Tim Savas
Homework 09

1 Odd Summing Circuit

Here is my circuit on Falstad, no signal B V compliance: https://tinyurl.com/y45zfba9 (for my own records)

Here is my circuit on Falstad, with signal B V compliance: https://tinyurl.com/y4z629ls

Current-to-voltage converter

First I deal with the current source signal. We have the source specification. We also have the output specification. The output should be 1V. We want this signal to be equally weighted with the other signal, which is 1V max. So we therefore need to install a current-to-voltage converter whereby the max of 100μA outputs 1V. That means it will have a R of 10K.

Followers

I install two followers after the two transducers, for good measure.

Summer, Flipper

Here I put in a summer that also amplifies the signal. We need to sum the signals such that at their max output of 1V each respectively, they output -4V. First I convert them to currents, because we are summing the converts not the voltages. I convert them to output .1mA each by causing their 1V to drop across 10K. They then sum to 0.2mA. Next it another Ohm's Law problem: what R should cause 0.2mA to flow across, with -4V on its other side? That is a 20K R. I add an inverting amplifier with a gain of -1 to flip it over to 4V.

Edit: I realized while answering this in the above, I did not account for the <0.1V output voltage compliance of signal source B. I went back and made what I think is the right adjustment. I'm keeping both answers for my own records. The below diagram is my response, top one is the one with the error.

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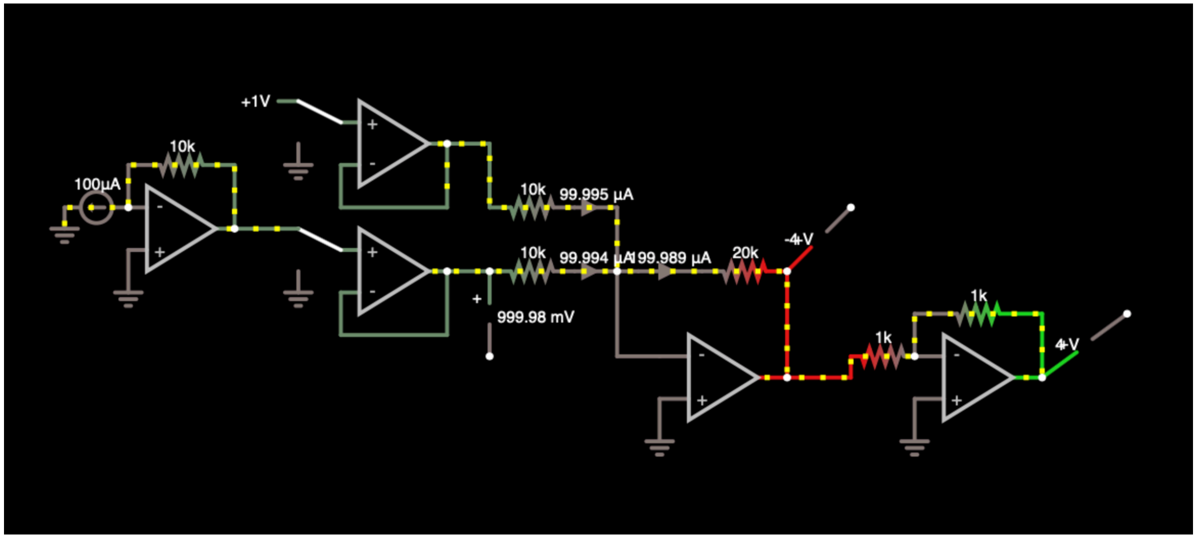
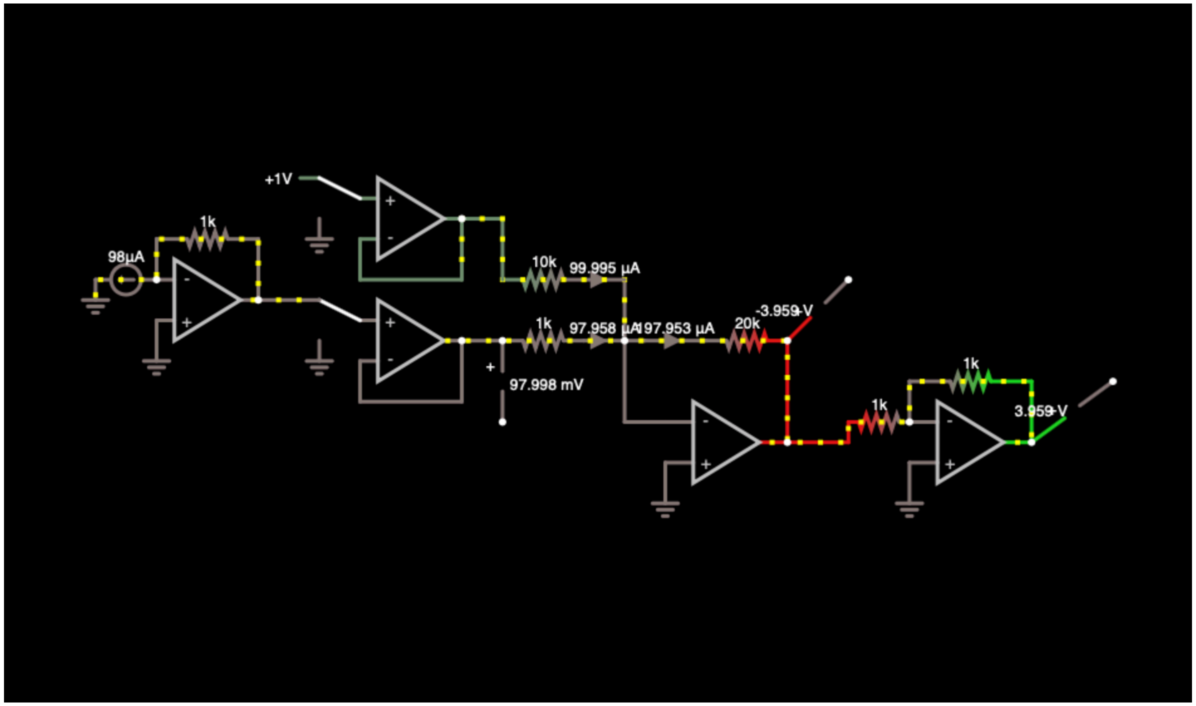




2 Lab Schmitt Trigger

No the Golden Rules don’t apply because they only apply during negative feedback setups. this is a positive feedback setup.

3 Thresholds

The two threshold voltages are contingent on what voltage we are feeding back to the non-inverting input of the '311. That's fairly straightforward looking at the V-divider that is placed in between the output and input.

Note that the output for this setup doesn't have much nuance to it—at all. It's either going to be 15V or -15V due to the super high gain of the setup. Therefore we will also only see two voltages fed back, proportional to those two outputs. They are 1/11th of 15V and -15V. For good measure, here's how we got there exactly:

Condition	V_{out}	R_1	R_2	$V_{threshold}$	Total
+	15	100000	10000	1.4	2.7
-	-15	100000	10000	-1.4	

So now we can think about how this kind of positive feedback will work in the setup:
- We turn it on and, say, it happens to be switched off.
- The pull up R gets pulled up to 15V.
- The non-inverting input sees 1.4V.
- The C had been discharged because we just turned on the power for the first time; the point above the C is just sitting at 0V.
- With 15V on the output, it starts charging the C: .1V, .2V, .4V, etc.
- The C stops charging at 1.4V, because the "comparator" sees a similarity and flips when it hits our 1.4V.
- Now it's -15V on the output.
- The threshold V immediately goes down to -1.4V on the non-inverting input.
- The C then starts to discharge.

*Note that we are assuming a linear slope for the charge of the C.

4 Frequency

This is a $I = C(\Delta V/\Delta t)$ equation question. We know everything except for time in our setup. What controls the time it takes the comparator to flip? Ultimately it's the time it takes the C to charge up and down to our threshold voltages. That's easy, that just goes back to our time-domain view of capacitors from Chapter 2:

What we know:
$I = 15V/100K = 15\mu A$
$C = .01\mu F$
$\Delta V = 2.8V$
$\Delta t = x$

$$I = C(\Delta V/\Delta t)$$
$$I\Delta t = C\Delta V$$
$$\Delta t = C\Delta V/I$$
$$\Delta t = .01\mu F(2.8V/150\mu A)$$
$$\Delta t = 187\mu s$$

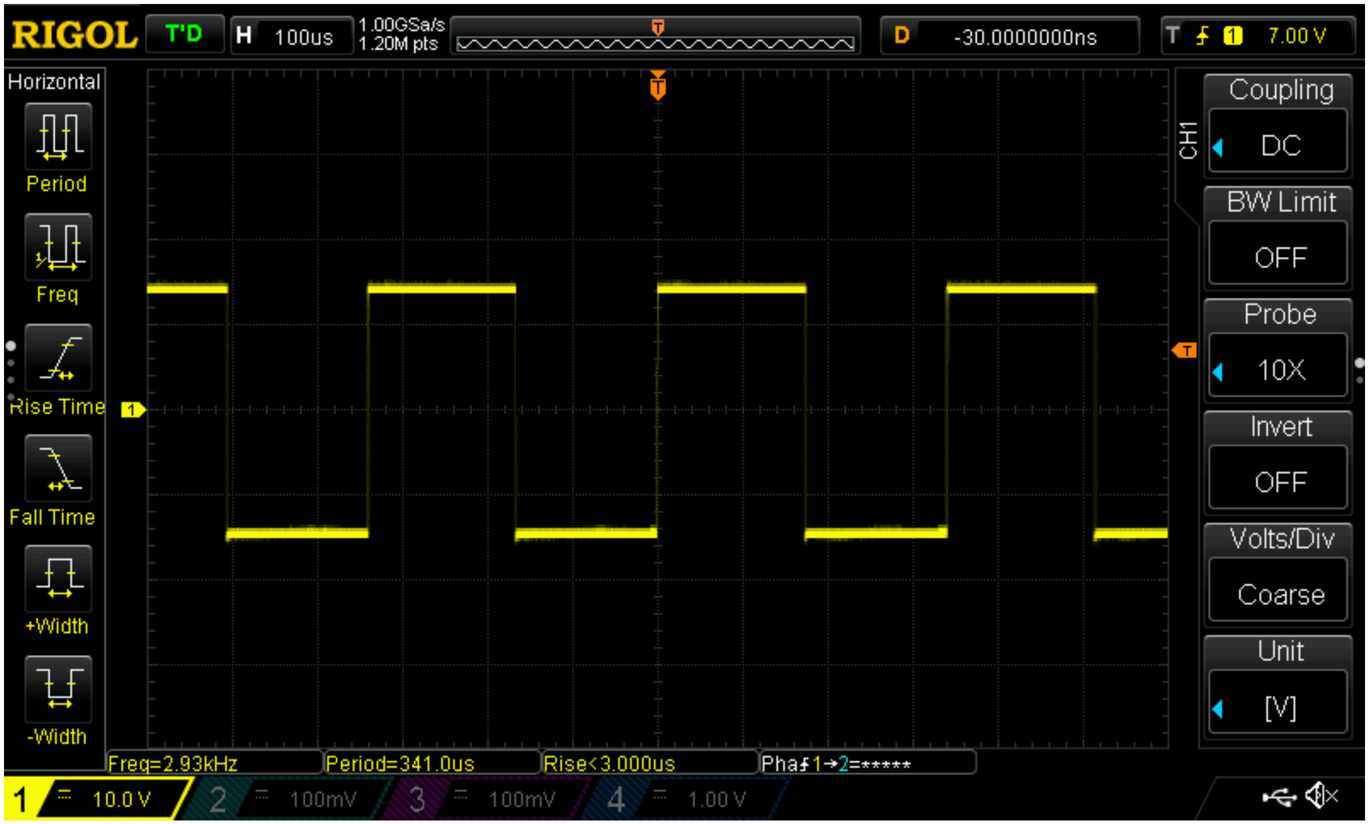
Note that we need to double this, because that's only half of a full period. Then we turn it into frequency:

$$f = 1/(\Delta t*2)$$
$$f = 2.6kHz$$

Here it is done out in a table:

Vout	$R_{feedback}$	I	C	ΔV	Δt	Δt doubled	f
15	100000	0.00015	0.00000001	2.8	1.87E-04	3.73E-04	2.68E+03

For my own records I'm submitting my lab screenshot of the waveform. Note that it's a bit higher here at 2.9kHz. I'm calling it a win though.



5 How Much Hysteresis?

I’ll say double it at 100 mV. See Figure 8N.12. Make sure your hysteresis is greater than V_{noise} peak to peak.

6 Comparator design exercise

Falstad: https://tinyurl.com/yy32vc4j

Ve and Vc:

A virtue of the '311 is that its output swings can be designated independent of the power supply rails. The question gives us these: ground and 5V, at negative and positive outputs respectively.

Hysteresis:

We can solve for this next. This is the fraction of Vout we want to set as Vfeedback for positive feedback. We can create a voltage divider according that ratio.

150mV/5V = .03
So we need a voltage divider that outputs 3% of its input.
That's the same as saying we need a R2 = 33R1

I will choose:
R2 = 100K
R1 = 3.3K or 3.1K

Here's the math done out in a table to compare 3.3K or 3.1K. Looks like 3.1K is the winner!

Ve	Vc	Vswing	R2	R1	Vfeedback fraction	Vthreshold +
5	0	5	3300	100000	23/720	0.1597
5	0	5	3100	100000	27/898	0.1503

Adjustable Threshold

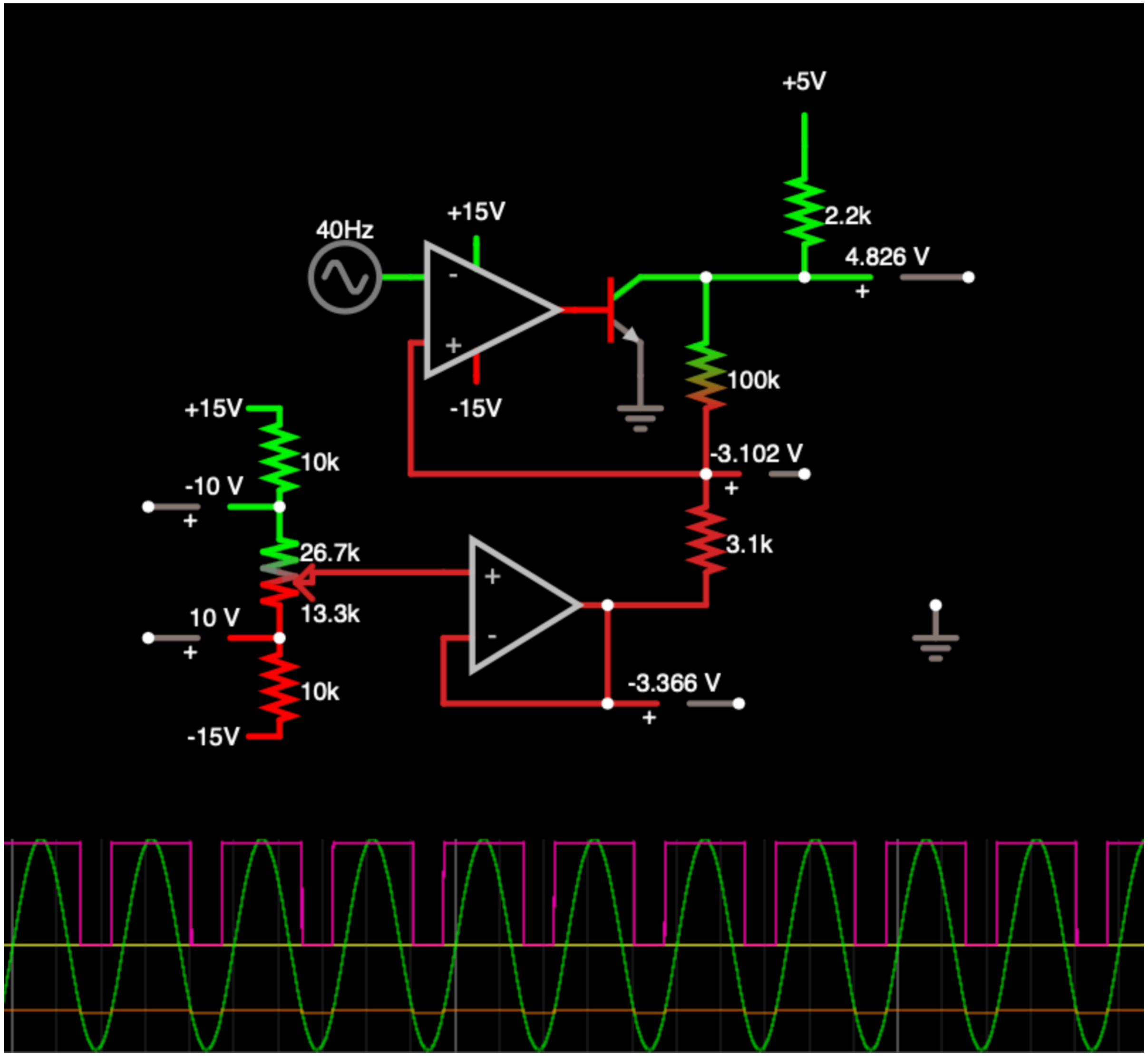
Note we are not setting a single threshold, but making it adjustable. There is an excellent walkthrough of solving for threshold, fixed and then adjustable, in the worked problems in chapter 8W. Here's how I might summarize why this is tricky:

Adjusting threshold means we must change the Vfoot of our voltage divider that determines our hysteresis.
In order to customize a our V of that foot, we need a second voltage divider. Naturally, the Rthev of that new divider then stands in for our R1.

That's all to say that changing the Vfoot alters the resistive divider, and thus consequently changes our hysteresis. Bummer!
So the solution is to add a circuit fragment that allows us to divide up some Voltage and have no consequence to the Rout of the circuit fragment. "Op-amps are cheap." This is a follower.

First we will setup the pot, fixed resistors, and supplies… So I am actually running out of time on wrapping this up and submitting. I'll pause here and here is my circuit:

Tim Savas


+5V
2.2k
40Hz
+15V
4.826 V
100k
-15V
+15V
10k
-3.102 V
-10 V
26.7k
3.1k
13.3k
10 V
10k
-3.366 V
-15V

7 Triangle or Sawtooth

I will take the approach of connecting an op-amp integrator and an op-amp comparator. For my records let me call out what they do: The integrator turns a square wave—a kind of binary signal from 0-5V—and turns it into a triangle wave.
The comparator is a super high gain diff amp. If one input is higher than the other, it says yes! at 15V on the output, and if its lower than the other, it says no! at -15V on the output.

It's logical to think that we can tie things together to do the work of creating a triangle wave. For now this setup outputs a 5V tall triangle wave centered on ground. We will adjust that offset later. The frequency is met by choosing the right R and C values, according to our I = Cdv/dt equation. Here's how that works:

We have either 15V or -15V at the comparator output. We loop that back to the inverting input of the integrator. See page 295, this is otherwise where we would be injecting a square wave power supply to an op-amp integrator. I put in a 150K R to give us a current. We can do the rest according to the equation:

Known:
I = 15V/150K = 0.1μA
ΔV = 5V – This is our desired amplitude of the triangle wave
Δt = 0.5ms – We use 1kHz frequency to figure out Δt. We can say that this integration happens 2000x per second.

Now we can solve for the cap:

$$I = C(\Delta V/\Delta t)$$
$$C = I/(\Delta V/\Delta t)$$
$$C = 10nF$$

R	V	I	ΔV	f	Δt	C
150000	15	0.0001	5	1000	0.0005	0.00000001

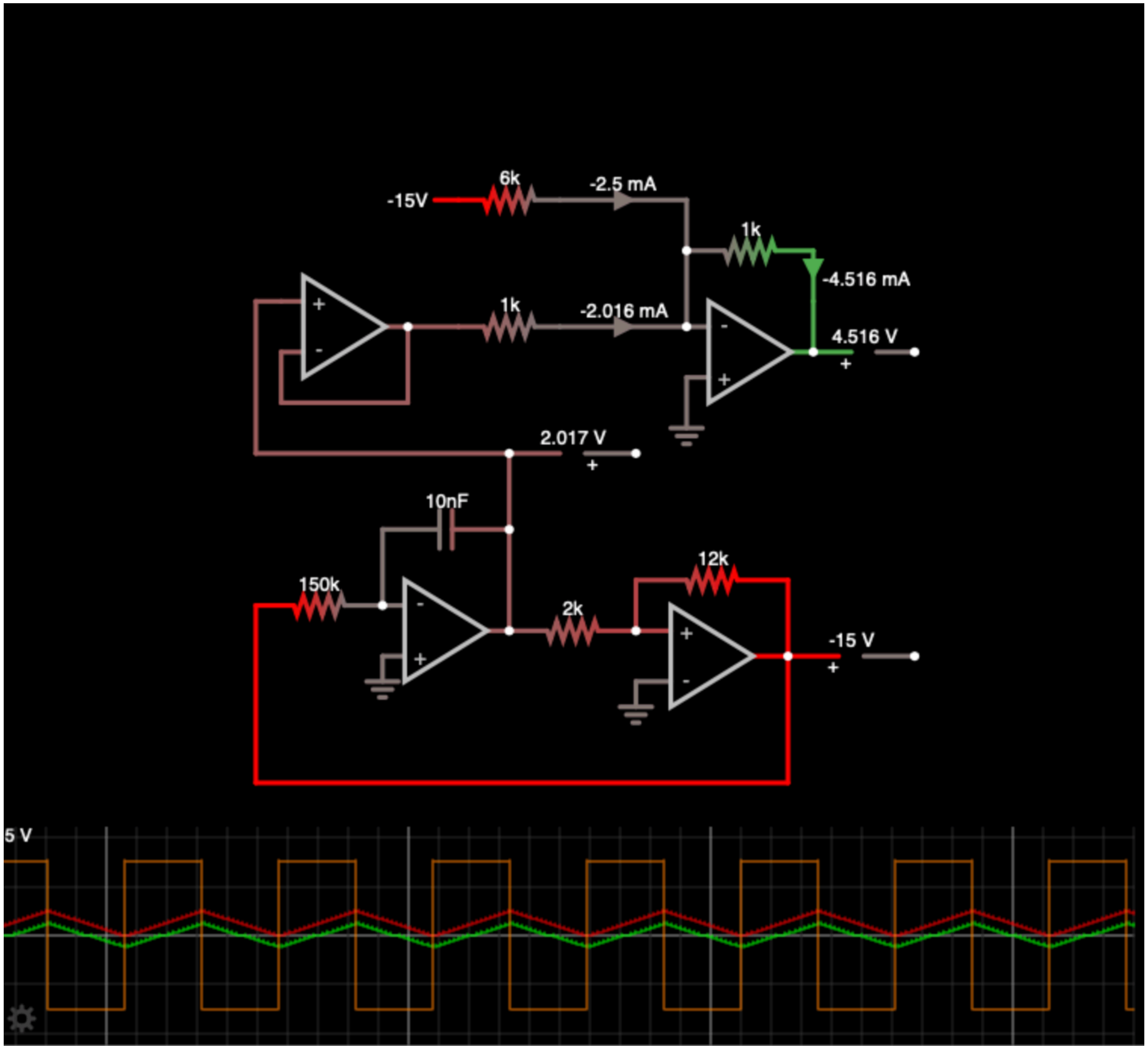
Solving for offset

Thus far we've created a triangle wave of 1kHz frequency, 5V tall, and centered on 0. This is labeled green in my simulator. We actually need this centered on 2.5V according to the given specifications. So we can create a summer and boost this same signal by 2.5V without changing it.

Note that I add a follower in between these stages. Those just seem like a good idea when in doubt about Rin and Rout between the stages.

Summers sum currents, not voltages. So I put the Vout of my follower over a 1K R to deliver a consistent current from -2.5mA to 2.5mA. What I would want on the other side of the summer is 0-5mA (or negative of that) in order to get the voltage conversion. I know I have a spare -15 or 15V power supply to work with. I put that over a 6K R, which I spec'ed according to the difference in current that I need. You'll see now on the output of that summer that the triangle has been lifted so that it's correctly centered. This is labeled red in the simulation.

Falstad: https://tinyurl.com/y3oeydo9


-15V
6k
-2.5 mA
1k
-4.516 mA
1k
-2.016 mA
4.516 V
2.017 V
10nF
150k
12k
2k
-15 V
5 V

7.2 Duty-Cycle Adjust Circuit

Overview

One thing I noticed about my solution to problem 6 is that when you input a sine wave into that circuit, and you toggle the threshold with the pot, the duty cycle of the comparator changes. It makes sense when you look at the waves against one another. For instance if you set the threshold up high, say at 4.8V, that's the narrow tip of the sine wave, and so from a time domain perspective it doesn't hang out at that latitude for very long. Therefore the comparator is saying "yes" versus "no" in proportional to this bandwidth of the sine wave.

That's all to say that this duty cycle question is a threshold question in disguise, from my perspective. So we will vary the foot of the divider just like for question 6. See my Q6 solution again for more reference : https://tinyurl.com/yyaga2tk

Hysteresis:

First I add some hysteresis. There's no particular spec in the question. I add 1% positive feedback for this, with a 100K || 1K voltage divider as seen in the circuit.

Duty Cycle

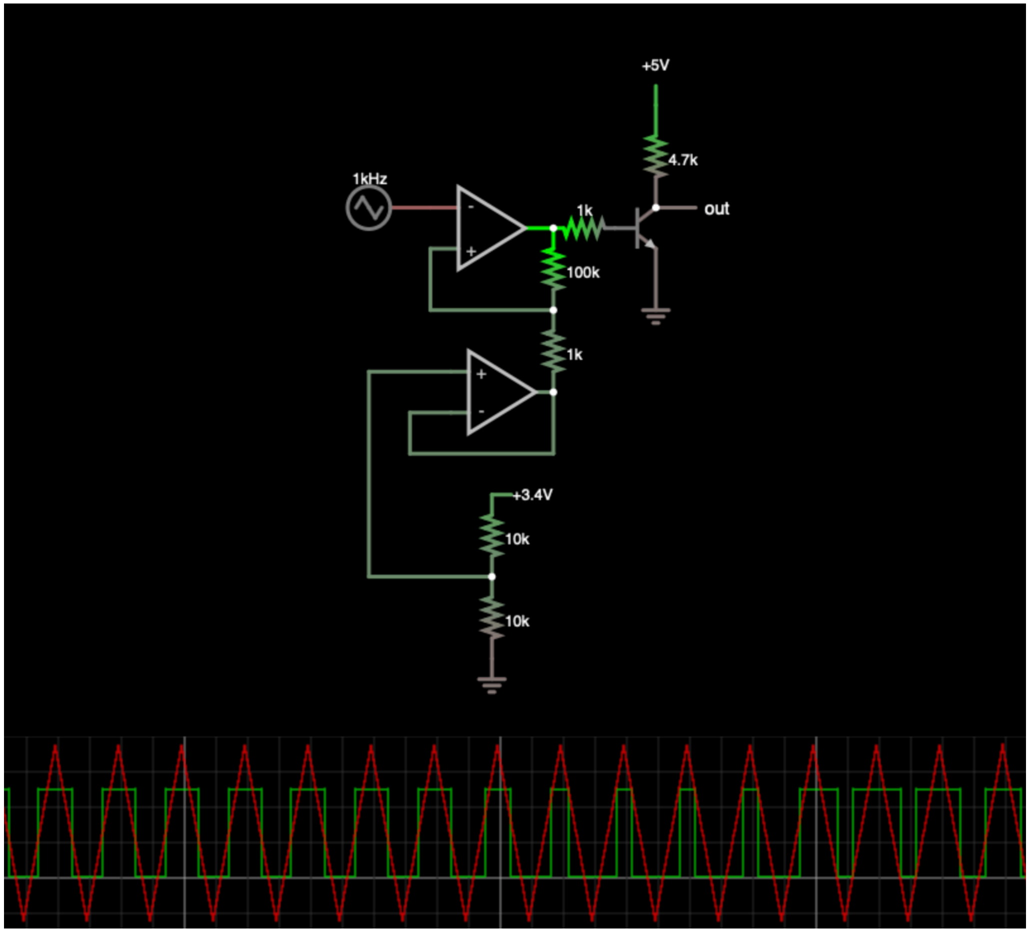
As I mentioned, we will now vary the foot of the divider according to the specs given. Here is how I think about this. The triangle wave input is 5V tall, from 0-5V. We therefore want to toggle the threshold of the comparator from 0-5V. Here are resulting scenarios of that:

1) When the threshold is super low on that range, at say 0.1V, the comparator stays high for a long time.
2) When the threshold is super high on that range. at say 4.9V, the comparator stays low for a long time.
3) When the threshold is in the middle of the range at 2.5V, then the duty cycle is 50%.

Control Voltage Split and Impedance Compensation

Note that our given control voltage is 0-10V, but we're looking for 0-5V at the foot, as I described. I setup a 10K || 10K voltage divider in order to split that control voltage by the necessary half we need. I buffer it through a follower in order to account for the impedance.

Falstad: https://tinyurl.com/yxpca28v



Appendix: Supplemental Notes

These are notes I would like to keep for my own records.

My response to Milo on Piazza:

Typing this sans glasses and book so I'll see how far I get :) I had similar questions earlier today!

It looks like you're already onto that 8W first worked problem, which I found super helpful. I journaled some notes for that and am sharing it here if you might find it helpful. It has some Falstad circuits demo'ing what a different Vfeedback does to the hysteresis.

Overall I recommend thinking about these attributes fairly discretely from one another: v-swing, hysteresis, and the voltage control for your threshold. Yes you're right about the pull-up R and +5V. The other extent of the Vswing can just be established with the emitter of the NPN transistor that's tucked into the op-amp. A virtue of the '311 is that its output swing can be designated independent of its power supplies.

I'd solve for hysteresis next. Check out my document if you need more notes than the W8.1 problem. Sounds like you may already have this!

For getting the -10 to10V swing, you're right that a 5V supply wouldn't do! Use something else like a -15V and 15V, with some adjustable voltage dividing mechanism between them. This is your thermostat. It's a knob you can turn to set the Vthreshold. Worked problem has a few nice examples of this—when it's fixed and also when we want to make it adjustable. For either situation you're going to vary the foot of the voltage divider you made for hysteresis, above.

I'm with you on the weird semantics of "threshold" in this section. I could be wrong but here is how I think of it. Without hysteresis, there is just the single threshold. Think of a thermostat, without any hysteresis. I set my thermostat at 72deg. Temp sensor senses a drop to 71 deg, my heater turns on. Temp sensor senses 73deg, heater turns off.

If there is hysteresis, there are really two thresholds (I think!). They are the lower and upper edges of the hysteresis. The original may still exist for our own intuition, most often centered between these extents. Like with the heater example, say you have 10deg hysteresis. The heater turns on at 67deg and off at 77deg. It actually doesn't do anything at 72deg, but that is the value of primary interest to the humans who set it up.

Another analogy that helps me, the hysteresis is a kind of no-man's land or "safe space". The thresholds are trip wires on either side. The signal can wiggle up and down all it wants between those bounds—or outside of them—and the output of the circuit won't flip. Once that signal crosses either of those tripwires, it flips. Hope part of this help and that not all of it is objectively false! :P

Practice: 8W.1 Schmitt trigger design tips

8W.1.1 Schmitt trigger design tips

It took some effort for me to understand certain aspects of setting up a Schmitt Trigger. The first is threshold setting. This homework problem asks for Vout to swing between 0V and +5V. That's a matter of setting up the '311's output transistor with +5V at the collector and 0V at the emitter. A virtue of the '311 is that your output swing can be designated independent of the +- power rails of the op-amp itself.

Still though I thought it was worth going through some of this worked problem. It tells you how to set a threshold symmetric about zero, or another value. "The key notion is that the foot of the divider is put at the midpoint of the output swing. You'd get the same tidy result if the thresholds were to be symmetric about 2.5V while the output swung between 0 and +5V, thresholds at 2.4 and 2.6V."

A question to come back to: I don't fully understand the calculation for this: "You'd get the same tidy result if the thresholds were to be symmetric about 2.5V while the output swung between 0 and 5V, thresholds at 2.4V and 2.6V." The lesson makes sense though: if you want to change the center point of the hysteresis, change the foot of the divider.

Here is that broken down:

Falstad	V_{foot}	V_e	V_c	Vswing	R2	R1	$V_{feedback}/V_{out}$ fraction	$V_{threshold+}$	$V_{threshold-}$	Lesson
link	0	15	-15	30	10000	150000	1/16	0.9375	-0.9375	The output flips at 1V feedback
link	0	15	-15	30	50000	150000	1/4	3.75	-3.75	The output flips at 3.75V feedback
link	0	15	-15	30	150000	150000	1/2	7.5	-7.5	The output flips at 7.5V feedback

8W.1.2

Suppose the task given is not "put thresholds at 1V and 1.1V but instead "set hysteresis at 0.1V; put thresholds close to 1V." Suppose output swing is 0 to 5V.

Hysteresis:

This is determined by the divider ratio: 0.1V/5V = 1/50th.
So we need to setup a divider that outputs 1/50th of the input.
That's the same as saying R2 = 50R1
Some good standard values for this are : R2 = 39K and R1 = 0.8K

Threshold:

This depends on to what V the foot of the divider is tied. This question is asking for 1V. In an ideal world we could just tie a 1V custom power supply to the foot of the divider and call it there. But let's use the original 5V power source and deliver 1V. So we need a second voltage divider that delivers ⅕ of the Vin. We also want this divider's R_{thev} to be equal to the R1 value we just determined, which is 0.8K.

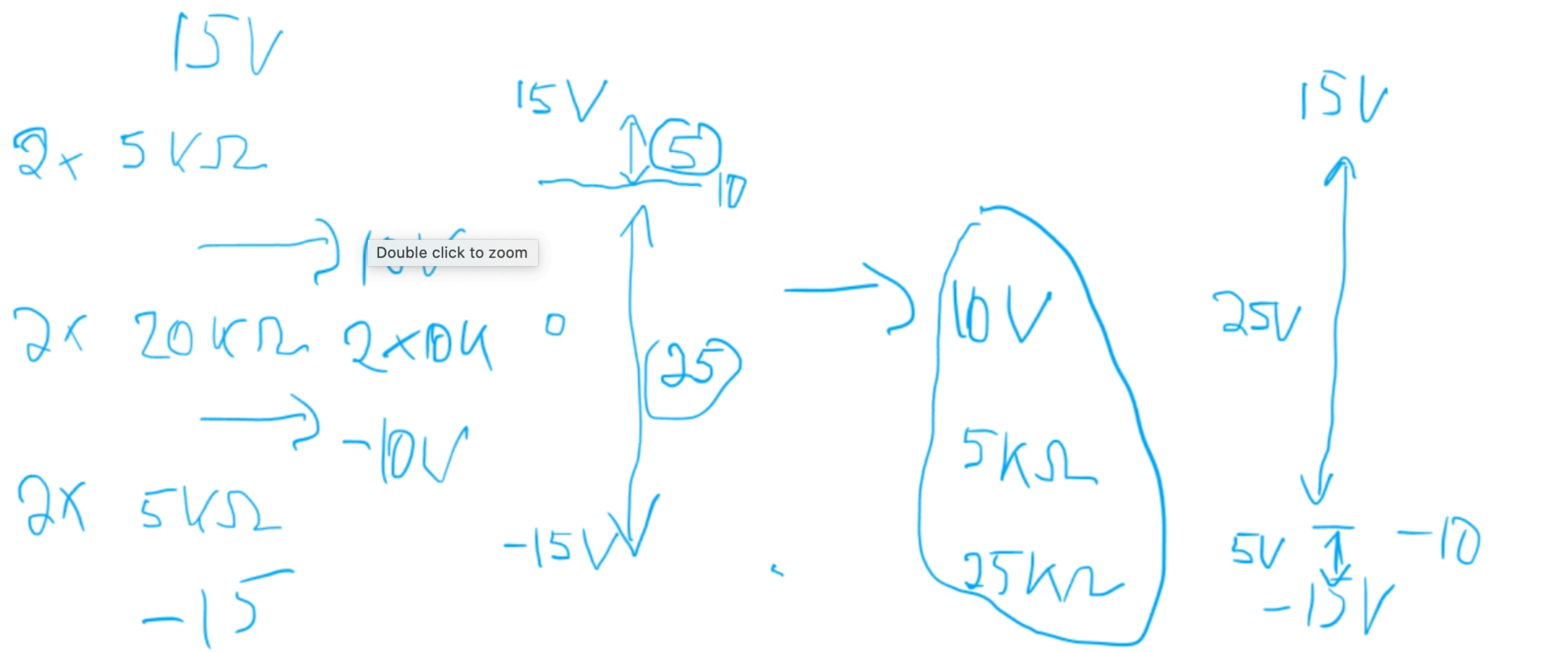
R_{thev} = $R_1 x R_2/R_1+R_2$ = 0.8K
R_1 = 1K
R_2 = 3.9K
V_{thev} = Vin(3.9K/4.9K)
V_{thev} = (1000/4900)*5
V_{thev} = 1V as desired

This all adds up to the circuit in figure 8W.3 on page 346

A wrinkle: adjustable threshold

So this is basically asking, we want to be able to change the V_{foot} without changing the value of the R1. Look back on how we did the previous problem. We added a new V divider, and the R_{thev} we set to the already established 0.8K value (which we got by needing to solve for $50R_1 = R_2$). But now we're saying that we want to vary voltage (the one controlling the threshold at the foot of the divider) without changing our R value! So we can use a follower. We can toggle voltage before it and the R on the output will not change.

Helmut's Help with figuring out the pot:



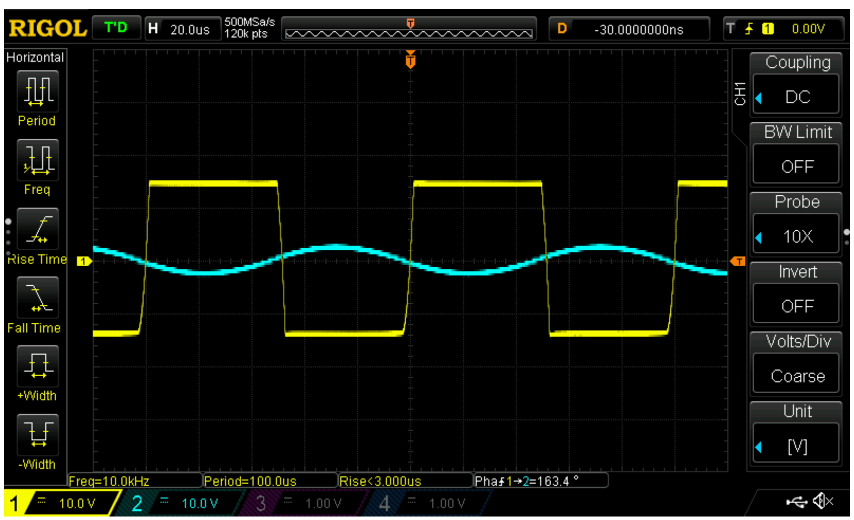
Lab 8L

8L.1 Two Comparators

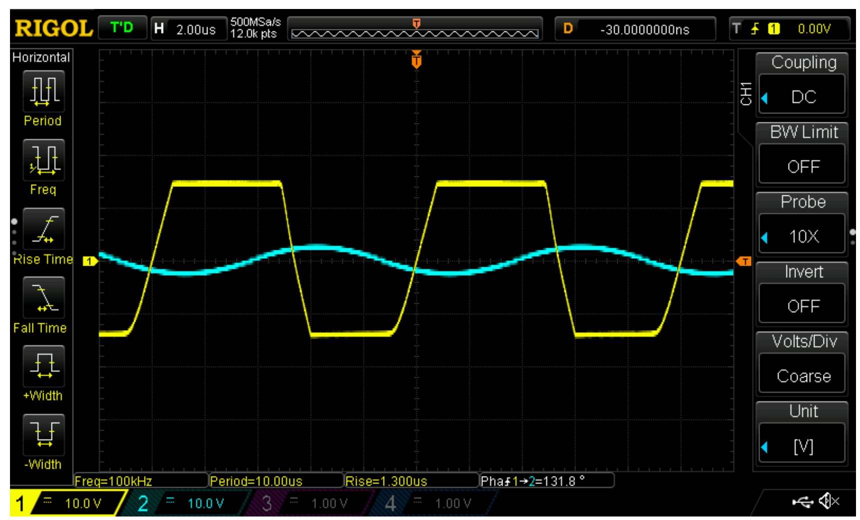
8L.1.1 Op-amp as comparator

This is a comparator. It's a high gain diff amp. We used to think such a thing—this crazy high gain—was not useful. But it is as a comparator. When we need something that just says "yes" or "no," almost like binary, this is great. It is just testing whether a signal is above or below a threshold (ground) and saying yes! or no!

In this chapter we learned the '411 can be used as a decent comparator, but it kind of falls apart at high frequencies. That super nice square wave—that fast response—can't keep up with high frequencies because of the '411's slew rate. That is to say, the rate at which its output can move its voltage. For comparison, here's a shot of the output vs. input at 10kHz and then at 100kHz.



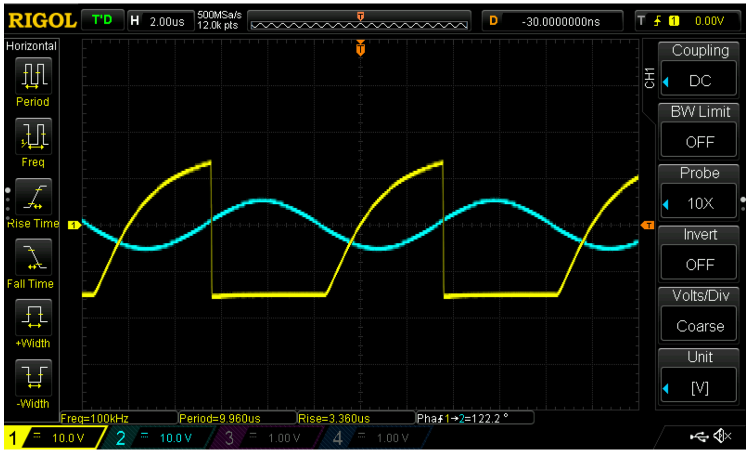
'311 @ 10kHz



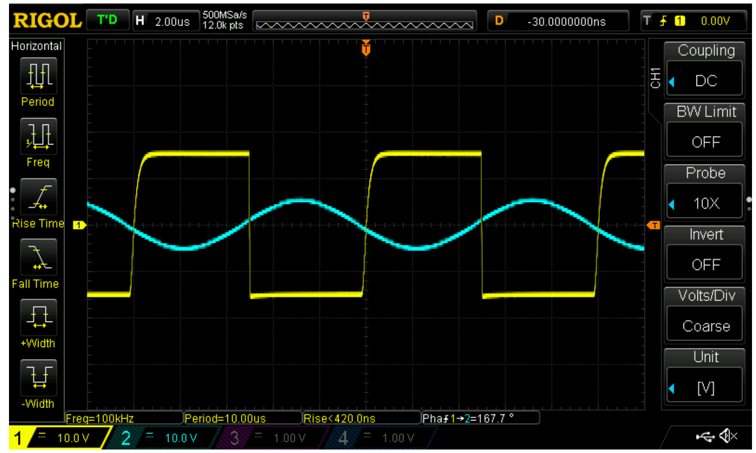
'311 @ 100kHz

8L.1.2 Special purpose comparator IC

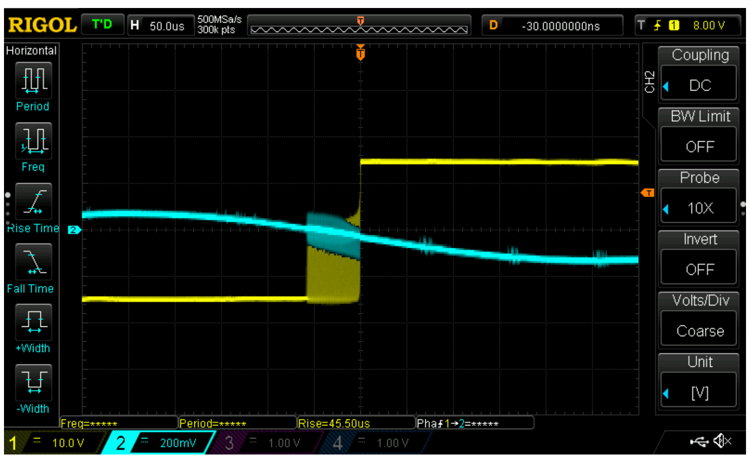
Yes confirmed that the ‘411 performs much better at that 100kHz high frequency. Still some weird slope on the rise but better nonetheless. Also note that I had made a mistake with my initial setup and didn’t get the right response on the uprise. I troubleshoot the pull-up resistor because that’s what matters for that side of the square wave.



I accidentally set it up with a 47K pull-up R and it did this.



‘411 @ 100kHz—better than the ‘311



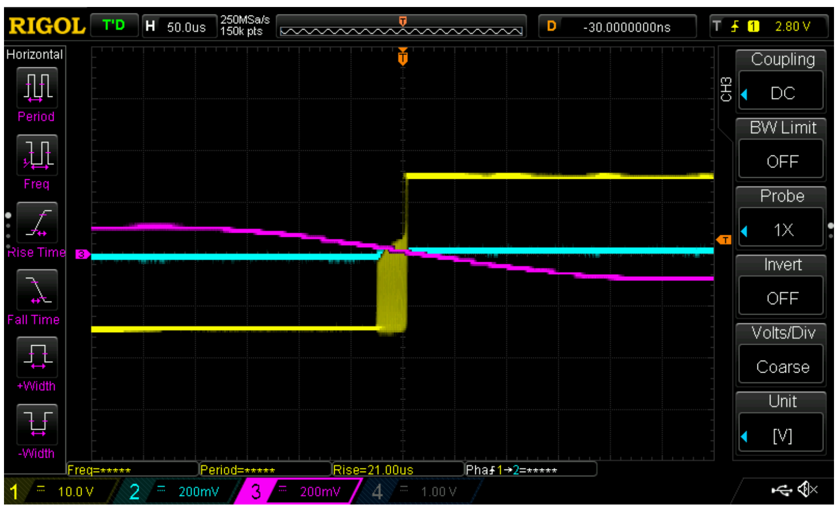
Also yes I confirmed that putting in a low frequency wave form provokes the ‘411 to jump the gun on the switch, causing chatter or bouncing as seen here. First I put in 50Hz at 10V and then 50Hz at 200mV. Definitely something like the Taj Mahal like the lab says.

8L.1.3 Schmitt trigger

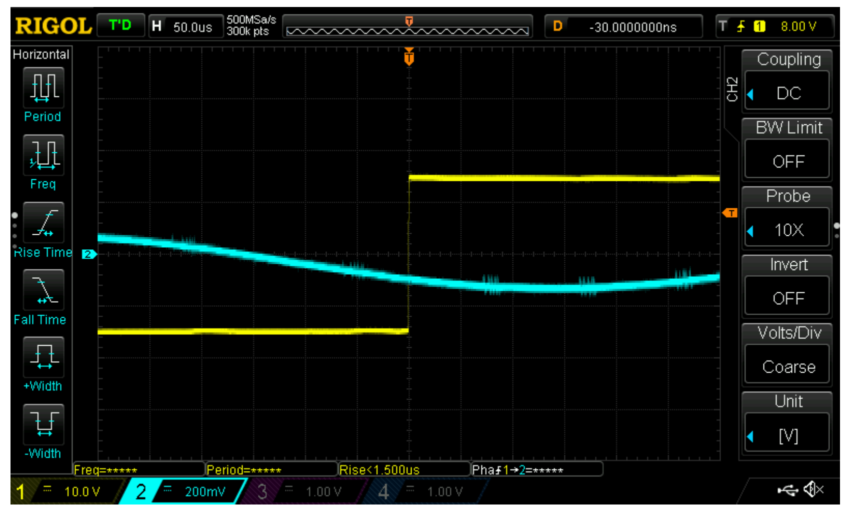
Here we add some positive feedback. There's a potentiometer on the voltage divider feeding back to the positive input. Without much feedback—the R turned down low—we see the chatter that we're trying to get rid of. The blue line is the feedback going to to the non-inverting input. It's just about at zero as we would expect.

Turning the knob and R up increases positive feedback. Notice the blue line forms its own square wave showing the feedback. Also the chattering decreases—because we now have hysteresis. Most importantly notice that the yellow square wave does not flip when the purple Vin crosses its original zero. It has shifted. This is a result of our hysteresis.

There seems to be an instability point when we feedback more than 100mV, which is the height of the signal in. That makes sense.



Pot turned down, no hysteresis keeps the chatter.



No pot shown, but you can see hysteresis when turned up.

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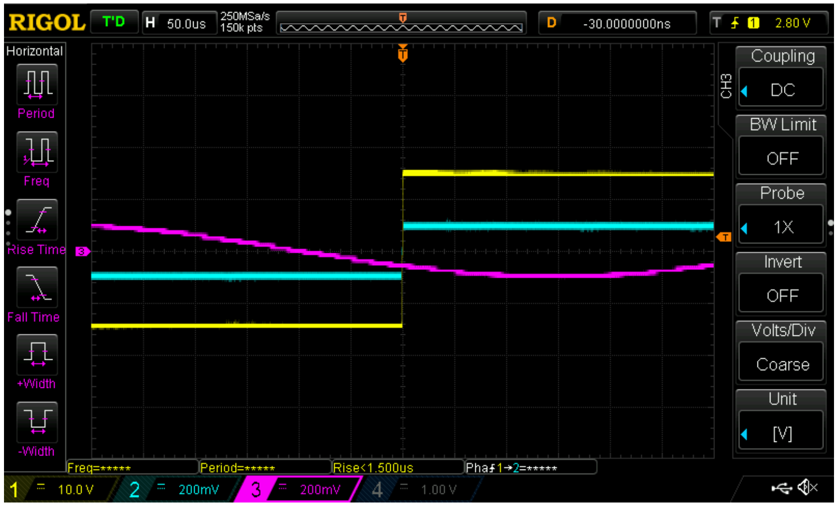
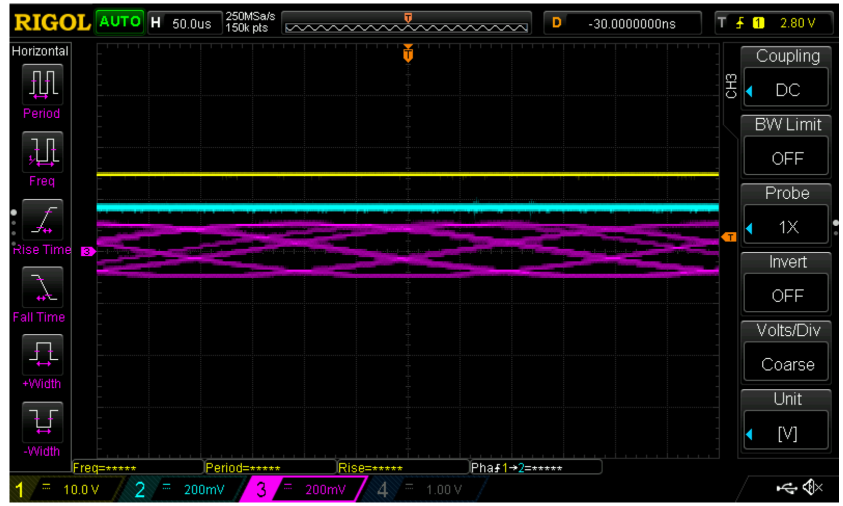


Pot up, feedback increased; no chatter but see the shift.



Feedback increased too much causes instability

8L.2 Op-amp RC relaxation oscillator

What's cool about this is that there is no input. The capacitor ramp up and down is causing the switch and also the subsequent frequency at which this switch occurs. We're now solving for the time it takes that switch to take place. Here is how to do that.

Solving for dV:

The two threshold voltages are contingent on what voltage we are feeding back to the non-inverting input of the '311. That's fairly straightforward looking at the V-divider that is placed in between the output and input.

Note that the output for this setup doesn't have much nuance to it—at all. It's either going to be 15V or -15V due to the super high gain of the setup. Therefore we will also only see two voltages fed back, proportional to those two outputs. They are 1/11th of 15V and -15V. For good measure, here's how we got there exactly:

Condition	V_{out}	R_1	R_2	$V_{threshold}$	Total ΔV
+	15	100000	10000	1.4	2.8
-	-15	100000	10000	-1.4	

Solving for I:

I = 15V/100K = 15mA

Solving for Δt:

$$C = .01\mu F$$
$$\Delta V = 2.8V$$
$$I = 15mA$$

$$I = C(\Delta V/\Delta t)$$
$$I\Delta t = C\Delta V$$
$$\Delta t = C\Delta V/I$$
$$\Delta t = .01\mu F(2.8V/150\mu A)$$

$$\Delta t = 187\mu s$$

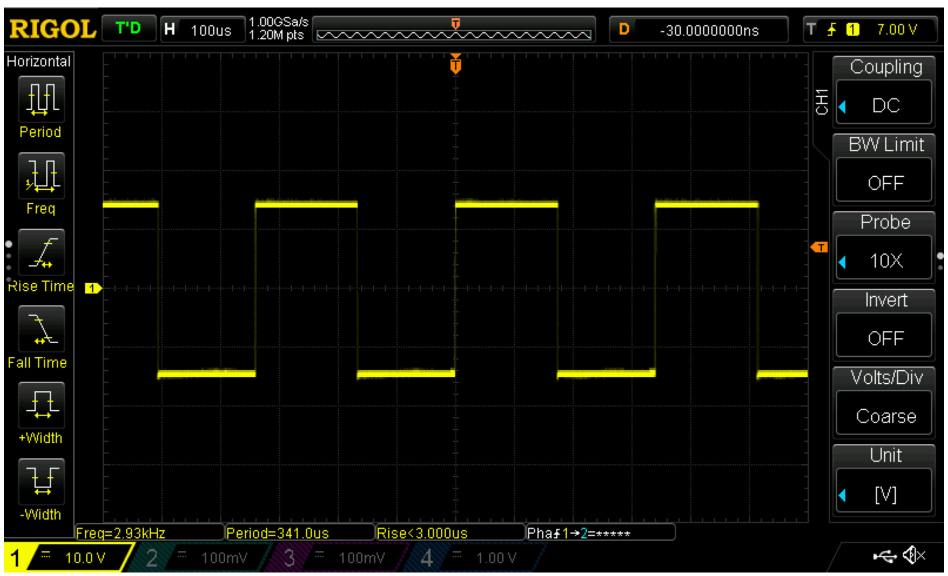
Note that we need to double this, because that's only half of a full period. Then we turn it into frequency

$$f = 1/(\Delta t*2)$$
$$f = 2.6kHz$$

Here it is done out in a table:

Vout	$R_{feedback}$	I	C	ΔV	Δt	Δt doubled	f
15	100000	0.00015	0.00000001	2.8	1.87E-04	3.73E-04	2.68E+03

So I calculate the frequency of this oscillator is about 2.6kHz. What does the scope say? Scope says 2.9kHz! I'll take it!



8L.3 Easiest RC oscillator, using IC Schmitt trigger

pick back up here.