UCI STUDY GROUP (2021)

CONSTANT CURRENT SOURCES

Theory of Operation

Constant current sources (CCS) are very handy circuits because they provide a constant current to our load regardless of changes in the load. If I want to power an LED and limit it to 20mA, a 2N2222 NPN transistor and a couple resistors can do the job. If I add another LED in parallel to the first, the current will remain the same.

Ohm's law states that when a constant voltage is applied across a resistor, the current through the resistor is also constant ($I = \frac{E}{R}$).

These circuits are great for providing reference voltages to ICs, Op Amps/Comparators, and battery chargers, etc. and are used inside the 555 Timer IC as well. As the load changes, the transistor is going to regulate the voltage to maintain a constant current. It does this by increasing its internal resistance between collector and emitter. This has the same effect as using a 470Ω instead of a 200Ω resistor in a simple LED circuit. Recall, that when the V_{CC} = 5 volts we used a 220 Ω current limiter to maintain 15mA (.015A). When we increased V_{CC} = 9 volts we used a 470 Ω to maintain the 15mA through the LED. The goal here is to create a circuit that will adjust the resistance automatically without external intervention.

Figure 1 shows how a simple voltage divider can supply a known voltage to the base of the transistor. This sets the forward bias of the transistor at a steady state. The current is controlled by the emitter resistor (R_E) which is connected to ground. A lower value emitter resistor allows more current to flow through the collector to the base and a higher value reduces current flow. The middle circuit shows how a Zener diode can be used to set the base voltage as well. Finally, a trim pot can be used to adjust the base voltage to accommodate higher power supply voltages to make an even simpler circuit.

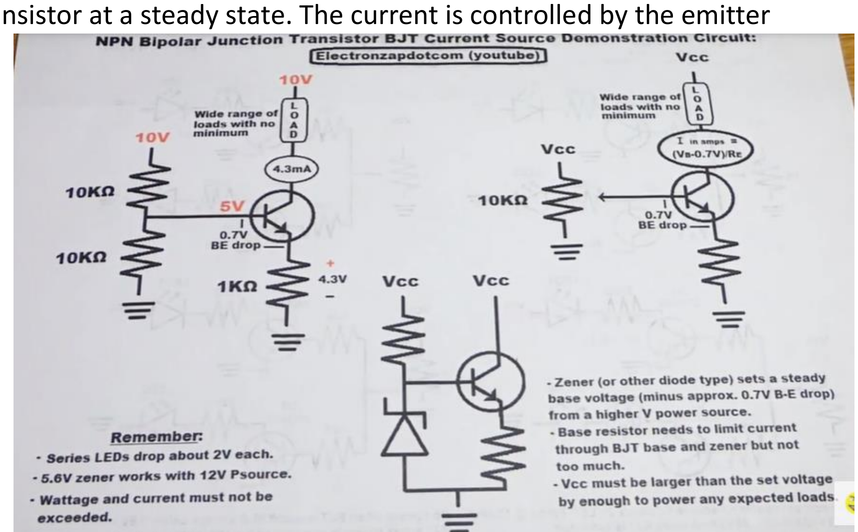

Figure 1: Three ways to create constant current circuit with an NPN transistor.

Setting Output Current

Think about the circuit on the left in Figure 1. Let's say we are using a red LED as the load. I know it can handle about 15mA max and it consumes about 1.7 volts. I am going to use the emitter resistor as the "current limiting" resistor. This is analogous to the resistors we used in our simple LED circuits. Also, keep in mind that the transistor drops about 0.7 volts across the base to emitter junction just like a diode does when it turns on.

So, first we need to calculate the voltage across our current limiter resistor. Assume a base voltage of 2.5v and a voltage drop of 0.7v, that gives us ~ 1.8v across the resistor. Next, we calculate the required resistor value. From Ohm's law, R = Voltage/Current. We want to limit the current to 15mA or .015 amps. Therefore, $R_E = \frac{1.8}{.015} = 120\Omega$.

Simulation of My Circuit

My first simulation in Multisim (Figure 2) shows the V_{BASE} ~=2.5v or ½ the Vcc input. This is what we would predict with the voltage divider (R_1 and R_2 in series).The current through the LED is 14.7mA which is very close to the desired amount of 15mA. Notice also the very small B-E current (I = 71.2µA) controls a much larger current (14.7mA) and that is why we say transistors amplifiy input signals. The Vcc, combined with R_3 results in a large **amplified voltage and current** across the collector to emitter. The actual amount of current is determined by the base voltage and R_3.

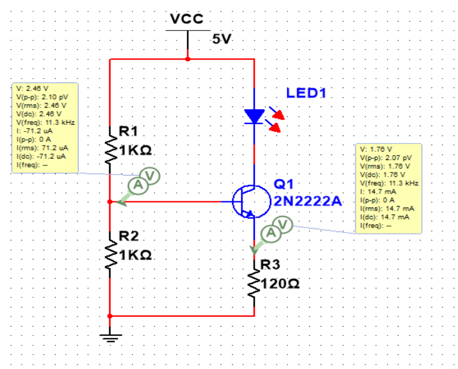

Figure 2: Constant current driver with one LED shows the desired ~15mA.

The amplification factor of transistors is described as *Beta* (B) in datasheets. The common formula is $I_{collector} = B \times I_{base}$ or the current through the collector = base current x Beta. If Beta = 100, it means the transistor may be capable of producing a current that is 100 times greater than the input current. Again, a small current is used to managed a much larger current. That is why BJT are so useful in audio amplifiers.

Effects of a Larger Load

The next simulation shows what happens when I add a second LED to the load in parallel to the first one without changing any components. The transistor maintains a steady 14.7mA as before. Keep in mind that with two LEDs, the voltage consumption is doubled to ~= 3.4V but the battery can still manage the load, so the circuit works fine. Notice we do not use resistors on the LEDs. R_3 functions as our current limiter.

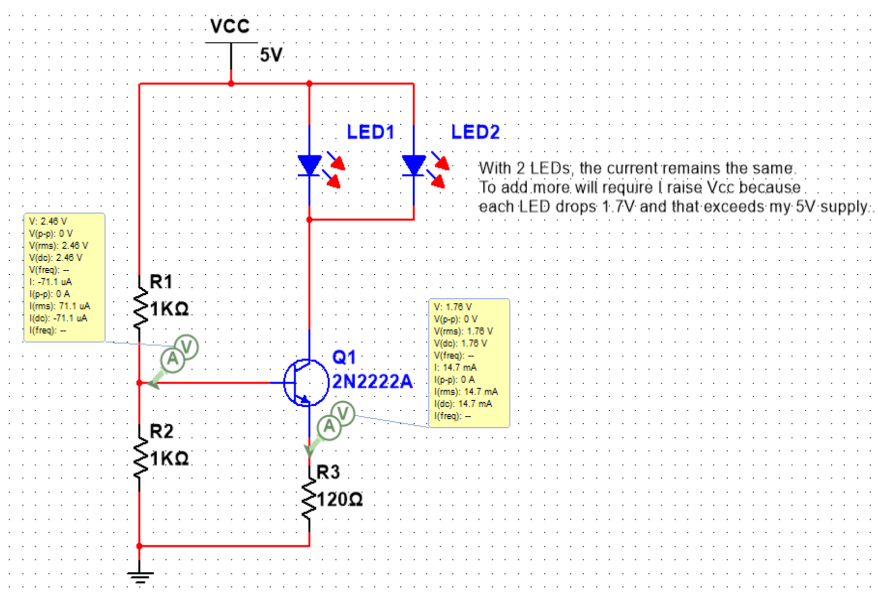

Figure 3: With two LEDs, the current is steady at ~15mA as calculated.

Now let's see what happens with 3 LEDs. Since the load needs 1.7V x 3 = 5.1V, the battery cannot supply enough power. If I use 6V it *will* work but it also increases the current output.

To remedy this, and to allow for varying current loads, I chose a 9V battery and modified the voltage divider. I still want ~17mA output and I want to keep the base voltage close to 3V. Therefore, I need 1/3 of the 9V battery. To do this, I made the voltage divider with a 3:1 ratio. By changing R_1 to 2K, it drops 2000/3000 or 2/3 of Vcc. Measuring from ground up, R_2 drops 1/3 of Vcc = 3v and 2/3 is dropped across R_1. Hence, I end up with ~3V on the base which will drive the transistor nicely while only increasing the output current by 1mA. The voltage divider formula is: $V_{out} = V_{in}(\frac{R2}{R1+R2})$. Therefore,

Vout = 9v(1000Ω/3000Ω) = <u>3v</u>.

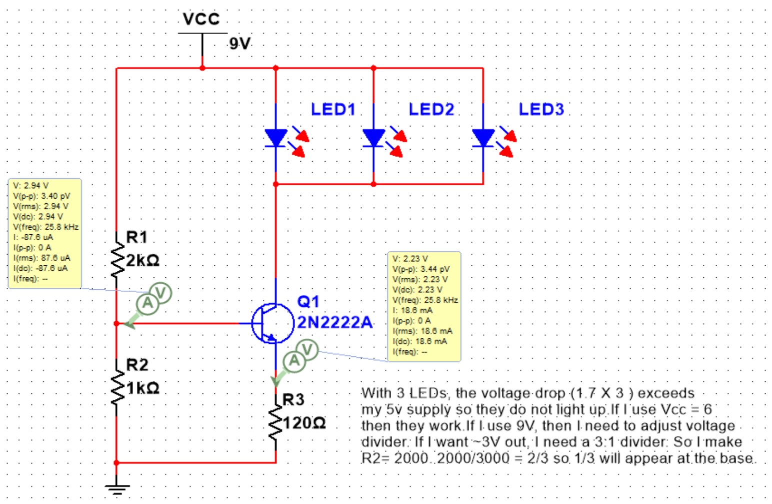

Figure 4: With 3 LEDs the Vcc must be increased. Here 9V Vcc drives the circuit. The divider must be modified to maintain 17mA.

Looking Inside a Transistor

These circuits have shown how a constant current can be supplied to a load that changes. But what exactly is happening inside the transistor? Let's consider a hydraulic example. If we make sure the control (Base) voltage is stable, then the output current must be stable. In other words, when we want constant output we make sure the input doesn't change.

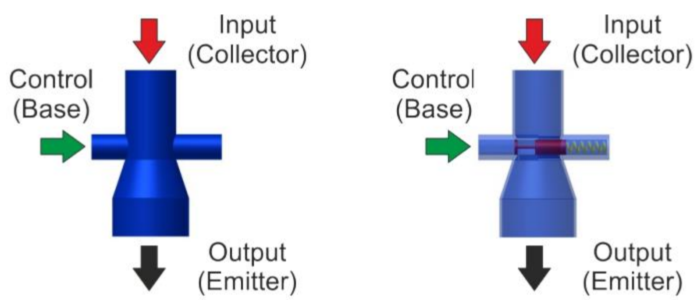

Figure 5: Transistor depicted as a controlled water valve. The amount of current on the Base-Emitter path directly controls the flow from the collector to emitter.

We have seen how the transistor amplifies the input voltage and current. We just don't want that amplified output current to change in this circuit. In Figure 5, notice the BJT base is like a control valve. As we open the valve, more water flows through the line between collector and emitter. Unlike a kitchen faucet, the transistor *"faucet"* amplifies our water flow as if we actually made the input pipe larger! So is this magic? No, it just seems like magic!

When you dig down deeper into the theory of transistors and what makes them work you discover they have some components in them that are rarely discussed. For example, ever wonder why they have an arrow in their symbol? Well, that indicates that the P-N junction of Base and Emitter is really a diode. And just like a diode, it takes about 0.7v to forward bias the BJT (turn it on) so current will flow. The base is the anode (+) and the emitter is the cathode (-) of this small diode structure. Also, the junction between the Base and Collector layers make up another diode but it is not shown in the symbol. You can test the transistor with and ohmeter and you will see it acts like two diodes back-to-back with low resistance in one direction and high resistance in the other direction.

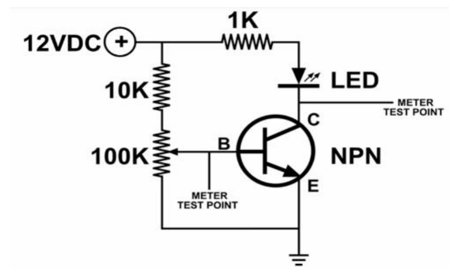

Figure 6: The BJT acts like it has a variable resistor inside. Here we simulate that with a real potentiometer. As the base voltage is raised/lowered, the resistance changes between collector and emitter.

In a real BJT like the 2N3904, it internally acts like a variable resistor. Look at Figure 6. When the potentiometer is rotated, the base voltage changes. When the base voltage = 0V, we say the transistor is in *cut-off*. That means the collector-emitter resistance is maximum and no current flows through the C-E layers and the transistor is *OFF*. When the base voltage increases to the recommened maximum of 6V (Figure 7), the collector-emitter resistance decreases to just a few ohms and maximum current can flow. This condition is described as *saturation*. The internal resistor value is now so low that the full collector current can flow through the C-E junction and we say it is turned on full blast! **In digital design, this is exactly what you want. You don't want the high frequency noise of changing states to interfere with how your logic gates perform. So you drive the transistor into full saturation.**

LIMITING VALUES

In accordance with the Absolute Maximum Rating System (IEC 60134).

SYMBOL	PARAMETER	CONDITIONS	MIN.	MAX.	UNIT
V_{CBO}	collector-base voltage	open emitter	–	60	V
V_{CEO}	collector-emitter voltage	open base	–	40	V
V_{EBO}	emitter-base voltage	open collector	–	6	V
I_C	collector current (DC)		–	200	mA
I_{CM}	peak collector current		–	300	mA
I_{BM}	peak base current		–	100	mA
P_{tot}	total power dissipation	$T_{amb} \leq 25$ °C; note 1	–	500	mW
T_{stg}	storage temperature		−65	+150	°C
T_j	junction temperature		–	150	°C
T_{amb}	ambient temperature		−65	+150	°C

Note

1. Transistor mounted on an FR4 printed-circuit board.

Figure 7: Maximum voltage ratings for the 2N3904.

Conclusions

- I hope you can now visualize how a transistor can maintain a constant ouput current through its collector by adjusting the voltage between base and emitter. This is exacly how a bench power supply works. You can set the maximum current you want, and it adjusts the voltage so as to maintain that set current. When the transistor is in saturation, current throught the C-E layer is at maximum and the voltage level is at a minimum. Somewhere in between cut-off and saturation, the current can be slowly increased or decreased by changing the resistance
- Don't forget the relationship between voltage and current:

  Current = $\frac{Voltage}{Resistance}$ so the transistor can adjust the collector-emitter resistance and thus change the current as in Figure 8.

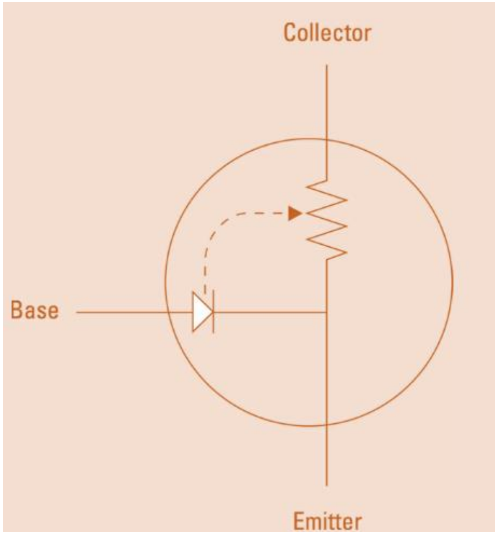

Figure 8: Transistor acts like it has an adjustable resistor inside of it. Courtesy of Doug Lowe "Electronics for Dummies", 2017.

- When transistors are used as audio amplifiers, designers adjust the base voltage so that all of the input signal (music, voice, etc.) will be faithfully and accurately reproduced at the output of the circuit. By knowing the peak-to-peak voltage of the AC input signal, the base voltage can be set to be exactly in the middle of that voltage range. That is refered to as DC biasing the transistor base. The constant voltage and the sound are then amplified together without distortion.