Objective

When we design a circuit using bipolar transistors, we use idealized equations and an idealized transistor. **PSPICE** describes this ideal NPN transistor using the dot-model statement in Figure 1.

![FIGURE 1](image)

**FIGURE 1**

PSPICE dot-model statement for the ideal bipolar transistor: \( \beta = B_F \), Early voltage \( V_{AF} \), and scale current \( I_S \); as shown by curly braces \{\}, these values are set using variables \( B_F \), \( V_{AF} \) and \( I_S \) from a PARAMETER box.

However, real circuits use real transistors. An example is the Q2N2222, approximated in **PSPICE** using the dot-model statement of Figure 2.

![FIGURE 2](image)

**FIGURE 2**

Dot-model statement of the Q2N2222 found by highlighting the device, right clicking, and selecting EDIT PSPICE MODEL.

If we design using the ideal transistor, and build using, for example, the Q2N2222, can we expect the built circuit to behave anything like the designed circuit? To have hope of success, our ideal transistor should have parameter values selected to match the Q2N2222 as closely as possible. In this lab we will determine the values of \( B_F \), \( V_{AF} \) and \( I_S \) that make an ideal transistor approximate the Q2N2222.

We compare the **PSPICE** results for a Q2N2222 with an ideal transistor using the setup of Figure 3 below.

![FIGURE 3](image)

**FIGURE 3**

Circuits for comparison of ideal transistor with shown dot-model statement with the Q2N2222; parameters \( I_S \) and \( V_{AF} \) are taken from the Q2N2222 dot-model statement, and \( \beta_{DC}(V_{CB}=0V) \) is taken from \( \beta_{DC} \) for the Q2N2222 in the **PSPICE** output file for this value of \( I_E \).

The results of the comparison are shown in Figure 4. It is clear that the two curves agree closely as to value and slope. That is, the ideal transistor with the appropriate values of parameters \( B_F \) and \( V_{AF} \) closely approximates the \( V_{CB} \) dependence of the DC \( \beta \) of the Q2N2222.\(^1\)

\(^1\) However, in the ideal transistor, the DC beta and AC beta values are the same, and \( \beta_{DC}(V_{CB}=0V) = B_F \). Also \( \beta_{DC} \) is independent of current. In the Q2N2222, these simplifications are not so.
Because $\beta_{DC}$ depends on current in the Q2N2222 (but does not depend on current in the ideal transistor) the value of $\beta_{DC}(V_{CB} = 0V)$ used for $Bf$ in the ideal transistor has to be set to agree with the PSPICE output file BetaDC for the Q2N2222 at $V_{CB} = 0V$ and the appropriate current. (For example, we force fitted the point at $V_{CB} = 0V$ in Figure 4). Agreement is not perfect in Figure 4 because the dot-model statement of the Q2N2222 is much more complicated than that for the ideal transistor, as shown above in Figure 2.

To summarize, in this lab we:
1. Learn how to measure values for $Bf$, $V_{AF}$ and $I_s$,
2. Learn a bit about the current mirror as an approximation to an ideal current source,
3. Learn a bit about the variability of device parameters,
4. Learn that circuit design is necessarily approximate because our models aren’t perfect, and
5. Learn how to use some features of EXCEL and PSPICE

Basic idea for finding parameter values

![Diagram](image)

**Figure 5**
Idealized circuit for measuring DC beta and Early voltage

Figure 5 shows the basic idea behind the measurement of $\beta_{DC}$ and $V_{AF}$. A known emitter current $I_E$ is driven into the transistor and a known collector-to-base voltage $V_{CB}$ is applied. The value of $\beta_{DC}$ is then:

**EQ. 1**

$$\beta_{DC} = \frac{I_E}{I_B} - 1.$$  

The value of $\beta_{DC}$ is plotted against $V_{CB}$ and fitted to the formula of EQ. 2 below:

**EQ. 2**

$$\beta_{DC} = \beta_{DC}(V_{CB} = 0) \left(1 + \frac{V_{CB}}{V_{AF}}\right).$$
The slope and intercept of the plot determine $\beta_{DC}$ at $V_{CB} = 0V$ and the value of the Early voltage $V_{AF}$. To implement EQ. 1 we need the value of the base current $I_B$. Therefore, we modify the circuit as shown in Figure 6, and determine the base current from the known value of resistor $R_B$ and the measured collector and base voltages as given in EQ. 3 below.

![Figure 6](image)

**Figure 6**
Circuit of Figure 5 modified to allow measurement of base current

**EQ. 3**

$$I_B = \frac{V_C - V_B}{R_B}.$$  

**Implementation of current source $I_E$**

To apply a known current $I_E$ as shown in Figure 3 we build an approximate current source using the circuit of Figure 7.

![Figure 7](image)

**Figure 7**
Circuit for a current mirror approximating an ideal current source

The applied bias $V_A$ in Figure 7 has been chosen to equal the base voltage of the two transistors, making the bias conditions identical for both transistors. Because both transistors have the same dot-model statements (we say they are *matched*), they draw the same collector currents. We can plot the input current vs. $V_A$ for this circuit to compare it with an ideal current source.
Examining the $I-V$ behavior of Figure 7, the current is nearly constant for $V_A$ below about $V_B = 12.92V$. As $V_A$ goes above this value, the current drops rapidly, because the transistor Q1 saturates, leaving the active mode. Thus, the circuit of Figure 7 is a pretty good approximation to an ideal current source delivering 12.81mA - 12.85 mA for voltages below about $V_A = V_B = 12.92V$. The current level delivered by the mirror is adjusted using the resistor $R_R$, as is suggested because the current in $R_R$ is $I_R = V_B / R_R$ and is nearly the same as the output current.

Calibration of the mirror

We cannot assume that both transistors in the mirror will be matched in the lab circuit, so we do a calibration run to find what current we actually get for a given bias condition. For example, suppose the two transistors have different scale currents $I_{S1}$ as shown in the dot-model statements of Figure 9 below.

```
.model Q2N2907A_IS1 PNP(I=I_S1) Xti=3 Eg=1.11 Vaf=115.7 Bf=231.7 Ne=1.829
  + Is=54.81f Iff=1.079 Xtb=1.5 Br=3.563 Nc=2 Isc=0 Ikr=0 Rc=.715
  + Cjc=14.76p Mjc=.5383 Vjc=.75 Fc=.5 Cje=19.82p Mje=.3357 Vje=.75
  + Tr=111.3n Tf=603.7p Itf=.65 Vtf=5 Xtf=1.7 Rb=10)

.model Q2N2907A_IS2 PNP(I=I_S2) Xti=3 Eg=1.11 Vaf=115.7 Bf=231.7 Ne=1.829
  + Is=54.81f Iff=1.079 Xtb=1.5 Br=3.563 Nc=2 Isc=0 Ikr=0 Rc=.715
  + Cjc=14.76p Mjc=.5383 Vjc=.75 Fc=.5 Cje=19.82p Mje=.3357 Vje=.75
  + Tr=111.3n Tf=603.7p Itf=.65 Vtf=5 Xtf=1.7 Rb=10)
```

FIGURE 9

Dot-model statements for the Q2N2907A with the scale currents made a parameter $I_{S1}$ or $I_{S2}$.
Figure 10
Current mirror with mismatched transistors: $I_{S2} = 5I_{S1}$

Figure 10 shows the current mirror with mismatched transistors: the currents in the two transistors are not the same, and the output current differs quite a bit from the current in $R_R$. We run an $I$-$V$ curve like Figure 8 so we can determine exactly what current is provided to our test Q2N2222. An example is shown in Figure 11. Using this plot we can find exactly what current is delivered if we know the voltage $V_A$.

Figure 11
Calibration run for the mirror in Figure 10

Fitting procedure
We first build a mirror like Figure 10, and make an $I$-$V$ calibration run. Then we hook up the Q2N2222 as shown in Figure 3, using the mirror in place of the current source to provide $I_E$. Then we measure $V_C$, $V_B$, $R_B$ and determine the value of $I_E$ for various $V_{CB}$ values, and put this data into an EXCEL spreadsheet. We make a best fit to this plot using the TRENDLINE feature of EXCEL, as explained next.

Data entry
The data is entered on the spreadsheet as shown in Figure 12 below. Measured data is outlined with boldface column headings. $R_B$ is unnecessarily repeated.
FITTING THE DATA

A plot is made of $\beta_{DC}$ vs. $V_{CB}$ as shown in Figure 13.

$$y = 2.4023x + 180.69$$

A TRENDLINE is found by right clicking on the curve and selecting ADD TRENDLINE, as shown in Figure 14.

We also select the LINEAR type, as shown in Figure 15, and choosing the OPTIONS tab we elect to DISPLAY EQUATION on the chart, as shown in Figure 16.
Choosing the LINEAR trend line

With the slope and intercept from the trend line equation in the form $y = mx + b$ we find the value of $\beta_{DC}(V_{CB} = 0V)$ and $V_{AF}$ using the equations

**EQ. 4**

$$\beta_{DC}(V_{CB} = 0V) = b$$ and $$V_{AF} = b/m.$$

Figure 17 shows the results.
FIGURE 17
Calculation of $\beta_{DC}$ and $V_{AF}$; the formula box shows EQ. 4
To obtain a formula in the formula box in Figure 17, we must name the variables M and B by highlighting P17:Q20 and using the menu INSERT/NAME/CREATE. See Figure 18 below.

FIGURE 18
Naming variables to obtain formulas in the FORMULA BOX
Another example of this procedure is shown in the Appendix.

The values in Figure 17 can be compared to the PSpice output file $\beta_{DC}(V_{CB}=0V) = 175$ and $V_{AF} = 74.03V$. Accuracy is as shown in Figure 17.

This procedure should be followed for three current levels near the values 100 $\mu$A, 1 mA and 10 mA, for two different Q2N2222 transistors. The results should be compared with each other and with the manufacturer’s data sheet and the differences summarized.

Precautions
The temperature will change as the transistor heats up – allow the transistor to cool between data points.

Finding the scale current
The base voltage of the Q2N2222 is given by

$$V_{BE} = V_{TH}/n \left( \frac{I_C(V_{CB} = 0V)}{I_S} \right) = V_{TH}/n \left( \frac{I_C(V_{CB} = 0V)}{1 + \frac{1}{\beta(V_{CB} = 0V) I_E}} \right),$$

where $V_{TH}$ is the thermal voltage, 25.864mV at 27°C. Your transistor may be at a different temperature: for one thing, it heats when drawing current. In EQ. 5, $I_S$ is the scale current. If there is no Early effect, the current does not depend on collector-base bias $V_{CB}$, but in our ideal transistor there is an Early effect and the current is given by EQ. 6 below. (The Q2N2222 uses a more complex equation, approximated by EQ. 6.2)

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2 In the Q2N2222 the current is given by PSpice as found on pp. 208-209 of the online manual PSpiceRef.pdf accessed from your START menu under START/PROGRAMS/ORCAD FAMILY RELEASE 9.2 LITE EDITION/ON LINE MANUALS/PSpice REFERENCE GUIDE/BIPOLAR TRANSISTOR
Because $I_C$ depends on $V_{CB}$, using a current corresponding to $V_{CB} > 0$ in EQ. 5 will lead to an incorrect $V_{BE}$. Also, note that in EQ. 5, the value of $\beta$ varies with current level $I_E$; that is, $\beta = \beta(V_{CB}, I_E)$.

According to EQ. 5, a plot of base voltage of the Q2N2222 vs. $ln(I_E)$ will have a slope of $V_{TH}$, and by doing a best fit we can find the best value of $I_S$. If $\beta \gg 1$, the error in neglecting variation of $\beta$ with $I_E$ when plotting will not have much effect upon the value obtained for $I_S$. Doing the fit with the largest and smallest $\beta$-value is a check on this particular error.

**Entering the data**

An example worksheet for finding $V_{TH}$ and $I_S$ is shown in Figure 19 below. The measured data is for the case $V_{CB} = 0$ V, or $R_B = 0$ Ω.

<table>
<thead>
<tr>
<th></th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
<th>K</th>
<th>L</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Fitted Values</td>
<td>$V_{TH}$</td>
<td>0.025868</td>
<td>100</td>
<td>0.0597</td>
<td>0.766</td>
<td>0.02597</td>
<td>1.1193E-14</td>
<td>0.7488599</td>
<td>0.42</td>
<td>0.750023</td>
<td>0.00</td>
</tr>
<tr>
<td>7</td>
<td>$I_S$</td>
<td>1.2678E-14</td>
<td>215</td>
<td>0.0441</td>
<td>0.730</td>
<td>0.025882</td>
<td>1.2458E-14</td>
<td>0.7316679</td>
<td>0.25</td>
<td>0.733569</td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>$B_{DC}$</td>
<td>162.6</td>
<td>464</td>
<td>0.0245</td>
<td>0.713</td>
<td>0.025820</td>
<td>1.3200E-14</td>
<td>0.7140578</td>
<td>0.19</td>
<td>0.714534</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>$B_{DC}(min)$</td>
<td>148.9</td>
<td>1000</td>
<td>0.0124</td>
<td>0.692</td>
<td>0.025764</td>
<td>1.3806E-14</td>
<td>0.6947137</td>
<td>0.33</td>
<td>0.693602</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>$B_{DC}(max)$</td>
<td>176.3</td>
<td>2154</td>
<td>0.0059</td>
<td>0.671</td>
<td>0.025763</td>
<td>1.4061E-14</td>
<td>0.6758291</td>
<td>0.41</td>
<td>0.671004</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>$V_{BE}$</td>
<td>0.0026</td>
<td>1000</td>
<td>0.0011</td>
<td>0.646</td>
<td>0.025751</td>
<td>1.4168E-14</td>
<td>0.6503854</td>
<td>0.46</td>
<td>0.646181</td>
<td>0.27</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>$V_{BE}$</td>
<td>0.0011</td>
<td>1000</td>
<td>0.0011</td>
<td>0.646</td>
<td>0.025751</td>
<td>1.4168E-14</td>
<td>0.6503854</td>
<td>0.46</td>
<td>0.646181</td>
<td>0.27</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>$V_{BE}$</td>
<td>0.0011</td>
<td>1000</td>
<td>0.0011</td>
<td>0.646</td>
<td>0.025751</td>
<td>1.4168E-14</td>
<td>0.6503854</td>
<td>0.46</td>
<td>0.646181</td>
<td>0.27</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>$V_{BE}$</td>
<td>0.0011</td>
<td>1000</td>
<td>0.0011</td>
<td>0.646</td>
<td>0.025751</td>
<td>1.4168E-14</td>
<td>0.6503854</td>
<td>0.46</td>
<td>0.646181</td>
<td>0.27</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>$V_{BE}$</td>
<td>0.0011</td>
<td>1000</td>
<td>0.0011</td>
<td>0.646</td>
<td>0.025751</td>
<td>1.4168E-14</td>
<td>0.6503854</td>
<td>0.46</td>
<td>0.646181</td>
<td>0.27</td>
<td></td>
</tr>
</tbody>
</table>

**FIGURE 19**

Worksheet for finding $V_{TH}$ and $I_S$; the TRENDLINE predictions also are shown.

**Fitting the data**

Measured data is in columns $R_R$, $I_E$ and $V_B$. $V_{BE}$ in Column J is calculated using EQ. 5 and the values of $V_{TH}$, $I_S$ and $\beta_{DC}$ in cells C8-C10. Then $V_{TH}(Q3)$ is found by making the calculated $V_{BE}$ of Column J agree with the measured value of $V_{BE}$ in Column G. To find this value of $V_{TH}(Q3)$, EXCEL tool GOAL SEEK is used. For example, we set the cursor in cell J8 and use the menu TOOLS/GOAL SEEK to obtain the GOAL SEEK menu in Figure 20. The SET CELL is $V_{BE}$ and the VALUE is the measured $V_B$. The CHANGING CELL is the thermal voltage $V_{TH}$. Hitting OK, $V_{TH}$ is changed to the value that makes $V_{BE} = V_B$. We copy this value and paste it into the column $V_{TH}(Q3)$. This procedure is followed for all the entries. At the bottom of the $V_{TH}(Q3)$ column, the average value of $V_{TH}(Q3)$ is found using EXCEL function AVERAGE(). Then this value is copied into $V_{TH}$, cell C8.

**Figure 20**

GOAL SEEK menu for finding the value of $V_{TH}$ (cell C8) that makes $V_{BE}$ (cell J8) equal $V_B$ (value .766 V for Row 8).

After the average $V_{TH}$ is found, the values of $I_S(Q3)$ are found the same way, and the average value of I_s is pasted into cell C9. Because $V_{BE}$ depends logarithmically on $I_S$, even a large change in $I_S$ hardly affects the fit. Therefore, the value of $I_S$ found by fitting is not very accurate.
ALTERNATIVE METHOD USING TRENDLINE

As a simpler alternative method, we might think to use the TRENDLINE feature of EXCEL as shown in Figure 21. Once the slope and intercept are found, they can be converted to values of $V_{TH}$ and $I_S$, as shown in Figure 22.

![Graph showing trendline equation](image)

$y = 0.027991 \ln(x) + 0.837392$

Figure 21
Using the TRENDLINE feature of EXCEL to find $V_{TH}$ and $I_S$.

![Spreadsheet showing trendline values](image)

Figure 22
Converting the slope and intercept to $V_{TH}$ and $I_S$.

The TRENDLINE approach gives a lower error of fitting (see Figure 19) than the more tedious approach using GOAL SEEK, but it does not give values as close to the true values. Therefore, the GOAL SEEK method, which fits $V_{TH}$ first and $I_S$ second, is preferred.

Prelab requirements

Decide what resistor values you will use in the lab. They should be standard values, but you will have to measure them to get accurate values.

Construct your spreadsheet using the standard resistor values you selected. Use one worksheet for $I_S$ and $V_{TH}$ determination, and a second worksheet for $\beta_{DC}$ and $V_{AF}$ determination. Both worksheets are in the same spreadsheet.

Make PSPICE simulations of the procedures you will follow to measure the transistor parameters and generate the plots you are going to use.

Test the spreadsheet using “imitation” data generated by PSPICE to see how close your fitting procedure comes to the values of the transistor parameters actually used in generating your “imitation” data.

Tabulate your actual values alongside the extracted values found using the fitting procedure.
In the lab

Here’s a brief summary of the things to be done in the lab that are discussed in this document.

1. Do parameter measurements for two Q2N2222 transistors at three current levels, levels near 100µA, 1mA and 10mA. Put your data on worksheets like Figure 12 and Figure 19, and make graphs like Figure 13 and Figure 21 showing both your data and your fits.

2. Plot your $\beta_{DC}$ vs. $I_E$ for both devices and from PSpice.

3. Compare the results for all parameters with manufacturer’s data sheets.

4. Summarize the differences and discuss whether they are within the range of values suggested by the manufacturer.

The temperature will change as the transistor heats up—allow the transistor to cool between data points. A heat sink for discrete Q2N2222’s is available.
Appendix

Pasting PSPICE data into EXCEL

The PSPICE data from a PROBE plot are copied to the spreadsheet from PROBE by highlighting the curve label in the caption of the PROBE plot. Then use the PROBE toolbar EDIT/COPY to copy the curve. Next the cursor is placed on the worksheet and the EXCEL menu PASTE is selected. Remove the unnecessary spaces in the column headings.

Using Visual Basic for Applications

Instead of repeating the sequence of operations to use GOAL SEEK for each row of the worksheet, you can use a MACRO based on VBA. For example, to set $V_{TH}$ using the procedure outlined above, the macro in Figure 23 can be used.

```vba
Sub Set_VTH()
    ' Set_VTH Macro
    ' Macro recorded 1/5/2005 by John Brews
    '
    ' Keyboard Shortcut: Ctrl+t
    '
    Dim J As Integer
    
    For J = 1 To 7
        ChangingCell:=Range("V_TH")
        Range("V_TH").Select
        Selection.Copy
        Range("V_TH_Q3").Cells(J).Select
        Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=False
        Range("V_BE").Cells(J + 1).Select
    Next J
    
    Range("H15").Select
    Selection.Copy
    Range("V_TH").Select
    Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
    False, Transpose:=False

End Sub
```

**Figure 23**

Macro to scan down the rows of the table in Figure 19 to adjust $V_{TH}$ so that $V_{BE} = V_{B}$; the underscore _ at the end of lines is a line continuation symbol.
For the macro to work, NAMED ranges have to be set up. For example, with the rows and columns highlighted as shown in Figure 24, the menu INSERT/NAME/CREATE is selected to obtain the CREATE NAMES menu in Figure 24. Click OK.

![Figure 24](image)

**FIGURE 24**

With the columns and their names highlighted, INSERT/NAME/CREATE names the columns: for example, column E8:E14 is named R_R.

In the macro of Figure 23, the language Range("V_BE")• Cells(J) then refers to the J-th cell of column variable V_BE. The macro is easily invoked using the keyboard shortcut Ctrl+t. To set up the shortcut, use the menu TOOLS/MACRO/MACROS/OPTIONS to obtain the menus of Figure 25.

![Figure 25](image)

**FIGURE 25**

Setting up a keyboard shortcut Ctrl+t to run the macro.

The macro is first recorded using the feature TOOLS/MACRO/RECORD NEW MACRO. The recording determines much of the language in the final macro. Then knowledge of VBA, which is a lot like BASIC, is used to introduce the names of ranges and the FOR-NEXT LOOP. It is not suggested that you learn how to use VBA. This example is intended to make you aware that this feature exists, and that it can be useful.