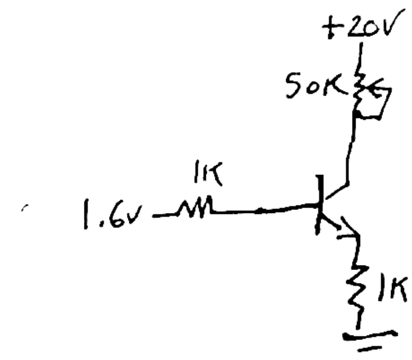
Tim Savas
Homework 06

Transistor Saturation Exercise

Leading up to the Homework 01 problem, I needed to develop my understanding of switches and transistor saturation. I ended up producing some study guides on this for myself. It helps me to understand these materials in sequence with one another and so I'm keeping them together. You're welcome to skip to the start of problem 01 in this document!

What is transistor saturation and when does it happen?
Here is the worked example on Falstad: **http://tinyurl.com/y6ob93ul**



	Collector			Base		Emitter			Source	Outcomes	
Scenario	R_{load}	I_C	V_C	V_B	V_{BE} Drop	V_E	R_E	I_E	V_{source}	Δ V_C, V_E	Is V_{CE} > .2V?
A	10	0.001	19.99	1.6	0.6	1	1000	0.001	20	19	yes
B	12000	0.001	8	1.6	0.6	1	1000	0.001	20	7	yes
C	18000	0.001	2	1.6	0.6	1	1000	0.001	20	1	barely

A) Low R_{load}, 10 Ohms

At a low RLoad of 10 Ohms, what is happening? I_C naturally equals I_E. In order to match the I_E of 1mA, the power supply of 20V of the collector only needs to kick in a small amount of voltage to go across the wire-like low R_{load}.

$$V = IR$$

$$.01V = 1mA \times 10\ Ohm$$

So on the V_C point, just after that R_{load}, you see the 20V -.01V, or 19.99V. It means there's a spare 19.99V of overhead left for the power supply to kick in under any higher loads, or of course, under higher current determined by the B and E. Notice that V_{CE} is 19V, which is well above the required .2V.

B) Nominal R_{load}, 12K

At a higher Rload of 12K, I_C still equals I_E. In order to match the I_E of 1mA, the power supply has to kick in more voltage, 12V, but it still has enough to spare for a good V_{CE}.

$$V = IR$$
$$12V = 1mA \times 12k$$

So V_C is then 8V, or the difference between the source and the drop across R_{load}. 8V is still plenty to clear our $V_{CE} > .2V$ rule.

C) Max R_{load}, 20K

We can figure out the maximum R_{load} working backwards, too.

We know we need V_{CE} to be at least .2V. Let's call this 1V. VE is 1V and therefore the lowest possible V_C we can have is 2V, roughly. This means that we can use up to 18V from our 20V power supply.

So now through our I_C (aka I_B) and known maximum V drop, we can figure out the maximum R_{load} of this transistor circuit.

$$R_{load\_max} = V/I_C$$
$$R_{load\_max} = 18V/1mA$$
$$R_{load\_max} = 18K$$

D) Higher loads

Under higher loads, things get weird. I_C and I_B no longer match, and generally the transistor becomes less magical and more Ohmic. The book has a good blurb on page 156:

> What if you take R_{load} to its maximum? Here, the answer is, "No. In this case, the current source fails." It fails because we have violated one of the assumptions that we mentioned in 4N.24... we can no longer satisfy the requirement that VC exceed VE, and the circuit cannot hold the current constant. The transistor can no longer do its magic—adjusting the voltage, VC, as needed to hold I_C constant. When VCE falls below a couple of tenths of a volt, the transistor is said to be saturated.
> When that happens, none of the usual rules that we have been advertising will hold. The circuit does become ohmic, the transistor looking like a small-valued resistor; further increases in Rload simply reduce Load. Setting Rload to 50K, for example, would take ILoad down to about 0.4mA

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Homework 06

4W.3 Transistor Switch & Saturation Exercise

I have worked part of 4W.3 as a bridge between the above saturation exercise and the switch problem in the homework. I am keeping these materials together as a study guide.

Switches need a few things in order to work:

> We want a low VCE, that minimizes power lost in the switch. I think that's the same thing as saying we want saturation.
> A switch should be purposefully overdriven, with about **10x the minimum base current to pass the required I_C**. That saturates the switch strongly, keeping VCE low to minimize power lost in the switch. The best switch would disappear electrically when ON, putting all power into the load, none into itself.

So looking at the circuit A at the top of page 186, and the worked problem, we can test to see if this switch meets those specifications. Here is the circuit on Falstad: http://tinyurl.com/y5vz4ncb

The book says that I_B of 4.4mA is ample to saturate the transistor. So what do they mean by that? I think what they mean is the following.

> I_{load} = 4.8V/50
> I_{load} = 100mA
> I_{load} is the maximum load before the transistor is loaded. Any higher and the V_{CE} is less than 0.2V.

Now that we know this, we can compare this spec to the current we're trying to apply at the I_C.

4.4mA at the base means 440mA at the collector, because of β. That also means 440mA for I_C. So this 440mA current is 4x the maximum I_{load} of 100mA. The transistor is definitely saturated!

	Collector			Base					Emitter			Source	Outcomes		Falstad
Problem	R_{load}	I_C	V_C	Vin	V_{BE} Drop	V_B	R_B	I_B	V_E	Beta	I_E	V_{source}	Δ V_C, V_E	Is V_{CE} > .2V?	
4W.3	50	0.44	-17.0	5	0.6	4.4	1000	0.0044	4.4	100	0.44	5	-21	No it's less, great!	link

1 Switch

1.1 Design

The first step to this problem is to understand I_{load}. This would be the maximum current at the collector before the transistor is saturated. In order for the switch to work well, the transistor should be substantially saturated. That means to say that V_{CE} should be well below 0.2V. So let's figure out I_{load}:

$$R_{load} = V/I$$
$$R_{load} = 25V/2A$$
$$R_{load} = 12.5\ Ohm$$

$$I_{load} = V/R$$
$$I_{load} = 24.8V/12.5$$
$$I_{load} = 2A$$

So now we know that we need to get past I_{load} of 2A in order to saturate the transistor. The book recommends 10x this value for guaranteed saturation. This seems kind of crazy to me personally. In the worked example I've done above, the book uses about 4x. I will use 2x for my solution here. That seems to be a good saturation guarantee.[1] Now we must determine the RB that will result in an 4A Iload at the collector.

$$I_C = 4A = I_E$$
$$I_E/beta = I_B$$
$$4/40 = 100mA$$
$$I_B = 100mA$$

Ok so we know we want 200mA at the base. What is the base voltage?

$$V_B = V_{in} - V_{drop}$$
$$V_B = 5V - 0.6V$$

[1] I have just logged into Canvas to submit my assignment to see the note about using 4x. I do not have time to make this change. I hope you can appreciate that I understand well this "saturation" state and simply chose a 2x value and not 4x. Also see my practice problem from the book above where I/we in fact do use 4x.

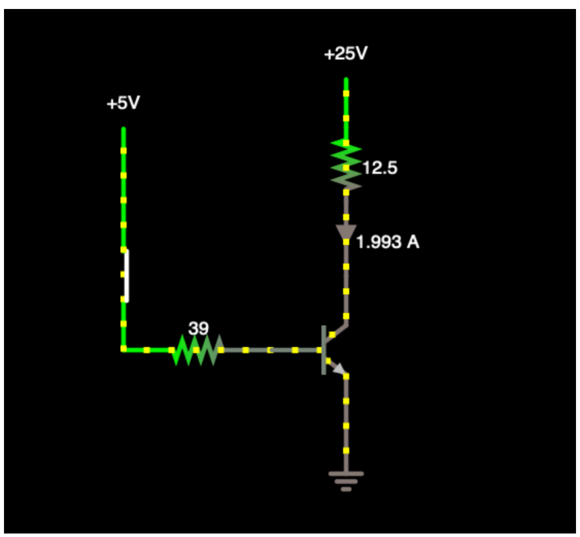
$$V_B = 4.4V$$

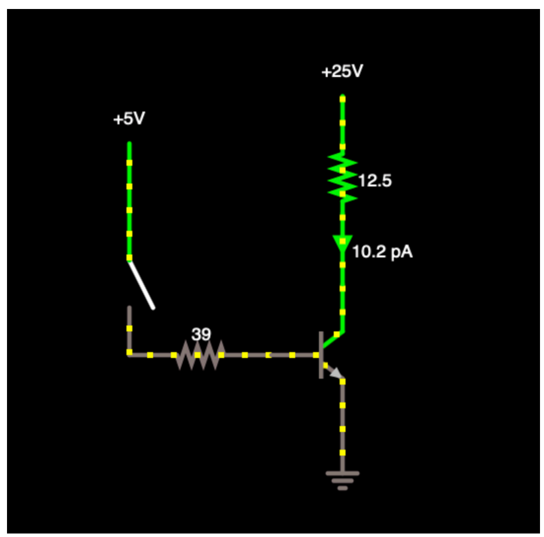
Now that we have VB and IB, we can spec the RB from Ohm's Law:

$$R_B = V/I$$
$$R_B = 4.4/.1$$
$$R_B = 44 \text{ Ohm}$$
$$R_B = 39 \text{ Ohm}$$

I'll use this standard resistor value.

	Collector			Base					Emitter			Source	Outcomes		Falstad
Problem	R_{load}	I_C	V_C	Vin	V_{BE} Drop	V_B	R_B	I_B	V_E	Beta	I_E	V_{source}	Δ V_C, V_E	Is V_{CE} > .2V?	
4W.3	50	0.44	-17.0	5	0.6	4.4	1000	0.0044	4.4	100	0.44	5	-21	No it's less, great!	link
HW 01	12.5	4.0	-24.6	5	0.6	4.4	44.4	0.1	4.4	40	4.0	25	-29	No it's less, great!	link
This table may seem arbitrary or redundant. In my non-pdf file it has equations embedded that help me to study. I keep 4W.3 to compare the approaches of the two problems.															





1.2 How to drive the switch

I believe this question is asking, can the motor be driven with 25mA going into the base of the transistor? Probably not. Let's figure it out.

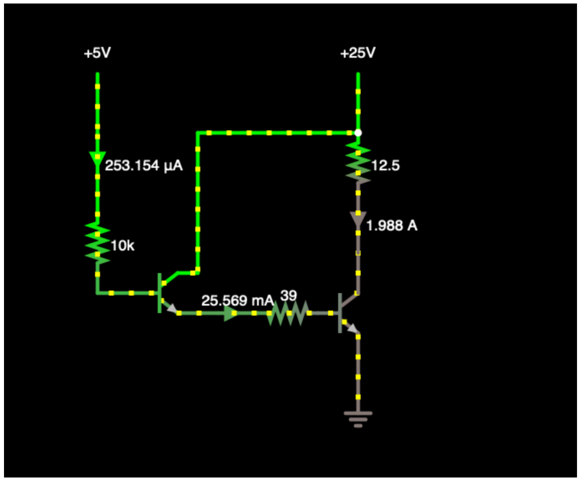
$$I_B = 25mA$$
$$I_E = IB * \beta$$
$$I_E = .025 \times 40$$
$$I_E = 1A$$
$$I_C = 1A$$

Bummer! No it doesn't work.

We need to increase the current going into the resistor by 2x. A solution would be to use a Darlington pair.

Here is the link to Falstad: https://tinyurl.com/y446o72p

I am looking at this drawing again and I think it is incorrect actually. I have 25mA going into the base, however I think that 25mA should be the source, coming before the first transistor. I'm running low on time and will need to submit this and hopefully come back to it!



2 How did we get away with ignoring Ebers-Moll on Day 5?

2.1 Where in Lab 5…

We're obliged to pay attention to the Ebers-Moll view in at 5L.1.7. This section asks us to remove the emitter resistors, which we know alters the gain equation in favor of barn-roof distortion.

> Stage 1: increase the gain of the bipolar differential amplifier.
>
> First circuit change: maximize gain: Remove the 100 ohm emitter resistors. Do you expect the circuit to lose temperature stability, with these gone? What happens to the constancy of gain?
> …to test the constancy of gain, use a small triangle as input, and see whether you notice the "barn-roof" distortion that we saw in Lab 4L.

2.2 How did we get away with ignoring E-Moll in Lab 4?

In Lab 4L.4 we were able to ignore Ebers-Moll because we had a good sized R_E on our amplifier circuit. I explain in problem 3 of this homework the details of R_E when it comes to gain, but I can explain here in short.

Punchline: an emitter resistor greatly reduces error (variation in gain, and consequent distortion).

Without our R_E, the gain equation looks like:

$$\text{Gain} = -R_C/r_e$$

With our R_E, the gain equation looks like:

$$\text{Gain} = -R_C/(R_E+r_e)$$

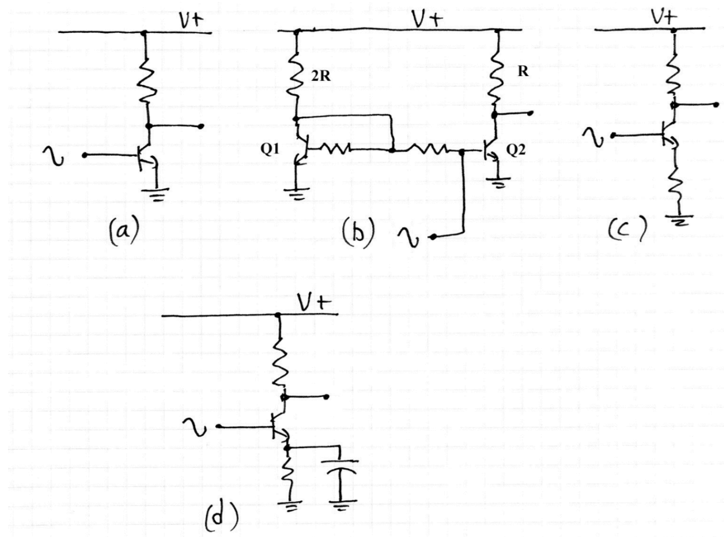
So having a constant R_E value provides a ballast for the denominator in the gain equation. A blurb from my answer below: the installed R_E provides constancy in our denominator for our gain equation, and thus the R_E dilutes the variability of r_e, assuming R_E is not itself insubstantial.

R_E Nevertheless, Ebers Moll still could have popped up in this circuit, so long as we might have tried to increase gain to too exceptional a level. But we did not in day 05. Look at the R_C and R_E. They're 10x apart, which is all the resulting gain we were asking for: 10x.

There is actually a part of the Day 5 lab where we don't ignore Ebers-Moll. It is Lab 4L.4.1 Maximizing gain: sneak preview of Ebers-Moll at work. Here we add a capacitor which shorts out R_E at high signal frequencies. Then we observe the barn door distortion. So maybe this homework problem is a trick question!

> Modify your common-emitter amp to make the amplifier shown in Fig. 4L.6 (similar to Fig. 5N.17). What circuit properties does your addition of the bypassing capacitor affect? It affects gain, because RE disappears from the gain equation.

3 High gain amplifiers



a) This puts out barn roof distortion due to poor linearity or constancy of the gain, if we were to feed the circuit a triangle wave. The book gives an excellent explanation of this which I snapshot below for studying purposes, but I'll summarize it in my own words as well. We have no R_E—it's a grounded-emitter amp—and so our gain equation is $G = -R_C/r_e$. But re unfortunately varies with I_C. More specifically re increases as V_{out} increases. Really it's a cascading effect of influences. Vout increases (swings up), which lowers I_C, which then increases re, and this—as the sole denominator in our gain equation—finally results in a lowered or distorted gain. See figure 5N.10 for an excellent visual breakdown of this distortion.

b) I think this circuit will also have some unfortunate distortion. It's emitters are tied erectly to ground, and so I would expect that scheme's results that I explain in circuits A and D. Denominator for the gain is just little re etc. Please see my notes on those other circuits.

c) The R_E is a solution to our problem in circuit A. This is the 5N.4.1 “Distortion remedy: emitter resistor—at the price of gain,” solution. We get much improved linearity or constancy of gain by adding the resistor to the emitter. This happens because the installed R_E provides constancy in our denominator for our gain equation, and thus the R_E dilutes the variability of r_e, assuming R_E is not itself tiny. I think that this solution is itself good reason for the big R_E vs. little re nemonic, as R_E predominates re in the gain equation. I quote the book for later studying purposes

> One cannot eliminate this variation in re, but one can make its effects negligible. Just add a constant resistance much larger than the varying re. That will hold the denominator of the gain equation nearly constant.
> With an emitter resistor added, the gain variation shrinks sharply, see Fig. 5N.13. re still varies as widely as before; but its variation is buried by the big constant in the denominator…
> Punchline: an emitter resistor greatly reduces error (variation in gain, and consequent distortion).

This question does not ask us to speak to other aspects of gain this circuit influences aside from linearity. But note that it brings a necessary compromise in the amplitude of the gain. We are of course increasing our denominator for the gain equation, and so the RE reduces gain in comparison to not having it there. It’s a safe trade off:

> This we get at the price of giving up some gain. (This is one of many instances of Electronic Justice: here, those greedy for gain will be punished: their output waveforms will be rendered grotesque.)

d) The linearity of gain of this circuit would depend on the frequency of the input signal. This is according to what we know about capacitors and also what we know about the relationship I described between R_E, re, and subsequent distortion. Assuming that R_E is of some adequate size, at low frequencies the cap acts like a high impedance resistor and the current only sees R_E. In this scenario there would be little distortion. But with higher frequencies, the capacitor looks more like a short to ground and so the circuit looks like problem A, resulting in distortion. The book goes over this in Lab 4L.4.1: Maximizing gain: sneak preview of Ebers-Moll at work.

> Now let’s try a case that our first, sample, view of the common-emitter amplifier does not describe accurately: check out Fig. 4L.6 to see what happens if we parallel the emitter resistor with a big capacitor, so that at “signal frequencies” R_E is shorted out.

4 Temperature Stability

a) Temperature-wise, this doesn't work. The temperature rise increases IC and thus saturates this transistor. Sad!

b) This is temperature stable through circuit symmetry. The book summarizes this solution which I find somewhat complex. I quote it here and I will return to study it further. Btw I am just noticing this problem is taken from the book :o

> Because the collector currents in the two transistors are equal, the two VBEs are equal. Imagine a change in temp—let's imagine a rise of about 9ºC. This drops the VBE of Q1 by about 18mV. If this were an unprotected circuit, like circuit (a), that change would reduce Q2's output to one half what it was: in other words the output quiescent voltage would be radically upset.
> But because Q2 is heated just as Q1 is, Q2's current is unaffected by the heating of both transistors. Heating reduced the VBE of Q1; but that reduced value evokes the original current form heated Q2. This stabilizing scheme might be called stabilization by compensation rather than by feedback: a change in a component, otherwise disturbing, is compensated for by a matching change in a second component.

c) Our R_E comes in handy for temperature as well as gain. The book explains the negative feedback mechanism well:

> I_C begins to grow in response to increased temperature;
> V_E rises, as a result of increased I_C (Ohm's Law)
> But this rise of V_E diminishes V_{BE}, since V_B is fixed. Squeezing V_{BE} tends to close the transistor "valve." Thus the circuit slows itself down (as the somewhat-grotesque hand in Fig. 5N.15 is meant to suggest).

d) This is temperature stable since we have an R_E. It has downsides described elsewhere. It has R_E that disappears at high signal frequencies.