisiveness.



This is an example of **positive feedback**: once the output moves into a given state, the threshold changes so that it becomes relatively difficult to leave that state.[1] The motivation for the hysteresis is that once your thermostat has switched on the furnace, you want to leave it on for several minutes, not just long enough to raise the temperature by something like 0.1°C. A real thermostat contains something analogous to a Schmitt trigger (but usually implemented very differently).

One handy circuit you can build using a Schmitt trigger is an **oscillator** (below):

[1] Sun Tsu writes that upon sailing to the enemy's beach, you must order your soldiers to burn their own boats.



Here's how it works. Suppose that $V_{\rm cap} = 0$ at $t = 0$. If $V_{\rm out}$ is in its LOW state, it is driven to -15 V (since pin 1 is connected to -15 V), which reduces $V_{\rm cap}$ with initial rate of change

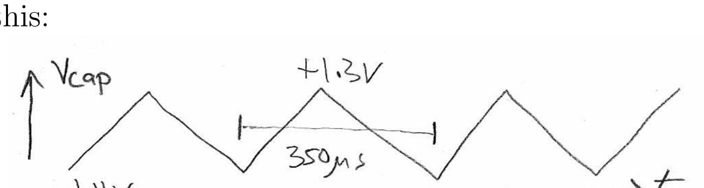
$$\frac{{\rm d}V_{\rm cap}}{{\rm d}t} = \frac{I}{C} = -\frac{(15\ {\rm V})/(100\ {\rm k}\Omega)}{0.01\ \mu{\rm F}} = -15\ {\rm V/ms}.$$

The threshold for leaving the LOW state is $(-15\ {\rm V})\left(\frac{10\ {\rm k}\Omega}{10\ {\rm k}\Omega+100\ {\rm k}\Omega}\right) \approx -1.36$ V.

Once $V_{\rm cap}$ reaches -1.36 V, $V_{\rm out}$ goes to the HIGH state, and is thus pulled up to $(+15\ {\rm V})\left(\frac{110\ {\rm k}\Omega}{114.7\ {\rm k}\Omega}\right) \approx 14.4$ V. The threshold for leaving the HIGH state to return to the LOW state is then $(+14.4\ {\rm V})\left(\frac{10\ {\rm k}\Omega}{110\ {\rm k}\Omega}\right) \approx +1.31$ V. The initial rate of change of $V_{\rm cap}$ is

$$\frac{{\rm d}V_{\rm cap}}{{\rm d}t} = \frac{I}{C} = \frac{(+14.4\ {\rm V} + 1.36\ {\rm V})/(100\ {\rm k}\Omega)}{0.01\ \mu{\rm F}} \approx +16\ {\rm V/ms}.$$

When $V_{\rm cap}$ reaches $+1.31$ V, it turns around again. The oscillation period is about $2 \times \frac{2.7\ {\rm V}}{15\ {\rm V/ms}} \approx 0.35$ ms, i.e. the frequency is about 3 kHz. A graph of $V_{\rm cap}(t)$ looks something like this:



So the circuit **oscillates** (deliberately): you could use it to make a clock. Eggleston's chapter 7 (which I doubt that I will ever assign for you to read) describes several different kinds of oscillators, in case you're curious.