Built your Own Electronic Piano Workshop for K-12 students

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Abstract — *This paper presents a K-12 workshop on Electrical Engineering concepts, in which students build several circuits including an electronic piano. The piano has been built successfully in all our visited schools. In addition, we encourage teachers to build the circuit and provide them with the Theory and Instructions and Materials List for replication with other groups. The purpose is to motivate students to pursue careers in engineering. Many of the ushers were undergraduate female EE students to serve as role models.*

Index Terms — *Electronic workshop, K-12 activities, piano circuit.*

INTRODUCTION

One of the main barriers in engineering education is to motivate elementary students to pursue careers in engineering, specially underrepresented minority and women. This paper presents a workshop offered to Hispanic students from several levels within the K-12 grade range. It includes a crash course in Electricity and Electronic basics and a hands-on activity in which students build several circuits from simple series circuit to more complex circuits, including an electronic piano circuit, as the highest difficulty. A group of students trained to serve as ushers in the workshop have accompanied the author in visits to several schools to offer this workshop, with great acceptance from the students. In the training session the ushers have to assemble all the circuits and make sure all the components are in good conditions. The ushers were undergraduate or graduate students from University of Puerto Rico at Mayaguez, (UPRM) Electrical and Computer Engineering Department. The piano circuit has been built successfully in all our visits to K-12 schools. In addition, we encourage teachers to build the circuit and provide them with the Theory Sheets, Instructions Sheet, and Materials List (in Spanish and/or English) for future replication with other groups.

Most children enjoy hands-on experiences in which they can build objects that can actually accomplish a task. With that in mind, we developed this workshop to demonstrate that electricity is not as complicated as often perceived. In fact it can be entertaining, fun, and a learning experience all at the same time, provided children are careful and know what they are doing. This workshop was presented before audiences of different levels and adjusted accordingly. For example, for smaller grades the workshops starts with an explanation of what is a conductor and an isolator material (see Isolating and Conducting Materials section below). Higher grades go directly to explaining the several electronic elements they will use and how to read a schematic and built it on the circuit board. Previous to the electronic piano, four different circuits were built by all the groups including a series and parallel circuit using Christmas light bulbs, an electromagnet, and an electronic doorbell. The groups were divided into small working groups of 3-4 students together with one usher.

Our main goal is to motivate K-12 students to pursue careers in electrical engineering, show them how engineering helps people's lives, and to demystify the difficulty associated with engineering fields. For this purpose, all hands-on activities are preceded with a Power Point presentation about what is Engineering, and within it, what is Electrical Engineering. In addition, many of the ushers participating are female to serve as role models for girls and boys. This also serves as a double purpose to train undergraduate and graduate students in outreach activities and motivate them to pursue their professional career in the academia.

Each section below explains a summary of the material presented to the students and the activities performed in each of the subjects.

BASIC CIRCUIT ELEMENTS

We begin our explanation by stating that electricity is the movement of small particles called electrons. Everything is composed of microscopic particles called atoms, inside of which are even smaller particles called electrons. Thousands of millions of electrons move creating a current [1].

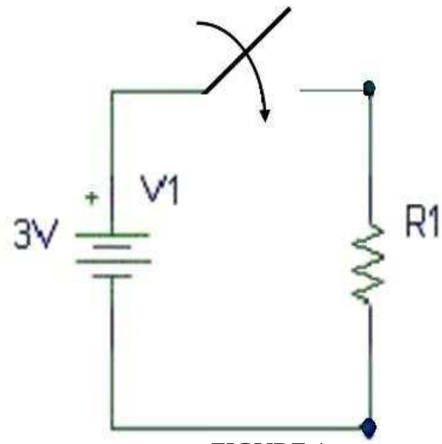


FIGURE 1
DIAGRAM OF A SIMPLE ELECTRIC CIRCUIT CONSISTING OF A 3 VOLTS BATTERY CONNECTED TO A RESISTOR AND A SWITCH. THE SWITCH HAS TO BE CLOSED TO ALLOW THE FLOW OF CURRENT.

Isolating and Conducting Materials

In this topic discussion, all students are told they each represent an atom. Some atoms have free electrons with higher energy which allows them to be easily detached from the atom's nucleus. These are atoms from a conducting material. Atoms from isolating materials have few, if any, free electrons. The whole group of students is first told they will play the role of an isolating material. Mint candy balls are distributed among a few of the students and we ask the students to pass the "electrons" (mints) to a nearby student every time we clap. Not much commotion is created in the room. We then distribute mint candies to almost all of the students in the group and tell them they now represent a conducting material. Again, every time we clap, they have to pass the electron to a student next to them. There is a big commotion in the room. This, we tell them, is similar to what's going on inside a conducting material; there are electronic movements (electrical current) within the material, but the net movement or current is zero because the "electrons" are traveling to different directions around the room. For a net current to exist there has to be a force that drives them all to the same direction (as if they all passed the candy to from one end of the room to the other in the same direction). This force is called a voltage potential and is provided by a power source such as a battery or an electric outlet. At the end of this section, all students are allowed to eat their "electrons".

Electricity has to travel in a complete closed loop (see Figure 1), from the battery (which supplies the power) to the appliance we want to operate electrically, such as a light bulb or a TV. This is represented with an R, which means resistance, because it resists or slows down the movement of electrons as it uses some of their energy. Later on, volunteering students will have a chance to represent a resistor or other component and be part of a "human" circuit.

Resistors

We explain that there are actual components that are also called resistors. These components reduce or resist the pass of electrons. This helps controls how much electricity travels in the circuit. Without them some components in the circuit could burn. Resistances are made of carbon inside, which is a poor conductor. Its value is measured in units called ohms [**Ω**]. Students will use resistors of fixed values and a potentiometer which is a resistor that can have variable value.

The value of the resistor depends on the concentration of carbon they have inside. Color coded bands on the resistor identify their resistance value as shown in Figure 2. We explain to the students the color code and ask them to determine the value of some resistors provided to them.

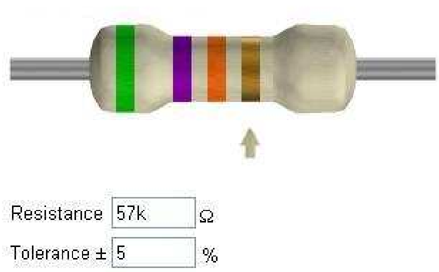


FIGURE 2
EXAMPLE OF A RESISTOR WITH THE COLOR CODE MEANING ON THE SIDE TABLE.[F HTTP://SAMENGSTROM.COM/ELEC/RESISTOR/]

Black	0
Brown	1
Red	2
Orange	3
Yellow	4
Green	5
Blue	6
Purple	7
Gray	8
White	9

FIGURE 3
PICTURE OF A LIGHT EMITTING DIODE (LED) AND ITS SYMBOL BELOW THE PICTURE.

Light emitting Diodes (LED)

Light emitting diodes will also be used by the students in several of the circuits to be built. LED's looks like regular tiny light bulbs (See Figure 3) but they are actually semiconductor devices that turn on only when the current flows on one particular direction. Students are asked to connect the LED with one battery in both possible polarities and see what happens. The longer LED pin is the positive and has to be connected with the positive terminal of the battery for a current to pass through it and light it up.

Capacitors

All capacitors do is store electrons! The simplest capacitors consist of two parallel metallic plates separated by a conductive material called dielectric (see Figure 4 for simple capacitor diagram, its symbol and how they usually look). First, if a capacitor is completely discharged (empty of electrons) and a voltage is applied to the capacitor by connecting it in series with a resistor as shown in Figure 5, it starts charging. As the capacitor starts charging with electrons, the applied voltage is the difference between the battery voltage and the voltage across the capacitor. Therefore, as the capacitor voltage gets similar to the battery voltage, it charges more slowly. This is call exponentially increasing, and for a 9 volts battery, it is expressed as (1).

$$v_c = 9(1-e^{-t}) \text{ [Volts]} \tag{1}$$

The capacitor also discharges exponentially (see Figure 6). Initially, the capacitor has the maximum voltage, therefore it discharges rapidly. In the next instance, it already has less charge, so it discharges more slowly. If we extrapolate the tangent of the discharging curve toward the time axis, we find it intersect at time equal to RC. This is called the ***time constant*** of the circuit. By varying the product RC, we can change the time it takes to charge and discharge. If we change the value of the capacitor only, we obtain a different time constant. [This is the principle we will use in the piano circuit to create vibrations of different speeds, each will correspond to a different sound tone].

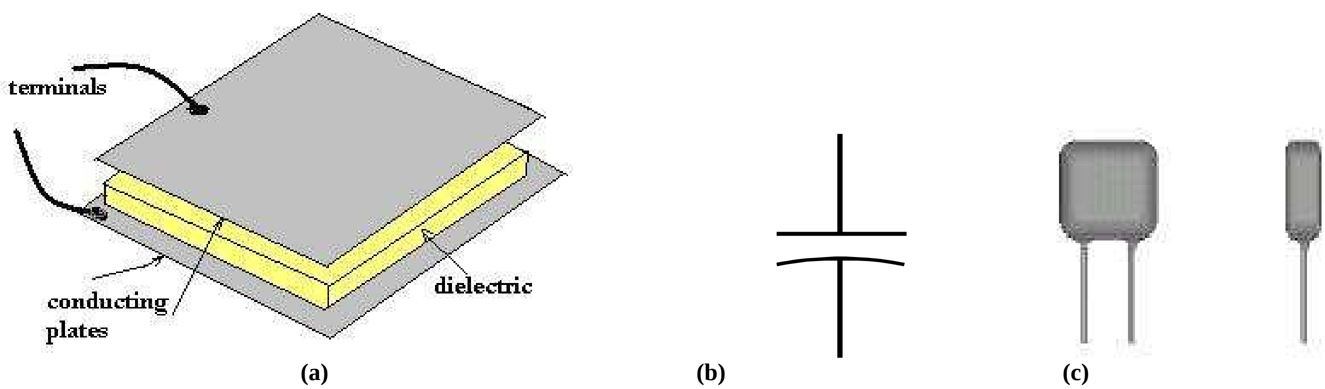


FIGURE 4
DIAGRAM OF A SIMPLE CAPACITOR (A) SIMPLE CAPACITOR, (B) CAPACITOR ELECTRIC SYMBOL, (C) TYPICAL CAPACITOR

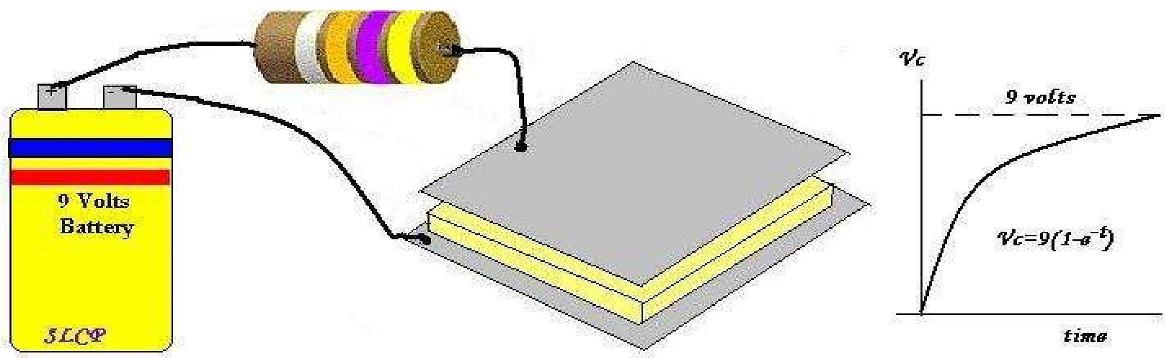


FIGURE 5
CAPACITOR CONNECTED IN SERIES WITH A RESISTOR AND A BATTERY IN CHARGING MODE. THE CURVE ON THE RIGHT REPRESENTS THE WAY THE VOLTAGE ACROSS THE CAPACITOR INCREASES WITH TIME AS IT CHARGES WITH ELECTRONS.

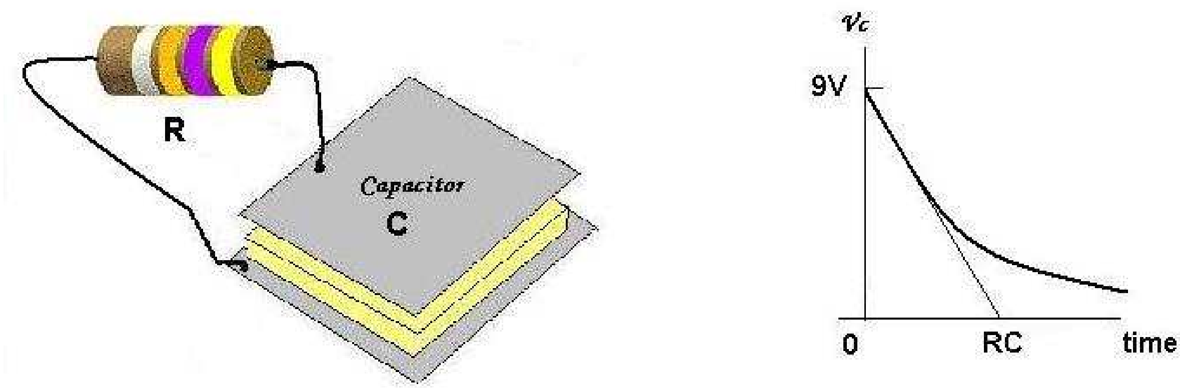


FIGURE 6
CAPACITOR CONNECTED WITH A RESISTOR IN DISCHARGING MODE. THE CURVE ON THE RIGHT REPRESENTS THE WAY THE VOLTAGE ACROSS THE CAPACITOR DECREASE WITH TIME AS IT DISCHARGES. THE CHARGING AND DISCHARGING TIMES DEPENDS ON THE NUMERICAL VALUES OF R AND C.

BASIC CIRCUITS PRESENTED

There are four basic circuits the groups have to assemble by following a circuit diagram. They are presented here (and to the students) in order of difficulty from easier to harder.

Series and Parallel

In this section, a few students are asked to come in front of the room and hold hands in different types of connections. They each represent an electrical component such as a resistor, capacitor or battery. They have to “connect” in parallel, series and in combinations, and we ask the other students in the audience what kind of connection the volunteering students are forming. We explained to them that in the series connection the voltage is divided among all the resistors but the current is the same, analogous to a current of water flowing through a water pipe. For the parallel connection we explain that, in this case, it is the current what is divided as if the circuit was made up of plumbing tubes with water current inside, and the voltage stays the same here, analogous to the potential energy between tubes at higher and lower vertical positions.

At this moment we introduce another electrical term; the node, which is further explained in the next section. Figure 7 show the series and parallel connections. The students will later be asked to connect both circuits using Christmas light bulbs and to determine which of the two connections allows for more bulbs to be lighted, and explain why in terms of amount voltage and/or current reaching the bulbs. The series and parallel circuits will be built by simply wrapping the light cable ends together, without the use of the circuit board.

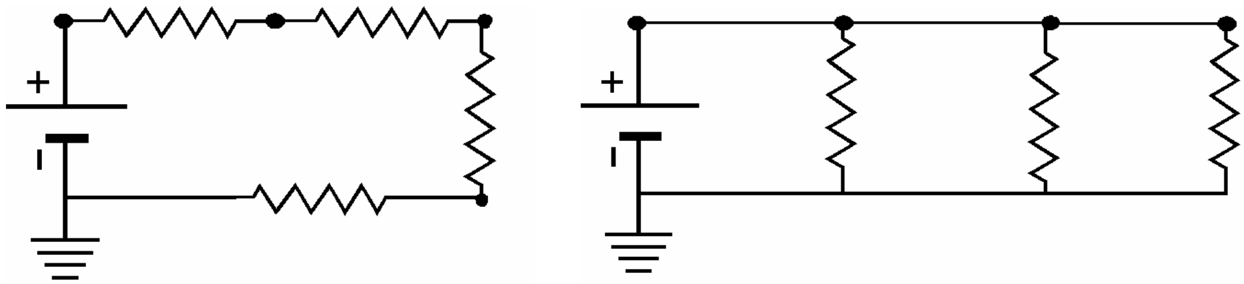


FIGURE 7
SCHEMATIC OF CIRCUITS WITH COMPONENTS CONNECTED IN SERIES (LEFT) AND IN PARALLEL (RIGHT)

What is a node?

A node is a point in which two or more elements connect. In the previous demonstration we ask the students in the audience to name the number of nodes in each of the "human circuits" made up of students. Then they are shown Figure 8 and asked again for this specific circuit, how many nodes are there in the circuit. They will need to master this concept to be able to connect the components on the circuit board later on.

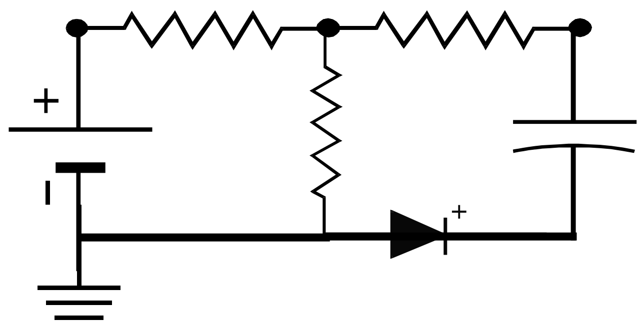


FIGURE 8
SCHEMATIC OF A CIRCUIT WITH FIVE (5) NODES

Circuit board

Figure 9 shows a representation of a circuit board used to connect electronic components. There are about 30 horizontal nodes, each consisting of 5 holes in a row. In addition, there are two vertical nodes at each side with 30 holes in a column. Anything that is plugged inside one hole of the node is connected internally to all the other components plugged into any holes of that node.

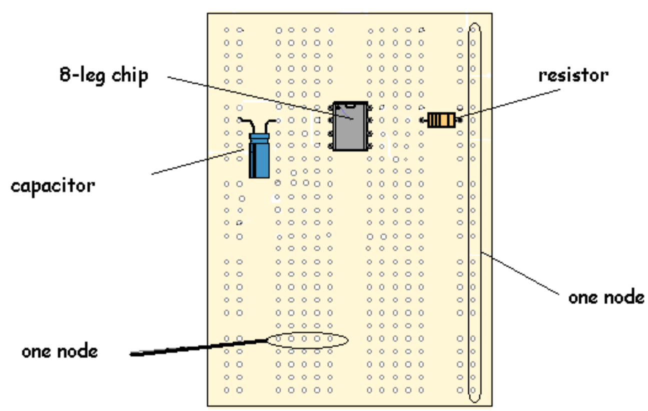


FIGURE 9
DIAGRAM OF THE CIRCUIT BOARD SHOWING THE POSITIONG OF THE 555 CHIP AND TWO KINDS OF NODES.

Electromagnet

Electricity and magnetism were once considered as separate physical phenomena. It wasn't until Prof. Oersted in Finland was explaining before a group of his students what these concepts were, when he noticed that an electrical current was causing a magnetic compass needle he had just used for his magnetism explanation, to move. This was the first indication, that electricity could produce magnetism. Eleven years later, at about the same time, Hertz and Henry demonstrated that magnetism can also produce electricity. This was the beginning of Electromagnetism, a field responsible for such applications as cell phones, satellite television, microwave ovens, and many others.

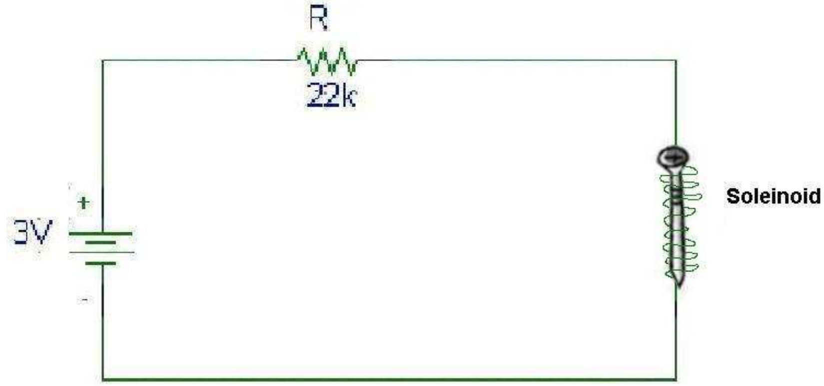


FIGURE 10
DIAGRAM OF THE CIRCUIT USED TO CONVERT A REGULAR METAL NAIL INTO A MAGNET. THE SOLENOID WRAPS AROUND THE NAIL. CONNECT FOR ONLY A FEW SECONDS AND BE CAREFUL BECAUSE THE CIRCUIT CAN GET VERY HOT.

In this section the students have to assemble the circuit shown in Figure 10. They need to be careful because the solenoid can overheat if the circuit is connected for more than a few seconds. The solenoid was assembled using a piece of plastic straw and wrapping a magnetic wire around it; then an aluminum nail is placed inside the straw. It is important to choose regular nails not special non-magnetized nails which will not work here. The current circulating the nail will induce a magnetic field which will turn the nail into a magnet by aligning all the free charges inside the nail's metallic material. After the students connect the circuit for about 10 seconds, they take the nail out and place it close around a compass provided to each team to try to move the needle of the compass with this new magnet. They can observe how the nail moves the needle, behaving as a magnet. This circuit is built on the circuit board.

Doorbell

Figure 11 shows a simple circuit that can be used as a doorbell. This circuit was first presented by us to a group of sixth grade girls as part of an electronic summer camp [2]. The circuit uses an LED in series to a resistor, battery and a single tone buzzer. Every time the circuit is closed the LED and the buzzer turn on acting as a doorbell. This circuit was also built on the circuit board.

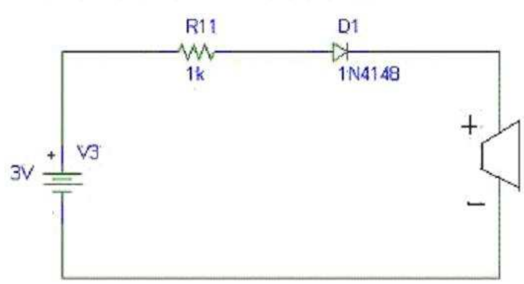


FIGURE 11
CIRCUIT DIAGRAM FOR THE ELECTRONIC DOORBELL.

PIANO CIRCUIT

An electronic piano consist of several electric components that produce a voltage signal with a varying frequency. This signal is fed to a speaker, which vibrates more or less depending on the frequency of the signal, hence producing sound of different tones. We need to build a circuit that will produce a voltage signal that varies its frequency within a range of audible frequencies for the human ear.

Speaker

A speaker has a small piece of rock called *piezoelectric* which shrinks or expands according to the electrical voltage applied to it [4]. This vibration (the shrinking and expansion) creates a sound wave in the air. When the electrical signal changes very rapidly (high frequency) it makes the speaker vibrate quickly producing a high pitch sound. When the applied signal is a slower varying voltage (low frequency), it produces a low pitch sound.

The 555 Timer Regulator Chip

In order to produce a time varying signal, we need a component that works similar to a clock, producing a periodic signal whose frequency can be controlled in some way by the outer components connected to it. For this purpose, we use an integrated circuit or *chip*, called the 555 timer regulator. Inside the 555, there are a lot of electronic micro-components made up with semi conductor materials. That's why it is called an integrated circuit. The 555 timer regulator is one of the more versatile integrated circuits ever produced. It can be used to build lots of different circuits. It contains 23 transistors, 2 diodes, and 16 resistors inside a very small package with eight legs type DIP (dual-in-line package) [3]. See Figure 12. The students are taught the pin number order on the chip.

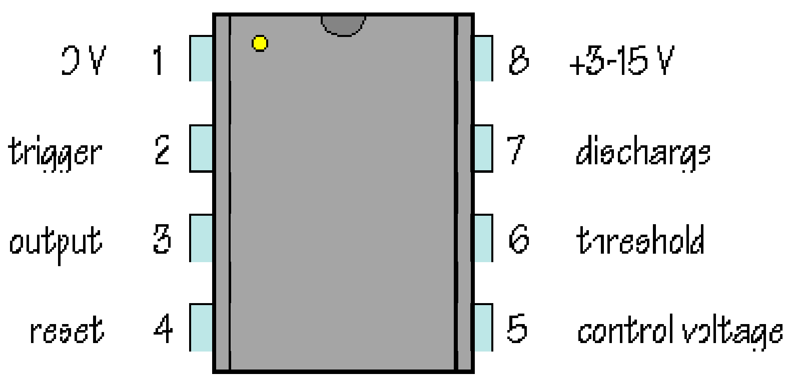
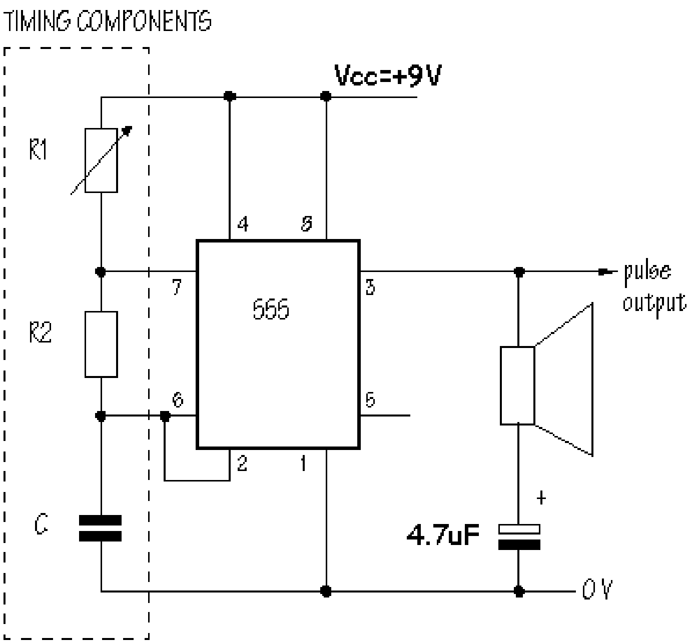


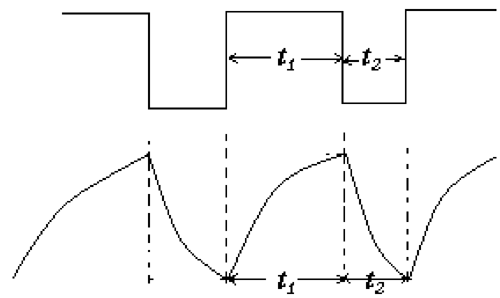
FIGURE 12
THE 555 TIMER REGULATOR PIN LAYOUT (FROM WWW.DOCTRONICS.CO.UK/555.HTM.

The 555 timer regulator can be used to build an astable circuit. Astable circuits produce pulses, like a digital clock. The connection most people use to make a 555 astable circuit looks like that in Figure 13. In this figure, R1 has an arrow which indicates change. This is because R1 is a potentiometer, a resistor with a variable resistance. Use a small screwdriver to turn the knob all the way clockwise to set it to its maximum value (100kΩ). Later this value can be adjusted to obtain a different tone. [We can also substitute the potentiometer by a 1.0 or 1.5 kilo ohms resistor with no adverse effect on the piano operation, except that the tones will be fixed. This turns to be simpler and easier to built for most students and teachers.]

Legs 2 and 6 are connected together so that the circuit triggers itself at every time cycle, behaving as an oscillator. The capacitor labeled C, is charged through the resistors R1 and R2, but is discharged using R2 only. The charge in C1 is between 1/3 *Vcc* and 2/3 *Vcc* (Here *Vcc*=+9V). The makes the oscillation frequency independent of *Vcc*.

To build the piano, we need to use different capacitors, one for each desired tone, as shown in Figure 14. Special care has to be exercised to connect the 4.7 μF capacitor with the right polarity, between the ground (0 volts) and the speaker since this is a special polarized capacitor, called electrolytic capacitor, which otherwise will burn. Students should use a battery of 9V with a battery snap adapter. We stress that the battery should be the last thing connected after an usher has verified the circuit to make sure all connections are correct. A long cable from pin 6 (or 2) should be used to connect to the various capacitors to listen to the different tones of the piano. The kids are usually let to play for a while with the newly built electronic piano.

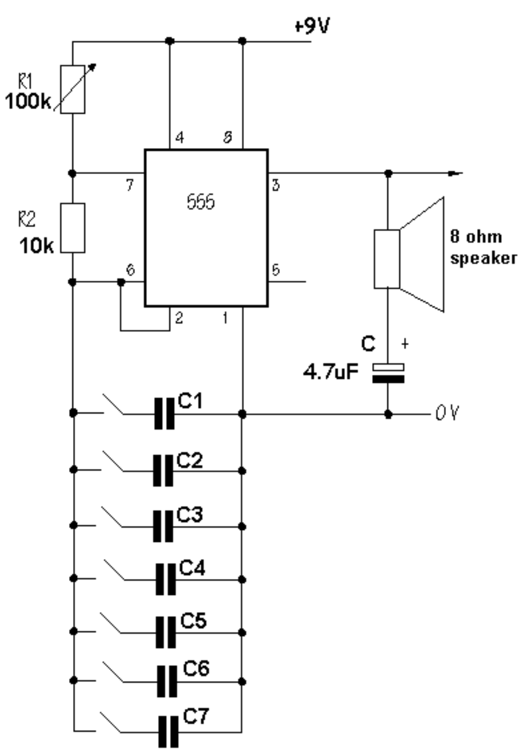




$$t_1 = .693(R_1 + R_2)C_1$$
$$t_1 = .693(R_2)C_1$$
$$frequency = \frac{1.44}{(R_1 + 2R_2)C_1}$$

FIGURE 13

DIAGRAM OF THE ASTABLE CIRCUIT WHICH OUTPUTS A PULSE SIGNAL SIMILAR TO THAT OF A CLOCK. THE FREQUENCY OF THE OUTPUT SIGNAL DEPENTS ON THE VALUE OF THE CAPACITORS USED IN THE CIRCUIT.



Values of the capacitors for audible frequency:

	C(µF)	Frequency (Hz)
C1	.100	111
C2	.068	170
C3	.047	230
C4	.033	348
C5	.022	490
C6	.015	718
C7	.010	1,173

FIGURE 14

ELECTRICAL SCHEMATIC OF THE ELECTRONIC PIANO SHOWINGF THE OUTPUT SIGNAL AND THE EQUATIOINS GOVERNING THE TIME CONSTANTS AND OUTPUT FREQUENCY.

SCHOOL VISITS

As part of the educational component of two NSF ERC (Engineering Research Centers), namely the Center for Subsurface Sensing and Imaging Systems (CenSSIS) and the Center for Collaborative Adaptive Sensing of the Atmosphere (CASA), we have participated in a series of visits to elementary, middle and high schools in the area. In addition, this summer this workshop was presented to a group of twenty 11th grade students participating in a Pre-Engineering Program.

(A)

(B)

FIGURE 15

(A) SIXTH GRADE STUDENTS BUILDING A CIRCUIT BY FOLLOWING THE ELECTRICAL DIAGRAM. AND (B) ONE OF THE USHERS (A GRADUATE STUDENT) SUPERVISING SIXTH GRADE RS TRYING OUT THE ELECTRONIC PIANO.

The reaction of the large majority of the students was very positive. The students seemed very motivated, and some expressed their desired to study engineering. When asked, all raised their hands indicating they enjoyed and learned from the workshop. Their favorite circuit was always the electronic piano. In order to reach out to more students this workshop was presented this summer to a group of twenty 5th - 9th grade teachers from Colorado, Arizona, Massachusetts, Oklahoma and Puerto Rico as part of the CASA Summer Institute for Teachers which took place in Amherst, MA on July 25-30, 2004. The teachers received workshops on several areas in addition to this workshop, including, radar systems, meteorology, binary logic, internet resources and grant writing. At the end of the week they expressed their excitement and their intentions to incorporate some of the material presented here in their curriculum.

FIGURE 16

SOME OF THE TEACHERS PARTICIPATING AT THE CASA SUMMER CONTENT INSTITUTE AT AMHERST, MA WITH DR. CRUZ-POL (CENTER STANDING).

FINAL COMMENT

This work was intended to create awareness among students from all age groups in the K-12 range of what is engineering as well as to motivate them to study engineering. It is also intended to show that engineering can be fun. The activities explained here are modified according to the level of the group presented and are performed with the help of university students that are previously trained to serve as ushers. Not only do the K-12 students benefit from these kinds of activities but the university students expressed their enthusiasm and willingness to participate in the activities. Most mentioned that they really enjoyed serving as ushers. In addition, the teachers that participated in the summer institute expressed that they learned a lot from the experience and that they plan to integrate some of the concepts learned in their curriculum. Many of these activities can be performed with materials of little cost and some of the materials are even offered free of charge by the NSF (http://www.sae.org/foundation/awim/).

ACKNOWLEDGEMENT

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[5] http://www.elexp.com/t_resist.htm