How to build a Nixie Clock

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Glossary

I. Abstract

Just about every few minutes these days we take a glance at some time keeping device to get the latest on our present temporal situation. From the earliest timekeepers used by monks taking advantage of the periodic dripping of water, to Galileo's pendulum clock and John Harrison's first navigational timekeeper, to the digital clock on the bottom right side of the computer screen on which this paper was written, people have dreamt up and constructed a myriad of ways to feel the ensuing comfort of knowing the time; and of course, I am no different. The original goal of this project was to construct a clock using Nixie gas tubes for a display and components found in the physics department electronics lab. Though some of the electronic components like breadboards and an oscillator were purchased online, the majority of what was used was what could be found in the lab; however, the ultimate limiting factor and consideration was the skill level and knowledge of electronic circuit design and manufacturing. Thus, the real goal of the project revealed itself to be learning competency in circuit board layout and construction, and circuit analysis. In the spirit of building a clock from discrete components, so too was the enclosure built from raw materials, most of which was taken from a scrap pile at a hardware store. Without knowledge of the details of the actual clock workings, the enclosure was built from wood and made to fit the tubes, leaving a hopeful amount of space for the clock innards. The lack of planning for the volume needed for the circuits in tandem with the size limitations of building the circuits with relatively discreet components ultimately lead to the incompletion of the clock as an independent unit; there was not enough room to fit all of the necessary components. Thus, in order for the clock to work, a new enclosure with more space must be built, the design and manufacture of the circuit boards must be outsourced to better technology to become more streamlined, or newer technology utilizing software and a microcontroller must be used; the latter of which will be utilized on the second attempt at completing the clock as an independent unit. Despite the incompletion of the clock, the project was not a failure however. Leaps and bounds were made in grasping concepts such as voltage regulation, current flow, properties and uses of particular integrated circuits, as well as improving skills such as etching circuit boards with acid, building power supplies, and good soldering technique. What was learned and the solutions to problems faced in these areas is what this paper will address.

II. Electronics Theory

To build a usable clock, a few key components must exist regardless of the housing in which the clock will reside and the type of display used to read out the time; these components will be discussed first. In order for there to be a readable time, something must be counting. In order for something to be counting, there must be something to count. In order for the clock to be of any worth, this thing to be counted must also be periodic with a fair amount of accuracy. This is where the oscillator circuit comes in. The oscillator circuit used in this project is designed around a quartz oscillator working in tandem with two fairly common integrated circuits: a 14 bit ripple carry binary counter (part # CD4060), and a CMOS dual JK Master-Slave flip flop (part #CD4027). The data sheet for both is shown in the index. The justification for using a quartz oscillator instead of the common RLC circuit with a 555 timer is that quartz oscillators function with extremely high accuracy. The quality factor Q for a typical RLC circuit is on the order of 10^1, whereas the Q factor for oscillator circuit utilizing a quartz crystal is on the order of 10^4. In other words, with an accuracy of about 0.040 ppm, a clock with the quartz oscillator circuit would lose about 1 second every 300 days, whereas a clock with an RLC oscillator circuit would have to be reset just about every couple of hours in order to see a time with any accuracy. The workings of a quartz crystal and an oscillator circuit will be discussed in the following section.

2.1 Fundamentals of Crystal Oscillation

The quartz crystal oscillator circuit functions because of a physical property of quartz called the *piezoelectric effect.* Quartz is not the only material that exhibits this property, but it is the one this paper will discuss. The *piezoelectric effect* describes the relationship between mechanical stress placed on a solid object and voltage. A simple physical representation of the *piezoelectric effect* can be seen in Figure 1.

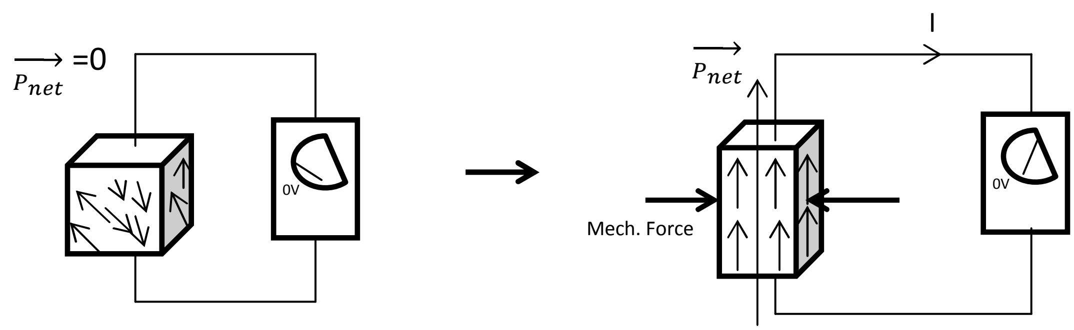


Figure 1: A piezoelectric material generates a voltage when a mechanical force is applied to it in the just the right way to align dipoles and/or move ions in the solid.

The piezoelectric effect in the quartz used in the clock is caused by inherent dipoles in the solid. The dipoles in the solid have regions of alignment, called Weiss Regions, but Weiss Regions themselves do not have a common axis of alignment, causing no inherent polarization in the solid. When a mechanical force is applied to the solid in just the right direction, it can vary the shape of the solid causing the dipoles to align, giving the solid an overall net polarization, as shown in Figure 1. With this net polarization, the piezoelectric material now has the ability to push charge (i.e. electrons) and apply a voltage. Another way to think about the crystal is that in a way it acts like a capacitor. A capacitor can be polarized by applying an electric field across it, which pushes negative charge to one side, and positive charge to the other side. However, in the case of the crystal, the mechanical force is what's pushing all like charges to one side to create the electric field. There is a case, however, in which an *electric field* instead of a mechanical force is used to vary the shape of the crystal; if a mechanical force can be applied to change the shape of the quartz and polarize it, then an electric field should also be able to polarize the solid, thus changing its shape. Indeed, this is the case and it is a phenomenon appropriately called the *inverse piezoelectric effect.* The importance of the *inverse piezoelectric effect* is that it works in tandem with normal *piezoelectric effect* to keep the crystal oscillating. When the oscillator circuit is first closed and an electric field is placed across the quartz, it becomes polarized, exhibiting the *inverse piezoelectric effect*. However, because of the elasticity of the quartz, it begins to rebound and invert its original shape, causing the dipoles in the quartz to align in the opposite direction; this would be the normal *piezoelectric effect.* It repeats in this fashion over and over, which is the origin of the oscillations. Like all oscillators though, it will need a driving force to overcome the inherent damping experienced by any system. The origin of this driving force is what will be discussed in the following section.

2.2 Oscillator Circuitry

Now that a basic understanding of the *piezoelectric effect* has been achieved, the quartz can be used as a time keeper. However, just because an electric field is applied to the quartz to get a voltage out doesn't mean it can just be hooked up to a decade counter and counted. There are a few specifications that have to be known in order for the quartz to oscillate, and furthermore, to oscillate with any useful periodicity. The first attribute of the crystal that must be known is its resonant frequency, which is determined by the thickness of the quartz. The resonant frequency is inversely proportional to the thickness of the quartz. For this project a frequency of 32.768 kHz was chosen because it is easily divided by 2 (15 times) to get to 1 Hz. Once the quartz is cut to the size needed, it is then metallized to make a connection to each side in order for the current to flow as shown in Figure 2.

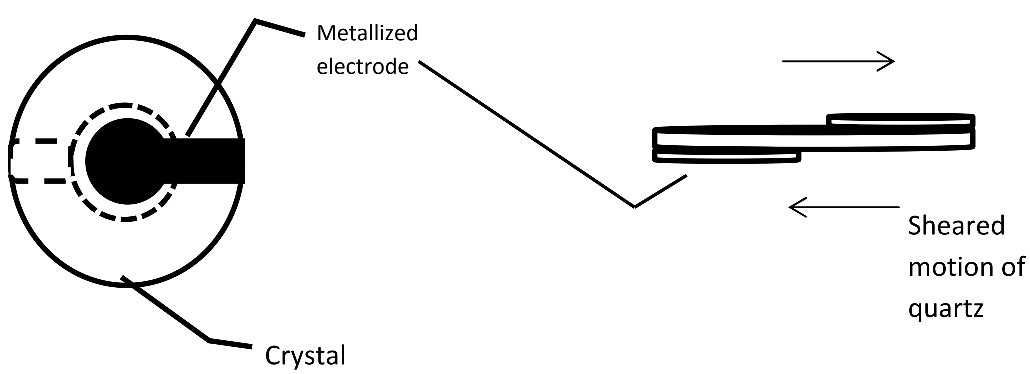


Figure 2: Actual motion of quartz with electrode connections.

This whole set up, shown in Figure 2, is the oscillator quartz itself, which takes the place of the resistor, capacitor, and inductor in an equivalent RLC circuit shown in Figure 3.

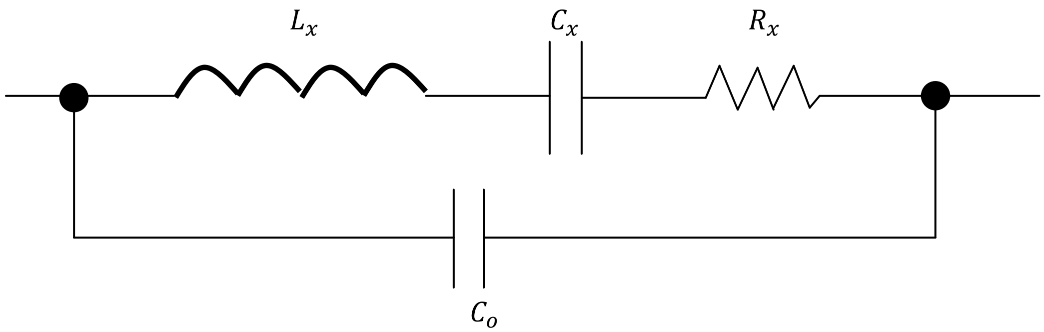


Figure 3: Equivalence circuit for quartz oscillator circuit at resonance where values subscripted with x are characteristics of the crystal and C_o is the capacitance of the electrodes.

It can be seen from the equivalence circuit for the quartz oscillator in Figure 3 that the quartz crystal must have some aspects about it that are inductive, some that are resistive, and some that are capacitive; and, indeed there are. The capacitor represents the ability of the crystal to store energy, the resistor represents the friction the crystal sees, and the inductor represents the inertia of the crystal. These aspects of the quartz are more of the specifications that must be known before the oscillator circuit is put together. An important aspect of the *oscillator circuit* is that it operates at the crystals resonant frequency, so that a predictable frequency is produced. In order for the crystal to control the oscillator circuit at its resonant frequency it must maximize the gain of the oscillator circuit at its resonant frequency and minimize it at all other frequencies. In order to achieve this it must first be decided whether or not the quartz is going to be placed in parallel or series resonance, because this will decide how much load resistance the crystal sees. In a series RLC circuit like the one in Figure 3, resonance is easy to achieve by minimizing the total impedance Z, which is done by matching the impedance of the capacitor X_C and inductor X_L so that the total impedance of the circuit is equal to R_x. This is implicated from equation 1 below.

$$Z = \sqrt{R_x^2 + (X_L - X_C)^2} \qquad \text{Eq. 1}$$

$$phase\ angle = \emptyset = \tan^{-1}\left(\frac{X_L - X_C}{R}\right) \qquad \text{Eq. 2}$$

This means that if a quartz oscillator were to replace its equivalent circuit all that would need to be done is place a current limiting resistor series with it and place an op-amp in the circuit with positive feedback and a gain greater than 1 to drive the crystal. From equation 2, it can also be seen that when the impedance of the inductor and the capacitor are matched, the driving voltage and the current are in phase, that is, $\emptyset = 0$, meaning that the crystal is oscillating at its maximum amplitude. This is another characteristic of an oscillator circuit oscillating at its resonant frequency (i.e. that the driving force and the current be in phase). This series resistant oscillator would be a poor oscillator, however, because it is very unstable and the design allows for too much noise which can offset the phase angle between the driving voltage and oscillator. Better series resistant oscillators can be built that fix these problems; however, for this project a parallel resistant oscillator was used.

As just mentioned, above a parallel resonant circuit was used for this project. The circuit diagram for the external part of the oscillator circuit used in this project is shown below in Figure 4, while Figure 5 shows the part of the circuit inside the IC.

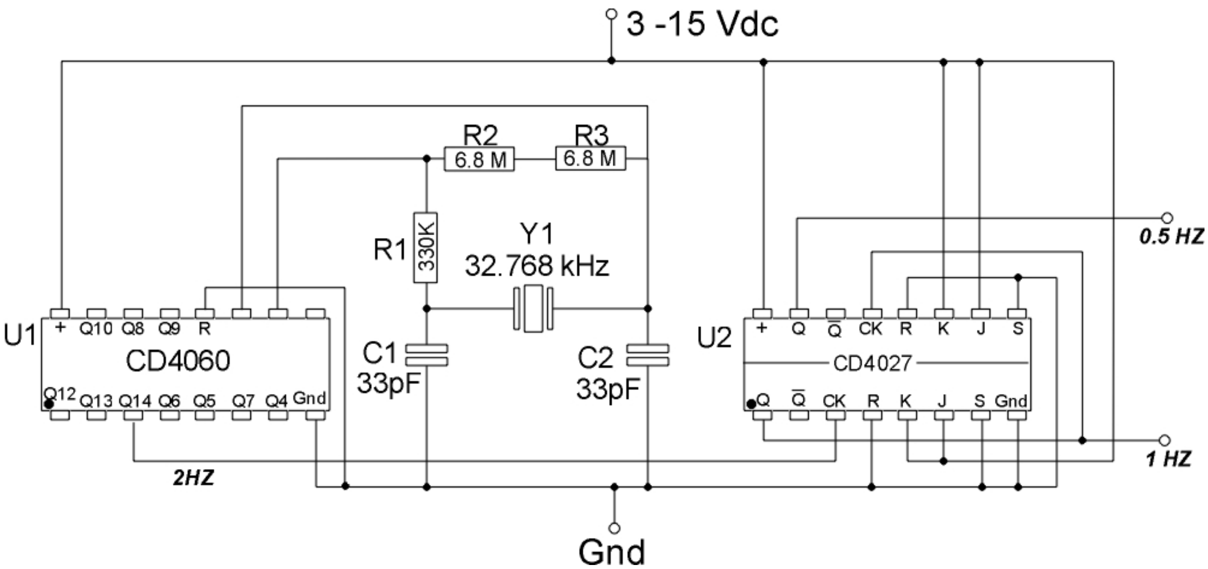


Figure 4: Oscillator circuit used for clock with quartz crystal.

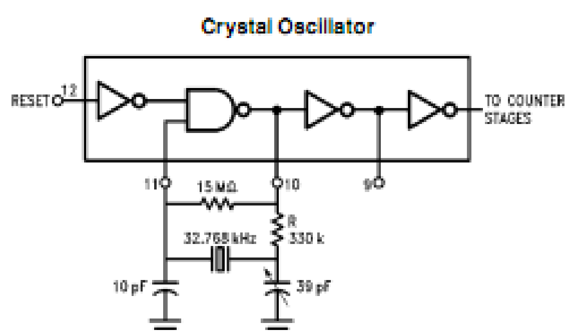


Figure 5: Part of the oscillator circuit inside IC

While a parallel resistant oscillator circuit doesn't affect the internal characteristics of the crystal, it does affect how the oscillator circuit oscillates. In order to understand why the schematic in Figure 4 works, an equivalent parallel RLC circuit will be looked at briefly.

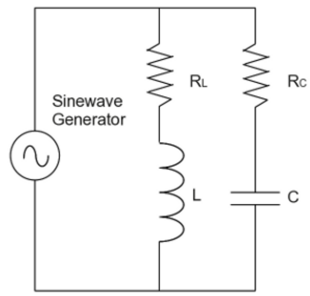


Figure 6: Parallel RLC oscillator circuit

As can be seen from Figure 6, the impedances of the inductor L and capacitor C as well as their respective resistors must be added inversely, as all parallel resistance does:

Eq. 3

where and

It might seem like the impedance of the capacitor and the inductor would simply add together, however, each Z is actually a vector in the imaginary plane whose components (x,y) are the resistance of the resistor and the resistance of the inductor or capacitor, respectively.
Each imaginary vector rotates about the origin, giving the overall varying impedance, but each has a different phase angle, making each branch in the circuit oscillate at a different phase than the other. The physical reason that each branch of the circuit has a different phase angle is because of the way each component reacts to a changing voltage, or driving force. When an increasing voltage is applied across an inductor the current lags the voltage by 90 degrees because of Lenz's Law, which states that the current in a wire will move to oppose a changing magnetic field. This gives the inductor a positive phase angle of ; because the charge build up on the inductor remains for a period of time after the applied voltage has begun to decrease. When a voltage is applied across a capacitor the voltage lags the current by 90 degrees, which is because it takes a period of time for the charge to build up on the capacitor plates, meaning it won't quite be fully charged by the time the driving voltage begins to decrease, but it will be slightly afterward. Because of this total 180 degree phase difference, the vectors must be added using complex methods. Skipping the algebra, equation 4 shows the sum of the impedances of a parallel resistant oscillator circuit found with complex methods:

Eq. 4

Remembering from above that one of the criteria for an oscillator circuit to oscillate at the crystals resonance is that the circuit maximizes its gain, we can see now from equations 3 and 4 that this happens when the phase angle between the driving force and the oscillator is $= 2n\pi$. Taking this information, now we can understand why some of the components in the circuit in

Figures 4 and 5 are there. The large amount of resistance is there to match the internal impedance of the quartz, thus making it resonate at its maximum amplitude, and therefore its resonant frequency. And also we can understand the placement of the two capacitors. Remembering that each capacitor causes the circuit to lag the driving voltage but 90 degrees, two capacitors are placed in the circuit to make the total current lag the driving voltage by 180 degrees. This 180 degree phase difference compensates for the inherent 180 degree phase difference caused by the NAND gate inside the IC, to which the circuit is hooked up to. These combined gives a total phase difference of 360 degrees, or $\varphi = 0$. The reason that it is desirable for the phase angle to be 0 in order to obtain oscillations with maximum amplitude, and thus, oscillate at the quartz's resonant frequency can also be illustrated with a person swinging on a swing. If the person wanted to reach the maximum amplitude possible then the driving force (i.e. the pusher) would push exactly in the direction of motion of the swinger, or, they would give pushes that were in phase with the swingers' oscillations. Intuitively this makes sense, however, most of us wouldn't think to apply this to a circuit, but the concept is the same.

2.3 Logic Gates in the oscillator circuit

Thus far the terms "gain" and "driving voltage" have been used without much explanation, so this section will expand briefly on what those terms actually mean to the oscillator circuit. In the analogy above of the swing, it is necessary for the pusher to apply a force to the swinger in order to gain back the energy lost as friction from the air and the metal connections. In the oscillator circuit, energy is also lost in the quartz due to internal friction and it is dissipated as heat. This means that the circuit must also gain back energy somehow to keep the oscillations going. As can be seen from Figure 5 above, the external part of the oscillator circuit is connected to a NAND gate inside the IC. This gate is what provides the gain which drives the circuit. To understand how this works lets first look at an illustration of what's going on inside the IC.

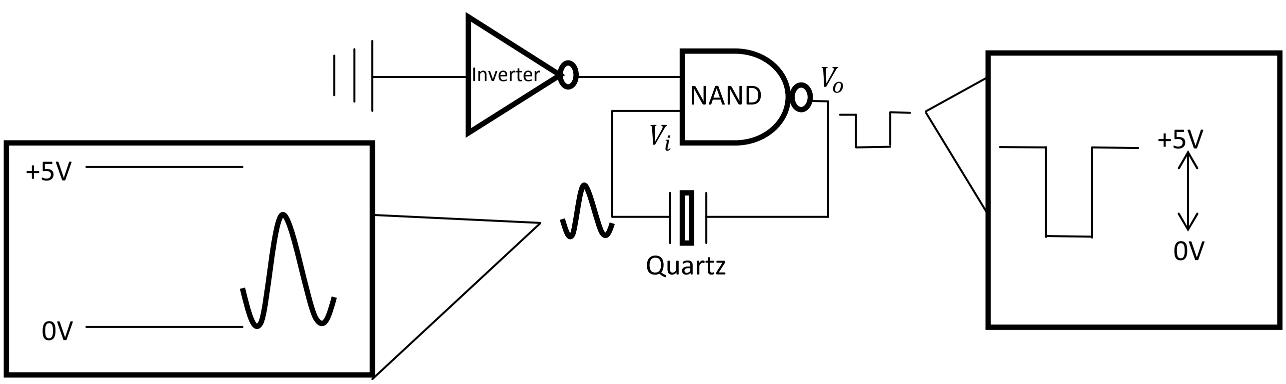


Figure 7: Quartz connection with logic gates

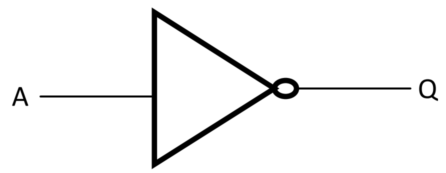
Figure 7 shows a simplified view of the connections between the external oscillator circuit and the internal logic gates. The first thing to note is the phase difference between the output of the NAND and the output of the quartz is 180 degrees, which is caused by how the logic of a NAND gate works. This is the inherent phase difference mentioned above for which the two capacitors were added to compensate for. The next thing to note in the figure is that the output of the NAND gate passes through the oscillator and is then fed back into its own input. This is what is meant by feedback, and it is the essence of the oscillator circuit being a self-sustaining oscillator. The top input of the NAND gate is always positive, which means that the quartz takes control of the circuits' oscillations. Each time a positive pulse is output from the quartz, it makes both inputs high into the NAND, which then in turn makes its output low and vice versa. This is how the oscillator circuit oscillates with the resonant frequency of the quartz. However, figure 7 also shows that the output of the quartz is less than that of the voltage from the output of the NAND gate, which means that there was some damping and the oscillations would die off very quickly. This damping is due to the internal resistance of the quartz and this is where the gain comes in. Because of the amplifying ability of the transistors that make up the NAND gate, the gate is able to output a steady voltage, despite the input voltage being less. This amplification is the gain and it is shown in equation 5 below:

$$\text{gain of circuit} \propto \frac{V_o}{V_i} \qquad \text{Eq. 5}$$

where V_o is the amplitude of the output voltage of the gate and V_i is the output of the quartz and the input to the gate. If the circuit is going to overcome the damping of the internal quartz resistance and resonate, then $V_o > V_i$.

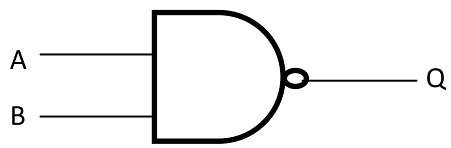
2.4 Boolean Logic

Up until now only the oscillator circuit has been discussed, a very important step in keeping the time. However, the oscillator circuit is only good if there is something that can count how many times it has oscillated. In this section the clock circuit will be discussed. In the above section a NAND gate was used as an amplifier to provide the driving voltage for the oscillator circuit. The NAND gate however, has many other uses, one of which is to count the oscillations and add them together. This is done by cascading a series NAND gates, and other logic gates similar in function, in a row. To understand a little about how the clock circuit works on the basis of using logic gates, once again we'll start with a diagram of some different types of logic gates and a few truth tables, which are shown below in figure 8.



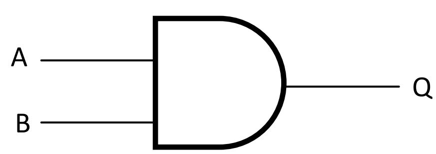
NOT Truth Table

A	Q
0	1
1	0



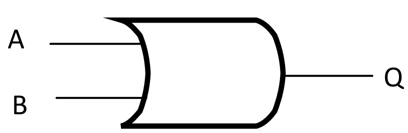
NAND Truth Table

A	B	Q
0	0	1
0	1	1
1	0	1
1	1	0



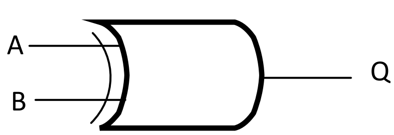
AND Truth Table

A	B	Q
0	0	0
1	0	0
0	1	0
1	1	1



OR Truth Table

A	B	Q
0	0	0
1	0	1
0	1	1
1	1	1



XOR Truth Table

A	B	Q
0	0	0
1	0	1
0	1	1
1	1	0

Figure 8: Logic gates with Truth Tables.

On their own, these gates are only so useful, but when you start hooking them up to each other, you can begin to make systems that add, subtract, multiply, and divide; and, ultimately after adding billions of these gates in a row, you can obtain a computer. But that's too advanced for this paper, so let's just talk about how these gates are hooked together to add, and make a clock. To begin we'll start with a simple system that can add two bits, or two pieces of information. In binary, adding two bits would look something like this:

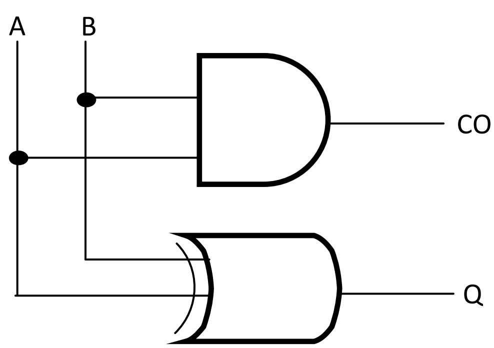
0	1	0	1
+0	+0	+1	+1
0	1	1	01

As you can see this is just the Truth Table for an AND gate shown in Figure 8, with the exception of the last addition which carries the one over to the second position, representing a 2 in binary. If we add a zero to the rest of the answers as follows:

0	1	0	1
+0	+0	+1	+1
00	10	10	01

we can see that this doesn't change the value of the final answer but now the second digit matches the truth table for an AND gate , and the digit in the first position matches the truth table for a XOR gate, both conveniently shown in figure 8 above. So, with this information, we *should* be able to construct a 2 bit adder with two outputs with the gates above if we connect

them in just the right way; one output being the usual Q and the other being the "carry out" or CO, which carries the overflow of the addition to the next logic system:

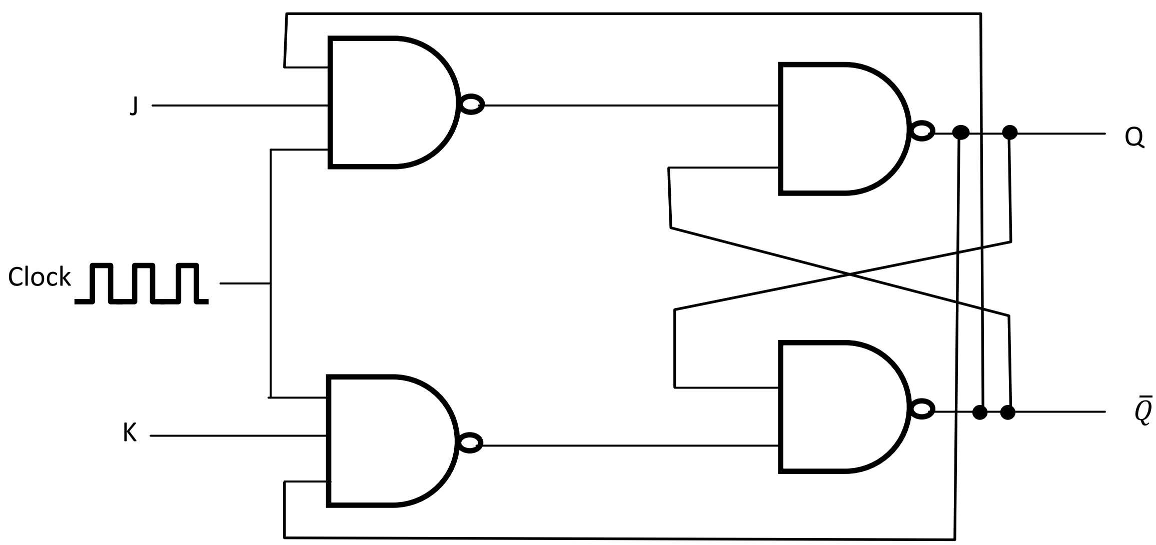


A	B	CO	Q
0	0	0	0
0	1	0	1
1	0	0	1
1	1	1	0

One can now see from the above picture how the addition above is translated into gate logic; where two inputs are used to control two outputs simultaneously instead of just one output. This method of logic is called Boolean Logic. Boolean logic is the whole basis of how the Nixie clock counts. This little model suffices to demonstrate the basics of Boolean logic; however, the actual logic used in the decade counters in the clock is much more complex, with strings of hundreds of gates together. Therefore, for the sake of brevity, only the JK flip-flop will be discussed.

2.5 JK Flip-Flop

Skipping ahead a bit in complexity from the two bit adder, we come to the JK flip-flop, which is a name for a way that the logic gates above are put together in order to keep track of the number of oscillations that have happened. The JK part of the name is thought to have come from the initials of the man who invented it, but this is only hearsay. The more important part of the name is the "flip-flop" part, which describes the toggling characteristic of the logic. As per the usual a diagram will be used to help explain how the flip-flop works, but first a few things must be prefaced. In addition to the logic gates above, there can also be logic gates by the same name and with the same function but with more inputs. The JK flip-flop will utilize some logic gates that have three inputs; however, the truth tables would remain essentially the same. Secondly, in addition to having more than two inputs, some logic gate outputs depend not on the state of an input, but rather how the state of the input changes. For the JK flip-flop, this particular input will depend on the transition from a high to low state, or a 1 to 0.



JK flip-flop Truth Table

J	K	Clock	Q	$\bar{Q}$
0	0	0 to 1	-	-
0	1	0 to 1	0	1
1	0	0 to 1	1	0
1	1	0 to 1	Toggle	Toggle

Figure 9: Circuit Diagram and Truth Table for JK Flip-Flop

Notice in the circuit diagram for the JK flip-flop that, like the oscillator circuit, there is feedback. Perhaps this is a chance to look at the function of the feedback in a new light. Before in the oscillator circuit we found out that there had to be feedback in order for the circuit to oscillate at resonance because the output of the NAND gate was driving the quartz, which then signaled the NAND gate's input, making a self-sustaining oscillation. Now, though, we can think of the feedback before as making the output of the NAND toggle, or "flip-flop" back and forth. In this case, instead of providing a gain for the circuit, the NAND gate and feedback are used to count the oscillations. It does this by essentially dividing the signal by two. In the truth table in figure 9 we see that if J and K are hardwired to stay high at +5 volts, then each rising edge of the clock pulse toggles Q and $\bar{Q}$. Therefore, every second pulse, Q will be either high or low (1 or 0), and vice versa for $\bar{Q}$, thus dividing by two. If one were to put enough of these JK flip-flops in a row, hooking either output into the next flip-flop as the clock signal, then it wouldn't take much understanding of electronics at all to see how this could be used to count how many oscillations have taken place; thus making a counter for the clock. Indeed, knowing the resonant frequency to be 32.768 kHz, it would take fifteen flip-flops to reduce the signal down to 1Hz. Taking this one step further, and knowing that we are interested in binary-coded decimal BCD for the output, all that needs to be done is place four JK flip-flops together to represent one decimal digit in the final read out. That is, for each number in the display of the clock, we will need one half of a byte, or four bits, each bit representing a JK flip-flop. Finally, knowing that there are six numbers in the display, two for hours, two for minutes, and two for seconds, and each digit needs four flip-flops, we can add up all the flip-flops needed for the clock to function: 6 x 4 + 15 = 39 JK flip-flops. Evidently, JK flip-flops are very important for this clock.

Luckily for us, instead of putting the hundreds of logic gates needed in exactly the right order, advanced technology has reduced the transistor to be on the order of micrometers, allowing for all of this to be placed on single integrated circuits that take up little space, a few of which were used for this project. The IC that was used for this clock circuit was the 7490 Decade Ripple Counter, the data sheet for which can be seen in the index.

2.6 The Nixie Tubes

Before talking about how exactly the IC's are hooked up on a circuit board to form the clock, the Nixie tube itself will be discussed in order to have a better understanding of why the IC's are connected as they are. One way to look at this project is that in a way it's combining technology from two different time periods; therefore, it's not exactly the simplest of tasks to interface the IC's to the Nixie tube display. Hence, a better understanding of its components is very helpful in assembling the clock as a whole.

The Nixie Tube display is a type of gas tube display that was invented in the mid 1930's by an electrical engineer by the name of Hans Boswau. It did not gain wide usage however, until the mid-1950's when the Burroughs Corporation, a major business equipment manufacturer, patented and mass produced a version of the tube that was designed by a smaller company known as Haydu. Evidently, the gas tube came to be known as a Nixie Tube because one of the engineers at Haydu first labeled the design as NIX#1 (Numeric Indicator Experiment #1). It was the Burroughs Corporation that then took this and patented the design under the name Nixie. The function of the Nixie tube is actually fairly simple and it begins with a glass tube with a mixture of Neon, Argon, and Mercury sealed in; these metals are chosen because of their low ionization energy and they are kept at low pressure to keep them gasified. Also within the glass tube are an oxidizing anode (gives up electrons), and ten reducing cathodes (accepts the electrons). The anode is a metal mesh that surrounds the cathodes which are in the shape of numbers 0-9 and are separated by ceramic spacers. Each anode and cathode is then connected to pins that are on the outside of the tube so that a voltage can be placed across them.

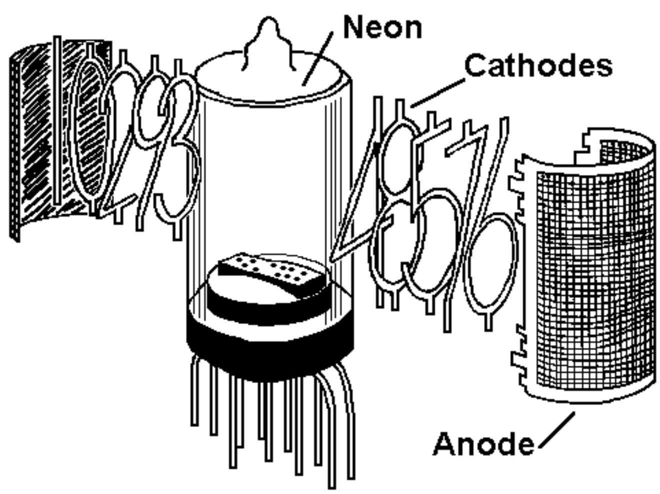
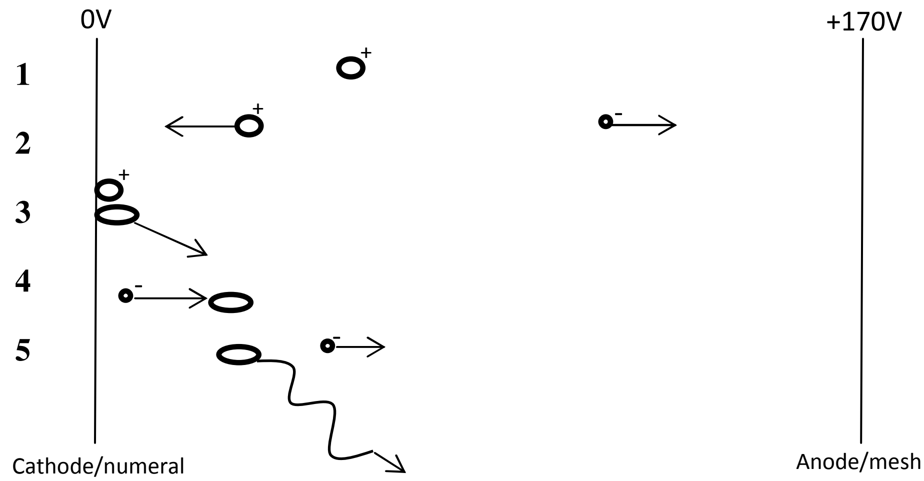


Figure 10: Assembly of Nixie gas tube

When a large voltage (~170V) is applied across the anode and cathode it ionizes the metal gas inside the tube, pulling the liberated electrons toward the positively charged anode, and the cations toward the negatively charged cathode. This is how the current flows through the Nixie tube. As the cations flow toward the cathode they convert the potential energy from the electric field into kinetic energy and strike the metal atoms on the cathode. Once they hit the cathode, most of the ions have enough energy to knock a metal atom off of the cathode, which is called a "sputtered" atom. Because the cathode is being oxidized by the electric field, it is also emitting electrons that flow from the cathode to the anode. These electrons then collide with the sputtered metal atoms that also just came from the cathode and excite them to a higher energy state, which then quickly decay back down to a lower energy state and emit a photon; giving the Nixie tube its glow. This whole process is illustrated below.



Step 1-Gas is at low pressure inside of Nixie tube
Step 2-Gas is ionized by applied electric field and opposite charges flow in opposite directions
Step 3-Gas ions collide with metal atoms in cathode and eject them
Step 4-Electrons from cathode collide with metal atoms and excite atoms to higher state
Step 5-Atoms decay back down to lower energy state and emit a photon

Figure 11: Diagram of how Nixie tube numbers glow

One can then see how by raising and lowering the voltage on the cathode, it is possible to start and stop this process on any particular cathode, thus, switching between different numbers. The Nixie tubes used for this project have a model number IN-18 and its data sheet is listed in the index.

Side note:

> If you were to look at the glowing number, you would notice that there is actually a small space between the glow and the metal number. This is because right after the electrons have left the cathode they have not yet gained enough kinetic energy in the E-field to excite the metal atoms. After the electrons travel the distance where their kinetic energy is equal to the excitation energy of the metal atoms, though, they can then excite the atoms.

Now that we understand how the oscillator circuit, the clock circuit, and the Nixie tubes work, we can finally bring them together to make a time telling Nixie clock. From here on out the physics of what is happening is simple and concepts of how components such as a transistor, diode, or a capacitor function are assumed to be known

III. Interfacing the Nixie Tubes and the Clock Circuit

Although simple in theory, interfacing the Nixie tubes with the clock circuit is what ultimately led to the incompletion of the clock as an independent unit. The reason for this is that because the tubes require such a large voltage in order to fire, they also require somewhat more robust components than what is in the electronics lab. In fact, the only integrated circuits designed specifically to handle the voltage needed for Nixie tubes were discontinued in the 1970's, making them a little more challenging to find. Thus, bulky components that took up the vast majority of the bread board space and volume in the enclosure had to be used.

3.1 Connecting the TTL with Nixie Tubes

The first thing that had to be considered when interfacing the clock circuit with the tubes was that the clock circuit output the time in BCD, and the tubes are, of course, are in decimal form because that's how us humans function. So, a chip was needed that converted BCD to decimal and the 7442 BCD to Decimal Decoder chip was chosen because it is what was available in the electronics lab. This meant that six more chips had to be introduced into the design, one for each number, which used up a large portion of the volume in the enclosure. Because the 7442 functions with the same Boolean logic concepts talked about earlier, it won't be discussed in detail; however, its data sheet can be found in the index. The next thing that had to be considered in interfacing the clock logic with the tubes was switching the five volts that the logic functioned at with the tube voltage of 170V. This was done (theoretically, very simply) with the MPSA42 transistor (which can handle voltages up to 300V) acting as a switch. The data sheet for the MPSA42 is in the index. Below in figure 12 is a diagram for interfacing one 7442 with one tube.

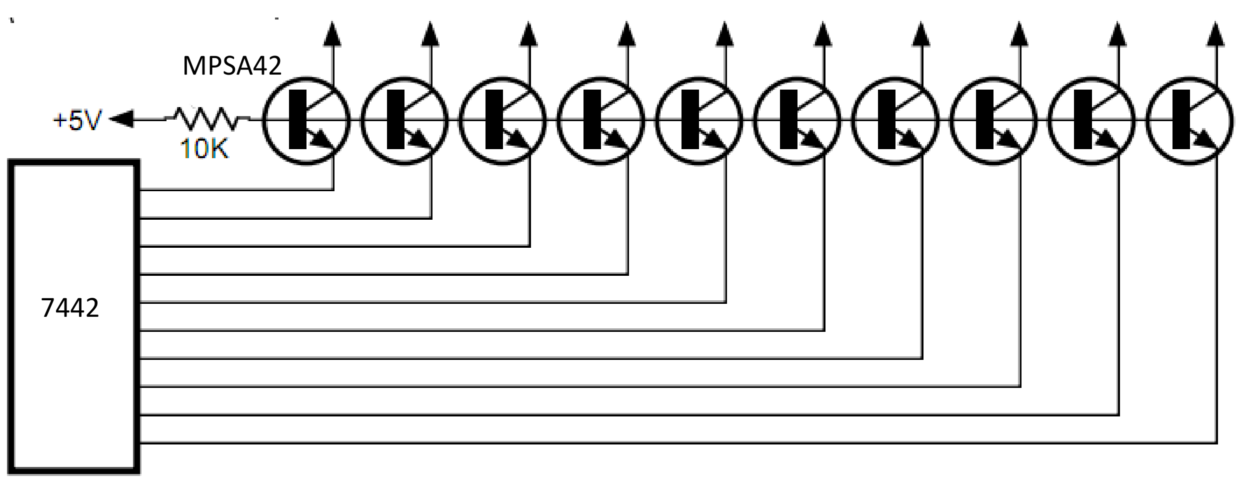


Figure 12: Power interfacing of TTL and Nixie tubes

From the diagram in figure 12 you can see that the base of the transistors are held at five volts, the collector is attached to the tube, and the emitter is connected to the 7442 IC. In more cases than not, transistors are "base-controlled," meaning that the base is raised to at least the minimum 0.707V above the emitter in order to switch the transistor on and let current flow. However, in this case, because the 7442 happens to be "active low," it was necessary to make the transistors emitter-controlled and drop the emitter voltage below the base. This is why the base on all transistors is hardwired to be five volts. One consideration for this design though, is that the 7442 needs to be able to sink the nominal current of the tubes. According to the datasheet for the tubes the nominal current is 6mA, which is well within the maximum short-circuited output current of -55mA listed on the 7442 datasheet. Because this design is straightforward, there isn't much to say about it other than that although simple in theory, it consumes a large amount of space and so it is necessary to be tactful about designing the circuit board on which this will be placed.

3.2 Power Supplies

3.2.1 +5V Power Supply

Up to this point it has been assumed that there was an adequate power supply to power all of the circuits discussed. But where exactly is the power coming from? Remembering what has been talked about so far we can deduce that two different voltages are needed: 5V for the logic, and 170V for the tubes. For the sake of simplicity and partly safety, a 5V power supply was ordered preassembled from DigiKey Corporation to power the logic. The benefit of doing this is that not only can it provide a far more regulated voltage than one put together in the lab, but also if there were to be a short circuit, the supply is designed to cut off the current so as not to cause a fire or burn out the IC's. The data sheet for this power supply is included in the index. Some considerations when buying this power supply were the power consumption of the IC's it would be powering. The typical power consumption of the 7490 and 7442 chip is about 0.25W. With sixteen IC's being used, that's about 4W of power needed. Or about 4W/5V = 800mA.

3.2.2 +170V Power Supply

Unlike the power supply for the logic, the one for the tubes was made in the lab and is extremely simple. All that is needed is a transformer with a 6:5 turn ratio and a half-wave rectifier.

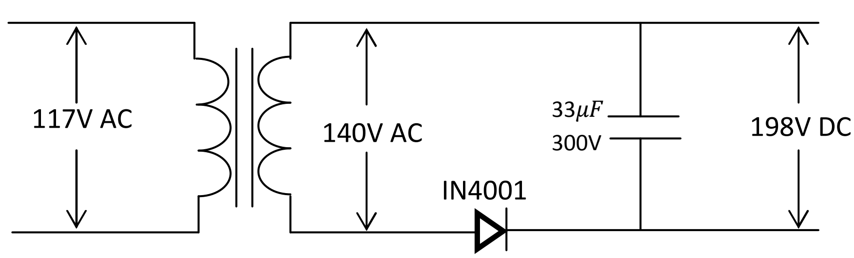


Figure 13: Nixie Tube Power Supply

The benefit of this power supply is that it is extremely simple and the parts are not uncommon. The drawback is that it can be dangerous if short-circuited because it is connected directly to mains, which means that it can supply as much current as the components will allow. According to the datasheet for the IN4001 rectifying diode it will breakdown at 1amp, which is much more than what's needed to kill a person. If the completed unit had come together as an independent unit it would have been necessary to add a fairly low current fuse. It is important to get the turn ratio in the transformer correct because of the limitations of the Nixie tubes. Using just the peak voltage of the mains out of the half-wave rectifier is not enough because it only has a peak of 165V and the nominal firing voltage for the tubes is 170V. 165V would be enough to dimly light about three tubes, but because of the capacitors low time constant, the 60Hz from the wall is not fast enough to charge the capacitor to the peak 165 for six tubes. Hence, a higher quality capacitor could be used, or a transformer could also be used. In this case a transformer was used because it was available in the lab. It's important not to overshoot the voltage either because according to the IN-18 Nixie tube data sheet the tubes have a breakdown voltage of 180V. Therefore, using a transformer with a turn ratio of 5:6 is ideal, which is shown below:

$$(6\ Nixie\ tubes)(3V\ drop\ each) = 18\ V\ drop\ total$$

$$170V\ DC + 18V\ DC$$

$$\frac{198V\ DC}{\sqrt{2}} = 140V\ AC$$

$$\frac{140V\ AC}{117V\ AC} = 1.2 = \frac{6}{5}$$

3.3 Setting the Time

The very last circuitry topic that needs to be covered in order for the clock to be of any use is human to clock interfacing. Or, how does one set the time? It doesn't matter if the clock is accurate if it doesn't tell the correct time; that is, unless you plug it in at exactly midnight. The first attempt at setting the time was to manually input a pulse into the clock using a de-bounced switch. As the de-bouncing switch would only take up more space inside the housing and was far more complex than it necessary, a much simpler, alternate method was derived If you refer back to figure 4 for the circuit diagram of the oscillator circuit you can see that pin 14 of IC CD4060 outputs 2Hz. All that need be done to set the time is to route this pulse to the numbers you'd like to set. This is done with three switches: one for the ones place of the minutes, and one for the ones place of the hours, and one to toggle between the two; it's really not necessary to set the seconds. What the first two switches do is toggle between the carry-out CO of the previous flip-flop and the 2HZ output of the oscillator circuit. However, before they connect to the 2Hz signal, they first pass through the third switch, which directs that signal either to the minutes or the hours.

IV. Possible Improvements to Circuit Design

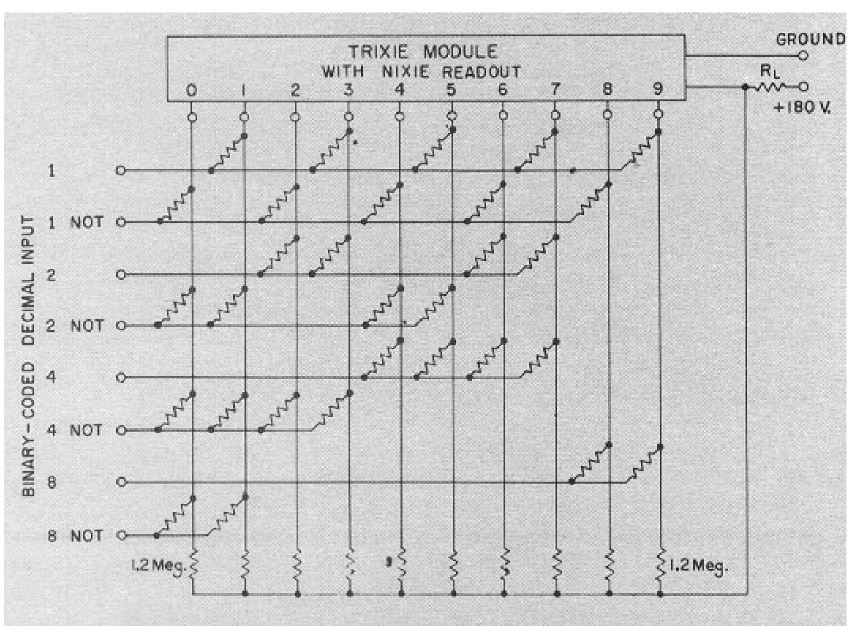
As has been made aware, the circuit design for the clock did not allow for the completion of the clock as an independent unit; its innards had to spill out into the table in order for the circuits to function. For this reason I am prompted to look at a few improvements that could be made to the overall design in order for the clock to work as originally imagined.

1) Streamline Breadboards

The biggest design flaw is the amount of crossing over from bread board to bread board, causing there to be literally hundreds of loose wires in the box, despite the amount of soldering and etching to copper plated boards to reduce this. A key in reducing the circuit size would be to utilize circuit design software such as DipTrace to design a single board which would require few to not wires to go from circuit to circuit. Designs on this program can be easily sent to companies to be professionally acid etched with precision unattainable in the lab.

2) Find More Efficient Ways of Building a Circuit

Since I began this endeavor of clock making I have come across a few alternative methods for building circuits that would reduce not only the size and messiness of the circuit, but could also reduce power consumption. One of the better circuits I found was for the interfacing of the BCD output of the clock circuit to the transistor switches. Instead of passing through the 7442 to decode the BCD to decimal, decoding and power switching can be done in one step with a resistor decoding matrix shown below.



This method not only reduces space usage, but also power usage by cutting out 6 IC's.

3) Software

It's pretty obvious that using software is an invaluable convenience when it comes to using computers. One way, and probably the best way, to reduce space and simplify the circuits inside the clock is to use a microcontroller. Though the microcontroller is not a piece of hardware than can withstand high voltages used in the tubes, with a little programming, it can replace all of the circuitry needed up to the point of switching the tubes from low to high, in which case it would then be a simple task to multiplex the output to once again reduce power consumption. Below is some programming done in C that can make an Arduino Uno Microcontroller act as a clock, reducing hundreds of wires, multiple breadboards, and thousands of solders down to the size of a dollar bill folded in half.

V. Conclusion

After spending at least 200 dollars, burning out countless electronic components, and passing away at least 150 hours teaching myself from the ground up, usually by trial and error, what is needed to build a Nixie clock, how to construct the circuits and the physics behind it all, I am fairly, actually very much, disappointed that I do not have something to show for all the effort and how much I've learned. Because of this, it was important to me that I found ways to improve my design in order to complete my original goal of building a functioning, portable and aesthetic Nixie clock. I am not, however, disappointed with the knowledge and problem solving skills I have gained from this experience. With so much technology around us all the time, it can all very quickly become overwhelming and intimidating, seeming to be far beyond the average person's comprehension. With this project I have gained the knowledge that all of it, from laptops, to TV's, to iPhones, is all based on a few simple concepts that are perfectly comprehendible to any person willing to take a minute to think about it rather than just use it; and ultimately its only limitation is the imagination creating it. Although not generally a scientifically minded, I have found much pleasure and fulfillment in learning about electronics as it has allowed for my logical side to work in tandem with my creative side, and indeed, I am excited to not only complete my clock, but to see how else I can apply what I have gained from this experience. I will walk away from this experience humbled by the will power and ingenuity it takes to invent something practical and simple, and I have a far greater respect for the technology that I usually take for granted and the effort that went into it. Although disappointed by having nothing tangible to take with me, I am happy to have chosen this project and in a way, happy that it sort of defeated me; you'll learn far more from your mistakes than your success.

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