Why Build Things Small?: Shrinking the Electronic Circuit

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I. Introduction

Why build things small? As you will learn throughout this course there are several reasons for doing so both for the sake of technology and of science. Nanoscale science and engineering, the fabrication and analysis of objects, devices, and systems on the length scale of 1 to 100 nm, is at the intersection of chemistry, physics, biology, and engineering. It is a field rich with opportunities where many new and exciting discoveries are being made.

Consumer electronics is currently a major economic driving force for building things smaller. Basically, smaller circuits are more compact, run faster, and are cheaper to manufacture. In this lab, you will take a look at two particular electronic circuits: the crystal radio (one of the earliest circuits to use a semiconductor device, popular in the 1920’s and 1930’s) and the Pentium processor (an integrated circuit that appeared on the market in 1993). By comparing these two circuits from different eras, some of the advantages of building smaller circuit elements will be illustrated. Appendix A contains more information about the historical development of the electronics industry and Appendix B contains an explanation of how a crystal radio works.

Photolithography is the technique that enables the manufacture of small circuits. It is a parallel fabrication process that uses light and photosensitive chemicals to transfer a pattern from a mask to a substrate. As engineers push the limits of this technique to smaller length scales, circuits become more powerful. You will learn more about photolithographic techniques in the following two labs. You will also gain experience in working with electronics that will be useful in subsequent experiments.

II. Procedure

Crystal Radio

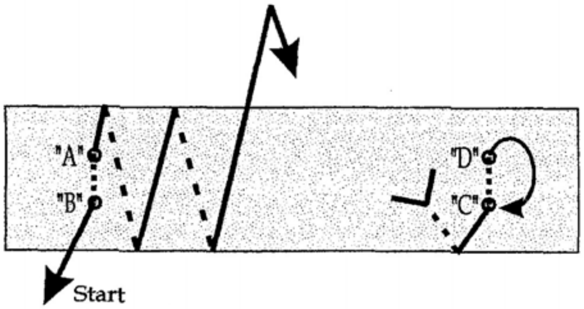


Figure 1

A. Make the coil:

1. Thread an end of the magnet wire through hole "A" of the PVC tube (see Fig. 1) and then back through hole "B." Leave 4" of wire coming out of hole "B."
2. Neatly wind the magnet wire as shown in Fig. 1 so that there are no overlapping wires and each turn is touching the previous one. This is critical!
3. When you reach hole "C," insert the magnet wire, feed back through hole "D" and then through hole "C" again as shown in Fig. 1.
4. Brush a thin coat of Q-dope on the outside of the coil. Clip the excess wire from the end of coil with holes "C" and "D." Set the coil aside to dry.

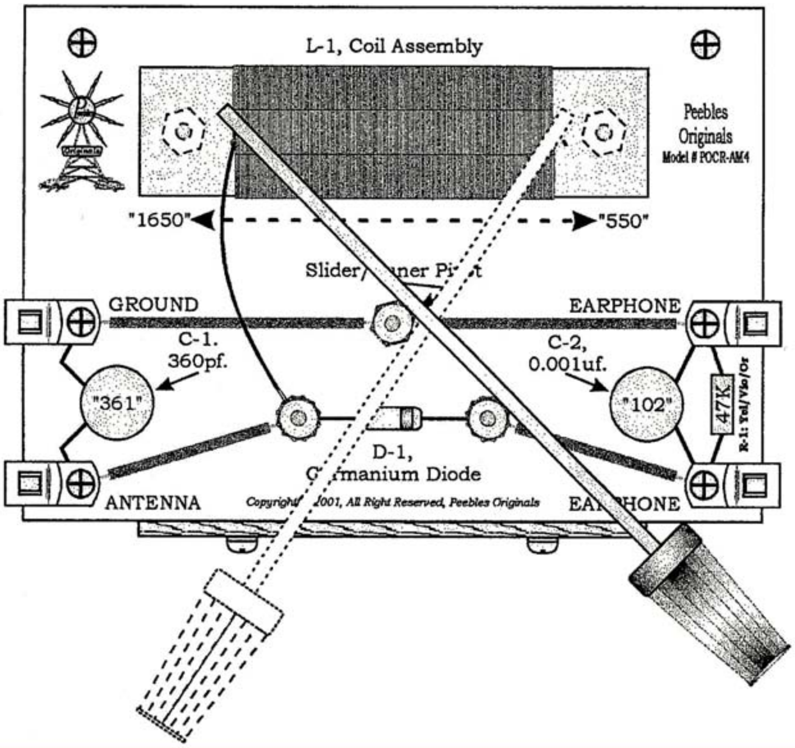


Figure 2

B. Solder the circuit:

1. The circuit layout in Fig. 2 shows where to attach wires and circuit components. Note the orientation of the diode (indicated by the dark band). See Appendix C for an explanation of the encoding for resistor and capacitor values.
2. For each circuit element, thread the end of each wire through the small hole of a solder lug and wrap the wire around to form mechanically stable connection. For wires, use a wire stripper to first remove insulation from each end before attaching to lugs.
3. Solder each joint by first heating both surfaces with a hot iron. Then touch solder on the heated area and continue to heat with the iron until the solder flows into the joint. Use only as much solder as needed.
4. Clip any excess wire with a diagonal cutter after the solder hardens.
5. Attach all circuit elements as shown except for the coil, ground and antenna. Attach the earphone where labeled.

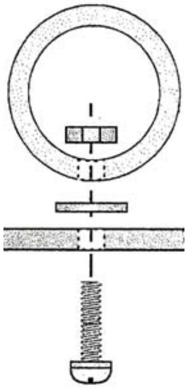


Figure 3

C. Attach the coil and slider rod:

1. When the coating on the coil is completely dry, bolt it securely to the board as shown in Figs. 2 and 3.
2. Using the emory cloth, remove the insulation from the end of the magnet wire from the coil. Solder a lug to the unattached the wire where indicated in Fig. 2.
3. Turn the nut attached to the copper slider rod onto the pivot screw, as shown in Fig. 2. Stop when the rod moves snugly across the top of the coil. Check that the pivot screw remains rigidly mounted to the board.
4. Note where the rod scrapes the top of the coil. Using the emory cloth, completely remove the coil coating and the magnet wire insulation in this area so the slider rod can make good electrical contact over the entire coil.

D. Testing the crystal radio circuit (SKIP this part if there is a thunderstorm):

1. Take your circuit to the antenna drop and attach the antenna and ground wires where indicated in Fig. 2.
2. Place the earphone in your ear and slowly move the slider rod across the entire width of the coil. Stop when you have tuned in a radio station.
3. If you fail to hear anything across the entire coil, hit the earphone on a hard surface and try again. If you still fail to hear anything, check your circuit.
4. Once you have located a station, attach leads from an oscilloscope to the "antenna" and "ground" terminals of the radio. Can you observe the amplitude modulation (AM) of the carrier frequency?
5. Measure the diameter of one of the wires in your circuit. Use a scale loupe to get an accurate measurement.

Pentium Integrated Circuit

A. Calibrate Etched Reticule on Microscope Eyepiece:

1. If necessary, turn on the power for the light source on the optical microscope, located at its base near the power cord. Adjust the light setting using the sliding switch.
2. Place the calibration slide under the microscope and focus on the metric crossbar at lowest magnification, 50X (the eyepiece is 10X and the objective is 5X). Align one arm of the crossbar the etched reticule on the microscope eyepiece.
3. Increase magnification by switching to higher power objective lenses. Refocus at each step until you reach highest magnification, 500X.
4. Record the number of marks of the etched reticule that correspond to a particular distance on the calibration slide. Use this information to calibrate the etched reticule.

B. Image the circuit:

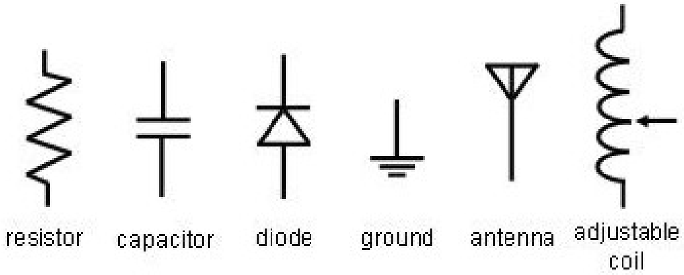
1. Return to the lowest power (5X) objective lens of the microscope. Place the Pentium chip under the lens and focus the image. Increase magnification and refocus at each step until you reach highest magnification, 500X.
2. Locate the narrowest interconnects you can find (interconnects are long metal strips that connect components in an integrated circuit, analogous to wires).
3. Measure the width of the narrowest interconnects using the eyepiece reticule and record this measurement.

C. Print your image:

1. If necessary, start the software for the digital camera by double clicking on the "PixeLink" icon on the desktop. A realtime image should appear as well as a control panel.
2. Click on the "Save As..." button at the bottom left of the control panel and enter the file name for your image.
3. Click the "Capture" button on bottom right of the control panel to save your image.
4. To print your image, open the saved image by double clicking on the file, choose "Print..." and select the Tektronix Phaser 740.
5. Label your image with object, magnification, date, and your name. Print one image for each person in your group.

III. Analysis

1. Draw a circuit diagram for your crystal radio, using appropriate symbols for components and labeling values where possible. Show connections with straight lines that meet at right angles and make the diagram as simple as possible.



2. Indicate the wire ("interconnect") you measured on the image of the chip and attach it to your report. What is the ratio of the width of a wire in the crystal radio to the width of an interconnect on the Pentium chip?
3. Using the ratio from question 2 as an estimate for linear scaling between the two circuits, calculate the area scaling ratio (hint: if the length of a side of a square triples, how does the area increase).
4. The Pentium chip contains 3.1 million transistors, which comprise most of the elements in the circuit. What is the ratio in the number of components in the Pentium chip to that of the crystal radio (not including wires)? How does this compare with the area scaling factor computed in question 3 (order of magnitude)?
5. If the Pentium chip were built of components the size of those in the crystal radio, how large an area would it cover? What advantage does a circuit with small components offer over one with components large enough to be assembled by hand?
6. Estimate how much time you spent per component for the circuit you assembled. If it took the same amount of time to solder each transistor in the Pentium circuit, how long would it take one person to assemble? What advantage does an integrated circuit offer over one with discrete components that must be assembled by hand?
7. Given that the crystal radio kit costs $14.95 and the processor chip is ~$500, calculate the cost per component for each circuit. What additional advantage does an integrated circuit offer over one with discrete components?

APPENDIX A

Brief History of Solid State Electronics

In 1906 Lee de Forrest (1873-1961) invented the vacuum tube. From 1906-1956, the vacuum tube was the mainstay of electronic circuits. The tube that de Forrest invented, called the triode, has three elements, a cathode which emits electrons, a plate (anode) which collects the electrons, and a highly transparent mesh electrode (grid) placed between the cathode and anode. The vacuum tube was an electronic switch, with the grid voltage controlling the current through the tube. For the vacuum tube to operate, the cathode-grid-plate structure is placed into a glass envelope from which air is evacuated to a pressure one billionth or less of that of standard atmospheric pressure. Since vacuum tubes, transformers, and discrete electronic components were all fairly bulky, consumer electronics was limited to radio, TV sets, and HI FI systems. All of this equipment was large, heavy, and consumed a lot of power, on the order of 200 Watts.

In the early days of commercial radio, when vacuum tube radio receivers were still fairly expensive, crystal set receivers were used by a large segment of the listening public. The crystals used in such sets were naturally occurring crystals of semiconducting material: galena (iron sulphide), fool's gold (iron pyrite), silicon, and germanium. The crystals were usually set in a small cup of solder and a thin wire, called a "cat's whisker" was moved around the crystal until a sensitive spot was found which would exhibit the required rectifying action. Rectification is the ability to pass current of only one polarity, i.e. one direction. Today such crystals are called point-contact diodes. Due to the erratic and unpredictable behavior of the crystal diodes, they were not used in the manufacture of radios. However, crystal radios are cheap and easy to build. Therefore, many people in the '20s and '30s who could not afford to buy radios built crystal sets. The large number of listeners using crystal radios contributed to the rapid expansion of radio stations in the '30s.

In the late 1930s Russell Ohl, a staff scientist at Bell Laboratories, became fascinated by the erratic behavior of silicon and its then poorly understood ability to rectify alternating currents. He became convinced that the erratic behavior was due to impurities in the silicon, and not to any intrinsic property of silicon itself. By 1939 he succeeded in making crystals that were 99.8 % pure, and sure enough, the rectifying behavior of such pure crystals was much more reproducible. Ohl also discovered that there are two types of silicon, One type has a surplus of current carrying electrons (n-type) and the other a deficit (p-type). He also showed that this property was due to impurities in silicon and that it could be produced in the laboratory by introducing small amounts of certain atoms into the material. The introduction of impurities is called *doping*. Because of Ohl's work on silicon just prior to WW II, the Allies had much better crystal diodes than the Axis, and hence more sensitive radar receivers. Ohl's work on silicon however had far greater consequences in that it opened up Bell Laboratories to the idea that silicon diodes could replace vacuum tubes.

Walter H. Brattain (1902-1987), also at Bell Laboratories, had been aware of Ohl's efforts to purify silicon, as well as his pioneering work on what today we call solar cells.

Brattain was investigating how electrons behave on the surface of a semiconductor (Why does the "cat's whisker work only on certain parts of the crystal?). Brattain's work with silicon, and later with germanium, led to the invention of the point-contact-transistor with John Bardeen (1908-1991) and William Shockley (1910-1989). The most amazing thing was that a small piece of silicon, gold, and plastic was all that was needed to construct the first solid state amplifier in December of 1947.

By 1958 the transistor was commonplace. The early point-junction-transistors were replaced by so called pn-junctions, and these could be fabricated easily and reliably. Transistors started to replace vacuum tubes in all electronics and the concept of making electronics small was born. However, transistors could not be made too small, since ultimately they had to be connected to wires and other electronic components. The size of transistors manufactured was essentially determined by how easily they could be handled and inserted into circuits by workers. At this point, people started to think about making the whole circuit, transistors, wires, resistors, capacitors, and inductors all in one package. If this could be done, then miniature circuits could be made, perhaps in only one operation.

The idea occurred to Jack Kilby at Texas Instruments in the summer of 1958. People knew how to make transistors small, but the idea of making resistors and capacitors out of semiconductors had not been attempted. By mid September, Kilby had built a working circuit the size of a pencil point. Six months later, Texas Instruments filed a patent for the first "Solid Circuit". The idea that a whole circuit could be constructed on a small chip occurred independently and almost simultaneously to Robert Noyce, working at Fairchild Semiconductor, a company that was just starting up. In this way the integrated circuit was born.

Much of what we think of now as nanotechnology started with the invention of the transistor in 1947 and the integrated circuit in 1958. Rapid progress was made in the five decades following these inventions in miniaturizing circuit components and building ever more powerful circuits. At the time of this writing, state of the art processors in personal computers contain several hundred million transistors within an area of approximately one square inch. This means that each transistor has been shrunk so that a thin layer called the "gate dielectric" is 1.4 nm thick; this is only 5 or 6 atomic layers of silicon dioxide! The "gate length" of each transistor, the distance over which current is switched on and off, is 60 nm or less. The fabrication tools and techniques that have been developed to build such tiny devices form the basis of our tool set for working in nanotechnology today.

APPENDIX B

How Does a Crystal Radio Work?

To understand how a crystal radio works, it is important to first review AM radio. “AM” stands for Amplitude Modulation. An electromagnetic wave with frequency 540 kHz to 1600 kHz, called the “carrier signal,” has its amplitude modulated according to the audio signal to be transmitted (voice, music, etc.). The amplitude modulation occurs at much lower frequencies than the carrier signal, usually within the range that can be heard by the human ear, 20 Hz to 20 kHz. For example, to transmit a pure tone such as the sine wave shown in the top part of the Fig. 1, the amplitude of the carrier signal would be modulated as shown in the bottom part of Fig. 1.

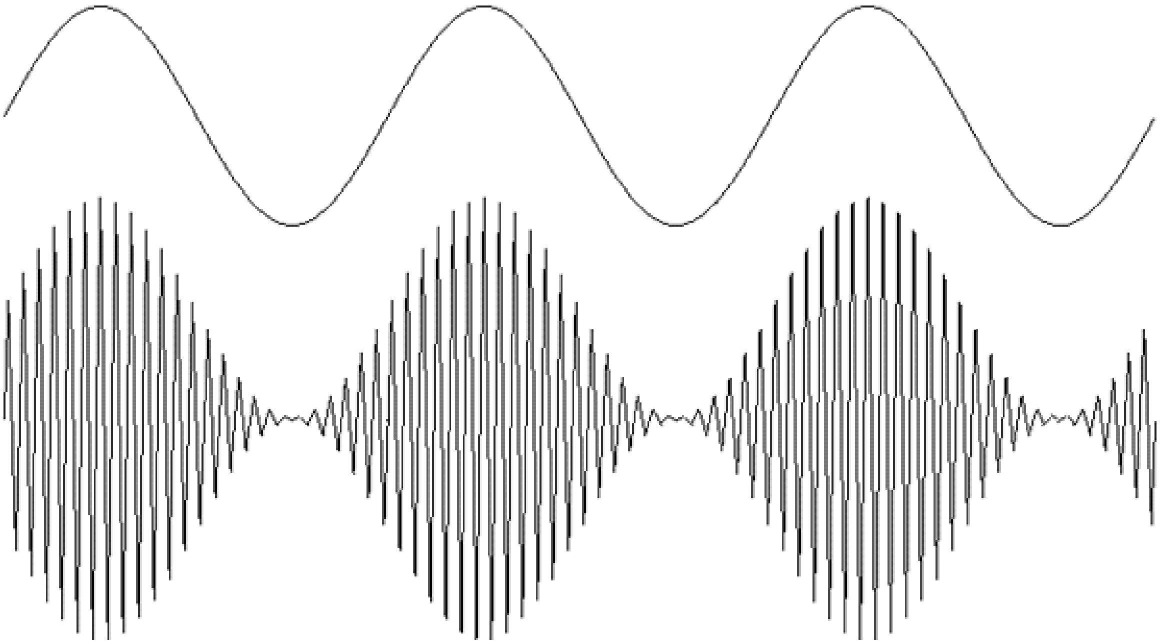


Figure 1. Amplitude modulation of a carrier signal.

Each AM station broadcasts at a different carrier frequency. An antenna positioned on the roof of Ward Lab detects the broadcast electromagnetic waves of all the AM stations in the area. Therefore, the first task of the radio is to select the carrier signal of just one station and reject the carrier signals of all other stations. The coil and the capacitor connected in parallel with it form a “band-pass filter.” Such a filter passes a small range of frequencies and attenuates all others. The inductance of the coil and the capacitance of the capacitor determine what frequency is passed without attenuation. In the radio you built, moving the slider arm changes the inductance of the coil by lengthening or shortening it. This allows you to adjust the frequency that is passed by the filter so that you can tune the radio to your favorite station.

Next, the signal is “rectified,” meaning that only the positive part of the signal is kept. Rectification is necessary for extracting the audio signal from the carrier signal (explained in the next paragraph). The diode in your radio acts to rectify the signal. Diodes allow current to pass through only in one direction and not the other. In a simple radio of the 1920's and 1930's, a chunk of semiconductor crystal contacted by a sharp metal wire or "cat's whisker" formed the rectifying device; hence the name "crystal radio." The top half of Fig. 2 shows a rectified version of the signal from Fig. 1.

In the final stage of signal processing, a "low-pass filter" averages the rectified signal. Note that the average of the signal before rectification is zero. After rectification, the averaged signal is proportional to the amplitude, as shown in the bottom part of Fig. 2. The low-pass filter, consisting of a resistor and a capacitor, passes only frequencies below a threshold frequency determined by the resistance and capacitance of these components. The crystal radio you built has low-pass filter with a threshold lower than the range of possible carrier frequencies and higher than the range of audio frequencies. Therefore, the filter will pass the low frequency modulation of the carrier signal, but not the carrier signal itself.

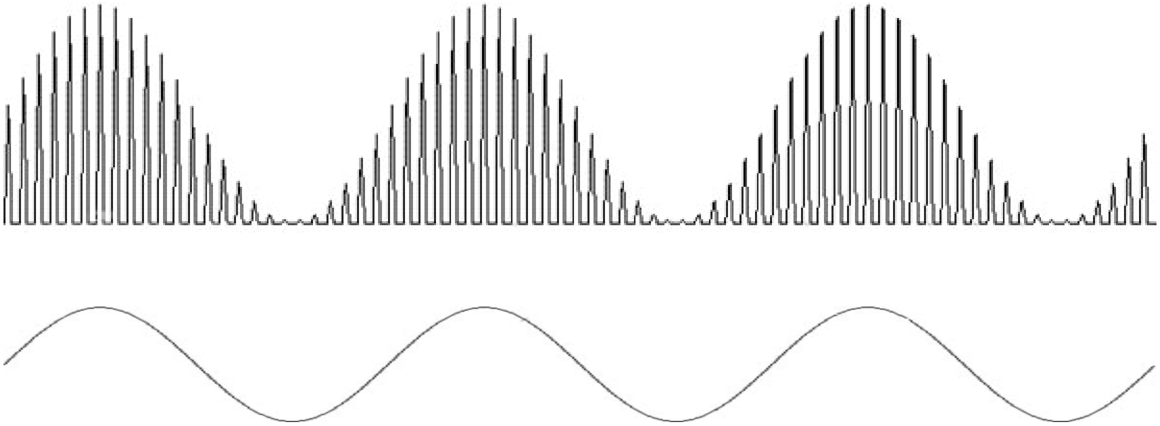


Figure 2. Rectified signal (top) and signal after low-pass filter (bottom).

The recovered audio signal then goes to the earphone. The earphone uses a piezoelectric device to convert the electrical signal back into sound. The main component is a metal disk coated with piezoelectric material that shrinks and expands as the voltage of the signal varies. This causes the disk to vibrate and generate sound waves that reach your ear.

No additional power is needed to operate the crystal radio. The broadcast signal drives the circuit as described above. However, this means that the volume cannot be adjusted and is entirely dependent on local signal strength. In Ithaca, you will be able to tune in two AM stations: 870 WHCU (talk radio) and 1470 WTKO (oldies).

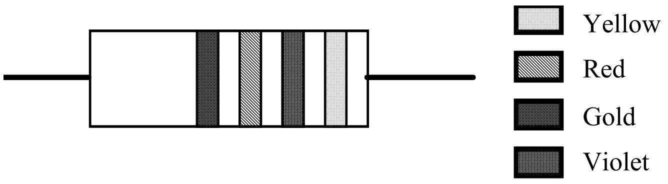
APPENDIX C

Reading Resistor and Capacitor Values

Most small resistors are color coded to indicate the value of their resistance. There are usually 4 colored bands on a resistor close to one end. The first two bands indicate a two digit number, the third band indicates a power of 10 multiplier, and the fourth indicates the tolerance.

The color code:	color	digit	multiplier	tolerance
	black	0	10^0	-
	brown	1	10^1	-
	red	2	10^2	2%
	orange	3	10^3	-
	yellow	4	10^4	-
	green	5	10^5	-
	blue	6	10^6	-
	violet	7	10^7	-
	gray	8	10^8	-
	white	9	10^9	-
	gold	-	10^{-1}	5%
	silver	-	10^{-2}	10%

For example, if you have a resistor coded gold/red/violet/yellow, you should realize that you must turn it around, since gold is not a valid digit. You will also notice that the yellow band is closer to one end than gold is to the other, another clue to start with the other end.



So make that yellow/violet/red/gold. Therefore, the two digits are 4 and 7, the power of ten of is 2 and the tolerance is 5%. This indicates a resistance value of $47\times10^2\ \Omega = 4700\ \Omega = 4.7\ \mathrm{k}\Omega$. The tolerance is 5% meaning that the actual resistance may be 5% greater or less than 4.7 kΩ if you measure it with a multimeter. Note that the interpretation of the significant digits and power of 10 are similar to, *but not the same as,* scientific notation in that the decimal point is *after* the first two digits, not between them.

Capacitors work in a similar way; however, numbers are used rather than colored bands to indicate capacitance values. Capacitance is assumed to be in picofarads or pF. For example, “103” stamped on a capacitor indicates a capacitance of 10×10^3 pF = 0.01μF.