

Mini-CT a Curve Tracer for the Shack

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There is a public misconception that techies, such as HAM radio enthusiasts, are inherently smart. On the contrary, they are inherently lazy....always looking for a simpler/faster way to get work done. As a good friend N7WB used to say “work is really getting in the way of my hobbies”. Unfortunately, even hobbies can become a burden when your favorite piece of equipment dies. This is when a curve tracer can make the difference between easy and hard.

Sure, a digital multi meter can determine if power is present and where the circuit is open or shorted. But can it peer into the condition of an unknown chip or identify if it is a JFET not a shorted bipolar transistor? Perhaps diode matching is needed for an SWR meter. Maybe a connector is intermittent and it needs verification. All this and more is possible with a curve tracer.

One drawback is that curve tracers, except surplus boat anchors, are expensive. The good news is that with modern microcontrollers and a Windows PC, it is possible to construct a low voltage/current version that can evaluate most of the parts and circuits found in today’s electronics. The “Mini Curve Tracer” is likely to detect damage of virtually all parts except inductors. Before embarking on the project, a little theory and a few examples may entice the skeptics of the claims for this miraculous device.

The basic curve tracer is no more than a Thevenin source that is applied to two nodes of a circuit. The source voltage provides D.C. or A.C. pressure to the circuit while the series resistance limits the available current to the device under test. The applied voltage can be adjusted as not to cause damage to the circuit under test. For example: a laser diode may not tolerate reverse voltage or a FET gate oxide may punch through if the voltage is too high. The series resistor is adjusted to keep the power dissipation in the test device from causing thermal degradation. The curve tracer described in this article is unlikely to damage most devices as the voltage is limited to 15V and the maximum current to about 20mA. Caution should be taken with commercial curve tracers as they can apply thousands of volts and many amperes of current.

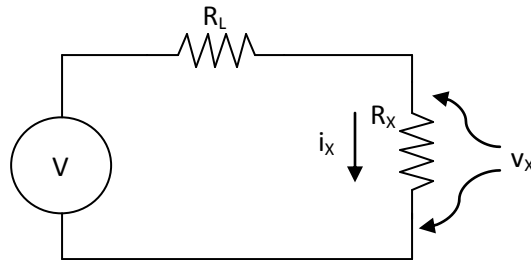
After applying voltage and current to the circuit, some sort of plot or “trace” is needed to represent the reaction of the circuit. Typically, the trace is a voltage-current X-Y plot but there are cases when voltage-voltage or current-current plots might be useful.

With a D.C. source, only a single point of data is generated with the exception of noise adding more points. Direct current measurement is useful for test nodes with high capacitance that can short A.C. signals due to reactance. It is also useful when evaluating very low levels of current as the test signal can be averaged (filtered) to reduce noise.

Alternating current sources provide voltage-current characteristics over a swept voltage range and the resulting trace gives a visual indication of linear and non-linear behavior of the circuit. Parallel and series combinations are visible in semiconductor-resistor circuits. It is possible to observe breakpoints that represent diode forward conduction or avalanche breakdown. Capacitance reactance produces loops that indicate the value of capacitance present. Inductors generally do not have enough reactance at the typical test frequency of 60Hz and they are observed as low resistance circuit elements.

To demonstrate the measurement capability of a curve tracer, three simple test cases will be examined: the resistor, the capacitor and the diode. The resistor is a linear device, the capacitor is a reactive device and the diode is a non-linear device. To characterize these devices, a 60Hz A.C. voltage source with a peak value of V_p is used along with a variable series resistance of R_L .

To predict the voltage and current trace for an unknown resistor R_x , two formulas are needed: Ohm's law and the voltage divider formula. The unknown resistor R_x is attached across the Thevenin voltage source and the rest is simple algebra.

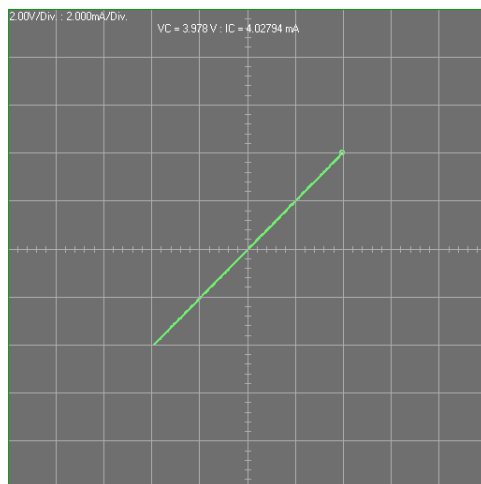


$$V = V_p * \sin \omega t$$

$$v_x = \frac{R_x * V}{R_L + R_x} = \frac{R_x * V_p * \sin \omega t}{R_L + R_x}$$

$$i_x = \frac{V}{R_L + R_x} = \frac{V_p * \sin \omega t}{R_L + R_x}$$

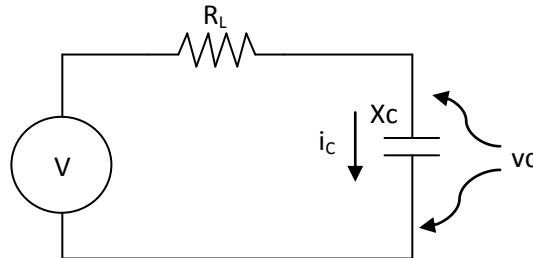
Since the phase is the same for the voltage and current, plotting voltage versus current yields a line with a slope of $i_x/v_x = 1/R_x$ and a zero intercept point. A short appears as a vertical line with infinite slope and an open appears as a horizontal line with zero slope. All other resistor values are slopes in between.



An example of a 1K Ω resistor trace with $V_p = 10V$ and $R_L = 1.5K\Omega$. The applied 10V peak voltage at the 1K Ω resistor is divided by $1K / (1K + 1.5K)$ or 0.4. The slope of the line is $1/1K = 0.001$. At 4V there is 4mA of current. The line is straight indicating the resistance is linear with applied voltage.

Note: For all examples, zero is mid scale.

Predicting the voltage and current trace for an unknown capacitor C_x requires a little calculus and trigonometry. Don't fear the math as it is simply another form of ELI the ICE man. It will be shown that current really does lead voltage by 90 in a capacitor. The same voltage divider formula as with resistors still applies except capacitive reactance $X_C = 1/j\omega C = 1/j2\pi fC$ is substituted for resistance.



$$V = V_p * \sin \omega t$$

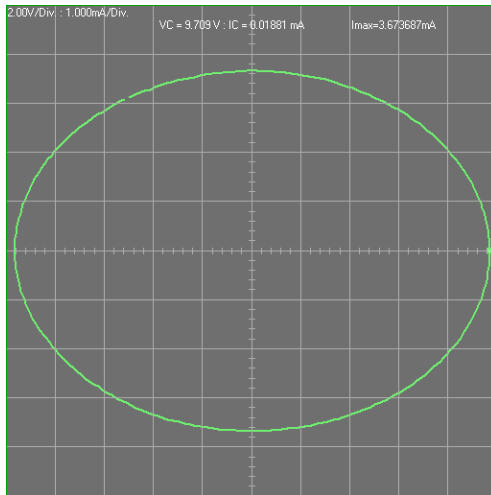
$$v_C = \frac{X_C * V}{R_L + X_C} = \frac{X_C * V_p * \sin \omega t}{R_L + X_C}$$

To simplify the math, only the voltage v_C across the capacitor is considered.

In a capacitor, $i_C = C \frac{\partial v}{\partial t}$ which is capacitance times the change in voltage divided by the change in time. This property can be used to calculate capacitance from a sine wave or even a ramp voltage. If the voltage ramps up at a constant rate, like in a triangle wave, the current becomes the constant value of capacitance times the voltage change per second.

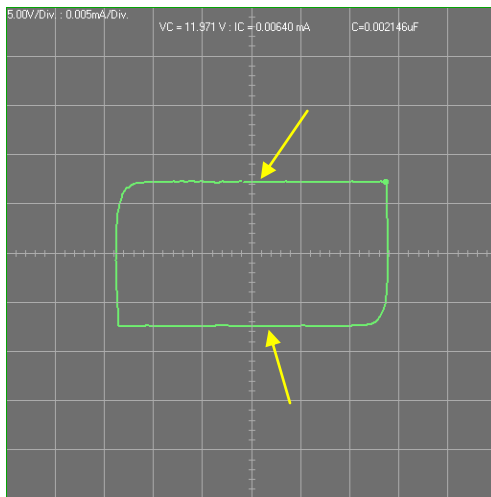
For a sine wave stimulus $i_C = C * V_C \frac{\partial \sin \omega t}{\partial t}$, the solution is: $i_C = C * V_C * \omega * \cos \omega t$ (V_C is the peak capacitor voltage)

The current is a cosine function of the same frequency and therefore it is also a sine function that leads the capacitor voltage by 90 degrees. Note that $C = \frac{i_C}{V_C * \omega * \cos \omega t}$ Since the capacitor current has the form $i_C = I_p \cos \omega t$, to calculate capacitance, simply divide the peak capacitor current by ω then by the peak capacitor voltage. Most test systems use 60Hz as the frequency so $\omega = 2\pi f = 377$ and $C = \frac{I_p}{V_C * 377}$.



With a 1.0uF capacitor, the peak capacitor voltage is 9.71V and the peak capacitor current is 3.67mA. At 60Hz, the capacitance calculates to 1.003uF. The curve tracer program has the ability to perform the capacitance calculation for sine and triangle waves.

The elliptical shape of this trace is the result of the 90 degree phase shift between current and voltage sine waves.



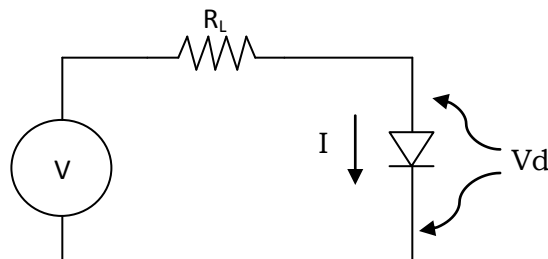
If the series resistor R_L is kept small as compared to the capacitance reactance, then the voltage from a triangle wave source will produce a near constant current mode for the plus and minus slopes. This 0.0022uF capacitor was tested with a 100K Ω series resistor.

Triangular waveforms are useful when measuring gate capacitance in MOS FETs. This topic is covered later.

So far, only linear components have been examined. The most common non-linear device found in electronics is the junction diode. The fact that it is found almost everywhere is one of the reasons the curve tracer is able to diagnose relatively complex semiconductor devices. To understand diodes, it is a good idea to look at mathematical models such as the diode equation.

$$I = I_S (e^{\frac{qV_d}{k\tau}} - 1)$$

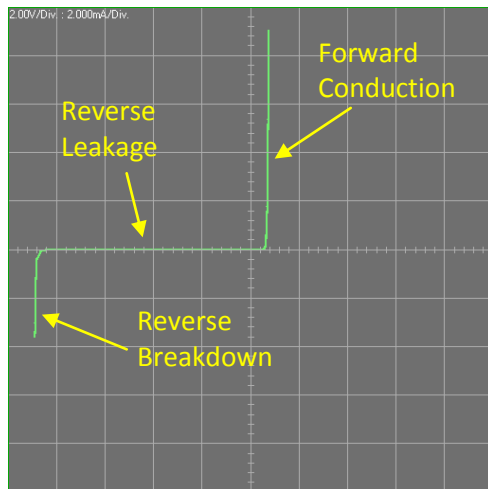
Where: I is the diode current, V_d is the diode voltage, q is the charge for an electron, k is Boltzman's constant, τ is the temperature in degrees Kelvin and I_S is the leakage current. It is very important to note that leakage current is not a constant. It varies logarithmically with temperature. Evaluating the voltage/current characteristic over temperature requires addition of this temperature dependence to the model.



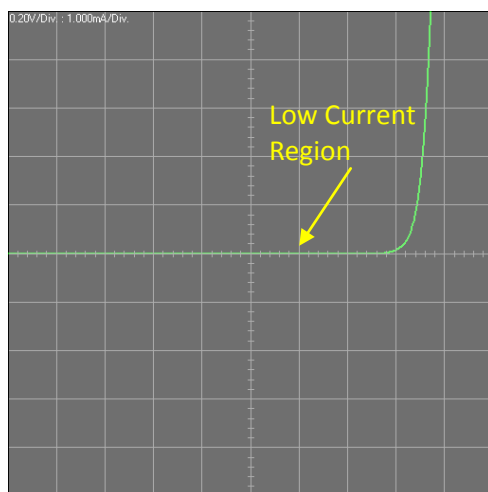
At room temperature $I = I_S (e^{\frac{V_d}{0.026}} - 1)$ and for forward biased circuits $V_d \approx 0.026 * \ln(\frac{I}{I_S})$

In reversed biased circuits $I \approx -I_S$ and a constant leakage current is expected for reverse voltages until Zener or avalanche breakdown occurs. At the reverse breakdown voltage, current increases rapidly with slight increases in voltage. This is why Zener reference circuits require current limiting resistors and power rectifiers fail when the peak inverse voltage rating is exceeded.

The model shows that diode current will increase logarithmically with applied forward voltage, it is a constant value over a limited reverse voltage range and it has a maximum voltage it can block in the reverse direction before high current flows.



The emitter to base junction of a bipolar transistor is an ideal diode for displaying the three major operating regions of a junction diode.



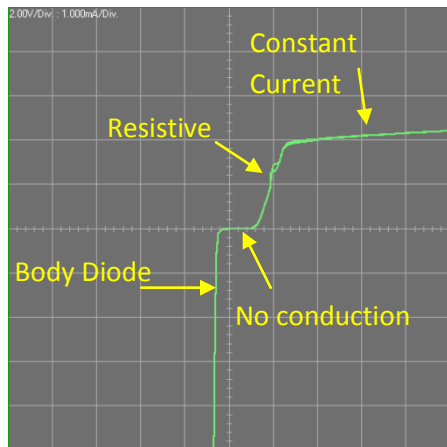
A closer look at the forward conduction characteristic shows most of the operation is between 0.6 and 0.8V. A non-zero or resistive slope in the low current region can indicate that the junction has been damaged. It is best to compare to a known good device

This is a silicon junction diode. Other diode types such as germanium and Schottky barrier diodes operate at lower forward voltages.

Earlier it was stated that diodes are found almost everywhere. This structure is inherent in integrated circuits and it is the key to identifying damaged circuits. It provides a conduction path to check for open or high resistance circuits. When other device structures such as gate oxide (a very small low leakage capacitor) is damaged, a leaky diode characteristic may be present. Diodes have a negative temperature coefficient for forward voltage at a constant current. It changes about 2mV/°C. So, unused pins on a device are potentially a temperature probe.

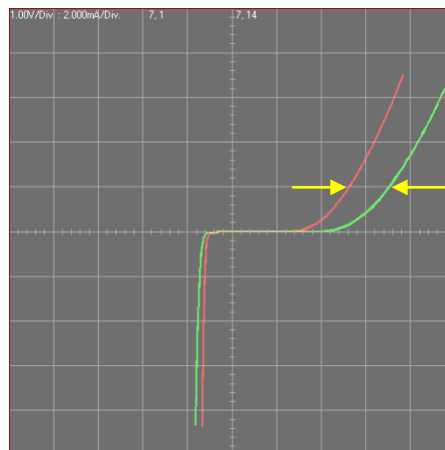
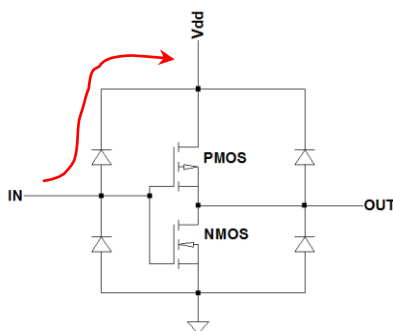
When evaluating component level integrated circuits, the power supply pins can provide information about the condition of the device. Normally, reversing polarity on supply pins will result in a diode curve. Caution is needed on some large scale low voltage logic devices as leakage is so high that good devices may appear as a resistance. In the normal forward voltage direction, there are several typical technology dependent curves.

Analog components, such as operational amplifiers, use internal current sources to bias the device. When the supply voltage is increased, there is a low voltage zero current break point followed by a resistive current increase and finally a relatively flat constant current characteristic.



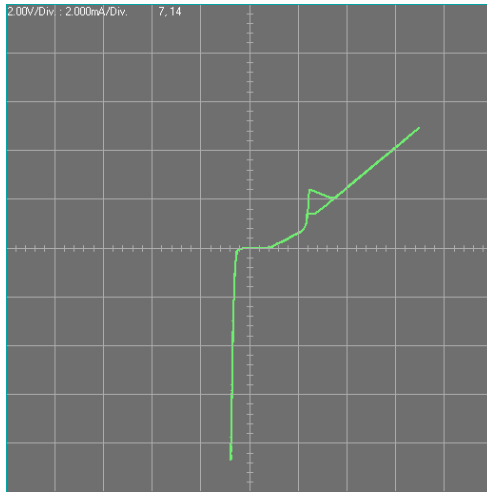
Vcc to ground on an LF356 starts to conduct around 1.2V and it goes into the constant current mode around 2.5V.

Complementary metal oxide semiconductor (CMOS) logic devices will have a low voltage region of low current followed by a break point where the current increases rapidly. This current increase occurs when gate threshold voltages for the complementary N-channel and P-channel FETs is reached. Both FETs turn on and the current increases. The trip point voltage may float around and push out to a higher value. Diode structures are present on both inputs and outputs. When testing I/O pins to ground, if the input voltage swing is high enough, it will power up the supply and a similar break point will be observed. Normally, I/O pins are only small capacitors for positive voltages and no current should flow to ground or the positive supply. To test I/O pins for leakage, keep the curve tracer peak voltage level below the supply turn on threshold.

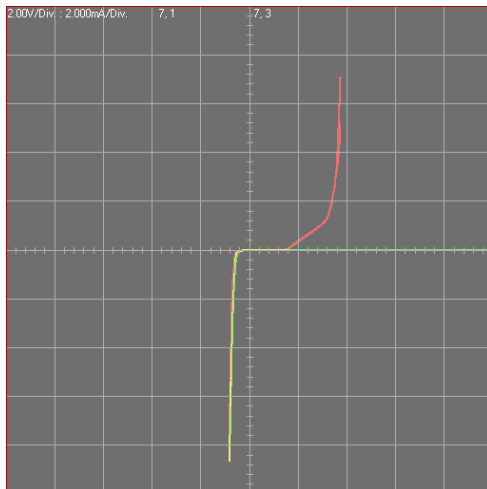


The red trace is Vdd to ground on a 74HC14 hex inverter. The green trace is input pin-1 to ground. Note the turn on voltage is a little higher due to the path through the diode. Inputs could be checked for leakage up to 1.5V.

Logic devices that use bipolar transistors such as LS TTL (low power Schottky transistor-transistor logic), are resistively biased. From supply to ground, a reverse bias body diode is present. In the forward direction, the supply has a low voltage breakpoint then a resistive slope as the supply voltage increases. Inputs to simple gates are often the emitter of an NPN transistor. With the supply pin unconnected, the input blocks current flow as it is a reverse biased diode. Outputs have a push-pull transistor structure that will turn on when swept with respect to ground.



Vcc to ground for a 74LS00 quad dual input NAND gate. After the supply exceeds a volt, the current increases resistively. A small hysteresis loop is present where internal circuits are biased on and off. The device would likely operate with Vcc 4V to 6V but with shifts in the logic voltages and timing.

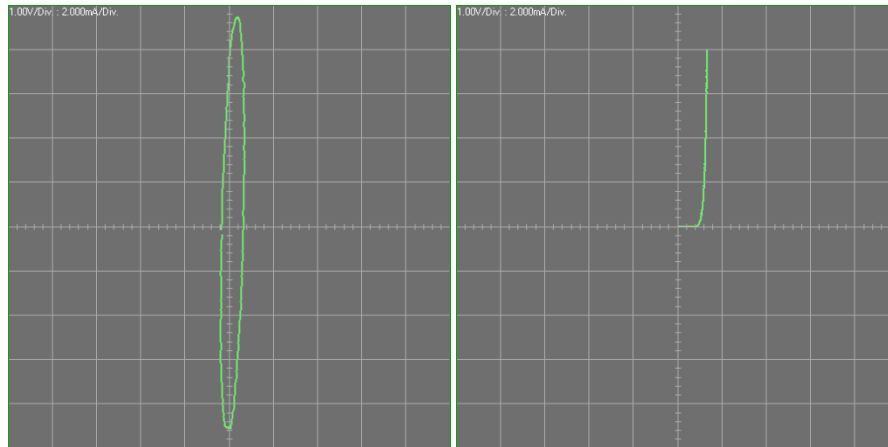


The input to ground for the low power Schottky TTL gate, green trace, appears as a diode. An unpowered device would not affect the circuit attached to the gate. The output to ground, red trace, has several break points in the curve. Inputs and outputs of an unknown device could be identified by testing each pin to ground.

Only a few of the pin-to-pin characteristic curve combinations have been examined. It should be apparent that with a little knowledge of the device internal construction, the device technology is identifiable. Comparing pins of two identical parts with respect to ground or the positive supply can identify damage if one of the parts good. If no comparison part is available, devices with multiple inputs and outputs provide comparison pins. The supply to ground characteristic will also give clues to whether the device is damaged.

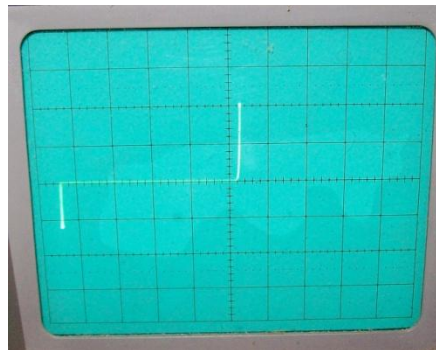
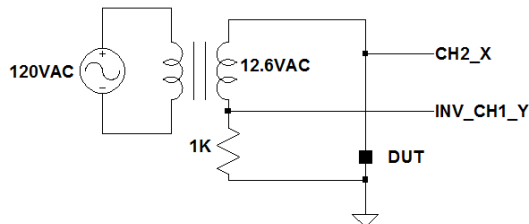
Before embarking on in-circuit and transistor testing, a few curve tracer circuits will be examined. The curve tracer requires three parts: 1) A voltage source and resistor, 2) Instrumentation to measure current and voltage and 3) Numerical or graphical display. Numerical displays are not as convenient as

graphical types as data must be recorded then plotted. However, under some conditions as with parallel capacitance, acquiring of single data points after charging intervals may be the only way to obtain a curve.



The trace on the left is a diode in parallel with 100uF. Swept at 60Hz, the diode curve is swamped by the capacitor loop. The right trace is the same circuit but with sampling of each point at 100ms intervals.

The simplest curve tracer is a fixed AC source using a small power transformer and the series resistor as the current measurement device. Three parts are needed: a transformer, a resistor and a dual trace oscilloscope. Winding capacitance limits the low current test capability since it can contribute several microamps of current. If a variable source is needed, attach a variac autotransformer to the 120VAC line in.



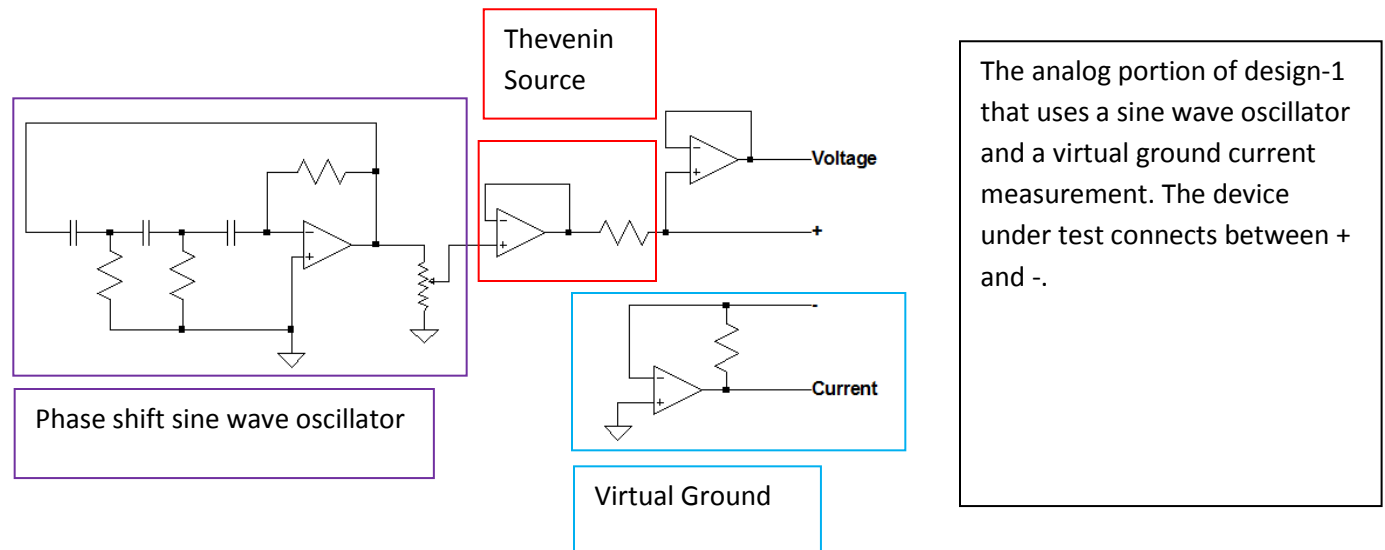
Set the oscilloscope to the X-Y mode and set channel-1 to inverted. With channel-1 at 1V/Div. the current is 1mA/Div.

Most commercial curve tracers use a form similar to circuit shown above. The transformer has more taps to allow testing to the KV range and a floating current sensor is used to measure current in the pA range. The design goal is to construct a low voltage and low current curve tracer. This allows construction of a voltage source from operational amplifiers. The second design goal is to use a personal computer to acquire the voltage and current data then graphically display it. Two types of analog front ends will be explored.

The first type of design examined uses a non-synchronous voltage source, i.e. a free running oscillator, with a virtual ground current sink. The oscillator may be a simple sine wave generator or a function generator. A simple single operational amplifier sine wave generator is possible with a phase shift oscillator. A more versatile oscillator can use an ICL8038 function generator chip with both sine and triangle wave outputs.

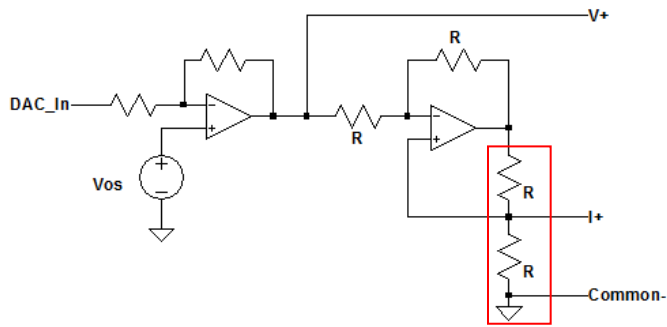
The virtual ground current sink is used to force the negative terminal node to zero volts. The current required to zero the negative terminal node is the loop current in the Thevenin circuit. Thus, the amplifier output voltage divided by the feedback resistor is the current measurement.

The disadvantages of the first design are that the negative terminal is not ground and the sampling points are random between identical traces. Also, the virtual ground is a feedback loop and it can become unstable in some instances. The advantage of the design is that it is simple to acquire data. The Voltage and Current outputs are voltages that need only scaling and an offset to be easily digitized by small controllers such as the Arduino Due.

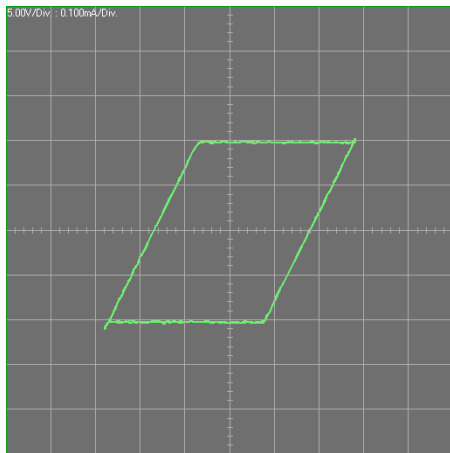


The second curve tracer design is a synchronous voltage source with a differential current measurement of the Thevenin resistor. The voltage waveform is generated with a digital to analog converter (DAC) and a lookup table. Data is sampled synchronously with each voltage step change.

The disadvantages are the step size is discrete and limited by sampling rate plus DAC resolution. The differential current measurement method can exceed the common mode limit of the amplifier resulting in errors. The advantage is that the wave shape can be arbitrary. With proper micro controller selection, both the DAC function for waveform generation and the ADC functions for sampling voltage and current are built in. The only external components needed are for analog level scaling, power and computer I/O.

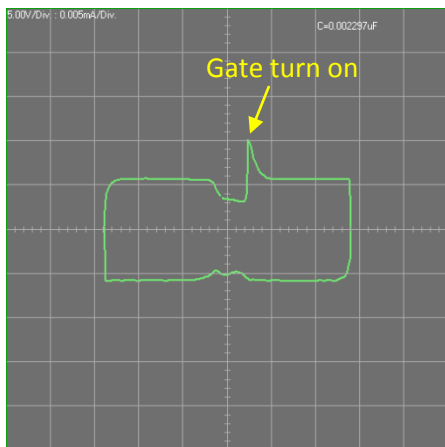


With a voltage to current converter, DAC generated voltages are changed to currents flowing to ground. Note the voltage divider in the leg of the current output. This limits the voltage range current is generated over.



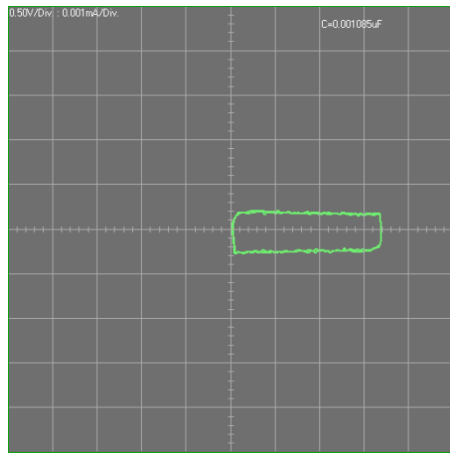
This loop is a trace (current is inverted) of a current source capable of $\pm 200\mu\text{A}$. At $+i_{\text{max}}$, it can operate between -14V and $+4\text{V}$. At $-i_{\text{max}}$, it can operate -4V to $+14\text{V}$. As current is reduced, the operating voltage range shifts. At zero, it is $\pm 9\text{V}$.

Before testing three pin devices with a step generator, start with a two pin test. A lot of information can be obtained, especially for in-circuit parts. With power MOSFET devices it is possible to measure gate to source capacitance, measure gate to source/drain capacitance, measure gate turn on voltage and to identify if the source to drain is shorted. The measurement only requires the source and gate pins. If the part is in-circuit and the impedance connected to the gate is high, no pin lifting is needed. Otherwise, separate the gate from the circuit and trace gate to source.

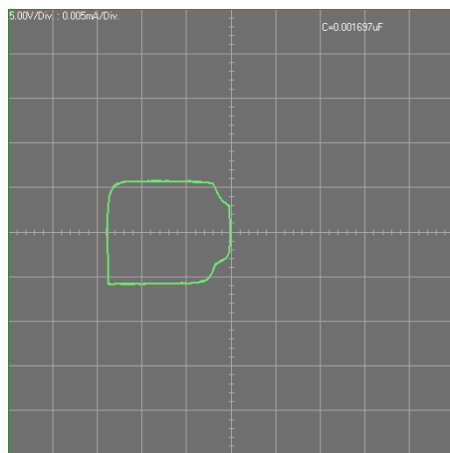


Measuring source to gate on an IRF530 shows the gate voltage threshold is 2.5V . The specification for this device is between 2 and 4 volts.

A triangle waveform is applied to form a square loop. Once the gate turn on voltage is reached, the capacitance loop is for gate to source plus gate to drain. Reverse bias is same as connection is through the body diode. If the source to drain was damaged, the loop would appear resistive or shorted.

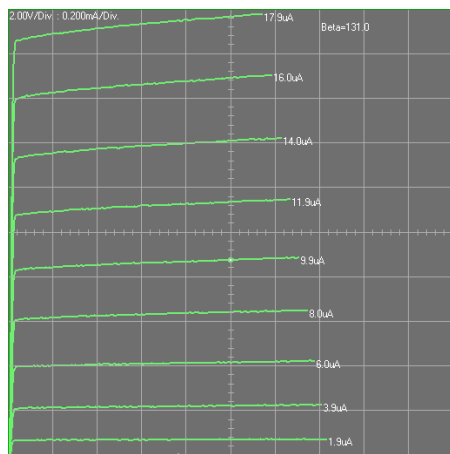


Using only a positive triangle wave and keeping the peak voltage below the gate turn on threshold allows measurement of the gate to source capacitance which is 1085pF.

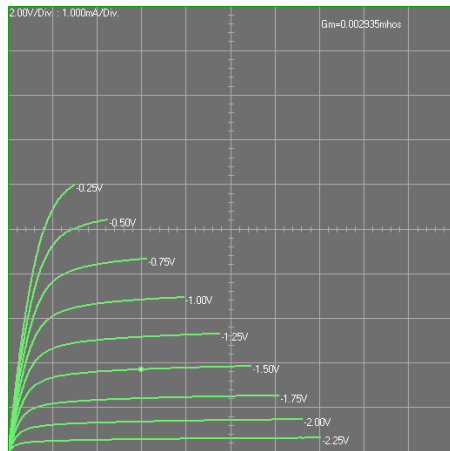


Using only a negative triangle wave to eliminate the gate turn on spike gives a more accurate estimate of source/drain to gate capacitance at 1697pF.

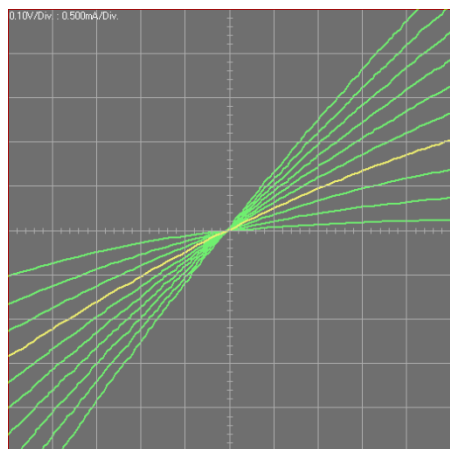
The capacitance values will vary from the manufacturer specifications. Drain to source voltage is generally not zero for the manufacturer typical values.



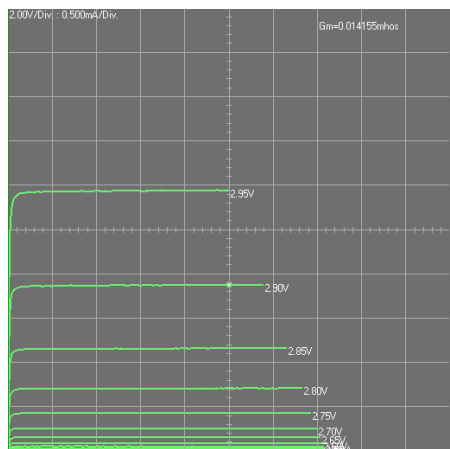
Current step generation is used to measure current gain for bipolar transistors. Base current steps of 2uA produced this family of curves. Note that at the lower current levels there is less gain (closer spaced curves).



Junction FETs are pinched off source to drain by applying a reverse bias to the gate. The FET is at full conduction with no voltage. Stepping the voltage negative cuts of the current flow.



If a junction FET source to drain voltage is kept small, it is possible to use the device as a voltage controlled resistor for AC signals.



Most power MOSFETs conduct by forming a channel source to drain (enhancement mode). Voltage applied to the gate to source creates the channel. The drain current increases rapidly once the gate threshold voltage is exceeded. MOSFETs have a very non-linear response to voltage and often it is best to generate one or two curves at the point of interest or to use non-linear gate voltage steps.

All of the above devices behave as constant current sources when the potential across the device is more than a couple volts. The flatter the slope, the closer the device is to an ideal current source. In fact, current regulator diodes are JFET transistors with the source and gate tied together. The voltage drop developed internally generates a self limiting pinch off current. Even tetrodes and pentodes have a current source characteristic. In the current source mode, the device has a high impedance. Some device are not controlled current sources. The triode, shown below, acts more like a voltage controlled resistor and its impedance is dependent on the grid to cathode voltage.

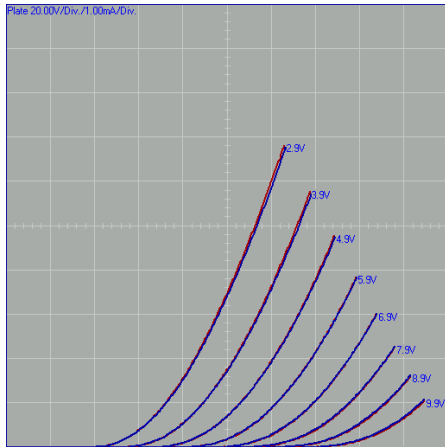
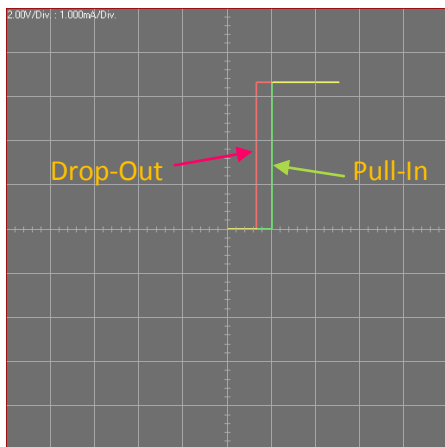
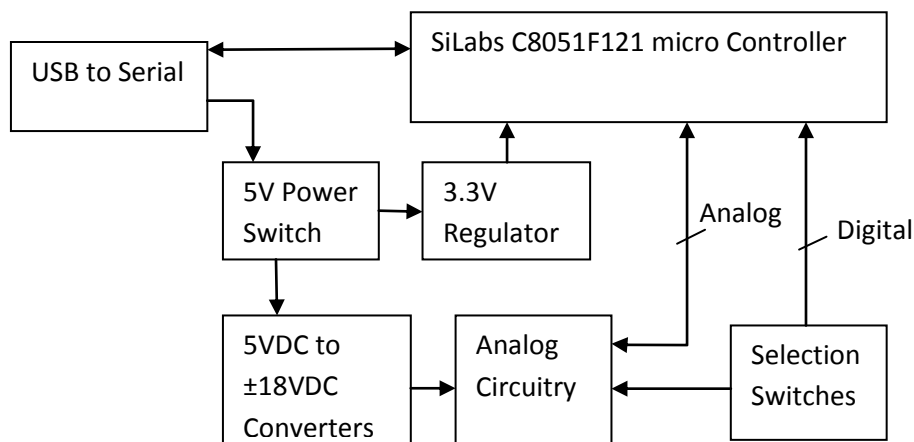


Plate to cathode sweeps of a 12AX7 dual triode using a special high voltage curve tracer. Note the slopes of the curves are resistive and not flat as in the semiconductor devices.

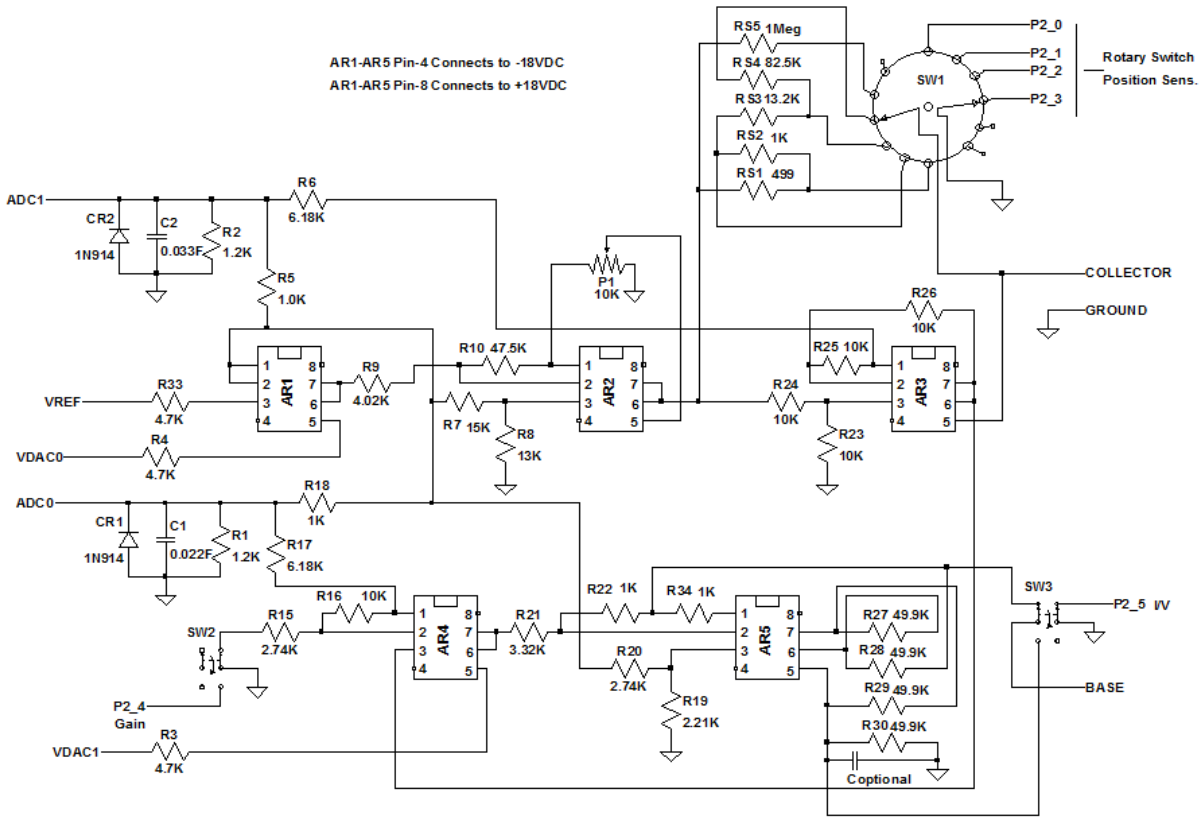


Sweeping the coil of a reed relay while monitoring the contacts is another way the step generator can be used to test a device. The pull-in and drop-out voltages are easily observed in this hysteresis loop.

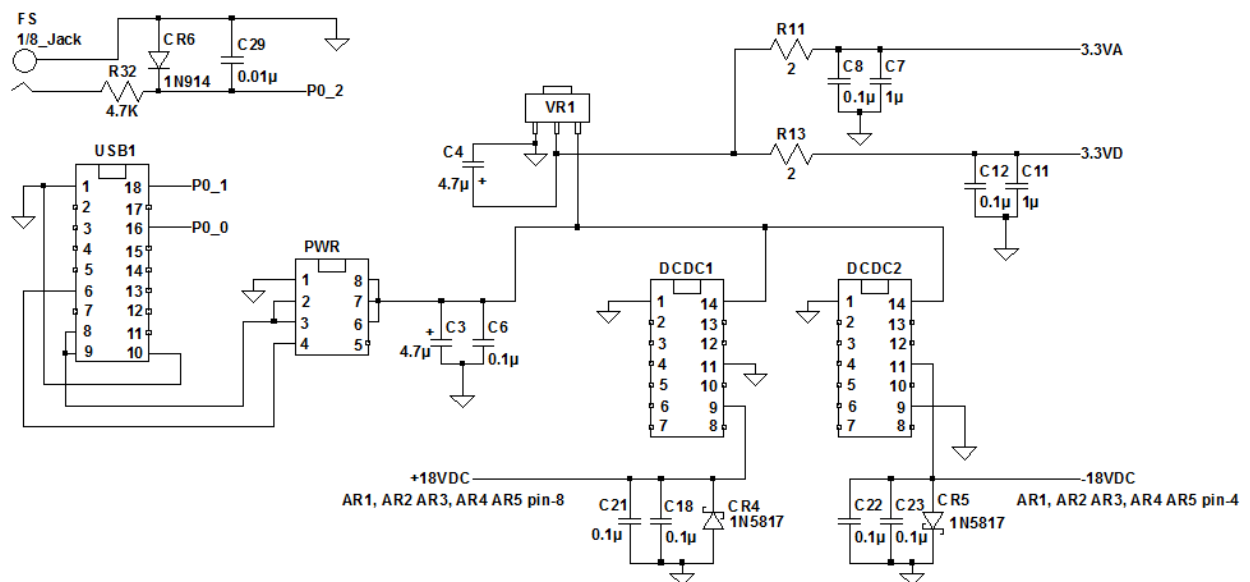
The above examples show the versatility of adding a step generator to a curve tracer. To put together a full test system, four basic parts are needed: 1) A data communications interface, 2) Supply voltage and regulation, and 3) Analog signal processing and 4) Digital signal processing. A simplified diagram of the test system is shown below.



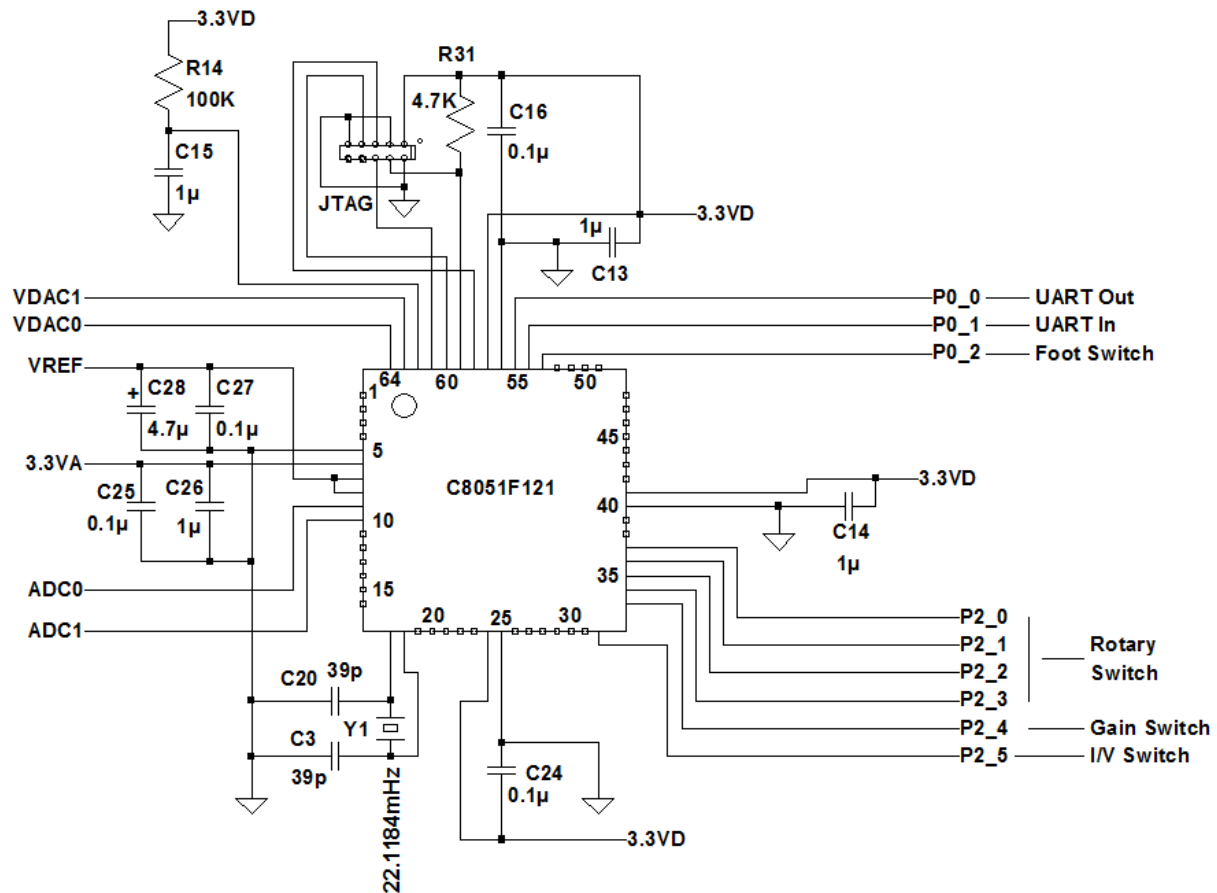
A schematic diagram of the analog processing block:



A schematic diagram of the communications interface and supply voltage generation:



A schematic diagram of the digital processor:

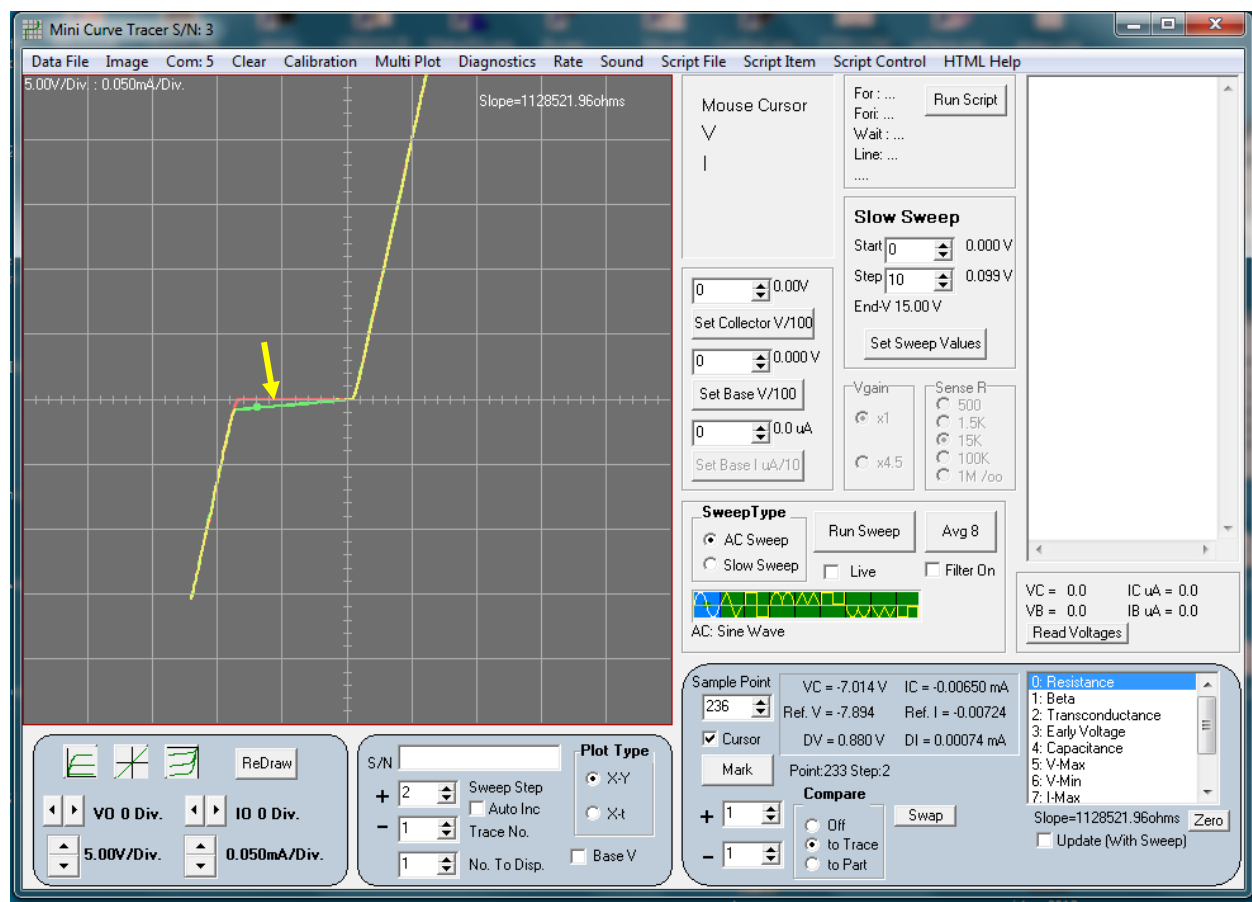


As with most modern equipment, the hardware is of little use without software to drive it and software to interface with the user. The software that goes into the C8051F121 device is little more than a sequential data acquisition program. It receives serial commands and returns voltage and current data. The user interface was designed with trouble shooting in mind. Traces are stored in the interface program and they may be saved and retrieved from a data file. The capability to compare any two traces, display multiple traces at once and to compare traces between two devices is essential in identifying circuit damage.

Note that comparison is the key when trouble shooting with a curve tracer. Comparison can be knowledge of what the device curve should look like. It can be comparison between two identical circuit nodes on the same card. It can be comparison between two parts or two circuit cards. There are some cases when two identical good circuits behave slightly different but this is generally the exception. In-circuit diagnosis requires comparison as there may be many circuit branches attached to the node under test.

Once a difference is identified, there are two general conditions that might exist. The first is leakage or shorting and the second is high resistance or an open. The slope of the curve or missing break points helps to identify the case. The cause is then investigated. Visual examination for physical damage is the first step. Leakage may be caused by bridging particles or moisture induced corrosion. Galvanic corrosion is a special case of leakage and it often produces a measurable potential or current if still wet. Open circuits are often related to cracked solder joints, wire fatigue, or corrosion. Catastrophic failure may result in high current fusing of conductors. These conductors may be small bond wires buried in a circuit chip. Plastic parts often bulge or have surface fissures caused by internal pressure after the wire fuses.

If no visible damage is present, then more traditional trouble shooting methods may be required. Anomalies detected by the curve tracer will provide a starting point for testing circuit function.



The compare trace function allows detecting a difference of a few micro amps between two circuits. If the two traces were identical, they would appear as a single yellow trace. The traces separate into red and green when they do not match.

Due to the many required disciplines, this is not a beginner's project but anyone with a little experience with computers and with building op amp circuits should be able to tackle the Mini-CT. There are a couple ways to approach building this project. The analog, power and communications interface can be constructed on a bread board. A C8051F120 proto board and USB debug programmer may be purchased from Mouser P/N 634-C8051F120DK and attached to the bread board. This is how the first prototype of the curve tracer was constructed. To those that would like a more compact package, a CAD file for PCB Express is available for clubs or schools that want to purchase enough cards to make the production run cost effective. The USB debug programmer is still required to upload the processor firmware. Instructions are available for the printed circuit board build along with a bill of materials.

Both the C8051F121 processor firmware and a Windows® curve tracer application are available at no cost. However, keep in mind that experience with microcontroller programming interfaces is required to upload the program to the microcontroller. The USB to serial converter also requires driver set up and configuration of the USB device using the FTDI Mprog.exe program.

For those that are just curious, the curve tracer application has several sample tracers that can be loaded and viewed.