

# Computer Controlled Curve Tracer

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**Abstract**—A computer controlled curve tracer was designed, simulated, and constructed. This curve tracer was implemented with operational amplifiers, a variety of bipolar junction transistor circuits, and 4000 series digital logic, and interfaced with computer software using an Arduino. The computer software was written in C# and R. The curve tracer was used to characterize resistors, a field effect transistor (2N7000), and a bipolar junction transistor (N2222).

## I. INTRODUCTION

A curve tracer is an instrument that can be used to measure various parameters of the device under test (DUT). Typically a curve tracer will stimulate the DUT with either a voltage or current and then use an ammeter or voltmeter to collect the appropriate data to plot an IV characteristic. From the IV characteristic various parameters can be estimated. For example, for a bipolar junction transistor the gain parameter  $\beta$  can be estimated by reading off the ratio of collector current to base current.

Curve tracers are typically designed to be able to test both two and three terminal devices. Additionally curve tracers are designed to be able to stimulate the DUT with either a voltage or a current. For certain types of devices a particular type of stimulus might be preferable. For example, in the case of a diode a curve tracer would stimulate the DUT with a current rather than the voltage since it would respond logarithmically in voltage rather than exponentially in current. An exponential result of stimulus requires significantly higher precision to resolve smoothly than a logarithmic response. Additionally it is much easier to exceed the power rating of diode by sweeping voltage than current, again because of the different response types.

Additionally curve tracers have multiple resolution settings. Analog to digital converters have a finite number of quantization levels. In order to have several resolution settings a curve tracer might have variable gains on ammeter and voltmeter portions of the instrument. For example one resolution settings on an ammeter might be to measure  $[-1, 1]$  mA with 256 (8-bit precision) quantization levels, and another might be to measure  $[-10, 10]$  mA with the same number of quantization levels. The first resolution setting will have a precision of 0.0078 mA while the second resolution setting will have a precision of 0.078 mA.

Some curve tracers output to oscilloscopes, some have integrated displays, and others connect to an external computer. Typically these curve tracers are able to display the IV

characteristics for the DUT for multiple stimuli parameters. For example in the case of a bipolar junction transistor, a curve tracer might display the collector current against a collector-emitter voltage sweep for several base current values.

The present curve tracer was implemented for both two and three terminal devices, has multiple ammeter resolutions, and multiple voltage sweep resolutions. The present curve tracer is also controlled by and displays its results on an external computer. The mixed-signal curve tracer circuitry interfaces with an Arduino, a microcontroller platform, in order to communicate with the external computer. The control interface, control logic, and communication system on the computer are written in the C# programming language while the plotting of the IV characteristics is done using the R statistical computing language. The IV characteristics are written in the Portable Document Format and can be saved for later study.

## II. SYSTEM DESCRIPTION

### A. Block Model

The present curve tracer can be broken down into several discrete functional blocks. These blocks are laid out in a hierarchy in Figure 1.

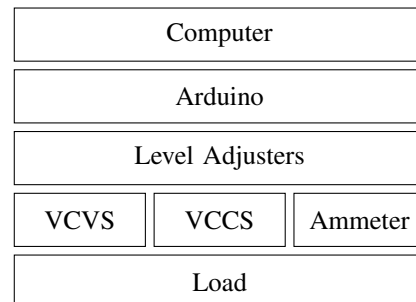


Fig. 1: A hierarchical diagram of the curve tracer.

a) *Computer*: At the top of the hierarchical model is the external computer. The computer runs the control program in which the user can set the stimuli parameters, the sweep resolution, and the ammeter resolution. The program can set the curve tracer into two terminal mode, three terminal bipolar junction transistor mode, or three terminal field effect transistor mode. In the two terminal mode the user can select a voltage sweep range and an ammeter range setting, both of which affect the final resolution of the instrument. Additionally the user can set the start and end points of the voltage sweep,

and the number of steps to take in between. If the user specifies a number of points that mathematically result in a resolution greater than the instrument can achieve, the device will instead trace with the number of points that will yield the greatest resolution. The instrument operates similarly in three terminal mode. The same settings for the voltage sweep and ammeter exist as in the two terminal mode. In the three terminal mode the addition is that the user can specify a range of base currents or gate voltages to plot IV characteristics for in the case of a bipolar junction transistor or field effect transistor being characterized. The computer interfaces by serial communication through its USB port with the Arduino. The computer sends what points to test at, and what resolution parameters to use to the Arduino.

*b) Arduino:* The Arduino acts as an interface between the computer and functional blocks built out of discrete components. The Arduino processes the commands from the computer and converts them into signals to be sent to the next hierarchical level down in the circuit. The Arduino has several types of I/O pins. The types used in the curve tracer were the analog read pins, PWM write pins, and the digital write pins. Each of these pins operate on the  $[0, 5]$  V range. The lower hierarchical levels, however require ranges of  $[-5, 5]$  V, therefore the next hierarchical level is a set of level adjusters to map  $[0, 5] \rightarrow [-5, 5]$  and  $[-5, 5] \rightarrow [0, 5]$ .

*c) Level Adjustment:* The level adjustment stage consists of several operation amplifier summing circuits and first order resistor-capacitor (RC) filters. The summing circuits exist to perform the voltage mapping while the RC filters exist to convert a PWM signal to a DC voltage. Additionally before reading by the Arduino, the measured signal is filtered to remove any spurious oscillations. The level adjusters interact directly with the functional blocks on the next hierarchical level.

*d) Discrete Components:* At the next hierarchical level is the mixed signal circuitry built up out of discrete components. This level consists of three functional blocks: a Voltage Controlled Voltage Source (VCVS), a Voltage Controlled Current Source (VCCS) and an ammeter. The VCVS has four settings shown in Table I and can supply a load with up to 1 A of current. Both the VCVS and VCCS have control voltages on the range  $[-5, 5]$  V. The present VCCS has one setting and can supply  $[-5, 5]$  mA which is more than enough to supply the base current needed to characterize ordinary bipolar junction transistors. The goal was to create a VCCS that could supply  $[-1, 1]$  A, however that implementation did not function correctly. The ammeter has four settings show in Table I, and is set up to measure the current provided by the VCVS to a load. The ammeter reports current readings as values on the range  $[-5, 5]$  V. The ammeter is essentially a current controlled voltage source. The settings on the ammeter and VCVS are changed by a digital signal from the level adjusters which interface with a 4028 BCD to decimal decoder which signals the control pins on a 4066 quad bilateral switch causing a gain resistor to be switched in each circuit. The specific resistor values corresponding to specific settings are

shown in Table I. The 4028s and 4066s are operating on  $[-5, 5]$  V which necessitates the level adjustments. These devices need to operate at these voltages to allow negative load voltages, and measurements of negative current.

*e) Load:* The load is the final hierarchical level. For a curve tracer the load is the DUT. The present curve tracer characterized three types of loads. First, resistive loads; in the case of resistor the VCCS goes unused, the VCVS sets the voltage on the load, and the ammeter measures the current on the load. Second, bipolar junction transistors can act as the load. In this case the VCCS sets the base current, the VCVS sweeps the collector-emitter voltage and the ammeter reports the collector current. Finally, field effect transistors can act as the load. In this case the VCCS in parallel with a resistor sets the gate voltage, the VCVS sweeps the drain-source voltage and the ammeter reports the drain current.

VCVS Settings		Ammeter Settings	
Range (V)	$R_g$ (k $\Omega$ )	Range (mA)	$R_s$ (k $\Omega$ )
$[-1, 1]$	3	$[-10^0, 10^0]$	0.33
$[-5, 5]$	78	$[-10^1, 10^1]$	3.3
$[-10, 10]$	101	$[-10^2, 10^2]$	33
$[-20, 20]$	121	$[-10^3, 10^3]$	330

TABLE I: Gain settings for the VCVS and the ammeter.

## B. VCVS

*a) Input Stage:* Figure 2 shows the voltage controlled voltage source. At the positive terminal of  $U_1$  we divided the input voltage (of  $[-5, 5]$  V) by a factor of 20 using  $R_1$  and  $R_2$ . The divided input signal was passed into the non-inverting terminal of  $U_1$ , while properly voltage divided feedback was passed into the inverting terminal of  $U_1$ . Since the 411 has high gain,  $U_1$  serves to set its output voltage such that the voltage on each of the input terminals will be extremely close. Capacitors  $C_4$  and  $C_1$  are used to eliminate high frequency noise.

*b) Voltage Gain Stage:*  $Q_3$  serves to invert the signal from the opamp without providing large amounts of gain or power loss. As the voltage at the output of  $U_1$  drops, the base voltage of  $Q_3$  will as well. Since  $Q_3$  is a PNP transistor, this drop in base voltage results in a larger  $V_{BE}$  and thus  $I_{CQ_3}$  will increase. An increase in  $I_{CQ_3}$  results in a larger voltage drop across  $R_{12}$ , leading to a higher base voltage on  $Q_2$ . This causes a  $V_{BE}$  thus increasing  $Q_2$ 's collector current. This increase in  $I_{CQ_2}$  results in a larger voltage drop across  $R_{15}$ . This means that the voltage at the start of the push pull pair will be lower. Thus,  $Q_2$  and  $Q_3$  serve to invert the output of  $U_1$  twice. This means the collector voltage of  $Q_2$  tracks the output voltage of  $U_1$ , but with significant voltage gain, which maps the output of  $U_1$  to be close to the range of  $V_{CC}$  to  $V_{EE}$ .  $C_3$  was used in order to minimize noise in this stage

*c) Output Stage:*  $Q_1$  and  $Q_4$  serve as a push pull pair, which moves the voltage on their base to the emitters (with a drop of 0.7 V along  $V_{BE}$ ) while providing current amplification.  $Q_5$  and  $Q_1$  behave as a Darlington pair. As the base voltage of  $Q_5$  increases,  $I_{EQ_5}$  follows. This increases the base

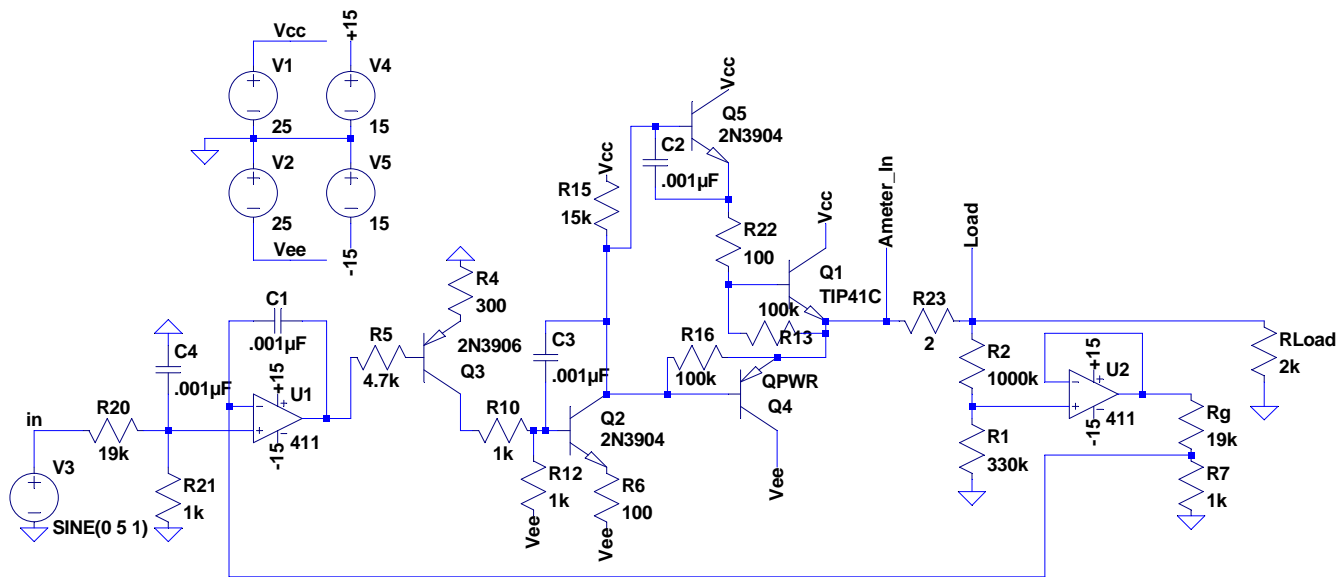


Fig. 2: VCVS

current in  $Q_1$ , and thus minimizes the gain  $Q_1$  must perform. The addition of  $Q_5$  thus makes our circuit much more power efficient.  $C_2$  is used to minimize noise across  $Q_5$ .  $R_{13}$  and  $R_{16}$  are safety features which provide a path for current when power is turned off. This ensures that  $Q_1$  and  $Q_5$  respectively will turn off.  $Q_3$  is used for positive output voltages, but turns off as the collector voltage on  $Q_2$  drops to zero. Below this, in the negative output voltage region,  $Q_4$  serves as a current sink for the load. Crossover distortion is eliminated by providing feedback with the output, which will be further explained in the final stage.

d) *Feedback:* Prior to the feedback and load is our ammeter. By tracking the voltage across  $R_{23}$  we can measure the load current.  $R_1$  and  $R_2$  serve as the first part of our feedback stage. They divide the output voltage by 4, allowing us to use a unity gain buffer ( $U_2$ ) powered on 15 V.  $R_1$  and  $R_2$  are selected to be very large to minimize their interference with the load. At the output of  $U_2$ , we used another voltage divider. By adjusting  $R_g$  on this divider we can set the ratio between our input and output current. Thus by multiplexing this resistor we can achieve our 4 states.

### C. Ammeter

The goal of the ammeter is to find the voltage across  $R_1$ . By using a difference amplifier with variable resistors, and the fact that  $R_1$ 's resistance is known, we can create an ammeter. The voltage on both sides of  $R_1$  was divided by 4 via  $R_9/R_{10}$  and  $R_7/R_8$ . It was then fed into unity gain buffers to preserve the divided voltages. The final part of the circuit is a difference amplifier. The difference amplifier finds the difference between the outputs of  $U_1$  and  $U_2$ . By changing both  $R_s$  we can change the gain of the difference amplifier. Since  $R_3$  and  $R_4$  are equal,

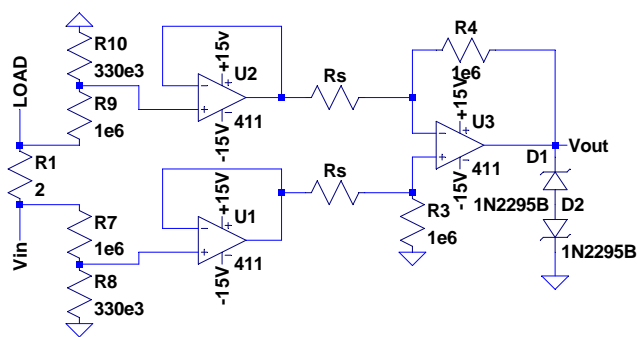


Fig. 3: Ammeter

and both  $R_s$  are equal, the gain of the differential amplifier can be approximated as  $R_4/R_s$ . Two zener diodes are used on the output of  $U_3$ . If the output would exceed 5 V  $D_1$  will enter reverse active mode and  $D_2$  will enter forward active. This means that  $V_{out}$  is constrained to at most 5 V, which will prevent us from destroying the Arduino when we try to read.

### D. VCCS

a) *Present VCCS:* A Howland Current source was constructed to provide the base current for testing bipolar junction transistors. With an additional resistor this source also doubled as a voltage source provided a the gate voltage for testing field effect transistors.

b) *Spec VCCS:* The voltage controlled current source (VCCS) has a very similar structure to the VCVS. The first part of the circuit up until the output of the push pull pair is exactly the same. However, the feedback voltage is generated via the ammeter. The ammeter structure for the VCCS is the

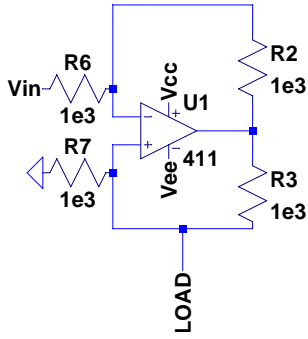


Fig. 4: Howland current source that provides a current for the load of  $[5, -5]$  mA for an input voltage of  $[-5, 5]$  V.

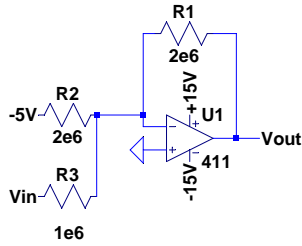


Fig. 5: Level Adjuster that maps  $[0, 5]$  V to  $[-5, 5]$  V.

same as that of the VCVS.  $R_{g1}$  and  $R_{g2}$  can be adjusted to change the ammeter gain and just set the voltage. The output voltage on  $U_5$  represents the current across  $R_{23}$  with proper scaling. As such, when this is fed back the output of  $U_1$  will set itself to match the necessary current on the load. The voltmeter was put in parallel with the load, using a large resistance of  $1000 \text{ k}\Omega$ .  $U_4$  served as a unity gain buffer, while  $U_6$  functioned as a difference amplifier. Changing  $R_{g3}$  and  $R_{g4}$  on the voltmeter allows one to change the gain. Unfortunately, while our simulation worked, the physical circuit did not. The output of the ammeter had too much noise to be used for feedback.

### E. Level Adjusters

Several different voltage adjusters were required to properly interface with the Arduino which has interface pins for  $[0, 5]$  V PWM write,  $[0, 5]$  V digital write, and  $[0, 5]$  V analog read (with a 10-bit precision analog to digital converter.)

a) *Arduino Digital to Board:* The Arduino can perform digital write with a 5 V high state, and a 0 V low state. On the board the 4066s, and 4028s, had a high state of 5 V and a low state of  $-5$  V, therefore a mapping of  $[0, 5] \rightarrow [-5, 5]$  was necessary. Instead a device that maps  $[0, 5] \rightarrow [5, -5]$  was constructed. This circuit is shown in Figure 5. It is a simple inverting summing circuit.

b) *Arduino PWM to Board:* On the Arduino's "analog write" pins the device outputs a pulse width modulation (PWM) signal. The premise of a PWM signal is to switch between a high and low state so that on average the amount of energy consumed would have been the same if the voltage

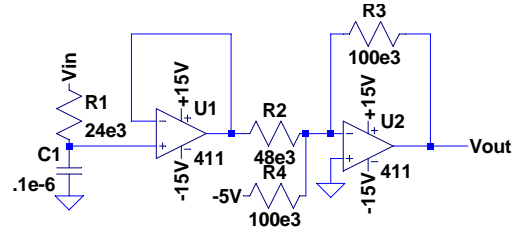


Fig. 6: Level Adjuster that maps PWM  $[0, 5]$  V to  $[-5, 5]$  V.

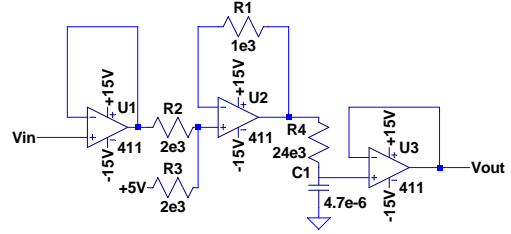


Fig. 7: Level Adjuster that maps  $[0, 5]$  V to  $[-5, 5]$  V.

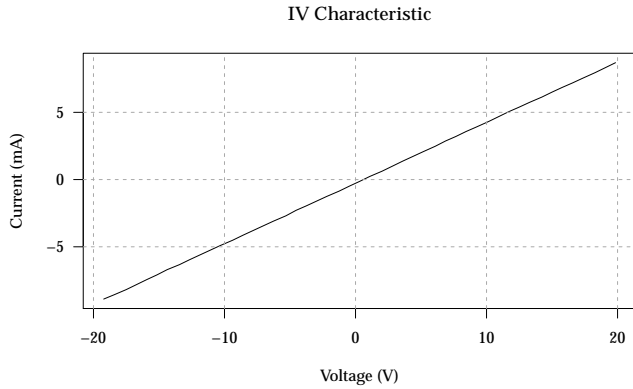
had been at some constant value in between the two states the whole time. This paradigm was not sufficient to act as a control voltage for the VCVS or VCVS. To create an appropriate control voltage of  $[-5, 5]$  V of constant value, the PWM signal was filtered and level adjusted. A low pass filter was used to convert the PWM  $[0, 5]$  V signal to an analog  $[0, 5]$  V. The low pass filter was a first order RC filter, with  $R = 24 \text{ k}\Omega$  and  $C = 0.1 \text{ }\mu\text{F}$ . The Arduino PWM signal operates at 64 KHz, and has 8 bits of precision for modulating the duty cycle from 0 to 100%. The cutoff frequency for the low pass filter was 66 Hz. The output of the filter goes to a unity gain operation amplifier which then goes to an inverting summer. This circuit is shown in Figure 6.

c) *Board to Arduino Analog Read:* The Arduino's analog read pins with 10-bit analog to digital converters operate on the range of  $[0, 5]$  V. The output of the ammeter was mapped from  $[-5, 5]$  to  $[0, 5]$  and put through a first order RC filter to remove spurious oscillations, finally because the Arduino read pins have surprisingly low impedance the signal was put through a unity gain buffer. This circuit is shown in Figure 7.

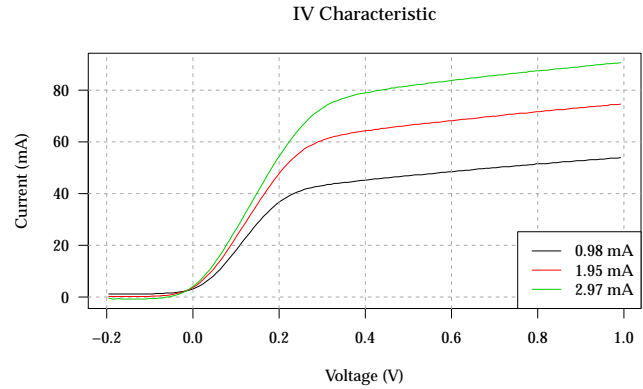
## III. MEASUREMENTS

### A. Resistor

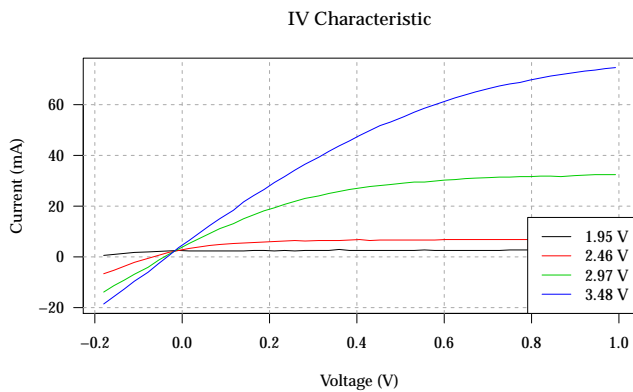
A resistor was characterized with the present curve tracer. A  $2 \text{ k}\Omega$  resistor was placed as the load of the VCVS, and the VCCS was disabled. The ammeter was placed in the  $[-10, 10]$  mA mode, and the VCVS was set to sweep over the full  $[-20, 20]$  V range. The results of this test can be seen in Figure 8a. Although the plot does not quite reach 10 mA at 20 V it comes very close indicating a reasonable performance of the curve tracer. Of notice is a slight DC offset; at 0 V the instrument does not read 0 mA, but it does come very close. These results are within an acceptable tolerance for an instrument constructed out of discrete components.



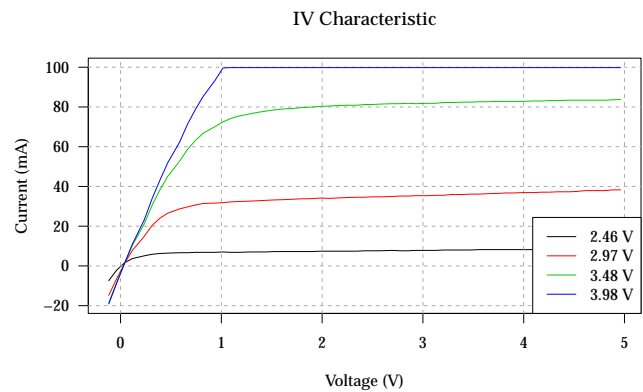
(a)  $2\text{ k}\Omega$  resistor current versus load voltage, over the fully supported voltage range of the VCVS.



(b) N2222 collector current versus collector-emitter voltage for several base currents.



(c) 2N7000 drain current versus drain-source voltage for several gate voltages.



(d) 2N7000 drain current versus drain-source voltage for several gate voltages.

## B. Bipolar Junction Transistor

A N2222 bipolar junction transistor was characterized with the present curve tracer. The VCVS was setup to sweep the collector-emitter voltage of the transistor over the range of  $[-0.2, 1]$  V, this means the VCVS was operating in the finest resolution  $[-1, 1]$  V mode. The ammeter was set to the  $[-100, 100]$  mA mode. These settings provided ample resolution to see the transistor smoothly switch between operating modes, as well as to see the Early effect. Based on the curves in Figure 8b the transistor has a gain parameter of  $\beta \approx 50$  which is within the acceptable range reported on the datasheet.

## C. Field Effect Transistor

A 2N7000 field effect transistor was characterized with the present curve tracer. The VCVS was setup to sweep the drain-source voltage of the transistor over two different ranges. Figure 8c shows the IV characteristic over the gate voltage range of  $[-0.2, 1]$  V. Figure 8d shows the IV characteristic over the gate voltage range of  $[-0.2, 5]$  V. With respect to the VCCS the transistor was placed in parallel with a  $1\text{ k}\Omega$  resistor to provide a controlled gate voltage. The ammeter was placed in the  $[-100, 100]$  mA settings. These curves appear within

the typical range for a 2N7000 as indicated by the datasheet.

## IV. DIFFICULTIES

We encountered a variety of difficulties along the way. Initially our VCVS design required using inverting amplifiers to invert the opamp signal twice. This produced an enormous amount of gain causing our circuit to operate at high power and temperatures. We modified our design by adding the Darlington pair in the push pull and using a PNP transistor for  $Q_2$ .

After constructing the circuit the next difficulty encountered was getting the feedback to work properly. We encountered an enormous amount of noise in very parts of the circuit. Ultimately, to solve this problem we needed to probe various locations with small bypass capacitors, to eliminate high frequency noise.

The next challenge was figuring out how to switch the states on our VCVS and ammeter. We did not want to use relays, so we opted for a semiconductor solution. Eventually we decided on powering the 4028 with  $[-5, 5]$  V and using it to control the 4066. Opamps were used to set the Arduino voltage into the proper range.

Our VCCS also presented much difficulty. While we were able to create the transistor stage and ammeter, the noise was too large to apply feedback with. Despite many attempts to adjust our ammeter circuit we were not able to circumvent this problem and had to switch to a less powerful current source.

We also encountered many difficulties with the Arduino serial read and write. This data stream is not buffered so if two things are written right after each other it creates issues. We ended up having to modify our code by adding many delays.

Finally, we encountered problems with the ammeter scaling. When tuning resistor values for one trace, after switching load the values did not seem to match up. We are not sure what exactly was causing this non-linear behavior but were able to minimize its effect by using large feedback and ammeter resistors.

## V. CONCLUSION

Overall, we were successful in creating a functional curve tracer. From our results, we observed common components we used in class and extracted IV characteristics. From our plots we were also able to approximate beta and other transistor parameters. This project has served as a valuable experience in which we learned a lot not just about the components we traced but the opamps, transistors and control system we used in our design. In the future we hope to apply the skill we've learned to solving other engineering problems.