	BJT 01 - The strange device

This project introduces the Bipolar Junction Transistor (BJT).

BOM	NPN transistor : BC574B Resistors: 100 Ω, 1 kΩ and 220 kΩ

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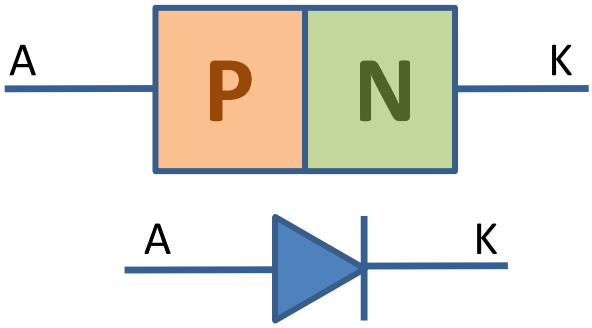
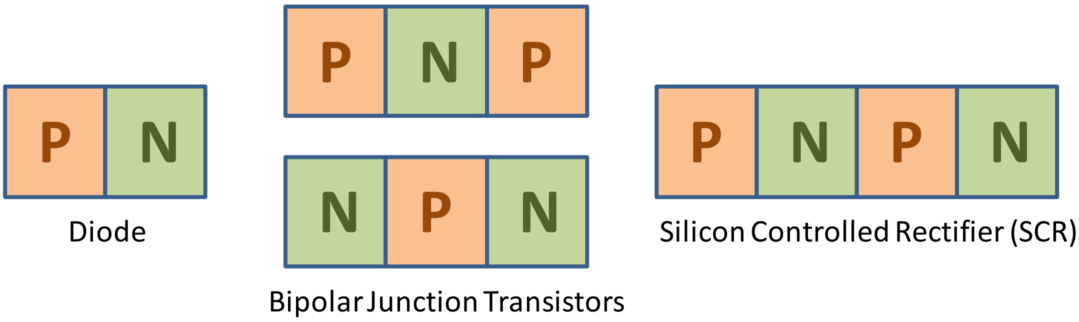
Meet the transistor

The semiconductor diode is the device obtained when you join an electron carrier rich N type semiconductor with a hole carrier rich P type semiconductor.



Although the physics of the device that give us the diode current vs voltage equations are quite complex, the operation of the device is intuitive: Current flows from anode (A) to cathode (K) because there are positive holes in the P region that can go from A to K and there are electrons on the N region that can go from K to A.
Using the same intuitive explanation we see that no current can go from K to A because there are (almost) no holes in the N region and (almost) no electrons in the P region.

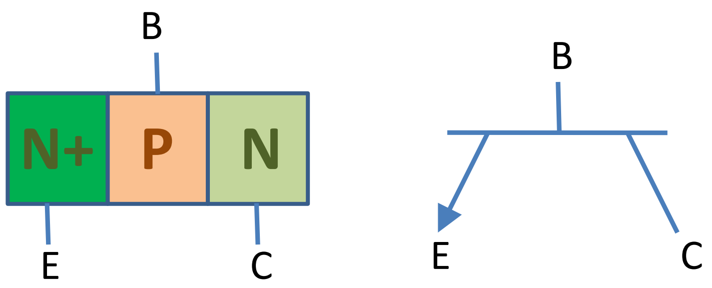
As we have obtained a useful device joining two different type semiconductor regions, it is immediate to ask ourselves if we can obtain more interesting devices by joining more regions. The spoiler result is that yes, we can obtain interesting devices joining three or four different kind semiconductor regions.



There are two ways to join three regions and we get the PNP and NPN Bipolar Junction Transistors (BJT) and there is only a way to join four regions obtaining the [Silicon Controlled Rectifier](#) (SCR).

We don't want to go too fast and we will leave the SCR for now and concentrate on the transistors. Both the PNP and NPN transistors operate in a similar way so we will explain first the NPN one and leave the PNP for later.

It would seem that the NPN BJT is a symmetrical device as we have one P region, that we call **Base (B)**, and two N regions. In fact, we could build symmetrical BJTs. In practice, however, the BJT operation benefits from having a non symmetrical design, so the two N regions are not equal. There is one N region called the **Emitter (E)** that usually have more free electron carriers that the other region that is called the **Collector (C)**. We can say that the emitter is more N than the collector, hence the N+ notation.

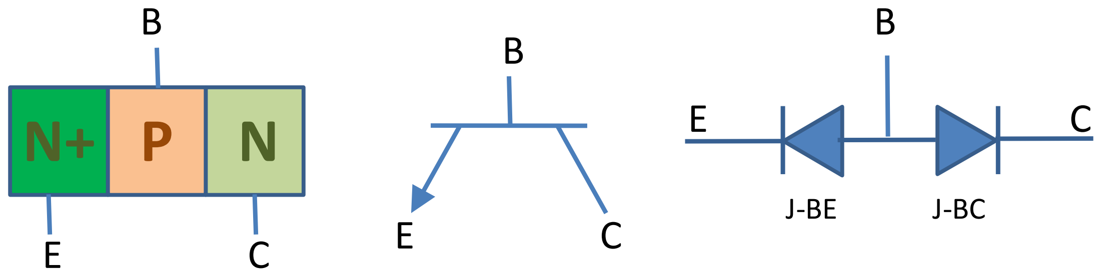


So, the real world transistor designs are not symmetrical and the device symbol is also not symmetrical so that we can locate the three terminals: Emitter (E), Base (B) and Collector (C) easily from its image.

Usually the density of free charge carriers increases from collector to base and to emitter so:

- The collector has a lot of free electron carriers
- The base has more free hole carriers that electron carriers have the collector
- The emitter has more free electron carriers that hole carriers have the base

We know that the joining of a P and N region generates a PN junction diode. The BJT features two PN junctions, one between the base and the emitter (J-BE) and one between the base and the collector (J-BC). So, we expect to obtain two diodes on a BJT transistor.



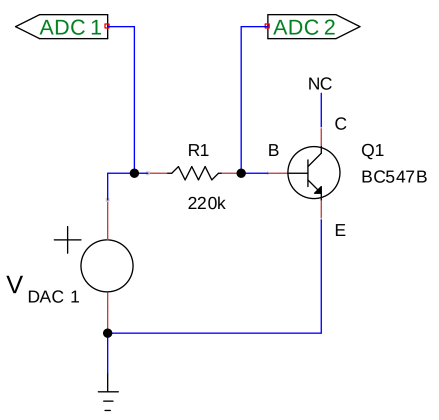
Let's check that.

Measuring the diode junctions

In this section we will measure a general purpose BC547B transistor. This transistor is one in the BC547 family that includes the "A", "B" and "C" kinds. We will use the "B" one.

	1	Obtain the datasheet of the BC547 transistor. Check that it is a three terminal device and locate the Emitter, Base and Collector terminals.

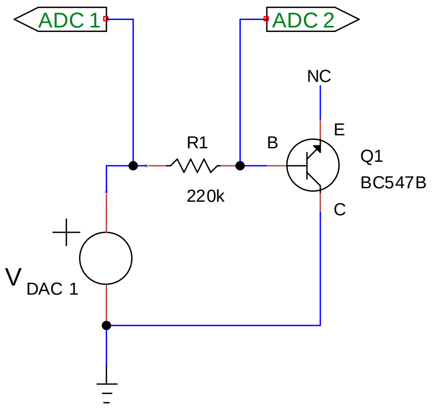
First we will see if the BE and BC junctions work, as we expect, as diodes.
We will start with the BE junction. Mount the following circuit. Note that "NC" in the collector means "Not Connected". That means that this terminal must be left unconnected.



Now, open a Python interpreter, import the slab module and connect to the board. In order to obtain the DC curve of the BE junction we will use the DC submodule. We will use the ***curveVI*** command of this module to show the DC I(V) curve for DAC 1 voltages between 0V and 2V. The use of the ***returnData*** option enables us to store the obtained measurements in the vbe and ibe variables. We specify R1 in kΩ so that the current is measured in mA.

```
>>> import slab_dc as dc
>>> vbe,ibe = dc.curveVI(0,2,r=220,returnData=True)
```

Now, do the same for the BC junction. Mount the following circuit.



And obtain its DC I(V) curve.

```
>>> vbc,ibc = dc.curveVI(0,2,r=220,returnData=True)
```

Now we can compare the two curves we have obtained:

```
>>> slab.plotnn([vbe,vbc],[ibe,ibc],\
>>> "","Vd (V)","Id (mA)",["BE","BC"])
```

🛠	2	Obtain the Ibe(Vbe) and Ibc(Vbc) curves. ¿Do they behave like diodes as expected? ¿How do they compare?

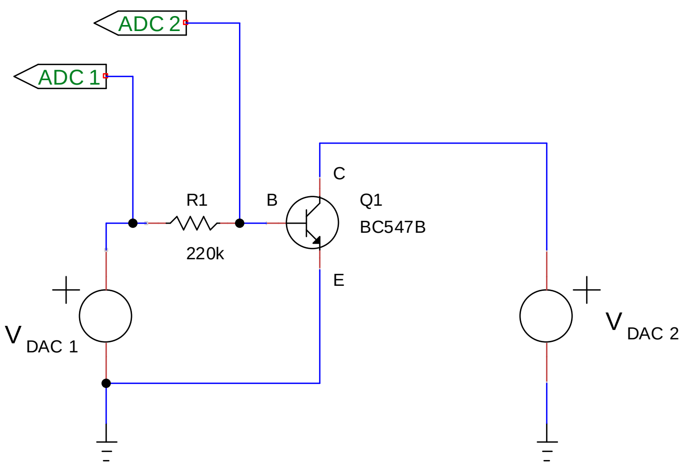
You should get a typical DC diode curve in both the BE and BC junctions. It seems that the transistor behaves as expected.

Take note of the approximate value of the threshold voltage for the curves (when they start to rise) because we will need to refer to them later.

BJT's strange behavior

It seems from previous measurements that the BJT really behaves like two diode junctions, one between B and E and another between B and C.
Let's try what happens if forward bias the BE junction again but, this time, instead of leaving the collector unconnected, we reverse bias its junction.

Mount the following circuit:



Now, if we set DAC 2 to 3 V and never let DAC 1 go over 3V, we can guarantee that voltage V_{BC} at the BC junction is never positive. So the BC junction is guaranteed to be reverse biased. Then we repeat the I(V) measurement of the BE junction.

```
>>> slab.setVoltage(2,3)
>>> vbe2,ibe2=dc.curveVI(0,3,r=220,returnData=True)
```

You can compare the new curve with the previous one obtained in 2, but they are easier to compare if drawn together:

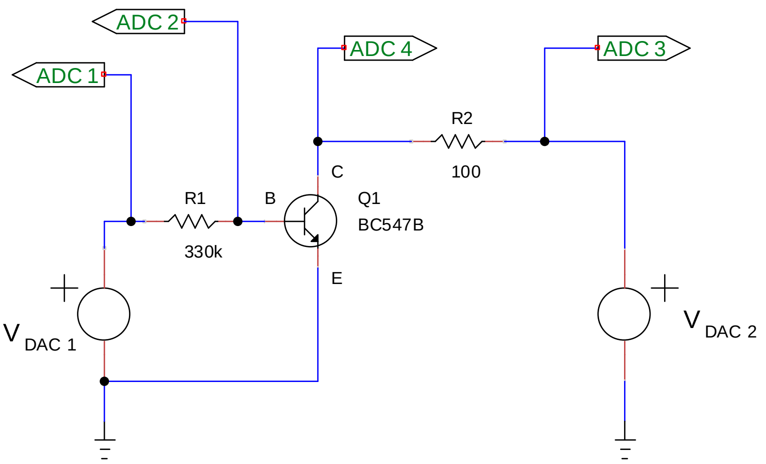
```
>>> slab.plotnn([vbe,vbe2],[ibe,ibe2],\
... "","Vbe (V)","Ibe (mA)",["BE1","BE2"])
```

	3	Mount the new circuit and obtain the Ibe2(Vbe2) curve. Compare it with the one obtained in 2. ¿How do they compare?

Things are getting strange at this point. From its construction, based on one P and two N regions, it seemed that the BJT behaves like two diode junctions. Measurements performed on 2 also seem to confirm that assumption. Now we see that the behavior of the BE junction is different depending if the BC is left open or reverse biased. We see, then, that the two junctions are not independent of each other.

The change of behavior looks like something is happening in the BC junction as this is the one that has changed in the two experiments. The best method to check what is happening is by performing new measurements.

We will add a 100 Ω resistor to the collector connection so that we can measure if any current is entering this terminal. The BC junction is reverse biased so, it seems that no current should enter this terminal.



We cannot use the ***curveVI*** command of the DC module because it only can give us the BE junction current. So, we will use the ***dcSweepPlot*** command. The following command will sweep the DAC 1 voltage between 0 V and 3 V and give us the DAC voltage and all four ADC voltages.

```
>>> d1,a1,a2,a3,a4=slab.dcSweepPlot(1,0,3,returnData=True)
```

Now we can calculate the BE junction voltage V_{BE}, the base current I_{BE} and the collector current I_{CE}. Remember that we need to give the resistances in kΩ to obtain the currents in mA.

```
>>> vbe3=a2
>>> ibe3=(a1-a2)/220
>>> ice3=(a3-a4)/0.1
```

Now we can draw the currents against the V_{BE} voltage.

```
>>> slab.plot1n(vbe3,[ibe3,ice3],\
... "","Vbe (V)","I (mA)",["Ibe","Ice"])
```

You should see something quite interesting: At some point the collector current rises to levels much higher than the base current. But we know that the collector junction is reverse biased. Isn't it? Let's check that.

We can compute and show the voltage on the BC junction:

```
>>> vbc3=a2-a4
>>> slab.plot11(d1,vbc3,"","DAC1 (V)","Vbc (V)")
```

	4	Mount the circuit and perform the requested measurements. Show I_{BE} and I_{CE} as function of V_{BE}. Check also that the BC junction is reverse biased.

You should see that the V_{BC} voltage is always negative so we know for sure that the BC junction is reverse biased. But we get also that there is a lot of current (I_{CE}) going in reverse on that junction.

This is strange.

It turns out that when you join three semiconductor regions of "N", "P" and "N" kind in sequence, you get a device where one junction conducts in reverse when the other junction is forward biased. If order for this effect to take place you need to have a very thin "P" region. Don't worry about that because the transistor manufacture takes care of this requirement.

If you want to obtain gain from a BJT, you forward bias the BE junction and reverse bias the BC junction. This mode of operation is called **Active** because it is the usually used in amplifiers.

Current gain

We see that the current I_{CE} in the reverse biased current is much greater than the current I_{BE} in the forward biased current. The ratio between those currents is called the forward current gain of the transistor and is identified with the symbol β_F.

$$\beta_F = \frac{I_{CE}}{I_{BE}} \qquad when \begin{cases} Junction\ BE\ forward\ biased \\ Junction\ BC\ reverse\ biased \end{cases}$$

The value of the current gain is usually specified in the BJT datasheet. In the case of the BC547 device we get the following table:

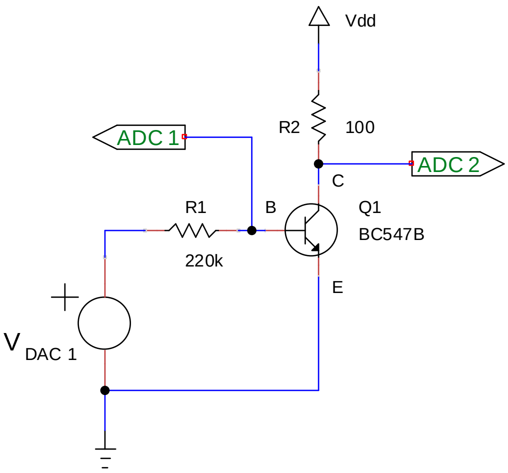
DC Current Gain		h_{FE}				–
(I_C = 10 μA, V_{CE} = 5.0 V)	BC547A		–	90	–	
	BC546B/547B/548B		–	150	–	
	BC548C		–	270	–	
(I_C = 2.0 mA, V_{CE} = 5.0 V)	BC546		110	–	450	
	BC547		110	–	800	
	BC548		110	–	800	
	BC547A		110	180	220	
	BC546B/547B/548B		200	290	450	
	BC547C/BC548C		420	520	800	
(I_C = 100 mA, V_{CE} = 5.0 V)	BC547A/548A		–	120	–	
	BC546B/547B/548B		–	180	–	
	BC548C		–	300	–	

From the table, for a collector current of 2 mA, we should expect a gain of 290 although we can get any gain between a minimum of 200 and a maximum of 450. Note the big range of gains we can get. This is typical for BJTs; you have a very imprecise knowledge of the gain you will get from a device that you buy.

```
>>> d1,a1,a2,a3,a4=slab.dcSweepPlot(1,0.5,3,returnData=True)
>>> ice=(a3-a4)/0.1
>>> ibe=(a1-a2)/220
>>> beta=ice/ibe
>>> slab.plot11(ice,beta)
>>> slab.plot11(ice,beta,"","Ic (mA)","Beta")
```

🛠	**5**	Obtain the current gain β_F as function of I_{CE}. Check if the gain at a current of 2 mA is within specs.

The DC module provides an alternative way to measure the base to collector current relationship. The ***transferCurveII*** command enables us to perform the DC sweep and the current calculations in one easy step. Mount the following circuit:



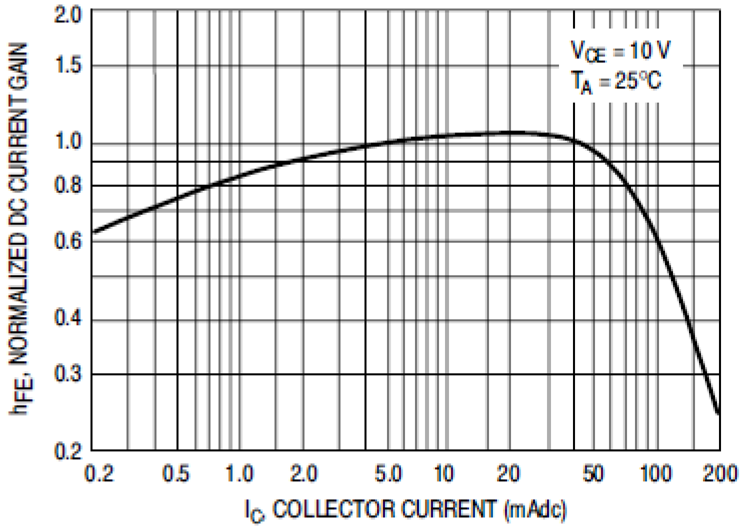
Now we request the command and store the base and collector currents we obtain:

```
>>> ib,ic=transferCurveII(0.6,3,ri=220,ro=0.1,returnData=True)
```

We can calculate the current gain and show it on a graph:

```
>>> beta=ic/ib
>>> slab.plot11(ic,beta,"","Ic (mA)","Beta")
```

You can see that the current gain drops for low currents. The BJT manufacturer usually provides the gain dependence with the collector current with a graph like the one below:



Note that the gain is normalized so it is only useful to see the trend of the gain, no its absolute value. You can see that the gain increases until a collector current of about 20 mA.

🛠	**6**	Check the gain with the new proposed method.

Going reverse

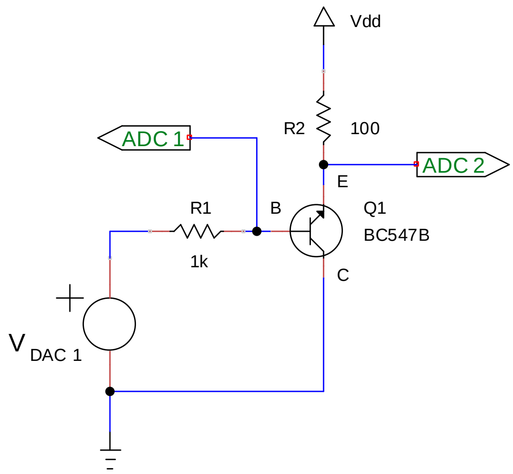
The BJT, due to its construction based on NPN or PNP regions is, in theory, symmetric. In practice the emitter and collector regions are neither equal on its electron carrier concentration nor on its physical construction. But a transistor, when you interchange collector and emitter should also work also as a transistor.

That means that if you make work the transistor in reverse by forward biasing the BC junction and reverse biasing the BE junction you get also a current gain.

$$\beta_R = \frac{I_{EC}}{I_{BC}} \qquad when \begin{cases} Junction\ BC\ forward\ biased \\ Junction\ BE\ reverse\ biased \end{cases}$$

As BJTs are optimized to work in the **Active** mode so, the current gain in the **Reverse** mode is usually quite low. As both modes can have gain, they are also called **Forward Active** and **Reverse Active**.

Take the last measured circuit, change the R1 220 kΩ resistor for a 1 kΩ resistor and interchange emitter and collector as shown in the figure.



Now obtain the current transfer curve:

```
>>> ib,ic=transferCurveII(0.6,3,ri=1,ro=0.1,returnData=True)
```

We can calculate the current gain and show it on a graph:

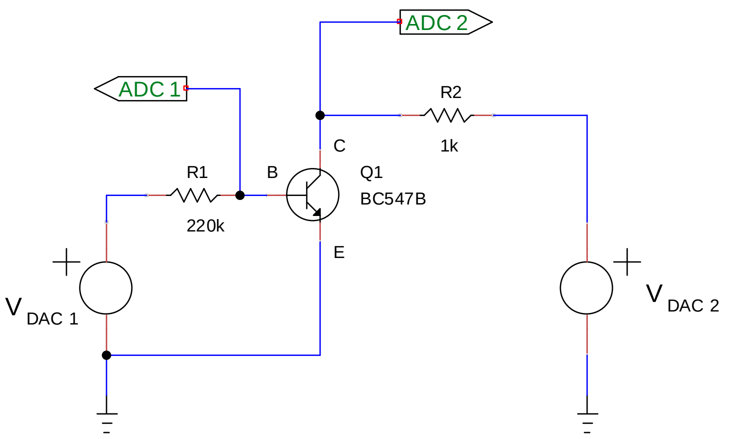
```
>>> beta=ic/ib
>>> slab.plot11(ic,beta,"","Ic (mA)","Beta")
```

7 Obtain the inverse current gain β_R.
How is it compared with the forward gain β_F?

Saturating the transistor

As explained before, the current gain the transistor provides require that the BE junction is forward biased and the BC junction is reverse biased. If you forward bias both junctions, the transistor enters the saturation region and collector current drops.

We can use a circuit similar to the one used in 4 to test the saturation. Note that R2 has changed from 100 Ω to 1 kΩ to provide a bigger voltage drop. Note also that we use only 2 ADCs instead of 4.



We can set DAC1 voltage to 2.5 V and DAC2 voltage to 3 V.

```
>>> slab.setVoltage(1,1.5)
>>> slab.setVoltage(2,3)
```

Now we can obtain the voltage at the base and collector terminals.

```
>>> vb=slab.readVoltage(1)
>>> vb
>>> vc=slab.readVoltage(2)
>>> vc
```

If the collector voltage is below 1.5 V, decrease the voltage in DAC1 until you go over this limit.

And calculate the currents and the gain. Remember that we give resistances in kΩ to obtain currents in mA. Change the first line if you used changed the DAC1 voltage in order to obtain the required collector voltage.

```
>>> ib=(1.5-vb)/220
>>> ib
>>> ic=3.0-vc
>>> ic
>>> beta=ic/ib
>>> beta
```

8 Build the circuit, perform the measurements, and check that we are in the Active region.

At this point we have the BJT inside the Active region. Now we will decrease the DAC 2 voltage, that will reduce the collector voltage and, as an effect, it will increase the V_{BC} voltage.

$$V_{BC} = V_B - V_C$$

With a low enough DAC 2 voltage we can guarantee that the BC junction is forward biased. We will use the ***dcSweep*** command to sweep DAC 2 values from 0 V to 3 V. This command is similar to the ***dcSweepPlot*** command but it doesn't generate any plot and automatically provides the output results. The command provides three vectors: the swept DAC voltage and the four ADC voltages. As ADC 1 measures V_B and ADC 2 measures V_C we use the **vb** and **vc** variable names to the ADC 1 and 2 outputs. Finally we calculate the collector current and show it on a graph.

```
>>> d2,vb,vc,a3,a3=slab.dcSweep(2,0,3)
>>> ic=d2-vc
>>> slab.plot11(vc,ic,"","Vce (V)","Ic (mA)")
```

The current starts to drop as soon as we forward bias the BC junction. We can check that this is the case by showing the current as function of V_{BC} instead of V_{CE}.

```
>>> vbc=vb-vc
>>> slab.plot11(vbc,ic,"","Vbc (V)","Ic (mA)")
```

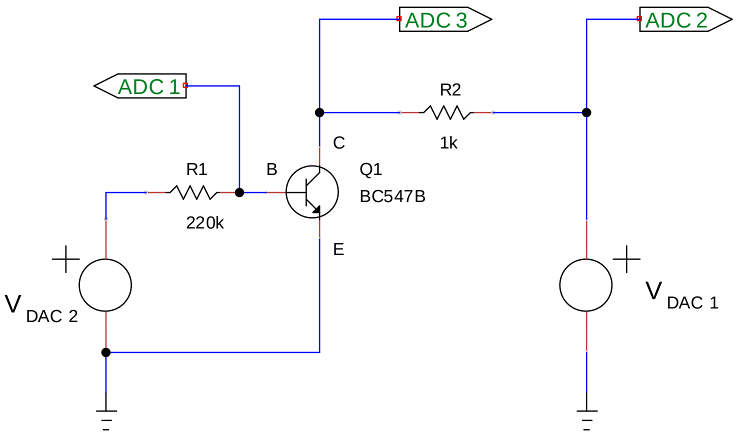
9 Obtain the collector current I_C as function of the V_{CE} voltage.

Check that the current drops at low V_{CE} voltages and that this happens when the V_{BC} voltage is about the threshold voltage of the BC junction obtained in 2.

The transistor curves

The $I_C(V_{CE})$ curve we have drawn in 🛠9 , together with the associated base current I_B, gives a lot of information about the BJT. From the I_C and I_B values you can compute the gain, and from the curve itself you can check when the device enters in the saturation region. This curve is usually drawn for several I_B base currents in order to show the global behavior of the BJT.

The drawing of this set of curves has been automated in the ***iDeviceCurve*** command of the DC module. Just build the following circuit and issue a command to obtain them. Note that although the circuit is the same we measured in 🛠9, the connections to the DACs and ADCs are different. This is due to historical reasons. First SLab hardware boards had less voltage range on DAC 2 and required the use of DAC 1 on the collector resistance R2.



Now execute the ***iDeviceCurve*** command. We set the DAC 2 input voltage from 0.6 V to 3 V in 0.25 V increments. We also set the DAC 1 output voltage from 0 V to 3 V in 0.1 V increments. And finally we set R1 to 220 kΩ and R2 to 1 kΩ.

```
>>> dc.iDeviceCurve(0.6,3,0.25,0,3.2,0.1,220,1)
```

The command takes some time to execute as it has to perform a double sweep on DAC 1 and DAC 2 voltages.

When the command ends you should get a set of 10 $I_C(V_{CE})$ curves. A legend should show also the I_B base current for each one of the curves.

🛠	**10**	Obtain the BC547B curve set. Take note of the approximate V_{CE} voltage where the BJT enters saturation.

Due to the voltage drop on R2, the curves with higher currents have smaller range for the V_{CE} voltage.

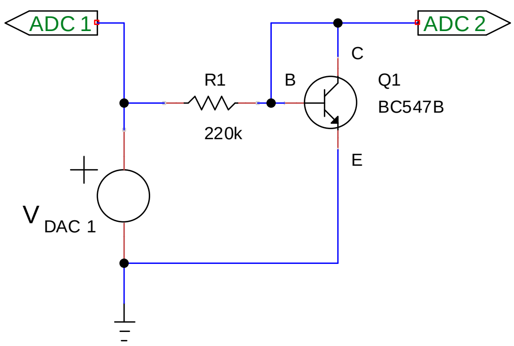
Food for thought

Before ending this lab project, let's add a little riddle.
In 🛠2 we have measured the I_{BE} and I_{BC} currents when the third terminal, Collector for I_{BE} and Emitter for I_{BC}, was not connected.
Recall that the I_{BE} current measured when we connected the collector to a 3 V supply in 🛠3 gave us different values.
The question is:

In which mode was the BJT during the measurements in 🛠2?

🛠	**11**	Make a hypothesis about the BJT mode of operation in the 🛠2 measurements. Design and perform a measurement that demonstrates the hypothesis.

Now consider the following circuit that joins the base and collector nodes:



Make a guess about the mode in which the BJT will operate.
Guess also how will be the $I_{R1}(V_{BE})$ curve in this case compared with the curves on 🛠2 and 🛠3.

🛠	**12**	Perform a measurement to measure the $I_{R1}(V_{BE})$. Compare the measurements with the curves on 🛠2 and 🛠3. Does it make sense? Can you obtain the $I_{R1}(V_{BE})$ curve from previous measurement data?

Last comments

In this document we started working with the BJT component. This component is strange. It seems that should work as two diodes but it turns out that one diode conducts in reverse while the other is forward biased. Not only that, the reverse biased junction current can be much greater than the current on the forward biased junction. Sorting out what is really happening inside the transistor deals with solid state electronics and is outside of the scope of this document.

We have seen that depending on the state of the two junctions the transistor can be in several modes of operation: **Forward Active** when BE is forward biased and BC is reverse biased, **Reverse Active** when BC is forward biased and BE reverse biased, and **Saturation** when both junctions are forward biased. As each junction can be forward or reverse biased there is a fourth **Cut-off** operation region where no current flow at any terminal because both junctions are reverse biased.

The next document will be devoted to modeling of the BJT so that we can perform calculations on circuits built around it. Like in the diode case, we can have several alternative models with different tradeoffs of complexity and precision.

References

SLab Python References

Those are the reference documents for the SLab Python modules. They describe the commands that can be carried out after importing each module.

They should be available in the **SLab/Doc** folder.

TinyCad

Circuit images on this document have been drawn using the free software TinyCad
https://sourceforge.net/projects/tinycad/

SciPy

All the functions plots have been generated using the Matplotlib SciPy package.
https://www.scipy.org/