Experiment 9
Single Transistor Amplifiers

1 Motivation

In this experiment you will continue your investigation of transistors by constructing a common-emitter amplifier. If you have time, you will also investigate the emitter-follower (aka common-collector) amplifier. These amplifiers are two of the building blocks often used for composite amplifying circuits, e.g., operational amplifier integrated circuits.

2 Background

The bipolar-junction transistor (BJT) is an "active" device that functions as a current-controlled current source, which makes it useful as a voltage amplifier. The common-emitter amplifier, shown in Fig. 1, has moderate gain and moderate input and output resistances. Resistors R_1 and R_2 are used to set the DC operating point for the base voltage, V_{B}. Resistor R_{E} provides negative feedback in the following way. If V_{B} is raised, I_{B} and I_{E} both increase. As the current in R_{E} increases, the emitter voltage, V_{E}, also increases since $V_{\mathrm{E}} = V_{\mathrm{EE}} + I_{\mathrm{E}}R_{\mathrm{E}}$. This prevents V_{BE} from changing very much, which in turn implies changes in I_{E} will not be very large. The amplifier's gain can be large if you choose small R_{E}, but the output signal will be distorted and sensitive to changes in temperature with overly large gain.

Before you come to lab, complete both Problem 8.7 in Sprott and the Prelab question. These involve the design and behavior of a common-emitter amplifier.

3 Equipment

For this experiment, you will use:

- One Topward dual DC power supply, set for independent supplies (slide switches)
- One DMM4020 digital multimeter
- One Tektronix MSO 2014B Digital Storage Oscilloscope
- One AFG2021 Arbitrary Function Generator
- One circuit board for testing single transistor amplifiers
- One 2N3904 NPN bipolar-junction transistor (parts cabinet)
- Two ELC variable resistance boxes
- One 4.7 Ω, 1 W carbon-composition resistor (parts cabinet)

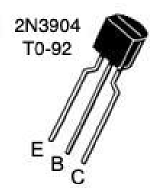


Figure 2: 2N3904 BJT

4 Procedure

Common-Emitter Amplifier: The circuit you will use is mostly pre-wired and mounted on the circuit board. The schematic is shown in Fig. 1. Look at the underside of the board to identify the key parts and their locations. Sketch the circuit in your lab notebook. (There are two capacitors in the actual circuit that are not included in the schematic in Fig. 1. These are used to decrease the AC impedance of the voltage supplies.)

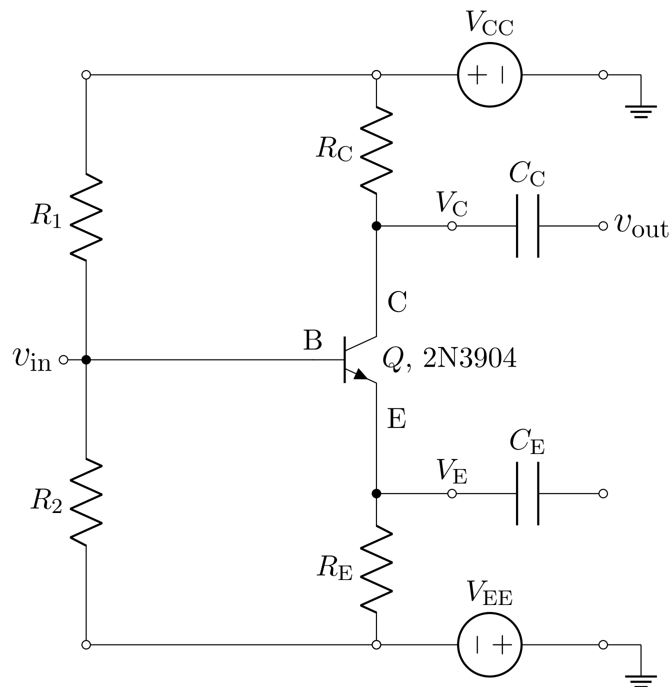


Figure 1: The Common-Emitter amplifier using an NPN BJT. (The schematic is drawn as viewed from the underside of the circuit board used for this experiment.)

1. Use the DMM to measure the resistances of all four resistors and record their values next to your labels on your sketch. The value of C_C will be determined later.
2. Check to make sure the Topward DC power supply is set for operation as independent supplies (slide switches). Connect one Topward DC supply between the terminals for V_{CC} and ground. Connect the other Topward DC supply between the terminals for V_{EE} and ground. The V_{EE} voltage needs to be negative relative to ground, so connect the supply's "+" (red) terminal to ground on the circuit board. Install the 2N3904 NPN BJT transistor in the socket on the circuit board, paying close attention to the proper orientation of the leads (Fig. 2). Do *not* connect the function generator to start.
3. Establish the DC operating point:
   (a) Turn on and set the supplies so that $V_{CC} = +20\,\text{V}$ and $V_{EE} \approx -1.5\,\text{V}$. Using a DMM, measure V_B and zero it to $V_B = 0 \pm 10\,\text{mV}$ by adjusting V_{EE}. The Topward supply is a bit difficult to fine tune at small voltages, but do you best to make V_B close to zero. (Zeroing V_B using two separate supplies avoids the use of an AC coupling capacitor at the base.) Be careful not to change these DC voltages in the steps below. Now use the DMM to measure V_{CC}, V_{CE}, and V_{EE}. Determine the value of I_C (its DC operating point) using your measurements of the voltages and resistances.
   (b) Print a copy of the 2N3904's collector characteristics shown in Fig. 3. You need two data points to define the DC load line. It is usually easiest to use the (x,y) axis intercepts. You can evaluate these intercepts using the measurements you have already taken. The y-intercept is the value of I_C when V_{CE}=0. (Imagine putting a short-circuit between the V_C and V_E terminals and use Ohm's law to determine the current between V_{CC} and V_{EE}.) The x-intercept is when I_C=0. (Imagine an open-circuit between the V_C and V_E terminals.) Draw the DC load line for your circuit on the plot of collector characteristics

and mark the DC operating point (based on your measurements above). Determine I_B at the DC operating point by interpolating between the nearest two collector characteristics. Calculate the transistor's current gain, β.

(c) Calculate the amplifier's expected values for voltage gain, A, as well as R_{out}, R_{in}, and r_{tr}. (Relevant formulas for the common-emitter amplifier are in Sprott §8.4.)

4. Establish AC operation of the amplifier:
   (a) Using a BNC-to-banana jack adapter, install a $4.7\,\Omega, 1\,\text{W}$ resistor across the output of the function generator to lower the output impedance. Use a BNC "Y" or "T" adapter on the generator's output to make a parallel connection to the circuit (v_{in}) and one channel on the oscilloscope to measure v_{in}. Set the function generator to produce a sine wave with frequency $f = 10\,\text{kHz}$.
   (b) Use a second oscilloscope channel to measure v_{out}. Adjust the generator's output so that $|v_{out}| = 2.0\,\text{V}$ rms. (Use the scope's rms measurement.) Measure the amplifier's gain, A, using the rms amplitudes of $|v_{in}|$ and $|v_{out}|$. Compare your measurement with the value of A that you calculated above. What is the relative phase between v_{in} and v_{out}?
   (c) Move the scope measurement from v_{out} to V_C. Notice the AC and DC components! Make sketches of v_{in} and V_C in your lab notebook.
   (d) To measure R_{in}, use a variable resistor box, R, placed in series between the function generator and the transistor's base. Adjust R until $|v_B|$ (or $|v_{out}|$) drops by a factor of 2. To measure R_{out}, place R across the *output* side of C_C to ground to establish a load resistance, $R_L = R$. Vary R_L until the output drops a factor of 2. (If you connect the resistor on the collector side of C_C you change the DC operating point of the amplifier!!) Compare your measurements of R_{in} and R_{out} with the values you calculated above.
5. Set $R_L = 3\,\text{k}\Omega$. Using the scope, measure and tabulate $|v_{in}|$ and $|v_{out}|$ as a function of frequency for $10\,\text{kHz} > f > 10\,\text{Hz}$. Measurements at three frequencies per decade (10, 5, 2, 1, ...) is sufficient, with a few extra measurements near the corner frequency. Make a log-log plot of A versus f. The falloff in the gain at low frequencies is caused by the growing impedance of C_C. Determine the high-pass corner frequency, $f_c = \omega_c/2\pi$, where A is decreased by $1/\sqrt{2}$ relative to its value at high frequency. Determine C_C from the corner frequency using the total series resistance for the output, $R_{out} + R_L$.
6. Remove R_L, set the frequency to $f = 10\,\text{kHz}$, and increase v_{in} to drive V_C into cutoff and saturation. (You may need to temporarily remove the $4.7\,\Omega$ resistor for this step). Make a sketch of V_C in your lab notebook and determine V_C (off) and V_C (sat).
7. Now configure the amplifier for "grounded-emitter" operation. Rather than grounding the emitter directly, "bypass" R_E using capacitor C_E. This maintains the DC operating point but short-circuits R_E for AC voltage.
   (a) Reinstall the $4.7\,\Omega$ resistor and connect the *output* side of C_E to ground. Adjust the input voltage to obtain $|v_{out}| = 5\,\text{V}$ peak-to-peak. Measure the gain, A, as before using the rms values measured by the scope. For grounded-emitter operation, $A = R_C/r_{tr}$. Use your measured A to determine the transresistance, r_{tr} and compare with its expected value, $r_{tr} = kT/eI_E$.
   (b) Switch the function generator to make a triangle wave and increase the output to $|v_{out}| = 8\,\text{V}$ peak-to-peak. Make a sketch of $V_C(t)$, including both the DC and AC parts. On the same graph, indicate the quiescent value of V_C, i.e. the value obtained with $v_{in} = 0$. Can you explain why V_C looks the way it does?

Emitter-follower (aka Common-Emitter) Amplifier: The emitter-follower amplifier has a gain $A \approx 1$, moderate input resistance, and very low output resistance. The circuit is similar to that above but with the output taken from the emitter.

1. Set the function generator frequency to $f = 10\,\mathrm{kHz}$. Measuring directly at the emitter terminal, adjust the amplitude of v_{in} to obtain $|v_{\mathrm{out}}| = 0.3\,\mathrm{V}$ rms. Sketch v_{in} and V_{out}, remembering to include both the AC and DC parts. Measure the gain and relative phase between v_{out} and v_{in}. Compare your results with expected values for the emitter-follower. (Use your prior measurement of r_{tr}.)
2. Use the following procedure to measure the output resistance of the amplifier. First, disconnect v_{in} and use the DMM to check that $V_{\mathrm{B}} = 0 \pm 10\,\mathrm{mV}$ (if not, adjust V_{EE} to zero V_{B}.) Now remove the $4.7\,\Omega$ resistor and install a $100\,\mathrm{k}\Omega$ resistor in *series* with the function generator output using a variable resistance box. Adjust the amplitude of the function generator to obtain $|v_{\mathrm{E}}| = 50\,\mathrm{mV}$ rms (AC component). Using a second variable resistance box, create a load resistance, R_{L}, between the output side of C_{E} and ground. Now adjust R_{L} to obtain $|v_{\mathrm{out}}| = |v_{\mathrm{B}}|/2$, where v_{out} is the voltage across R_{L} and v_{B} is the AC voltage at the base (you will need to add a scope measurement for v_{B}). For this R_{L}, the midpoint of the voltage divider formed by R_{out} and R_{L} is divide-by-two, so $R_{\mathrm{out}} = R_{\mathrm{L}}$. Note that as you adjust R_{L}, both v_{out} and v_{B} change, so you must measure both v_{out} and v_{B} simultaneously. Compare your measurement of R_{out} with the expected value for the emitter-follower amplifier.

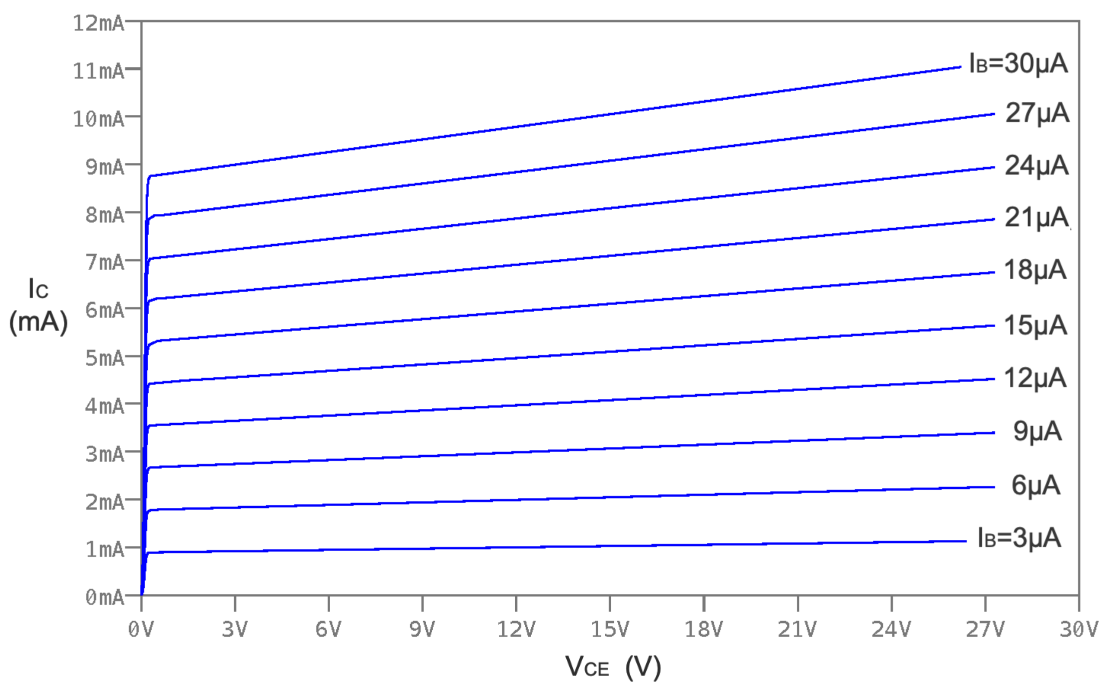
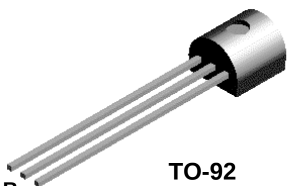
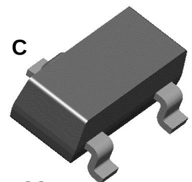


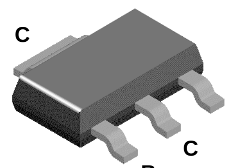
Figure 3: Collector characteristics for a 2N3904 NPN bipolar-junction transistor. These were generated using a SPICE model for the 2N3904 manufactured by NXP. The collector characteristics are sometimes provided on a manufacturer's data sheet. They can also be measured for a particular transistor using a "curve tracer," which your lab instructor might have running for demonstration.

FAIRCHILD
SEMICONDUCTOR TM

2N3904 MMBT3904 PZT3904







NPN General Purpose Amplifier

This device is designed as a general purpose amplifier and switch. The useful dynamic range extends to 100 mA as a switch and to 100 MHz as an amplifier.

Absolute Maximum Ratings*

$T_A = 25°C$ unless otherwise noted

Symbol	Parameter	Value	Units
V_{CEO}	Collector-Emitter Voltage	40	V
V_{CBO}	Collector-Base Voltage	60	V
V_{EBO}	Emitter-Base Voltage	6.0	V
I_C	Collector Current - Continuous	200	mA
T_J, T_{stg}	Operating and Storage Junction Temperature Range	-55 to +150	°C

*These ratings are limiting values above which the serviceability of any semiconductor device may be impaired.

NOTES:
1) These ratings are based on a maximum junction temperature of 150 degrees C.
2) These are steady state limits. The factory should be consulted on applications involving pulsed or low duty cycle operations.

Thermal Characteristics

$T_A = 25°C$ unless otherwise noted

Symbol	Characteristic	Max			Units
		2N3904	***MMBT3904**	****PZT3904**	
P_D	Total Device Dissipation Derate above 25°C	625 5.0	350 2.8	1,000 8.0	mW mW/°C
$R_{\theta JC}$	Thermal Resistance, Junction to Case	83.3			°C/W
$R_{\theta JA}$	Thermal Resistance, Junction to Ambient	200	357	125	°C/W

*Device mounted on FR-4 PCB 1.6" X 1.6" X 0.06."
**Device mounted on FR-4 PCB 36 mm X 18 mm X 1.5 mm; mounting pad for the collector lead min. 6 cm^2.

NPN General Purpose Amplifier
(continued)

Electrical Characteristics

T_A = 25°C unless otherwise noted

Symbol	Parameter	Test Conditions	Min	Max	Units
OFF CHARACTERISTICS					
$V_{(BR)CEO}$	Collector-Emitter Breakdown Voltage	I_C = 1.0 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} = 3V		50	nA
I_{CEX}	Collector Cutoff Current	V_{CE} = 30 V, V_{EB} = 3V		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
SMALL SIGNAL CHARACTERISTICS					
f_T	Current Gain - Bandwidth Product	I_C = 10 mA, V_{CE} = 20 V, f = 100 MHz	300		MHz
C_{obo}	Output Capacitance	V_{CB} = 5.0 V, I_E = 0, f = 1.0 MHz		4.0	pF
C_{ibo}	Input Capacitance	V_{EB} = 0.5 V, I_C = 0, f = 1.0 MHz		8.0	pF
NF	Noise Figure	I_C = 100 μA, V_{CE} = 5.0 V, R_S =1.0kΩ,f=10 Hz to 15.7kHz		5.0	dB
SWITCHING CHARACTERISTICS					
t_d	Delay Time	V_{CC} = 3.0 V, V_{BE} = 0.5 V,		35	ns
t_r	Rise Time	I_C = 10 mA, I_{B1} = 1.0 mA		35	ns
t_s	Storage Time	V_{CC} = 3.0 V, I_C = 10mA		200	ns
t_f	Fall Time	I_{B1} = I_{B2} = 1.0 mA		50	ns

*Pulse Test: Pulse Width ≤ 300 μs, Duty Cycle ≤ 2.0%

Spice Model

NPN (Is=6.734f Xti=3 Eg=1.11 Vaf=74.03 Bf=416.4 Ne=1.259 Ise=6.734 Ikf=66.78m Xtb=1.5 Br=.7371 Nc=2 Isc=0 Ikr=0 Rc=1 Cjc=3.638p Mjc=.3085 Vjc=.75 Fc=.5 Cje=4.493p Mje=.2593 Vje=.75 Tr=239.5n Tf=301.2p Itf=.4 Vtf=4 Xtf=2 Rb=10)

NPN General Purpose Amplifier
(continued)

Typical Characteristics