BEE 332 Lab 1
BJT characterization
Spring 2017

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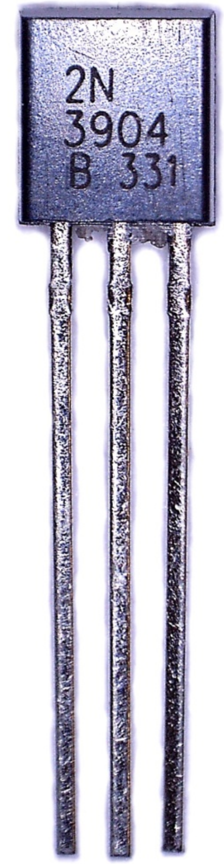
https://faculty.washington.edu/kd1uj

Lab 1: Characterizing bipolar junction transistors (BJTs)

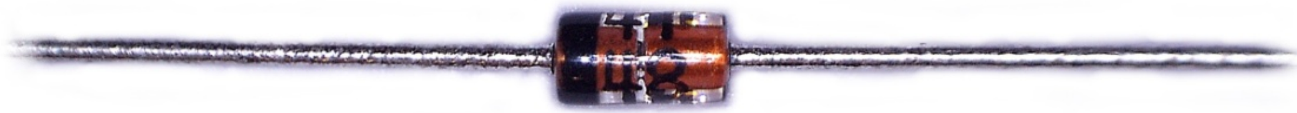
1. Identify BJT leads

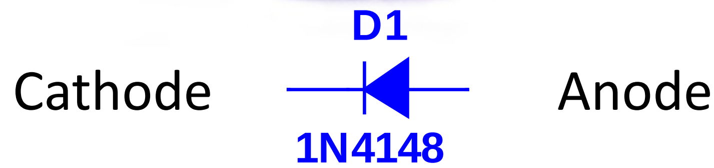
1N4148 diode

2N3904 transistor

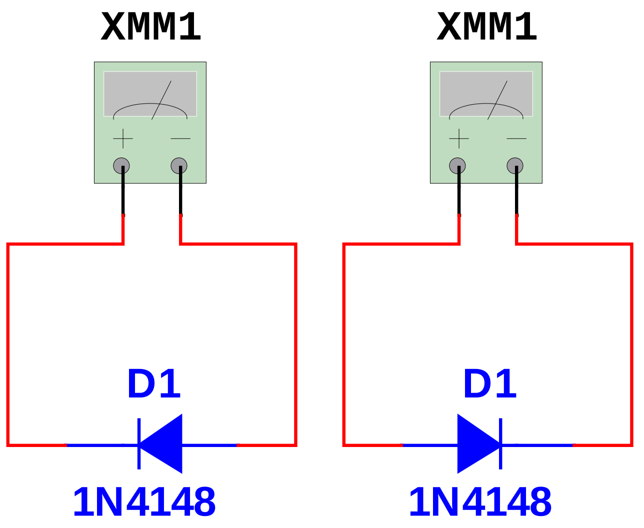


1N4148 diode





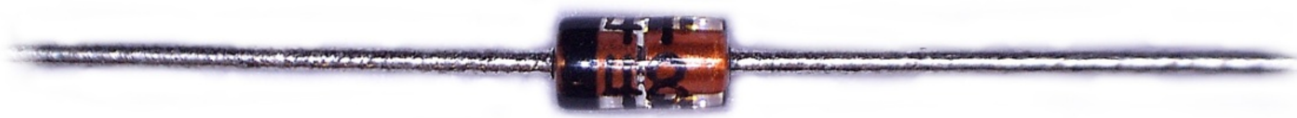
1. Measure forward and reverse biased resistance.
2. Use “diode test” feature to measure the turn-on voltage of the pn junction.

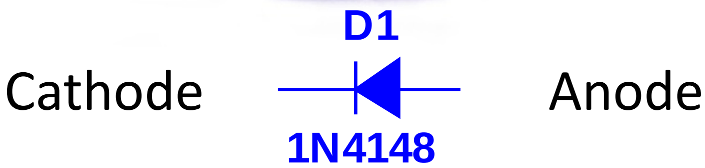


Continuity or diode test

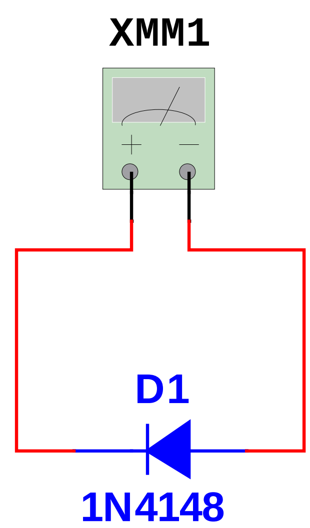
Toggles between continuity and diode test. In diode test mode, it measures the voltage across the diode.

1N4148 diode

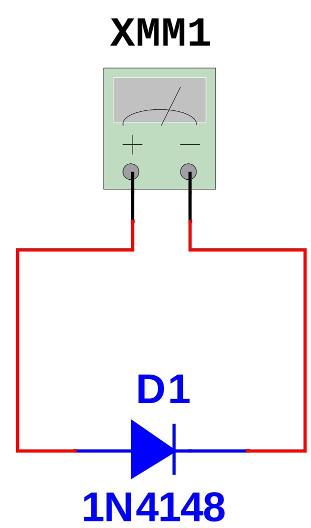




1. Measure forward and reverse biased resistance.
2. Use “diode test” feature to measure the turn-on voltage of the pn junction.



0L/0L

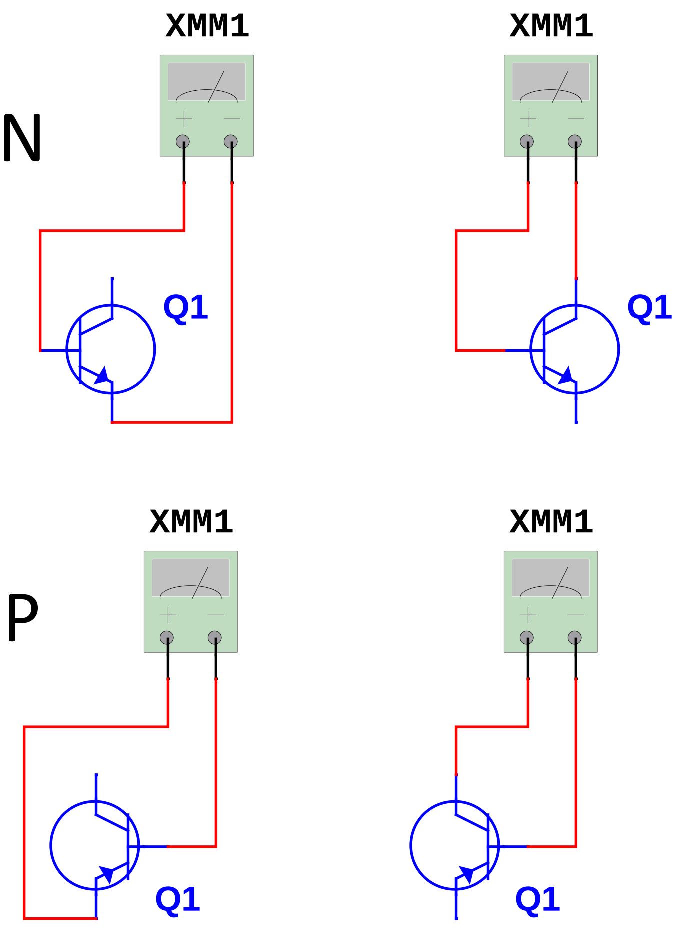


269 KΩ
0.606 V

Decide whether it’s NPN or PNP and identify the base.

NPN

PNP



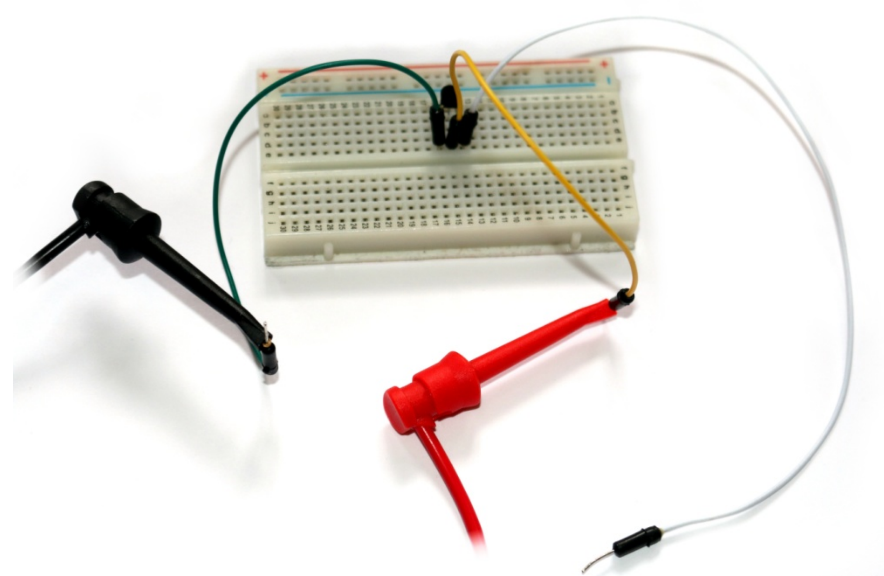
These will be on.
All others will be off.

Determining emitter versus collector

1. A little hard to tell just by resistance measurement.
2. RBC should be slightly lower than RBE because the emitter is more highly doped.
3. May not be measurably different with all transistors.
4. Real test is to build an amplifier: $\beta_F >> \beta_R$

Hopefully, you'll notice

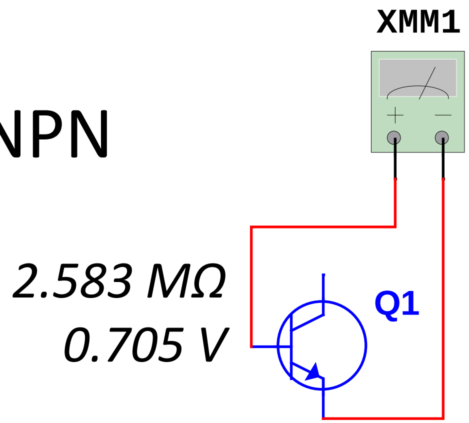
The hard way.

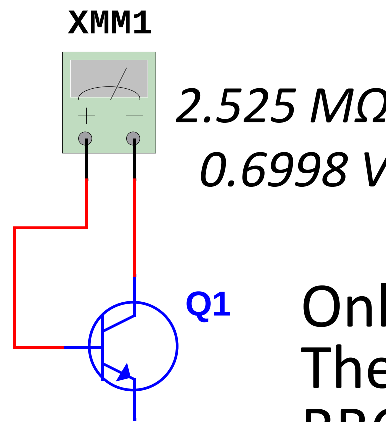


The easy way.

My results

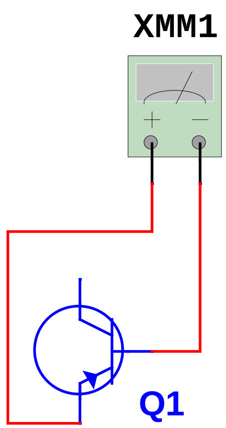
NPN

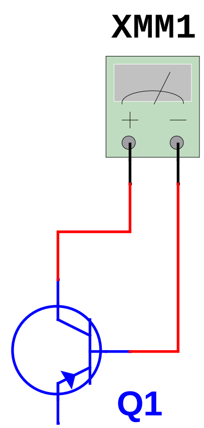




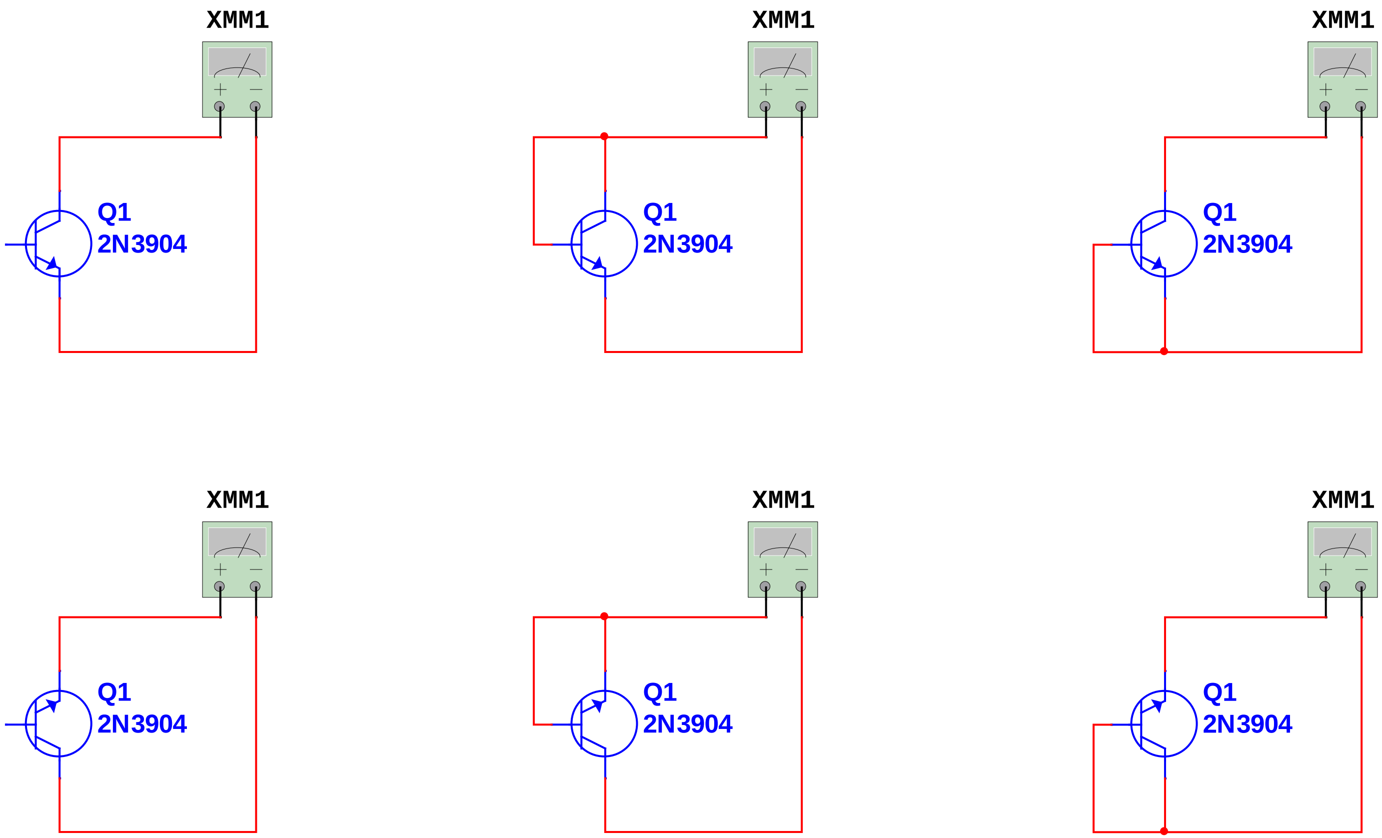
Only these were on.
The transistor is NPN.
RBC slightly < RBE.

PNP

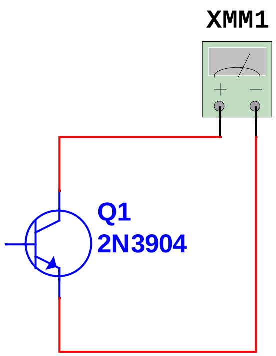




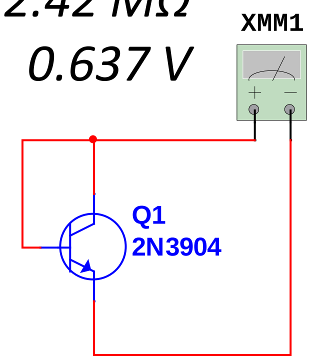
Take 6 resistance and diode test measurements to identify the other leads.

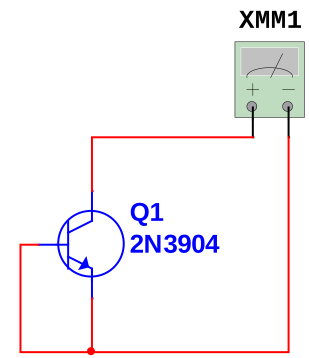


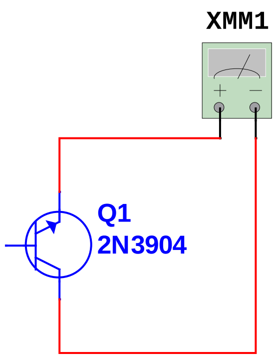
My results



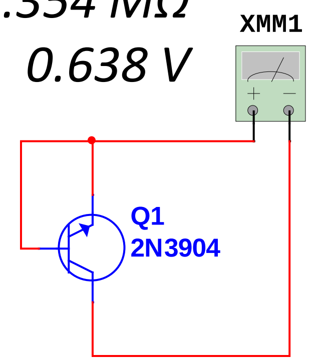
2.42 MΩ
0.637 V

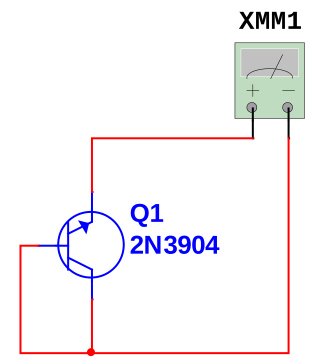




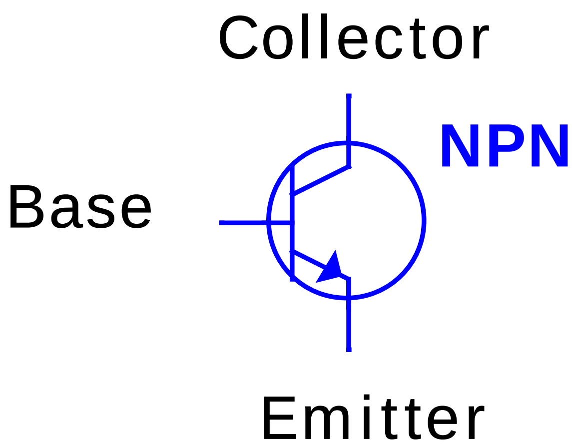


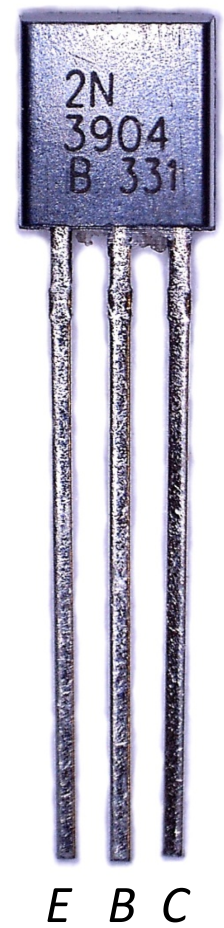
2.354 MΩ
0.638 V



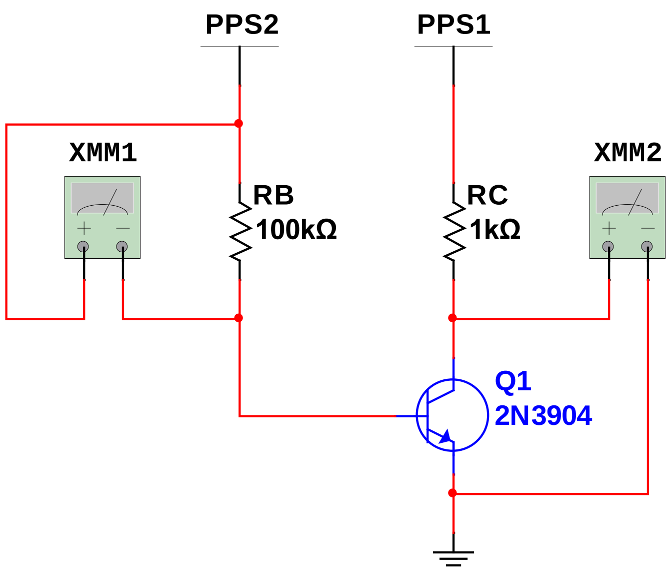


All others were 0L/0L.


Collector
NPN
Base
Emitter


2N
3904
B 331
E B C

2. Build a large table of measurements for various values of PPS1 and PPS2, then plot the characteristics.



for PPS2 = 1.0 V to 1.75 V by 0.25 V

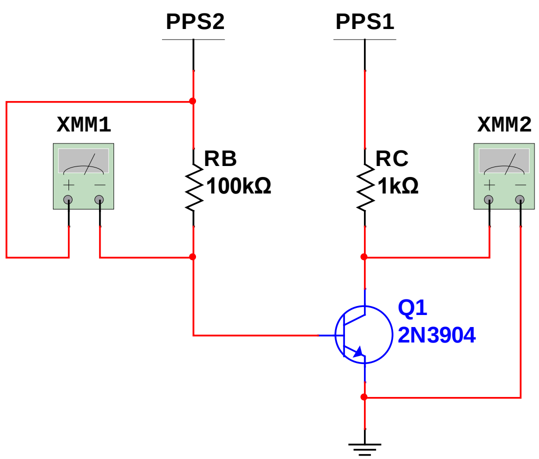
for PPS1 = 0 V to 10 V by 1.0 V

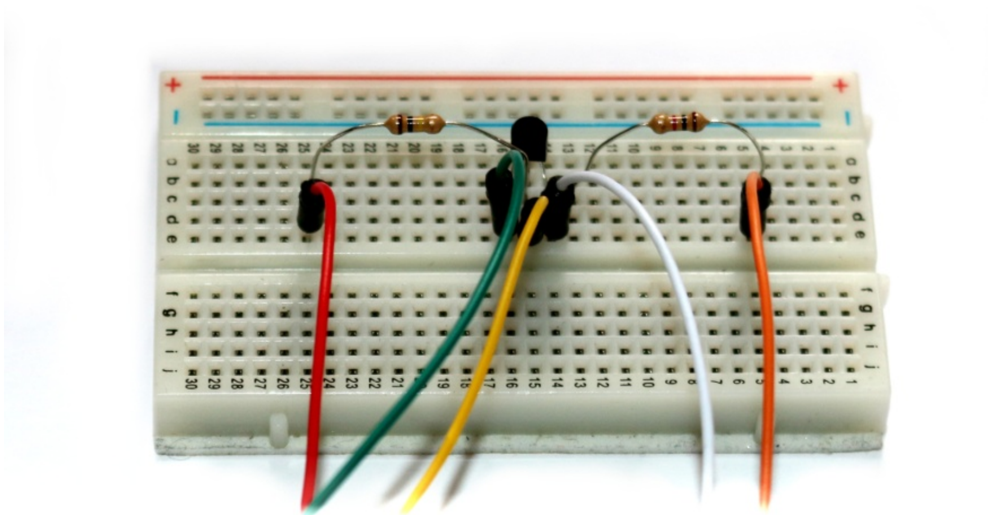
measure VRB, VCE

Plot IC versus VCE.

Plot β_F versus IC for VCE = 3.0 V.

My results





Measured values (Ω)

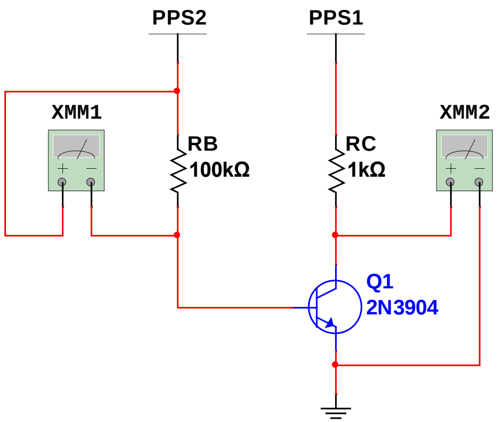
RB	99,080
RC	982

Calculated values

$$I_B = \frac{V_{RB}}{RB}$$

$$I_C = \frac{PPS1 - V_{CE}}{RC}$$

$$\beta_F = \frac{I_C}{I_B}$$



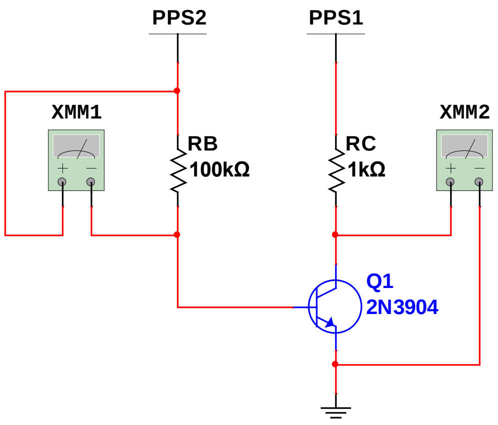
PPS2 = 1.0 V

PPS1	VRB	VCE	IB (μA)	IC (mA)	IC / IB
0	0.470	0.005	4.744	-0.005	-1.013
1	0.360	0.159	3.633	0.857	235.817
2	0.352	0.851	3.553	1.170	329.432
3	0.353	1.840	3.563	1.181	331.557
4	0.354	2.830	3.573	1.191	333.470
5	0.354	3.821	3.573	1.201	336.035
6	0.354	4.811	3.573	1.211	338.886
7	0.355	5.801	3.583	1.221	340.773
8	0.356	6.793	3.593	1.229	342.083
9	0.357	7.784	3.603	1.238	343.669
10	0.357	8.774	3.603	1.248	346.495
Interpolated at VCE = 3.0 V					
4.172	0.354	3.000	3.573	1.193	333.910

PPS2 = 1.25 V

PPS1	VRB	VCE	IB (μA)	IC (mA)	IC / IB
0	0.713	0.006	7.196	-0.006	-0.849
1	0.610	0.127	6.157	0.889	144.409
2	0.590	0.211	5.955	1.822	306.003
3	0.588	1.072	5.935	1.963	330.829
4	0.589	2.052	5.945	1.984	333.694
5	0.590	3.035	5.955	2.001	336.035
6	0.591	4.013	5.965	2.023	339.223
7	0.592	4.996	5.975	2.041	341.547
8	0.593	5.982	5.985	2.055	343.353
9	0.594	6.965	5.995	2.072	345.663
10	0.595	7.947	6.005	2.091	348.134
Interpolated at VCE = 3.0 V					
4.964	0.590	3.000	5.954	2.000	335.952

VRB and VCE were measured. Other columns were calculated.



PPS2 = 1.5 V

PPS1	VRB	VCE	IB (μA)	IC (mA)	IC / IB
0	0.955	0.006	9.639	-0.007	-0.678
1	0.860	0.113	8.680	0.903	104.080
2	0.839	0.156	8.468	1.877	221.702
3	0.828	0.326	8.357	2.723	325.829
4	0.828	1.285	8.357	2.765	330.837
5	0.829	2.256	8.367	2.794	333.967
6	0.830	3.225	8.377	2.826	337.333
7	0.830	4.172	8.377	2.880	343.776
8	0.835	5.148	8.428	2.904	344.618
9	0.836	6.128	8.438	2.925	346.619
10	0.837	7.100	8.448	2.953	349.580
Interpolated at VCE = 3.0 V					
5.768	0.830	3.000	8.375	2.819	336.552

PPS2 = 1.75 V

PPS1	VRB	VCE	IB (μA)	IC (mA)	IC / IB
0	1.192	0.007	11.920	-0.007	-0.549
1	1.107	0.103	11.070	0.897	80.993
2	1.087	0.139	10.870	1.861	171.196
3	1.075	0.181	10.750	2.819	262.268
4	1.070	0.533	10.700	3.467	324.019
5	1.071	1.485	10.710	3.515	328.198
6	1.073	2.437	10.730	3.563	332.060
7	1.075	3.382	10.750	3.618	336.558
8	1.078	4.330	10.780	3.670	340.445
9	1.080	5.300	10.800	3.700	342.593
10	1.082	6.260	10.820	3.740	345.656
Interpolated at VCE = 3.0 V					
6.596	1.074	3.000	10.742	3.596	334.740

VRB and VCE were measured. Other columns were calculated.

Interpolation

You're asked to plot β_F versus IC for VCE = 3.0 V.
But few of your measurements will happen to be exactly at VCE = 3.0 V.

PPS2 = 1.0 V

PPS1	VRB	VCE	IB (μA)	IC (mA)	IC / IB
0	0.470	0.005	4.744	-0.005	-1.013
1	0.360	0.159	3.633	0.857	235.817
2	0.352	0.851	3.553	1.170	329.432
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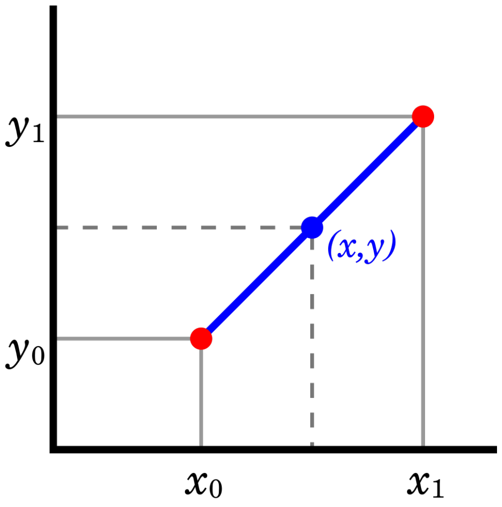
7	0.355	5.801	3.583	1.221	340.773
8	0.356	6.793	3.593	1.229	342.083
9	0.357	7.784	3.603	1.238	343.669
10	0.357	8.774	3.603	1.248	346.495

Interpolated at VCE = 3.0 V

4.172	0.354	3.000	3.573	1.193	333.910

You have to *interpolate* between the samples to estimate the values at VCE = 3.0 V.

Simple interpolation
Approximating with a straight line



Choose the points on either side of the point you'd like to estimate.

$$\frac{y - y0}{x - x0} = \frac{y1 - y0}{x1 - x0}$$

Given the desired x:

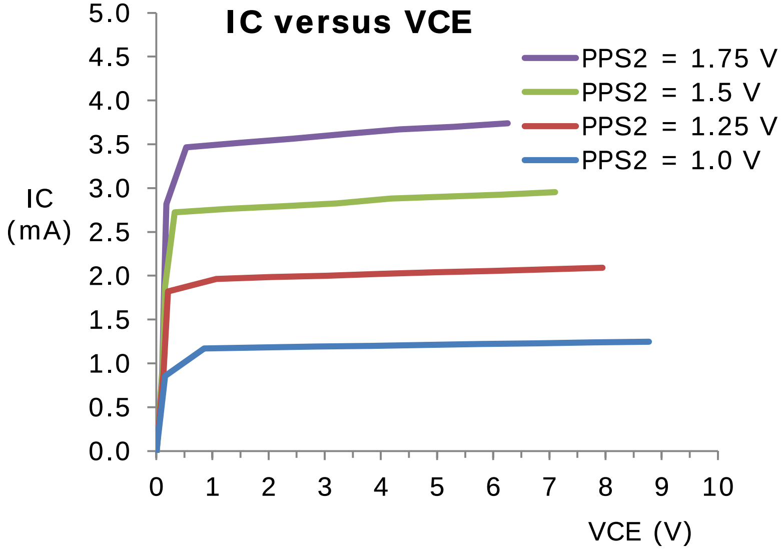
$$y = y0 + (y1 - y0)\left(\frac{x - x0}{x1 - x0}\right)$$

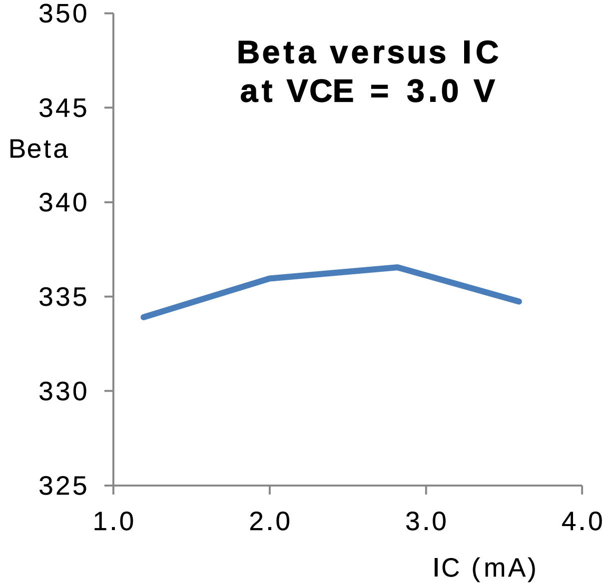
Given the desired y:

$$x = x0 + (x1 - x0)\left(\frac{y - y0}{y1 - y0}\right)$$

Image source: https://en.wikipedia.org/wiki/File:LinearInterpolation.svg

My results





I've deliberately chosen not to let Excel smooth the curve because I don't like overshoot produced by the (undefined) polynomial fit they use.

No one will confuse that if we had enough points, the curve would be smooth.

In the real part, there isn't any overshoot.

Manufacturer's spec

NPN General Purpose Amplifier
(continued)

2N3904 / MMBT3904 / MMPQ3904 / PZT3904

Electrical Characteristics

TA = 25°C unless otherwise noted

Symbol	Parameter	Test Conditions	Min	Max	Units
OFF CHARACTERISTICS					
$V_{(BR)CEO}$	Collector-Emitter Breakdown Voltage	I_C = 10 mA, I_B = 0	40		V
$V_{(BR)CBO}$	Collector-Base Breakdown Voltage	I_C = 10 µA, I_E = 0	60		V
$V_{(BR)EBO}$	Emitter-Base Breakdown Voltage	I_E = 10 µA, I_C = 0	6.0		V
I_{BL}	Base Cutoff Current	V_{CE} = 30 V, V_{EB} = 0		50	nA
I_{CEX}	Collector Cutoff Current	V_{CE} = 30 V, V_{EB} = 0		50	nA
ON CHARACTERISTICS*					
h_{FE}	DC Current Gain	I_C = 0.1 mA, V_{CE} = 1.0 V I_C = 1.0 mA, V_{CE} = 1.0 V I_C = 10 mA, V_{CE} = 1.0 V I_C = 50 mA, V_{CE} = 1.0 V I_C = 100 mA, V_{CE} = 1.0 V	40 70 100 60 30	 300 	
$V_{CE(sat)}$	Collector-Emitter Saturation Voltage	I_C = 10 mA, I_B = 1.0 mA I_C = 50 mA, I_B = 5.0 mA		0.2 0.3	V V
$V_{BE(sat)}$	Base-Emitter Saturation Voltage	I_C = 10 mA, I_B = 1.0 mA I_C = 50 mA, I_B = 5.0 mA	0.65	0.85 0.95	V V

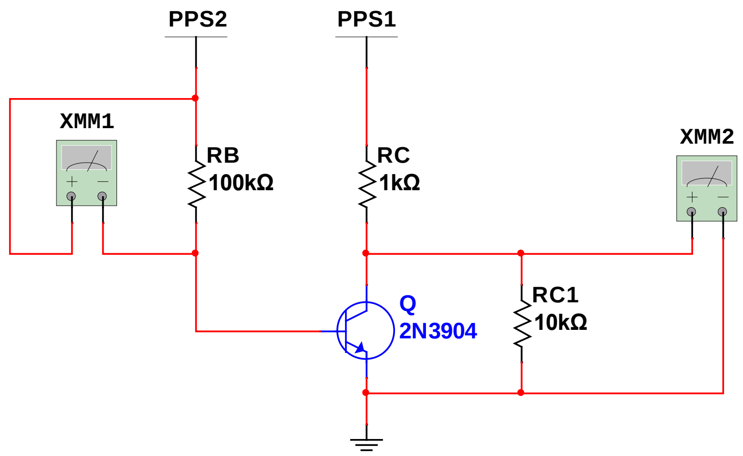
Source: National Instruments.

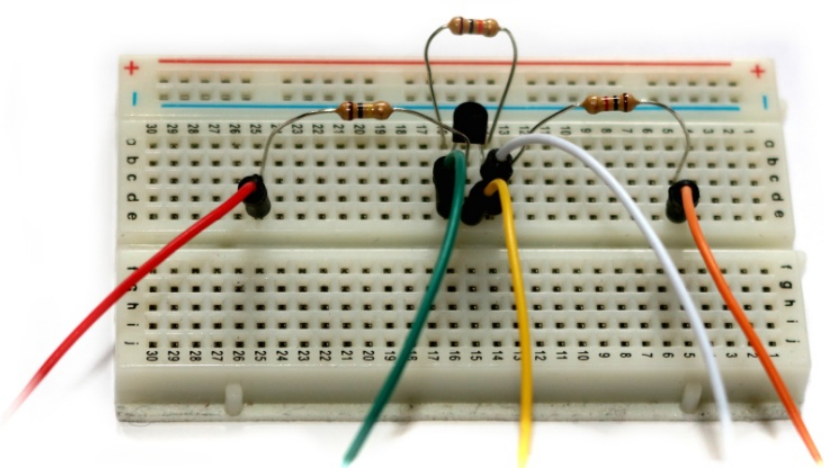
The transistor I measured came with a kit left over from last fall. Yours came in a different batch.

The manufacturer specs a DC β of roughly 100 to 300 at VCE = 1.0 V. I measured around 335 at 3.0 V. My sample appears to have been better than promised.

YMMV. It would not be surprising if your sample is quite different.

3. Repeat with this circuit.





Measured values (Ω)

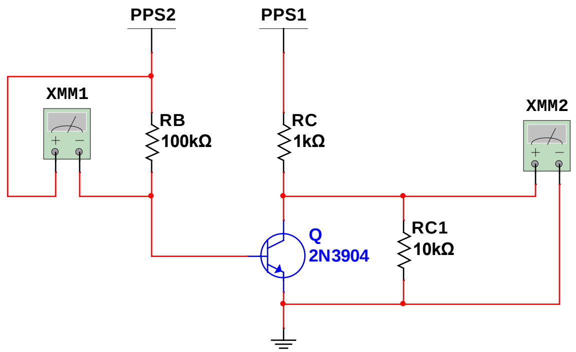
RB	99,080
RC	982
RC1	9,724

Calculated values

$$I_B = \frac{V_{RB}}{RB}$$

$$I_C = \frac{PPS1 - V_{CE}}{RC}$$

$$\beta_F = \frac{I_C}{I_B}$$



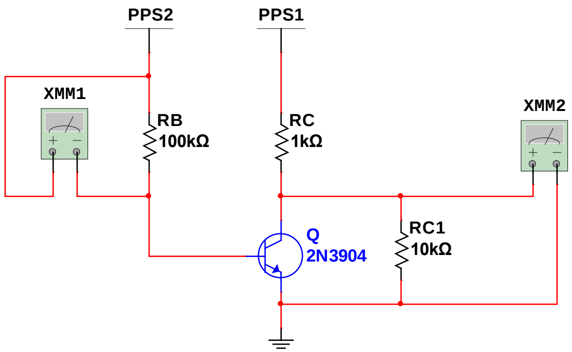
PPS2 = 1.0 V

PPS1	VRB	VCE	IB (µA)	IC (mA)	IC / IB
0	0.470	0.004	4.744	-0.004	-0.943
1	0.359	0.157	3.623	0.859	236.971
2	0.348	0.752	3.512	1.271	361.834
3	0.349	1.649	3.522	1.376	390.575
4	0.349	2.547	3.522	1.480	420.063
5	0.349	3.446	3.522	1.582	449.262
6	0.350	4.345	3.532	1.685	477.095
7	0.350	5.245	3.532	1.787	505.922
8	0.351	6.143	3.543	1.891	533.801
9	0.351	7.044	3.543	1.992	562.259
10	0.352	7.942	3.553	2.096	589.898
Interpolated at VCE = 3.0 V					
4.504	0.349	3.000	3.522	1.531	434.777

PPS2 = 1.25 V

PPS1	VRB	VCE	IB (µA)	IC (mA)	IC / IB
0	0.710	0.005	7.166	-0.006	-0.776
1	0.607	0.127	6.126	0.889	145.078
2	0.584	0.206	5.894	1.827	309.967
3	0.582	0.952	5.874	2.085	355.009
4	0.582	1.842	5.874	2.198	374.113
5	0.582	2.734	5.874	2.308	392.836
6	0.583	3.624	5.884	2.420	411.199
7	0.584	4.516	5.894	2.530	429.154
8	0.584	5.407	5.894	2.641	447.986
9	0.585	6.300	5.904	2.749	465.674
10	0.586	7.188	5.914	2.864	484.164
Interpolated at VCE = 3.0 V					
5.299	0.582	3.000	5.877	2.341	398.324

VRB and VCE were measured. Other columns were calculated.



PPS2 = 1.5 V

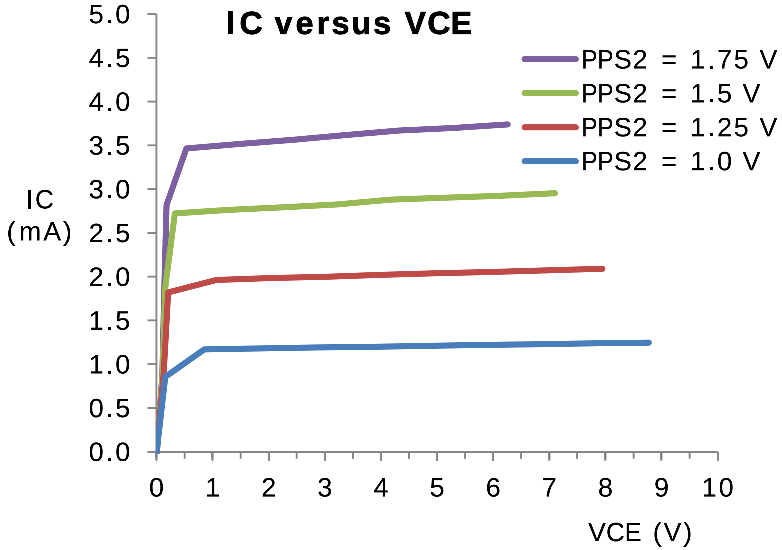
PPS1	VRB	VCE	IB (μA)	IC (mA)	IC / IB
0	0.955	0.006	9.639	-0.006	-0.655
1	0.858	0.112	8.660	0.904	104.369
2	0.834	0.156	8.417	1.878	223.052
3	0.820	0.256	8.276	2.794	337.608
4	0.819	1.076	8.266	2.978	360.220
5	0.819	1.956	8.266	3.100	375.003
6	0.820	2.840	8.276	3.218	388.819
7	0.821	3.730	8.286	3.330	401.864
8	0.822	4.613	8.296	3.449	415.736
9	0.823	5.497	8.306	3.567	429.452
10	0.824	6.377	8.317	3.689	443.625
Interpolated at VCE = 3.0 V					
6.180	0.820	3.000	8.278	3.238	391.164

PPS2 = 1.75 V

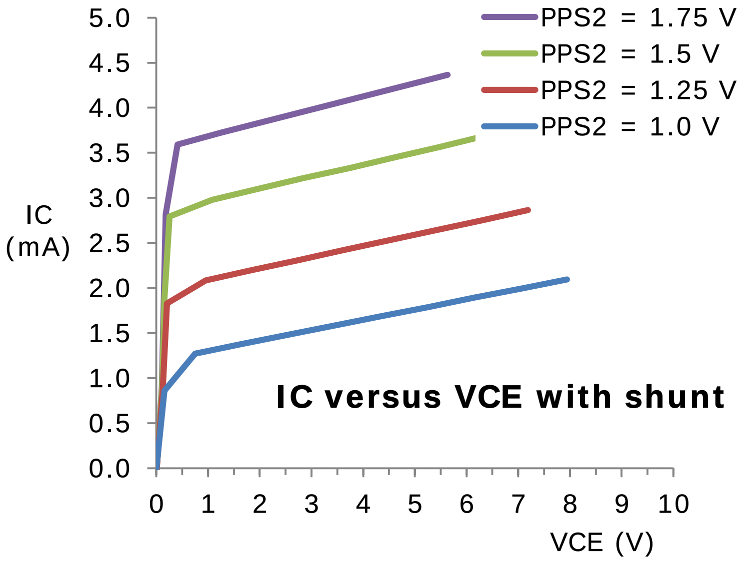
PPS1	VRB	VCE	IB (μA)	IC (mA)	IC / IB
0	1.198	0.007	11.980	-0.007	-0.553
1	1.109	0.104	11.090	0.896	80.789
2	1.084	0.141	10.840	1.859	171.481
3	1.068	0.182	10.680	2.818	263.882
4	1.059	0.407	10.590	3.593	339.282
5	1.058	1.272	10.580	3.728	352.363
6	1.059	2.144	10.590	3.856	364.117
7	1.060	3.018	10.600	3.982	375.660
8	1.062	3.891	10.620	4.109	386.911
9	1.063	4.761	10.630	4.239	398.777
10	1.064	5.633	10.640	4.367	410.432
Interpolated at VCE = 3.0 V					
6.979	1.060	3.000	10.600	3.979	375.423

VRB and VCE were measured. Other columns were calculated.

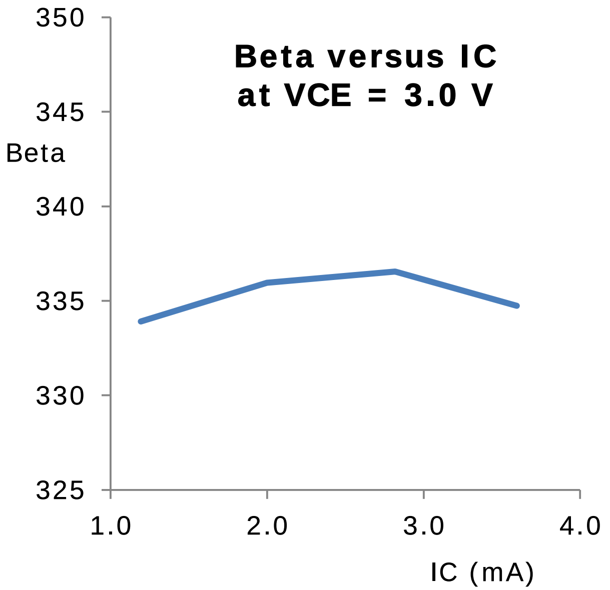
My results



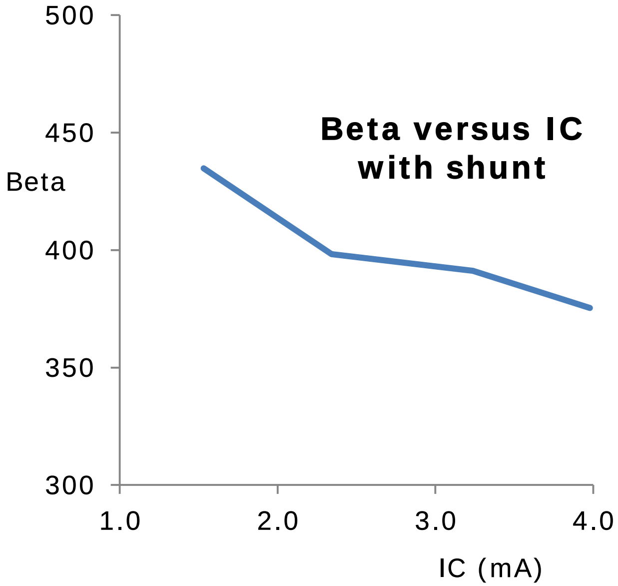
IC versus VCE
PPS2 = 1.75 V
PPS2 = 1.5 V
PPS2 = 1.25 V
PPS2 = 1.0 V
IC (mA)
VCE (V)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
5
6
7
8
9
10



PPS2 = 1.75 V
PPS2 = 1.5 V
PPS2 = 1.25 V
PPS2 = 1.0 V
IC versus VCE with shunt
IC (mA)
VCE (V)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
5
6
7
8
9
10



Beta versus IC at VCE = 3.0 V
Beta
IC (mA)
350
345
340
335
330
325
1.0
2.0
3.0
4.0

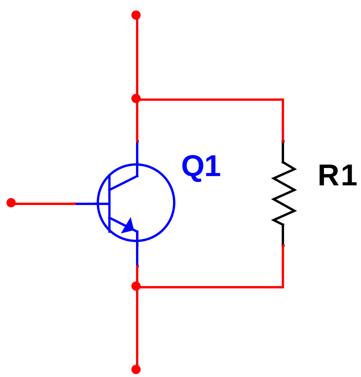


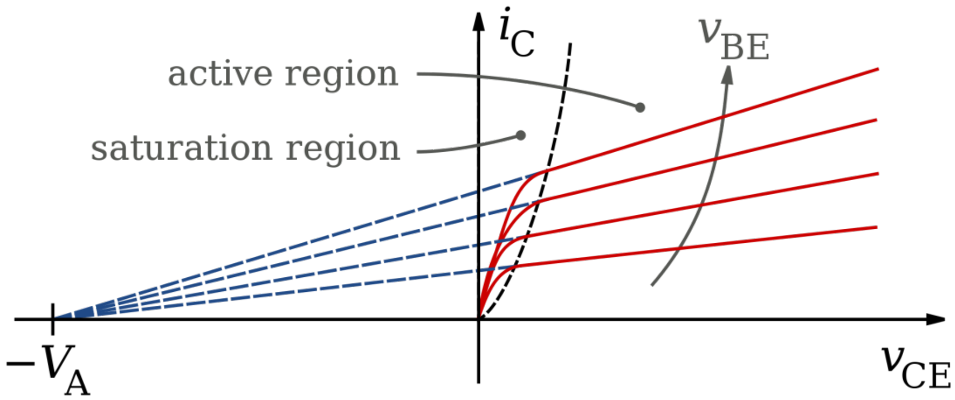
Beta versus IC with shunt
Beta
IC (mA)
500
450
400
350
300
1.0
2.0
3.0
4.0

Early voltage

The tilting is due to a conductance through the transistor in the active region that behaves as if there was a resistor (whose value depends on VBE) in parallel with the transistor.

Named after James M. Early, who discovered it, not because it happens "early".

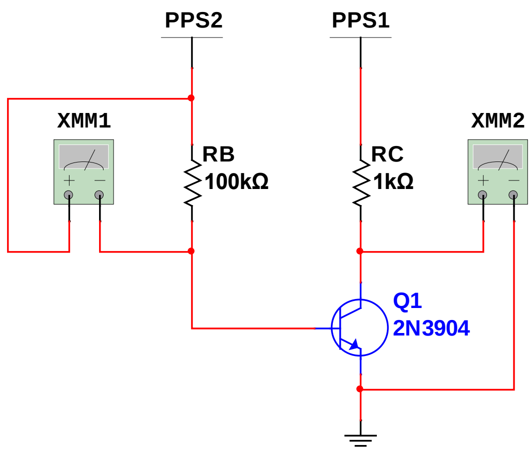




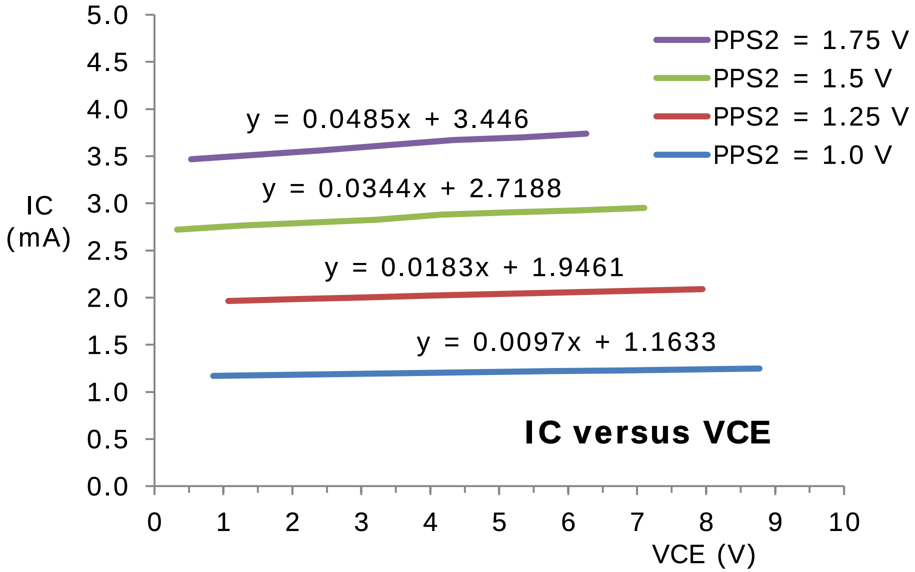
From the data, we can estimate VA and slopes of the lines for various values of VBE.

Image source: https://en.wikipedia.org/wiki/File:Early_effect_(graph_-_I_C_vs_V_CE).svg

Estimating VA, ICsat and λ

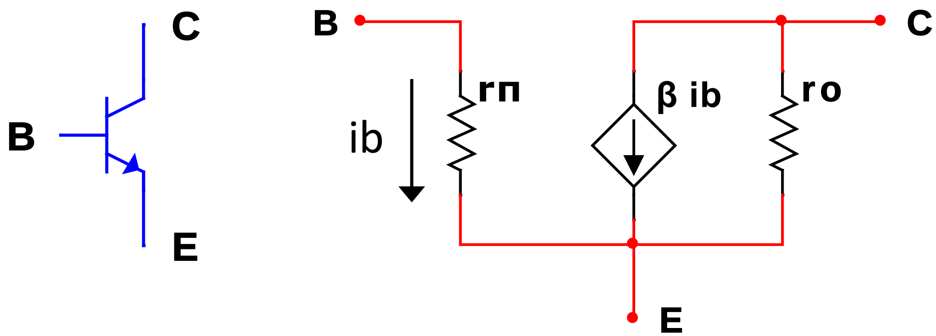


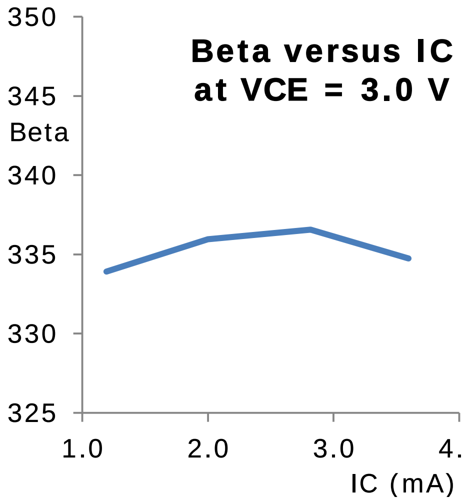
1. Use data from the circuit without the bypass resistor.
2. Identify the straight parts of the curves.
3. Do straight line fits.
4. ICsat is calculated at VCE = 0 on each *fitted line* (as if the straight part was extended.)



PPS2 (V)	ICsat (mA)	Slope (mA/V = mS)	VA (V)	λ = Slope/ICsat (1/V)
1.00	1.1633	0.0097	119.928	0.00834
1.25	1.9461	0.0183	106.344	0.00940
1.50	2.7188	0.0344	79.035	0.01265
1.75	3.4460	0.0485	71.052	0.01407

We can now fill in the Hybrid π model



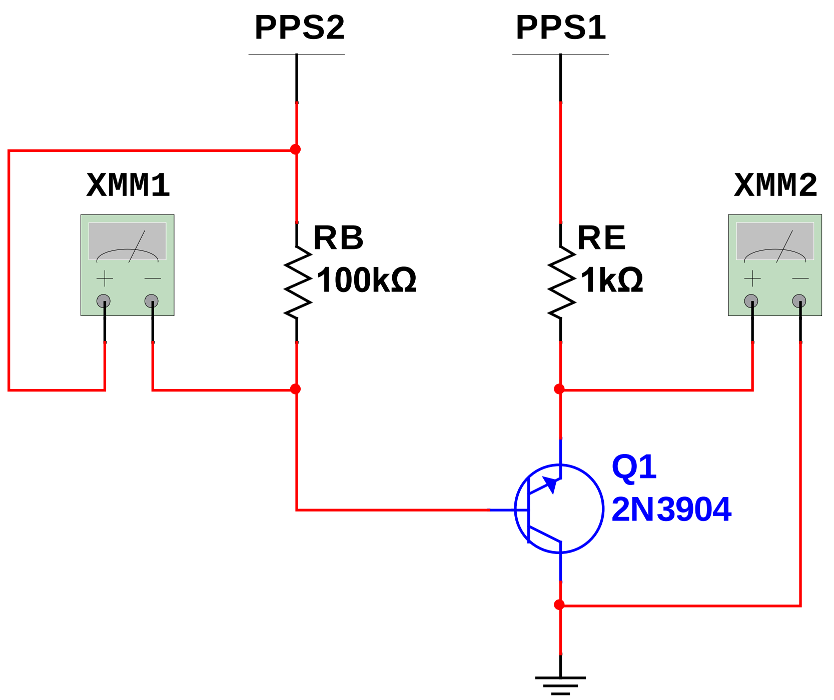


$$r_\pi = \frac{\beta}{g_m} \qquad g_m = \frac{I_C}{V_T} \qquad r_o = \frac{V_A}{I_C}$$

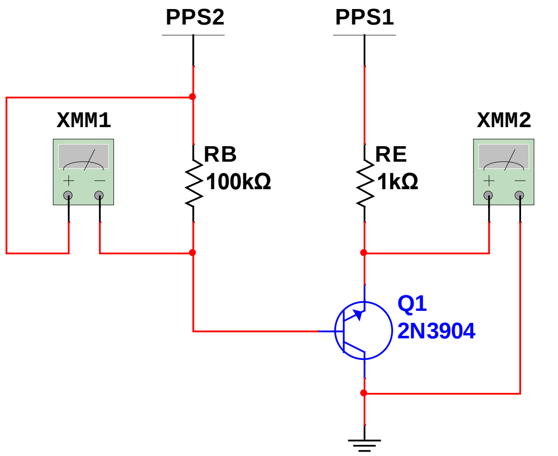
$$V_T = Thermal\ voltage = 25\ mV$$

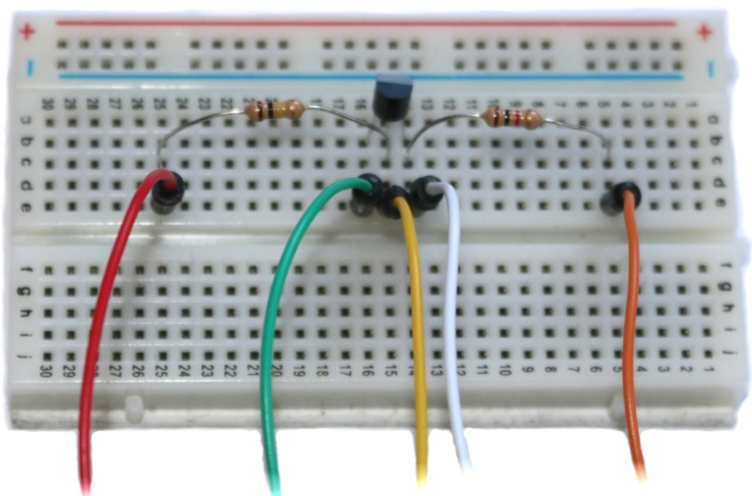
PPS2 (V)	ICsat (mA)	Slope (mA/V = mS)	VA (V)	λ = Slope/ICsat (1/V)
1.00	1.1633	0.0097	119.928	0.00834
1.25	1.9461	0.0183	106.344	0.00940
1.50	2.7188	0.0344	79.035	0.01265
1.75	3.4460	0.0485	71.052	0.01407

What happens if you flip the transistor upside down?



Reverse active





Measured values (Ω)

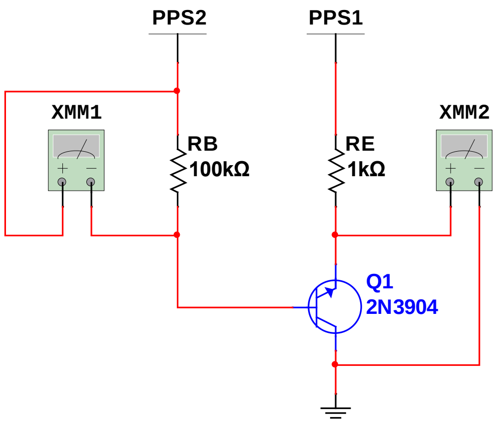
RB	99,080
RE	982

Calculated values

$$I_B = \frac{V_{RB}}{RB}$$

$$I_E = \frac{PPS1 - V_{EC}}{RE}$$

$$\beta_R = \frac{I_E}{I_B}$$



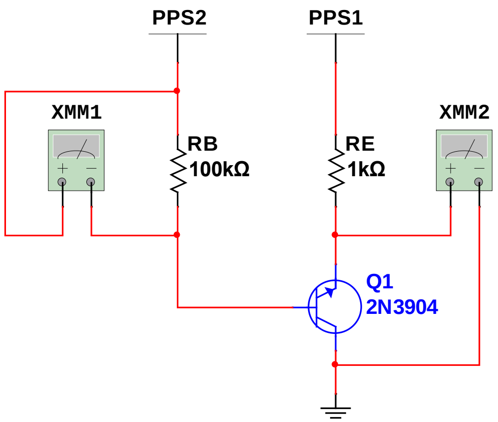
PPS2 = 1.0 V

PPS1	VRB	VEC	IB (μA)	IE (mA)	IE / IB
0	0.478	0.000	4.824	0.000	-0.018
1	0.478	0.987	4.824	0.013	2.786
2	0.478	1.986	4.824	0.015	3.018
3	0.478	2.985	4.824	0.015	3.082
4	0.478	3.985	4.824	0.015	3.208
5	0.478	4.985	4.824	0.016	3.230
6	0.477	5.983	4.814	0.017	3.511
7	0.475	6.981	4.794	0.019	4.015
8	0.472	7.978	4.764	0.023	4.767
9	0.467	8.969	4.713	0.032	6.698
10	0.453	9.942	4.572	0.059	12.963
Interpolated at VEC = 3.0 V					
3.015	0.478	3.000	4.824	0.015	3.084

PPS2 = 1.25 V

PPS1	VRB	VEC	IB (μA)	IE (mA)	IE / IB
0	0.717	0.000	7.237	0.000	-0.005
1	0.716	0.981	7.226	0.020	2.711
2	0.716	1.979	7.226	0.021	2.934
3	0.716	2.979	7.226	0.022	3.016
4	0.716	3.978	7.226	0.023	3.157
5	0.716	4.977	7.226	0.024	3.269
6	0.715	5.975	7.216	0.026	3.556
7	0.714	6.971	7.206	0.029	4.056
8	0.710	7.966	7.166	0.035	4.888
9	0.704	8.951	7.105	0.050	7.051
10	0.686	9.891	6.924	0.112	16.105
Interpolated at VEC = 3.0 V					
3.021	0.716	3.000	7.226	0.022	3.019

VRB and VEC were measured. Other columns were calculated.



PPS2 = 1.5 V

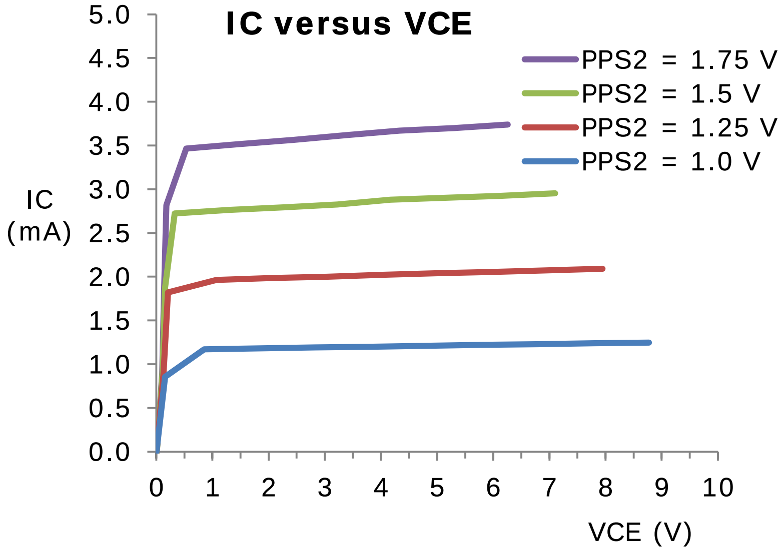
PPS1	VRB	VEC	IB (μA)	IE (mA)	IE / IB
0	0.958	0.000	9.669	0.000	-0.001
1	0.958	0.974	9.669	0.026	2.717
2	0.958	1.972	9.669	0.028	2.928
3	0.958	2.971	9.669	0.029	3.044
4	0.958	3.970	9.669	0.031	3.170
5	0.957	4.969	9.659	0.032	3.321
6	0.956	5.966	9.649	0.035	3.620
7	0.955	6.961	9.639	0.040	4.141
8	0.952	7.952	9.608	0.049	5.055
9	0.947	8.931	9.558	0.071	7.394
10	0.921	9.807	9.296	0.197	21.187
Interpolated at VCE = 3.0 V					
3.029	0.958	3.000	9.669	0.029	3.047

PPS2 = 1.75 V

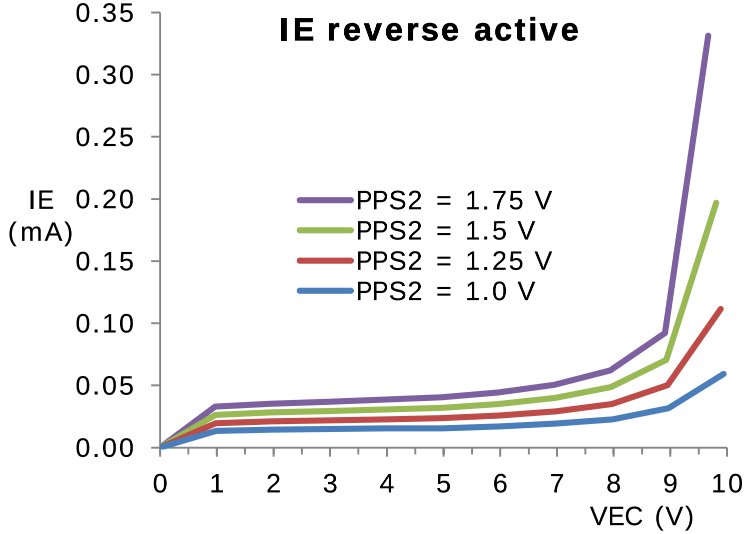
PPS1	VRB	VEC	IB (μA)	IE (mA)	IE / IB
0	1.202	0.000	12.020	0.000	-0.003
1	1.201	0.967	12.010	0.033	2.742
2	1.201	1.965	12.010	0.035	2.940
3	1.201	2.963	12.010	0.037	3.064
4	1.201	3.961	12.010	0.039	3.214
5	1.200	4.960	12.000	0.040	3.375
6	1.198	5.956	11.980	0.044	3.706
7	1.194	6.949	11.940	0.051	4.238
8	1.187	7.938	11.870	0.062	5.232
9	1.580	8.908	15.800	0.092	5.829
10	1.064	9.669	10.640	0.331	31.128
Interpolated at VCE = 3.0 V					
3.037	1.201	3.000	12.010	0.037	3.070

VRB and VEC were measured. Other columns were calculated.

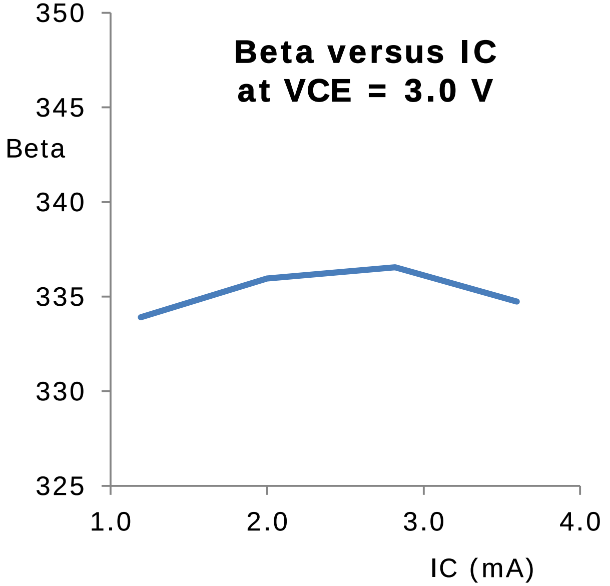
My results



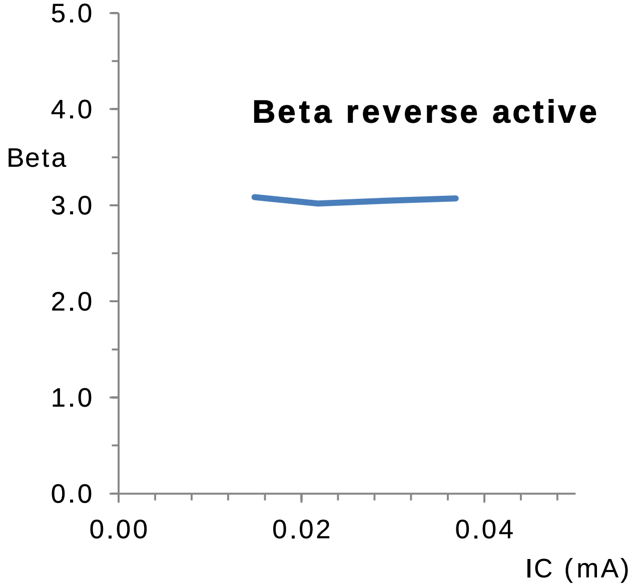
IC versus VCE
IC (mA)
VCE (V)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
5
6
7
8
9
10
PPS2 = 1.75 V
PPS2 = 1.5 V
PPS2 = 1.25 V
PPS2 = 1.0 V



IE reverse active
IE (mA)
VEC (V)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
1
2
3
4
5
6
7
8
9
10
PPS2 = 1.75 V
PPS2 = 1.5 V
PPS2 = 1.25 V
PPS2 = 1.0 V



Beta versus IC
at VCE = 3.0 V
Beta
IC (mA)
350
345
340
335
330
325
1.0
2.0
3.0
4.0



Beta reverse active
Beta
IC (mA)
5.0
4.0
3.0
2.0
1.0
0.0
0.00
0.02
0.04

As predicted

Difficult to tell emitter from collector with an ohmmeter.

Not at all difficult to tell the difference between β_F and β_R.

β_R is only about 1/100-th β_F and the transistor enters breakdown at only about 9 V.