Op-Amps & 555 Timers

One of the requirements for your 401 project is it must include an integrated circuit (IC). Usually, this is an op-amp, a 555 timer, or a PIC processor.

Operational Amplifiers (Op-Amps)

Op-amps are really useful devices that can do all sorts of things. With op-amps, you can build

- Comparitors
- Schmitt Triggers
- Half-wave and full-wave rectifiers,
- Envelope detectors
- Amplifiers
- Filters

to name just a few. Op-amps are just darn useful.

Op-Amps in CircuitLab

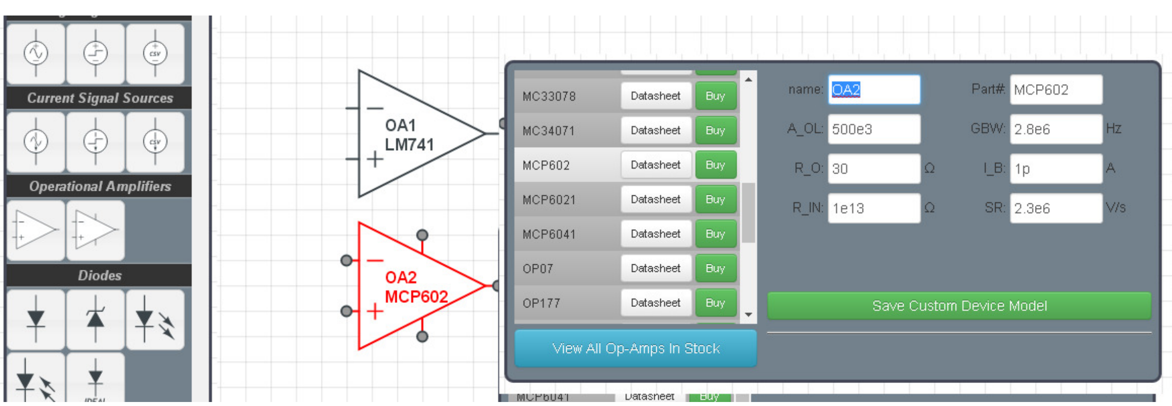
Two types of op-amps are available

- No power supply: Unlimited output
- Power Supply: Limits the output to Vcc & Vee

The type of op-amp you use depends upon the circuit you're building.

- If the op-amp should never clip (the output voltage is always in-between Vmin and Vmax), you can use the op-amp without a power supply. This is usually what you do in analog electronics.
- If the output's output rails at the power supplies, you need to use the latter op-amp. This is usually what you use in digital electronics.

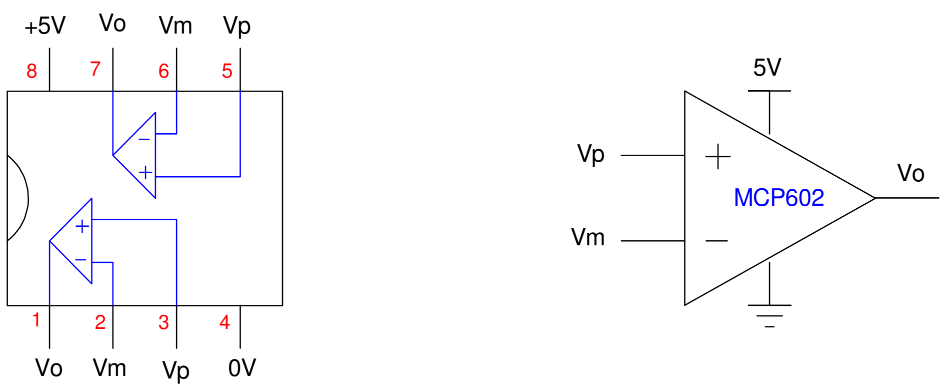
If you double clock on the op-amp, you can also adjust the parameters for the op-amp you're using



You can use op-amps where the power is specified (lower) or where not.
If not, CircuitLab assume there is no limit on the output voltages (OK for analog circuits)

The heart of all of these circuits is an op-amp, such as an MCP602. An MCP602 is used in Senior Design I since

- It can operate from a single 5V power supply (range is 3V to 6V)
- It's a rail-to-rail op-amp. If you connect 0V and 5V to power and ground, the output can go all of the way down to 0V and all the way up to 5V (rail-to-rail).
- It's a dual op-amp: you get two op-amps in each IC



MCP602 op-amp: the heart of a comparitor

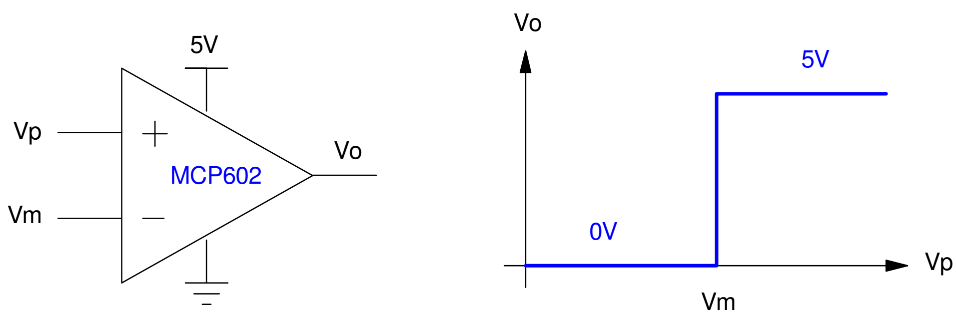
Op-amps in general are high-gain differential amplifiers. The MCP602, for example, has an output which is

$$V_o = 200,000(V_p - V_m)$$

where Vo is clipped at the +5 and 0V power supplies (you can't get more voltage out than you put in).

What this means is

- If Vp > Vm, the output rails at the upper power supply (5V)
- If Vp < Vm, the output rails at the lower power supply (0V)



Comparitor: Output is 5V if Vp > Vm

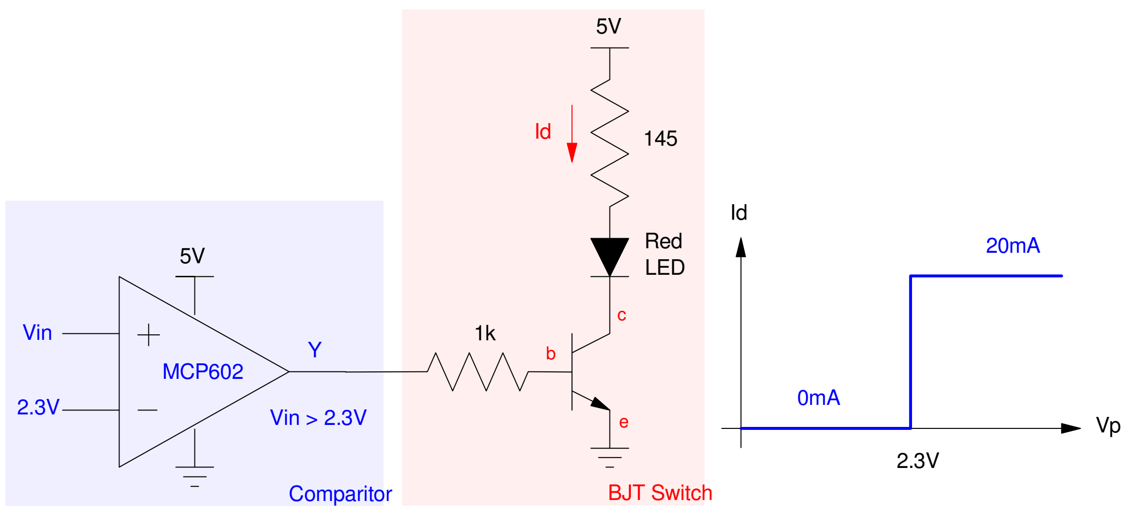
This allows you to build several different circuits.

Comparitor: Y = (Vin > 2.3V)

If you want to turn on an LED when Vin > 2.3V, you could use a comparitor along with a BJT transistor:

- Connect Vin to Vp
- Connect 2.3V to Vm
- This produces the function: Y = Vin > 2.3V

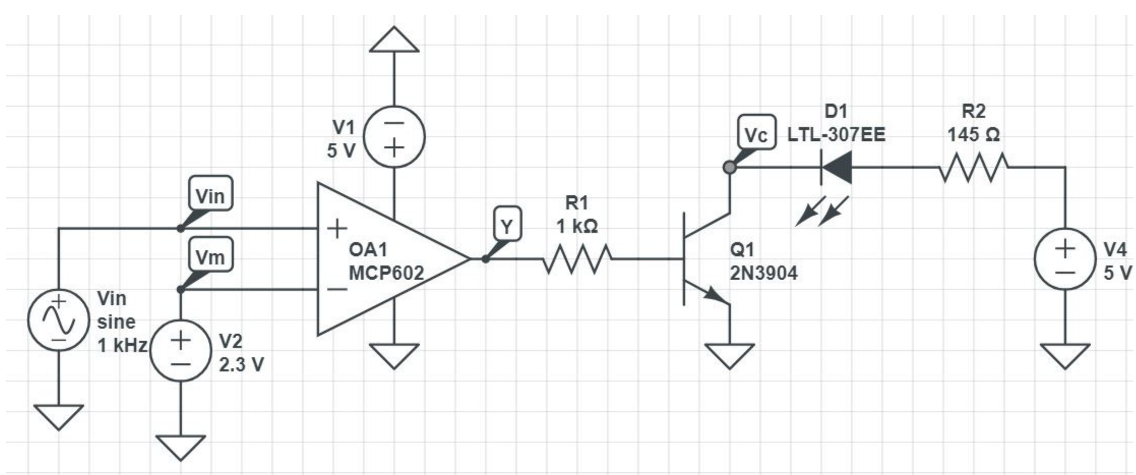
If you swap Vp and Vm, you get the opposite (Vin < 2.3V)



Comparitor with a BJT switch. LED is on when Vin > 2.3V

In CircuitLab, you can check this design:

- Use an op-amp with the voltage inputs: CircuitLab needs to know what is logic 1 (5V) and 0 (0V).
- Use an AC input for Vin.
  - When Vin > 2.3V, Y slams to 5V.
  - When Vin < 2.3V, Y slams to 0V



CircuitLab simulation for a comparitor circuit

Running a time-domain simulation for 2ms shows the comparitor turning on and off:

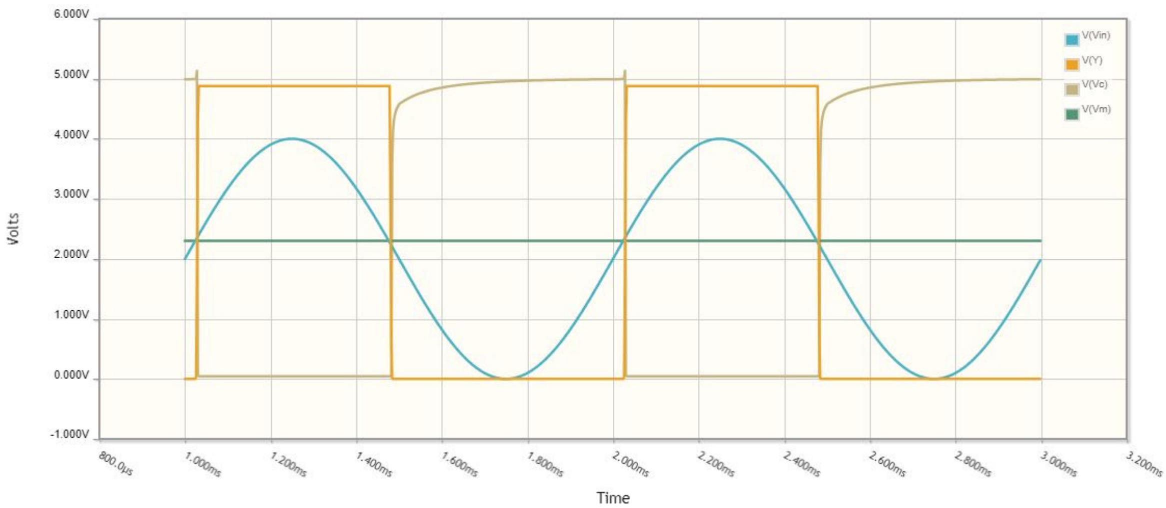
When Vin > 2.3V

- V(Y) = 5V (on)
- Vc = 0.2V (the transistor is saturated)

When Vin < 2.3V

- V(Y) = 0V (off)
- Vc = 5V (off)

The simulation also shows that it Y takes a little time to get up to 5V when the transistor turns off. This is due to the diode in the transistor having a small inherent capacitance



Time-Domain Simulation Result showing the voltages

Comparitor: Y = (T > 20C)

If you want to turn on an LED when the temperature is more than 20C,

- First, convert temperature to resistance. A thermistor such as the ones used in ECE 376 will do that

$$R = 1000 \cdot \exp\left(\frac{3905}{T+273} - \frac{3905}{298}\right)\Omega$$

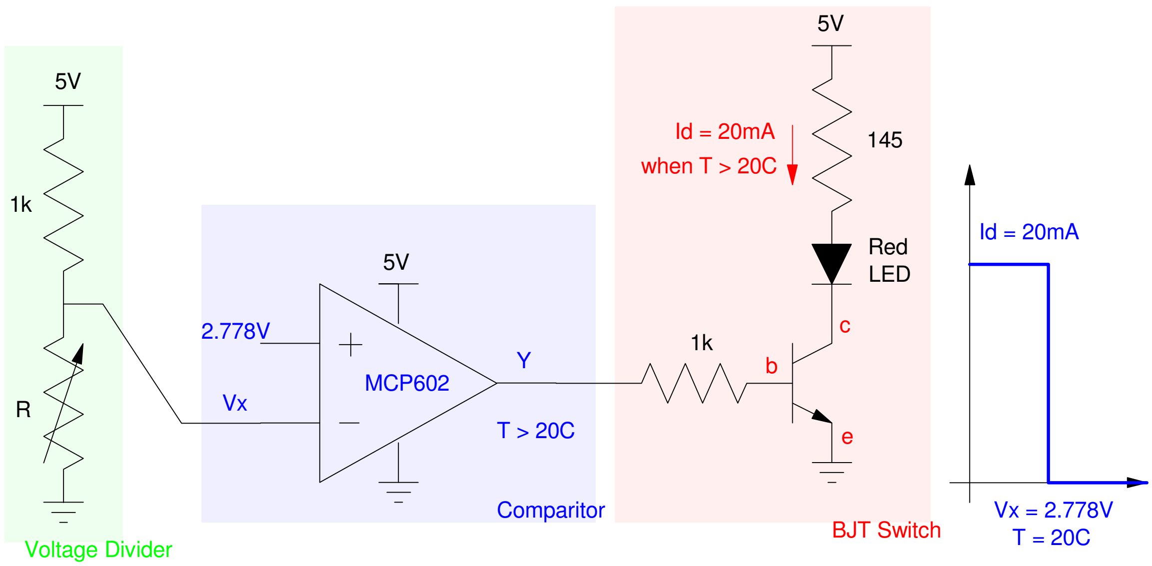
- Next, convert resistance to voltage. A voltage divider will do that
- Connect Vm to the output of the voltage driver.
  - As temperature goes up
  - R goes down
  - Vx goes down
  - Y goes up
- Connect Vp to the voltage you get at 20C

$$T = 20C$$

$$R = 1250.59\Omega$$

$$V_x = \left(\frac{R}{R+1000}\right) 5V = 2.778V$$

The final design of the comparitor circuit is as follows.



Comparitor with a temperature sensor. LED is on when T > 20C

Note

- If you swap Vp and Vm, you get the opposite (light is on when T < 20C).
- If you change R to a light sensor, the LED turns on and off with light level
- If you change R to a magnetic field sensor, the LED turns on and off with magnetic field strength

Schmitt Triggers

A problem with comparitors is they tend to be noisy:

- When Vp = Vm, the output will chatter between 0V and 5V
- This can cause multiple reads on counters, noise on a speaker, etc.

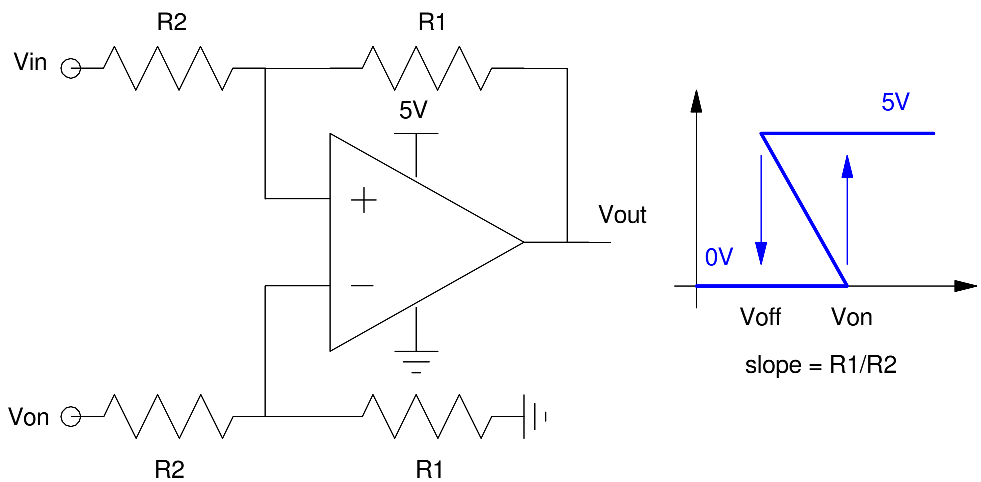
To prevent this, a Schmitt trigger can be used.

Schmitt Triggers are one of the few circuits you'll ever see which use positive feedback. Positive feedback tends to make things unstable:

- If something is too hot, add more heat
- If the voltage is too high, go higher
- If you're going too fast, go faster

This is intentional with the Schmitt Trigger: you want the output to rail at either +5V or 0V.

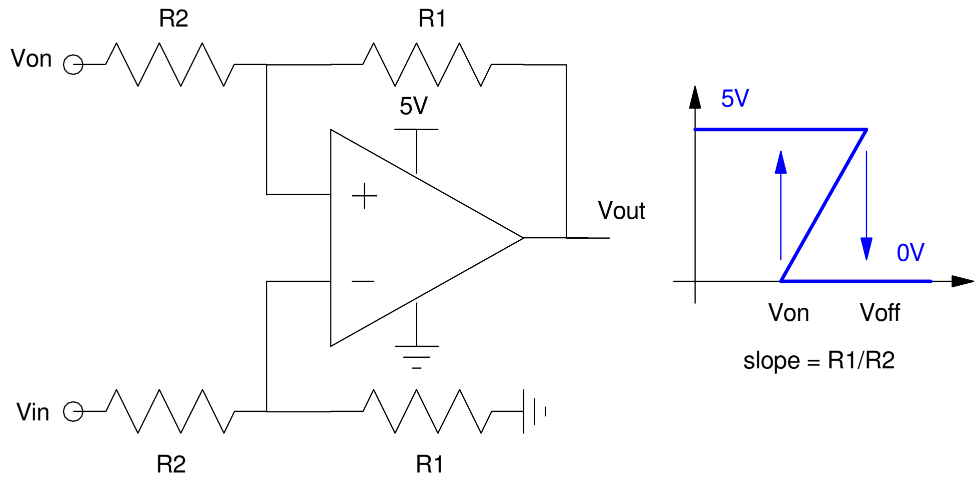
With a comparitor, the on voltage is the same as the off voltage. With a Schmitt trigger, the two are different. When the on-voltage is more than the off-voltage, the input is connected to the plus input:



Schmitt Trigger when Von > Voff

When the on voltage is less than the off voltage, Vin is connected to the minus input:

What the positive feedback does is it changes the on/off voltage when the output switches, creating hysteresis.



Schmitt Trigger when Von < Voff

For example, design a circuit which turns an LED

- On when T > 25C and
- Off when T < 20C

When 20V < T < 25C, the LED remains unchanged (on or off).

Similar to the comparitor, the procedure is to first, convert temperature to a voltage and find Von and Voff. A voltage divider and a thermistor works for this.

Assuming a thermistor where

$$R = 1000 \exp\left(\frac{3905}{T+273} - \frac{3905}{298}\right)\Omega$$

along with a voltage divider with a 1k resistor, you get

At 20C:

$$R = 1250.59\Omega$$

$$V_x = \left(\frac{R}{R+1000}\right)5V = 2.778V$$

$$V_{off} = 2.778V$$

At 25C

$$R = 1000\Omega$$

$$V_x = 2.500V$$

$$V_{on} = 2.500V$$

Since Von < Voff, connect to the minus input

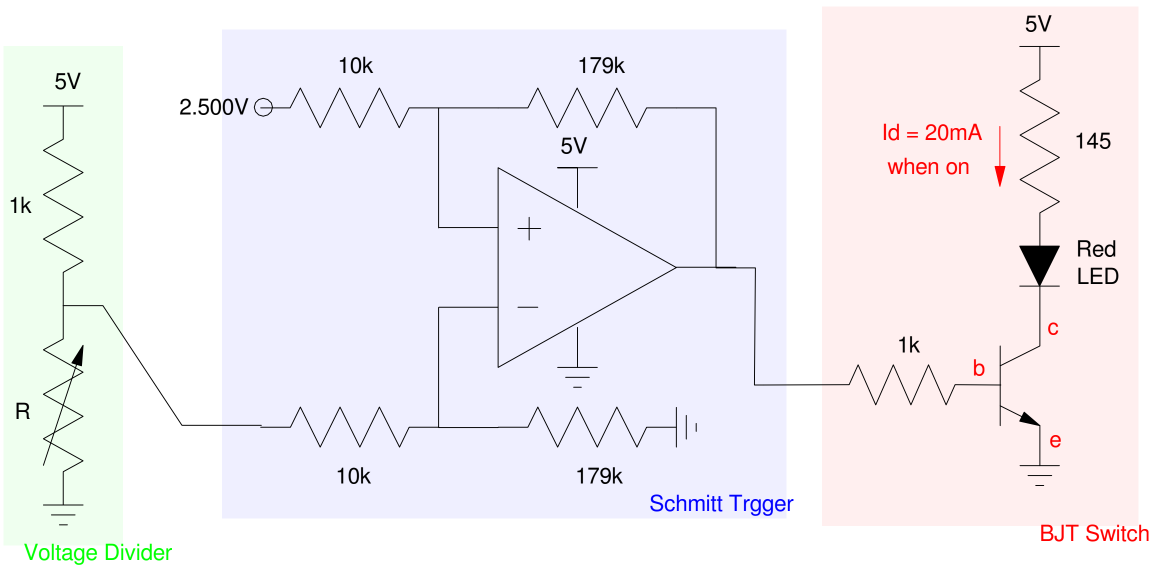
The gain needed is

$$gain = \left(\frac{\text{change in output}}{\text{change in input}}\right)$$

$$gain = \left(\frac{5V - 0V}{2.778V - 2.500V}\right) = 17.96$$

A 10k resistor and a 179k resistor works.

The net circuit is then:



Schmitt Trigger: Diode is turned on at 25C (2.500V) and turned off at 20C (2.778V)

555 Timers

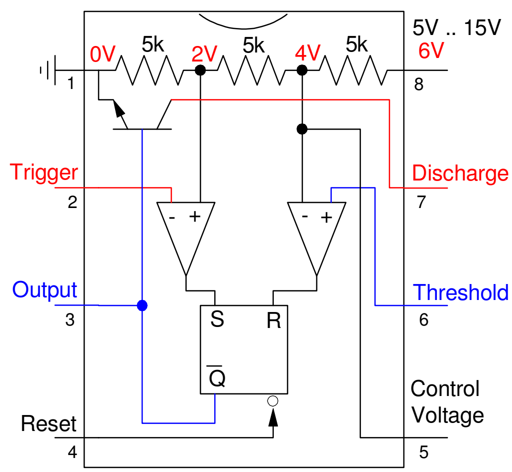
Finally, lets look at 555 timers. 555 timers are one of the more useful tools in designing an analog circuits. With it, you can build:

- An oscillator - allowing you to keep track of time, make lights blink, speakers buzz, etc.
- An oscillator whose frequency depends upon temperature, light, water, etc.
- A voltage-controlled oscillator - allowing you to make siren noises, and
- A one-shot - allowing you to do something one time after an event (such as turn on a light for 30 seconds when motion is detected.)

The following circuits are for an oscillator. The other circuits are covered in ECE 320 Electronics I.

555 Timer:

555 Timers get their name from the use of three 5k resistors in series. These resistors create two reference voltages equally spaced between ground and the power supply (6V in this example).



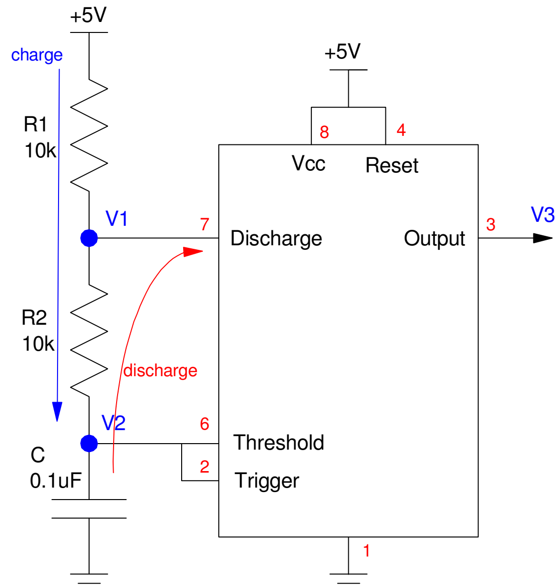
555 Timer Schematic. The 555 refers to three 5k resistors from power to ground.

The function of the pins are as follows (assuming a 6V power supply):

- Power and Ground: self explanatory. Power can be anything from 5V to 15V.
- Trigger: When Trigger < 2V, the SR flip-flop sets and the output goes high.
- Threshold: When Threshold > 4V, the SR flip flop clears and the output goes low
- Control Voltage: Allows you to change the threshold voltage from 4V if you like
- Discharge: When the output is low, Discharge is shorted to ground through a transistor. Otherwise, Discharge is a floating pin.

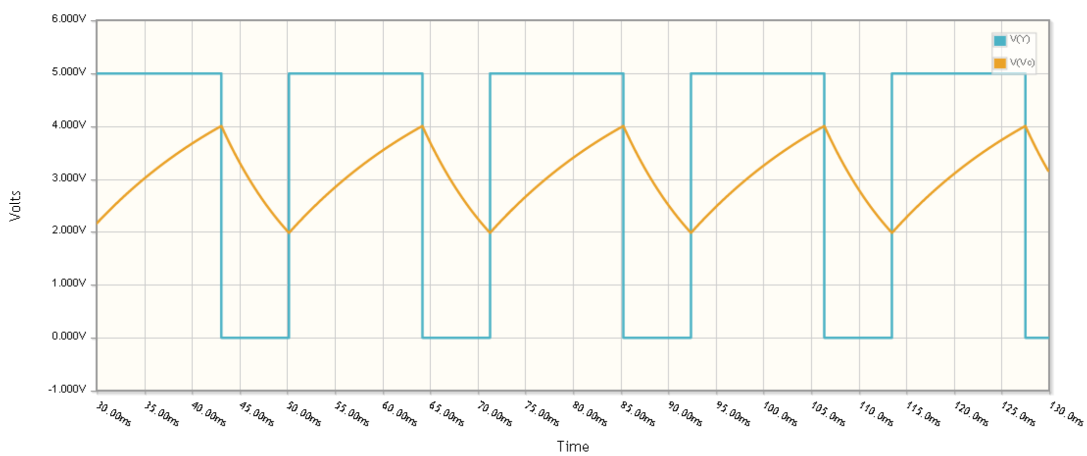
555 Oscillator (take 1): The basic circuit for a 555 oscillator timer is as follows. The way it works is

- The capacitor charges up to 2/3 of 5V through R1 and R2. Once it reaches 3.333V
- Pin 7 is tied to ground, resulting in the capacitor discharging down to 1/3 of 5V through R2. Once V2 reaches 1.667V,
- Pin 7 is turned off, allowing the capacitor to charge back up again,
- And the process repeats.



555 Timer in CircuitLab.
C1 charges through R1 and R2. It discharges through R2

This shows up on the voltages you see at V2 and V3:



Voltage at Vc (orange) and Y (output = blue)

The on and off times for V3 are set by R1, R2, and C as:

$$T_{on} = (R_1 + R_2) \cdot C \cdot \ln(2)$$

$$T_{off} = R_2 \cdot C \cdot \ln(2)$$

$$T = Period = T_{on} + T_{off} = (R_1 + 2R_2) \cdot C \cdot \ln(2)$$

For the values given, this works out to

$$T_{on} = 1.386ms$$

$$T_{off} = 0.693ms$$

$$T = Period = 2.079ms$$

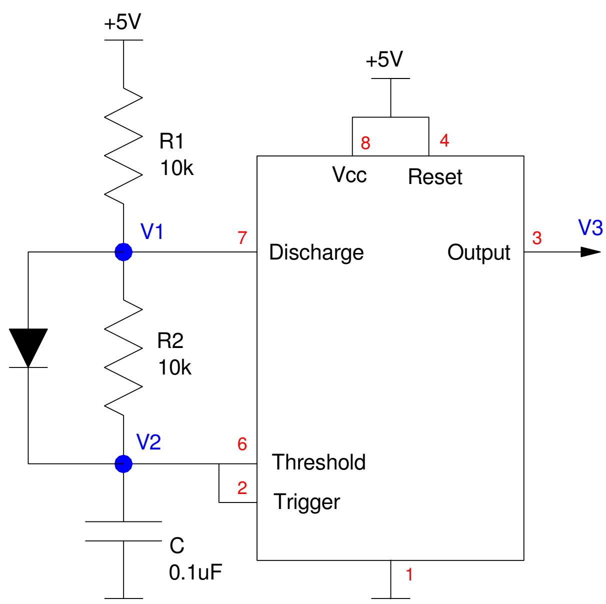
$$f = \frac{1}{T} = 480.9Hz$$

Note

- The on time is twice as large as the off time. This is due to C charging through R1 and R2, while discharging through R2.
- If you replace either resistor with a thermistor or a photo-resistor, the period (and frequency) will change with temperature or light.

555 Oscillator (take 1): A slight improvement is to add a diode as follows. This results in

- C charging through R1 (R2 is bypassed by the diode), and
- C discharging through R2 (when pin 7 of the 555 timer is grounded).



Improved 555 Oscillator. R1 sets the on-time (charging C) and R2 sets the off time (discharge C)

This results in

$$T_{on} \approx R_1 \cdot C \cdot \ln(2)$$

$$T_{off} = R_2 \cdot C \cdot \ln(2)$$

(Ton is approximate due to ignoring the voltage drop across the diode when computing Ton).

By adjusting R1 and R2, you can set the on and off times to anything you like. For example, if they're both 10k resistors,

$$T_{on} \approx 0.693ms$$

$$T_{off} = 0.693ms$$

$$T = T_{on} + T_{off} = 1.386ms$$

$$f = \frac{1}{T} = 721.3Hz$$

If you want 1 100Hz square wave, then

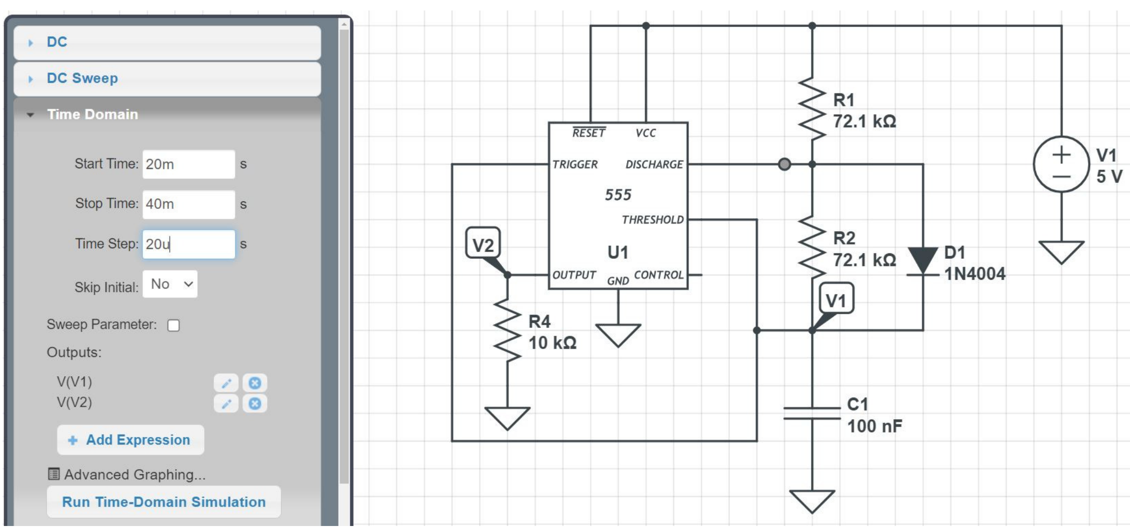
$$T_{on} = 5ms \approx R_1 \cdot C \cdot \ln(2)$$

$$T_{off} = 5ms \approx R_2 \cdot C \cdot \ln(2)$$

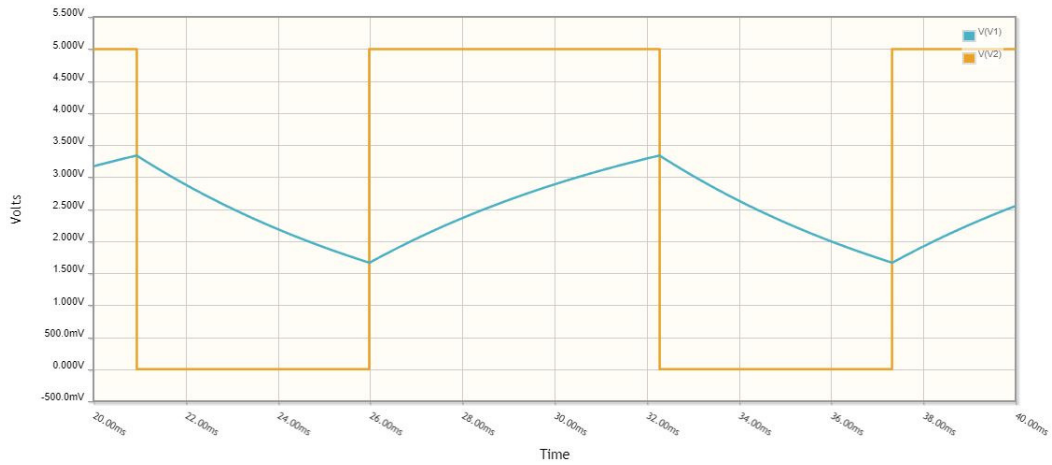
The reason it's approximate is these calculations ignore the 0.7V drop across the diode. If C = 0.1uF, then

R1 = R2 = 72.13k Ohms

Check this in CircuitLab. Build the circuit and do a time-domain simulation:



Measure the on and off times



Time-Domain simulation. T(on) = 6.824ms, T(off) = 5.04ms

The off time is good, meaning leave R2 alone.

The on time is too large (due to the diode). To bring it down to 5.00ms, scale R1

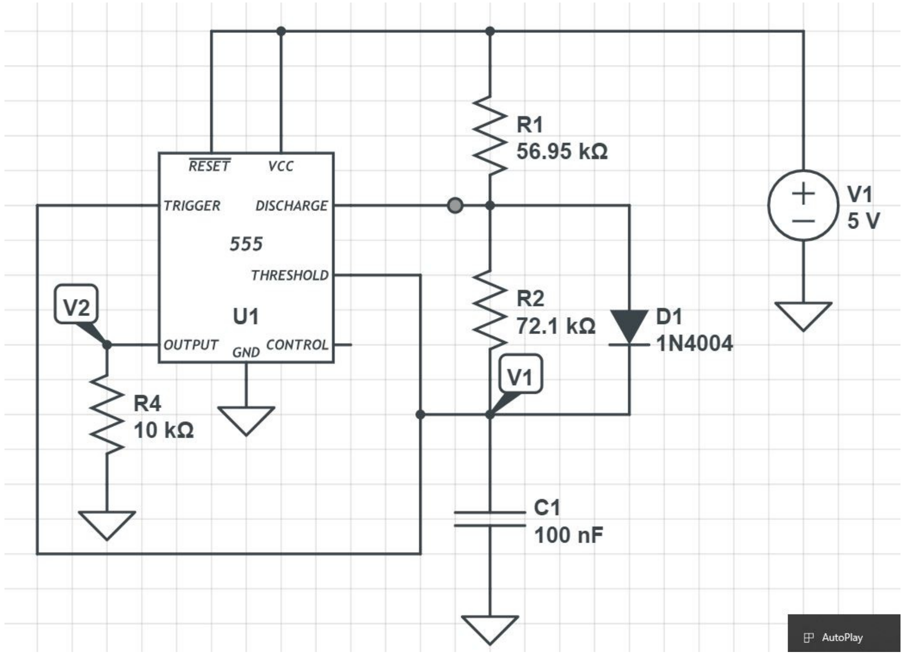
$$R_1 \rightarrow \left(\frac{5ms}{6.824ms}\right) 72.13k = 52.85k\Omega$$

Rerun the simulation and you get T(on) = 4.64ms. Iterate again...

$$R_1 \rightarrow \left(\frac{5ms}{4.64ms}\right) 52.85k\Omega = 56.95k\Omega$$

ant T(on) = 5.04ms. The final design is then

- C = 0.1uF
- R1 = 56.95k
- R2 = 72.13k



Final design for a 555 timer with a 100Hz, 50% duty cycle output

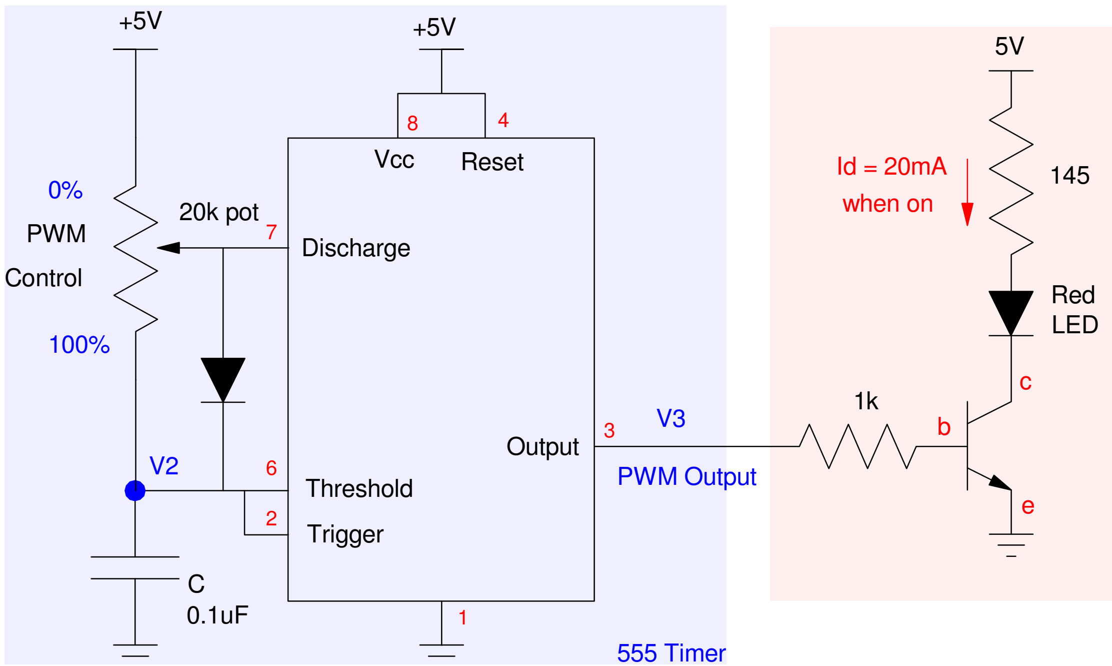
Note:

- Hand calculations get you close, but they're usually a little off due to approximations and assumptions.
- CircuitLab simulation results should be more accurate.
- The acid test is build the circuit on a breadboard and take measurements.

LED Brightness Control

By varying R1 and R2, you can adjust the on and off times for a 555 timer. An easy way to do this is to use a potentiometer for R1 and R2:

- When the pot is at the top, the on time is zero and the off time is 1.38ms (0% duty cycle)
- When the pot is at the bottom, the on time is 1.38ms and the off time is zero (100% duty cycle)



Brightness Control using a 555 Time

With a 20k pot, the frequency should be:

$$T \approx (R_1 + R_2) \cdot C \cdot \ln(2)$$

$$T = 20k\Omega \cdot 0.1\mu F \cdot \ln(2)$$

$$T = 1.386ms$$

$$f = \frac{1}{T} = 721.3Hz$$

For a 20% duty cycle

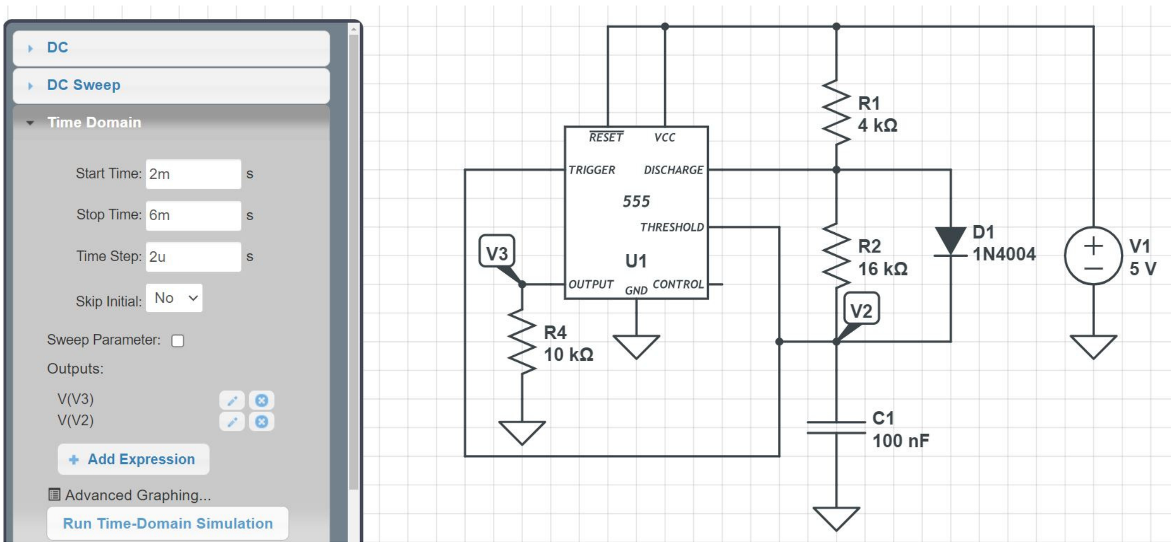
$$R_1 = 0.2 \cdot 20k = 4k\Omega$$

$$R_2 = 0.8 \cdot 20k = 16k\Omega$$

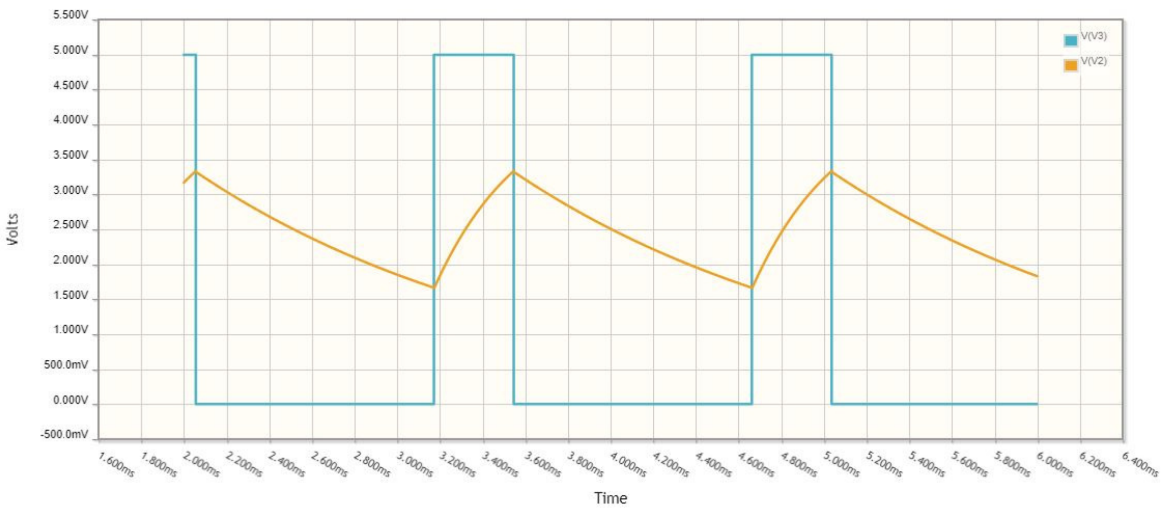
Checking in CircuitLab (just simulating out to V3)

- The period is 1.486ms (1.386ms calculated)
- The on time is 0.374ms (25.2% vs. 20.0% calculated)
- The off time is 1.112ms (74.8% vs. 80.0% calculated)

The timing is a little off due to the calculations ignoring the 0.7V drop across D1. By adjusting R1 and R2, you can get the duty cycle closer to 20.0% if you want.



CircuitLab Simulation for 20% Duty Cycle



Resulting Voltages: The period is 1.486ms and the duty cycle is 25.2%