Design of an Educational Oscilloscope

A Hands-On Learning Tool

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Abstract— **Paradoxically, most engineering students do not possess an in-depth knowledge on how an oscilloscope works. Automation is partly to be blamed for this problem. In fact, the existence of the "auto scale" button has eliminated the hassle of making adjustments, but at the price of dampening the students' curiosity and removing their need for deep understanding.**

We have found a powerful way of stimulating students' curiosity and of bestowing them with knowledge of the basic oscilloscope operation: While still using an oscilloscope-set, although merely as a display unit, we have by-passed its fundamental components (namely the vertical amplifier, the time base and the trigger circuit), with our own designed components, built outside of the oscilloscope-set. Our teaching strategy provides students with hands-on experimentation of the circuits that control vertical gain, the time scale and the trigger level. Our educational tool is *implemented in hardware*; it is not another simulation oscilloscope.

The effects of our didactic tool are highly positive, as demonstrated by student evaluation of circuit laboratories that took place before and after we incorporated the Educational Oscilloscope into the engineering curriculum. This paper provides the reader with the following educational facilities: the Educational Oscilloscope circuit schematics, as well as the explanation of its several components as provided to the engineering students at SUNY New Paltz.

Keywords-component; design; education; oscilloscope.

I. Introduction

Research has been conducted on the use of the oscilloscope as a tool for learning different topics. Examples of these topics include the engineering concepts of sampling and quantization [1], or even unsuspected topics, such as how to improve word-pronunciation by obtaining feedback from the speaker's voice signal displayed on the oscilloscope screen [2].

The focus of this paper is however on teaching the operation of the oscilloscope itself. Many books on the topic exist [3 -5], but of course they provide knowledge that is theoretical rather than practical.

Several tutorials exist on the Internet where practical operation of the oscilloscope operation is taught via the use of oscilloscope simulation. In [6], the author discusses how to implement one such oscilloscope simulation with the objective of using it for on-line teaching.

Although the oscilloscope simulation approach has the advantage of showing what the different knobs and switches do, it has the disadvantage that it does not teach *why* they do it. Our educational objective is for engineering students to learn not only what the different control elements do, but mainly which circuits they control inside of the oscilloscope. We believe that students will have a better chance to achieve this objective by learning from a hardware circuit than from a simulated one. This belief created the concept of the Educational Oscilloscope.

The need for the Educational Oscilloscope was motivated by assessment of the SUNY New Paltz engineering course "EGE322 Electronics I Lab," performed by the paper's first author. As part of this assessment, there was a survey answered by the course students. One of the survey questions was: "Were you able to use the lab measuring instruments properly?" The common response of many students was that they were expected to use the instruments in the laboratory but had not received any training on how to do it. Such an obvious action had been overlooked! Using this student feedback, teaching of laboratory instrument operation was incorporated into the curriculum.

Although this action had a positive effect, student complaints about the use of the oscilloscope still remained, as evidenced by the following student's comment: "However, I still do not understand completely how to use the oscilloscope. Whenever I could not get a steady image, I would call the instructor, and he would touch the trigger control and make it work. He did not have time for explaining what he did in detail, as he was busy assisting other students."

To fix this problem, the Educational Oscilloscope was created. In order to implement the Educational Oscilloscope idea, a Senior Design Project was utilized. This Senior Design

Project was executed by this paper's second author and supervised by the first author.

II. THE EDUCATIONAL OSCILLOSCOPE

A. The Main Design Idea

The basic design idea is explained with the aid of Figure 1:

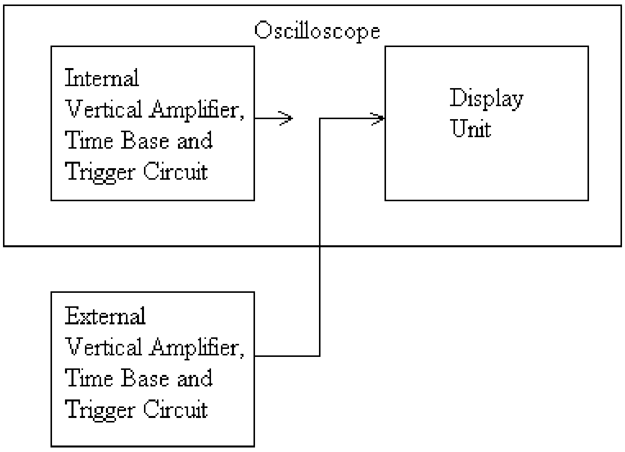

Figure1: The main idea in the Educational Oscilloscope

The oscilloscope internal components Vertical Amplifier, Time Base and Trigger Circuit are being by-passed by corresponding external components, which were designed in a Senior Design Project. The only unit retained from the oscilloscope is its display system (CRT electron beam and phosphorous screen).

With this action, the Vertical Amplifier, Time Base and Trigger Circuit have been "brought outside" of the oscilloscope unit, and therefore, students have now direct access to them. They have access to a circuit whose components they can see, touch and understand. They are able to relate operating on these components to the effects produced on the oscilloscope screen. This hand-on cause-effect interaction has a powerful didactic effect on the students' understanding of the oscilloscope operation.

It must be clarified that the external Vertical Amplifier, Time Base and Trigger Circuit are not as complex and elaborated as the corresponding components inside. As a matter of fact, for didactic reasons, our goal was to make them as simple as possible, as long as they are able to capture the essence of the internal components' functionality. As it turns out, this can be achieved by using simple Operational Amplifier, gate and flip-flop circuits, whose knowledge is acquired by SUNY New Paltz students in the Circuit Analysis and Digital Circuits courses.

B. General Block Diagram

The general block diagram is shown in Figure 2:

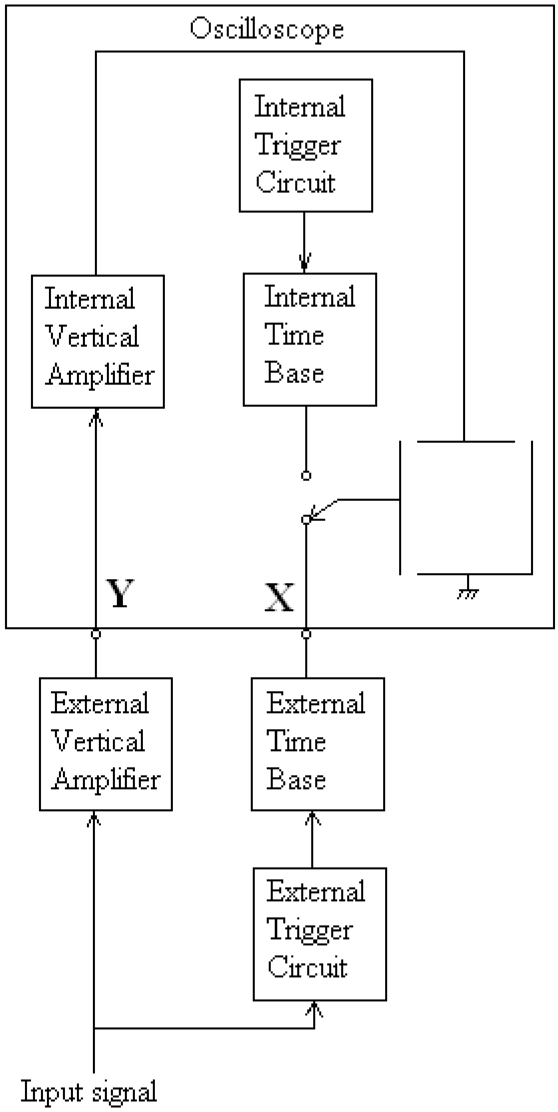

Figure 2: General block diagram of the Educational Oscilloscope

The signal to be displayed is input to the external Vertical Amplifier. This amplifier amplifies this signal with a gain that is controlled by the user. In other words, the user can control the "volts/division" by changing the amplifier's gain. The amplified signal is then output to the **Y** input of the oscilloscope. It must be noted that, although the signal experiences further amplification inside the oscilloscope, the gain of the vertical amplifier inside the oscilloscope is left fixed at a certain value, which gives the user total control of the signal amplification. (Accurately speaking, the Vertical Amplifier is the only of the three external units that does not by-pass the corresponding internal unit; it just adds to it. On the other hand, as will be seen next, the external Time Base and Trigger Circuit completely by-pass the internal ones.)

The external Time Base generates a saw-tooth waveform whose slope is controlled by the user. By changing the slope, the user controls the "Time/Division". The saw-tooth waveform is input to the "X" input of the oscilloscope and the oscilloscope is set in the **XY** mode. *This is the key idea of the design*! As illustrated in Figure 2, with this simple action, the external Time Base (controlled by the external Trigger Circuit) completely by-passes the internal Time Base (controlled by the internal Trigger Circuit). The oscilloscope's **X** input, which is normally used to produce Lissajous figures, is now used to connect the external Time Base.

By adjusting knobs on the external Trigger Circuit, the user can control the starting time of the saw-tooth waveform produced by the external Time Base. This in turn controls the instant of time at which the input signal starts being displayed. Details of the three external units are provided in the next section.

C. Individual Blocks of the Educational Oscilloscope

This section has two objectives: a) To explain to the reader the individual blocks of the Educational Oscilloscope and b) to outline the theoretical explanation on the Educational Oscilloscope that is provided to students. Accomplishing objective b) is the reason why the reader who is experienced in electrical engineering will find the following explanation simplistic. In addition, recall that the value of the paper is on education, not hardware design. The educational strategy is precisely to design very simple external circuits that are still able to capture the essential functionality of the internal ones.

<u>External Vertical Amplifier</u>:

The external Vertical Amplifier is shown in Figure 3:

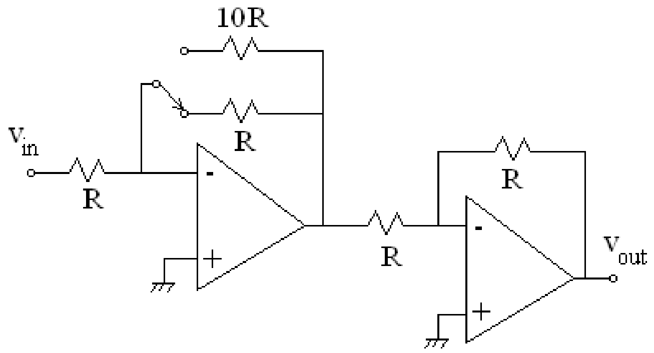

Figure 3: Schematic of external Vertical Amplifier

The equation of this circuit is:

$$v_{\text{out}}(t) = K_1 v_{\text{in}}(t)\,, \quad (1)$$

where in the example, constant K_1 can take the values $K_1 = 1$ or $K_1 = 10$, depending on the position of the switch. The input signal to be displayed is connected to v_{in}, and v_{out} is connected to the **Y** oscilloscope terminal. Now, the vertical displacement $y(t)$ on the oscilloscope screen is proportional to the voltage applied to the **Y** terminal, that is:

$$y(t) = K_2 v_{\text{out}}(t)\,, \quad (2)$$

where K_2 will keep the same value provided that the vertical gain control on the oscilloscope panel is not changed. Combining equations (1) and (2):

$$y(t) = K_1 K_2 v_{\text{in}}(t)\,. \quad (3)$$

This means that the vertical displacement is proportional to the input signal through the proportionality constant $K_1 K_2$, and that thereby the "volts/division" can be adjusted externally by changing the value of K_1.

<u>External Time Base</u>:

The external Time Base is shown in Figure 4:

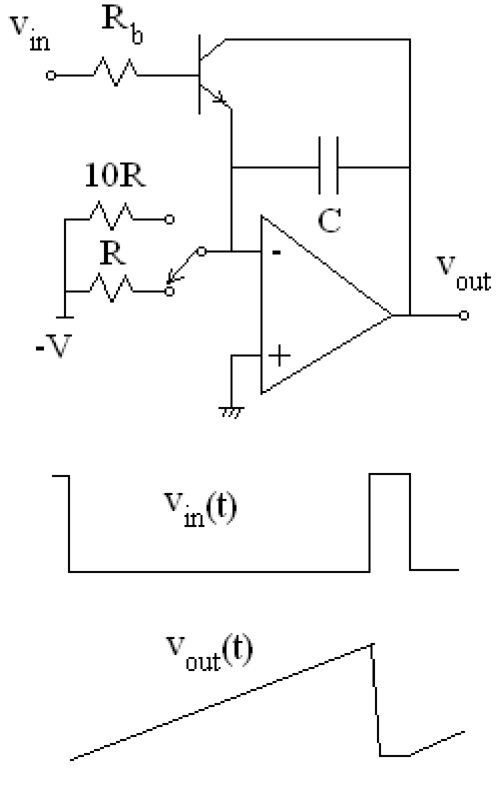

Figure 4: Schematic of external Time Base

The signal v_{in} is a digital signal. On one hand, when $v_{\text{in}} = \text{LOW}$, the transistor is off, which allows capacitor C to charge at a constant rate. This results in the output voltage being a ramp, whose equation is:

$$v_{\text{out}}(t) = K_3 t \quad \text{for} \quad v_{\text{in}}(t) = \text{LOW}\,, \quad (4)$$

Where $K_3 = V/(RC)$ or $K_3 = V/(10RC)$, depending on the position of the switch. On the other hand, when the input voltage is high, the transistor saturates and shortens the capacitor, which produces:

$$v_{\text{out}}(t) = 0 \quad \text{for} \quad v_{\text{in}}(t) = \text{HIGH}\,. \quad (5)$$

The result is a saw-tooth waveform $v_{\text{out}}(t)$ (see Figure 4), which is connected to the **X** oscilloscope terminal. Now, the horizontal displacement $x(t)$ on the oscilloscope screen is proportional to the voltage applied to the **X** terminal, that is:

$$x(t) = K_3 K_4 t \quad (\text{for } v_{\text{in}} = \text{LOW}) \quad . (6)$$

This means that the horizontal displacement is proportional to "time" through the proportionality constant $K_3 K_4$, and that thereby the "seconds/division" can be adjusted by changing the value of K_3, which is the slope of the ramp (Equation 4). It also means that "time" starts at the instant where signal v_{in} becomes LOW and stops at the instant when signal v_{in} becomes HIGH. In order for the input signal image to be steady on the oscilloscope screen, the start and stop times have to be synchronized with the input signal. This is accomplished by the circuit described next.

<u>The External Trigger Circuit</u>:

The action of the external trigger circuit is explained with the help of Figure 5:

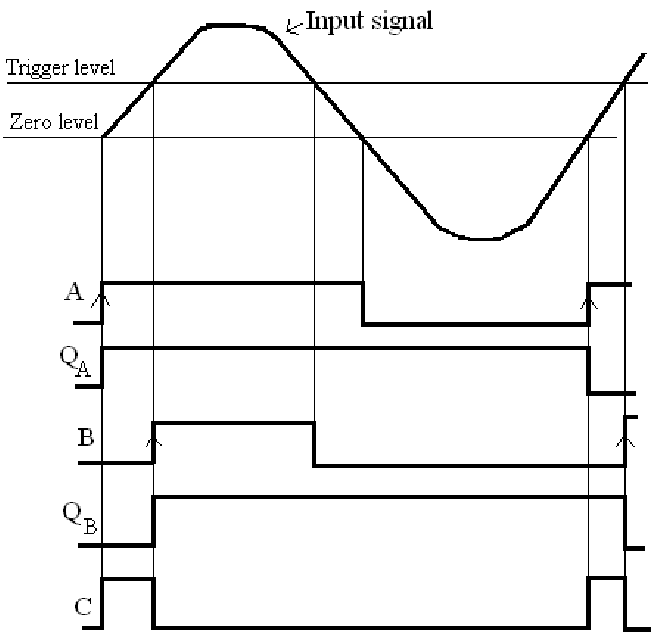

Figure 5: Waveforms in external Trigger Circuit

As illustrated by the waveforms in Figure 5, the external Trigger Circuit is very simple (remember the idea is just to capture the essence of the trigger functionality). The objective is to generate waveform C so that it can be applied to the input v_{in} of the external Time Base circuit (Figure 4). We achieve this objective in the following way: First we generate signal A, as the result of comparing the input signal with zero volts. The leading edge of signal A will be used to clock a "toggle" flip flop, thus producing signal Q_A. Then, we generate signal B, as the result of comparing the input signal to a triggering level selected by the user. The leading edge of signal B will be used to clock a "toggle" flip flop, thus producing signal Q_B. Finally, from Figure 5, note that signal C is an "exclusive or" (XOR) of signals Q_A and Q_B, that is:

$$C = Q_A \overline{Q}_B + \overline{Q}_A Q_B = Q_A \oplus Q_B \,. (7)$$

Using the precedent analysis, the circuit design of the external Trigger Circuit is straightforward, as shown in Figure 6:

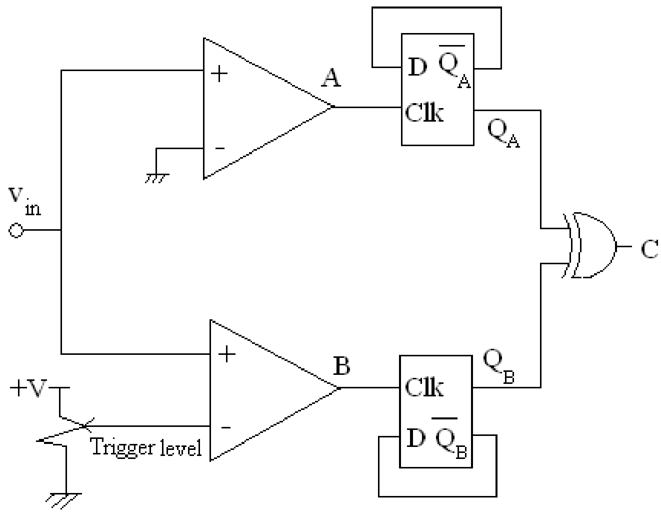

Figure 6: Schematic of external Trigger Circuit

The input signal to be displayed is connected to terminal v_{in} of Figure 6, and C is connected to terminal v_{in} of Figure 4. This means that C is the signal that controls the Time Base ramp waveform. In fact, C switching to the LOW state starts the ramp and C switching to HIGH stops the ramp. Therefore, by changing the trigger level (C switching to LOW), the user controls the start of the ramp, and thus the starting value of the displayed input signal.

In this very simplistic Trigger Circuit, the ramp is terminated when the signal crosses zero with a positive slope, and the saw-tooth waveform remains at zero value during the time interval when $C = \text{HIGH}$. Since our elementary external Trigger Circuit does not suppress the oscilloscope electron beam during this time interval, the displayed image will exhibit "retrace". Also note that this elementary trigger circuit lacks other features, such as the possibility of triggering the ramp with the negative slope of the input signal. Nevertheless, these inconveniences do not subtract from the didactic value of the circuit, which still manages to capture the essence of the trigger circuit operation.

Finally, Figure 7 is a snapshot of the input and output waveforms of the external Trigger Circuit. The sinusoid is the input waveform and the rectangular pulse is the output waveform (signal C in Figure 5).

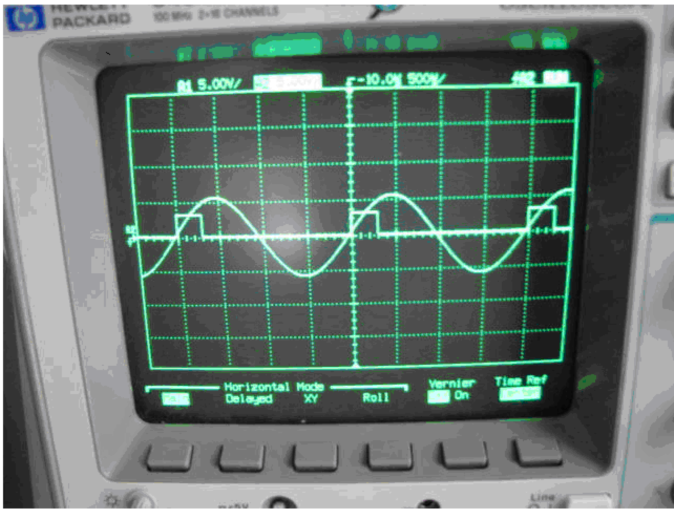

Figure 7: Waveforms of external Trigger Circuit

Figure 8 shows the previous sinusoid waveform plus the saw-tooth waveform produced by the external Time Base.

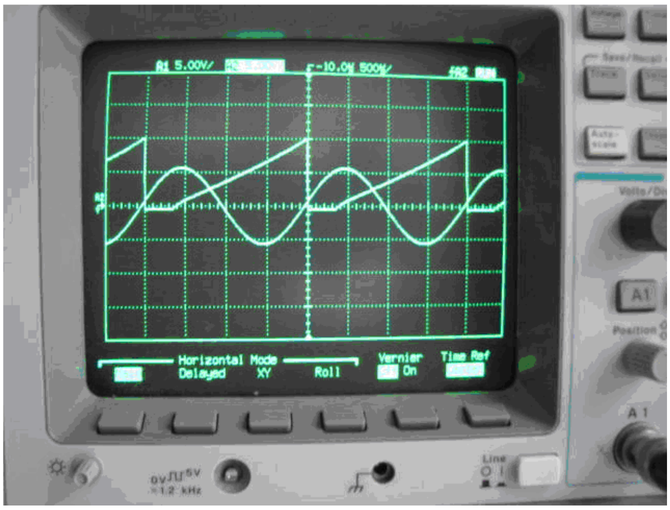

Figure 8: Saw-tooth waveforms of external Time Base

III. IMPLEMENTATION OF THE EDUCATIONAL OSCILLOSCOPE TOOL

The Educational Oscilloscope tool should not be implemented in an introductory level course such as Circuit Theory, because students have not yet acquired the theoretical knowledge needed to understand it. Therefore, students taking an introductory circuit laboratory should manage via the simplistic approach of hitting the "auto scale" button. Their time for learning the oscilloscope in more depth will come later.

At SUNY New Paltz this time is at the beginning of the course EGE322 Electronics 1 Lab. By the time that students take this lab, they already have acquired knowledge on the Operational Amplifier (as a block) and on gates and Flip Flop digital circuits, which is essential to understand the circuits used in the Educational Oscilloscope.

The Educational Oscilloscope is first introduced to the students as a lecture, which was basically outlined in Section II. After the lecture, and before students are allowed to put their hand on the Educational Oscilloscope, they are required to answer a set of questions. The objective of these questions is to force students to generate a theoretical expectation for what the consequences of their experimental actions will be. Without the students being able to produce this theoretical expectation, the didactic experience would have little value.

The questions were carefully devised to guide the learning process. There are three sets of questions: 1) Questions on the Vertical Amplifier, whose objective is for students to learn why and how the "volts/division" scale is changed; 2) Questions on the Time Base, aimed at teaching students why and how the "time/division" scale is changed; and 3) Questions on the Trigger Circuit whose objective is to teach students: a) why the time base generator has to be synchronized with the input signal and b) How to control the instant of time when the input signal starts being displayed.

Once students have answered this set of questions satisfactorily, they proceed to make measurements. By verifying their answers experimentally they gain powerful knowledge and understanding, as corroborated in the next section.

IV. ASSESSMENT OF THE EDUCATIONAL OSCILLOSCOPE

A specific assessment in the course EGE322 Electronics 1 Lab. was designed to test the efficiency of the Educational Oscilloscope tool. This assessment was conducted at the beginning of the fall 2008 semester, without the Educational Oscilloscope, and at the beginning of the fall semester of 2009, right after the Educational Oscilloscope was implemented for the first time.

The following rubrics were used in the assessment:

TABLE I: RUBRICS USED FOR ASSESSMENT

4	Deeply understands the oscilloscope operations. Consistently does all or almost all of the following: Is able to obtain the desired image on the oscilloscope screen by taking actions (operating on knobs and switches) based on his/her deep understanding. Does not need any help from the instructor.
3	Has an intuitive understanding of the oscilloscope operation. Does most or many of the following: After struggling for some time, is able to obtain the desired image on the oscilloscope screen. His/her actions (operating on knobs and switches) are based on intuition and on memorization of previous experiments. Needs minimal or no help from the instructor
2	Has a weak understanding of the oscilloscope operation. Does most or many of the following: After operating some knobs and switches, is able to get a non-stationary image on the oscilloscope screen. At this point, in order to get a steady image on the oscilloscope, he calls the instructor for help.
1	Has no understanding of the oscilloscope operation. Consistently does all or almost all of the following: After connecting wires, immediately calls the instructor for help. Usually uses the excuse: "I have connected everything like in the lab schematics, but it does not work".

Figure 9 shows the results of the assessment. The vertical bars represent the percent of students that fall in a particular rubric, as defined in Table 1. The white bars correspond to assessment performed in the fall of 2008, without the Educational Oscilloscope, and the black bars to assessment performed in the fall of 2009, with the Educational Oscilloscope.

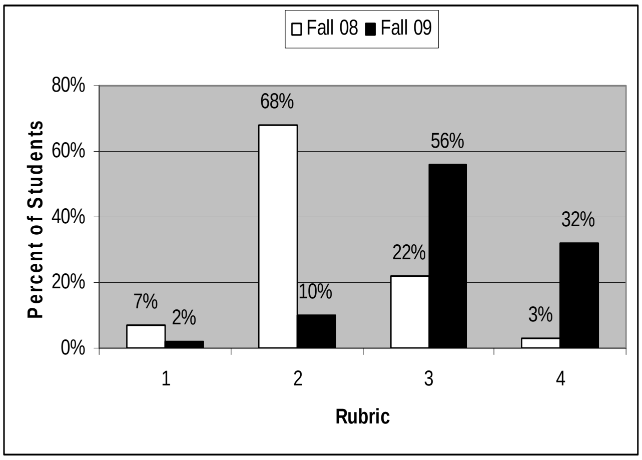

Figure 9: Assessment of Electronics 1 Lab without and with the Educational Oscilloscope

Incorporating the Educational Oscilloscope has the effect of shifting students from the lower to the higher rubrics. In fact, the student population migrates into the higher rubrics 3 and 4.

V. CONCLUSIONS

We have utilized a Senior Design Project to develop an Educational Oscilloscope, which is a powerful tool for teaching students how the oscilloscope works. The main idea is to by-pass the oscilloscope internal components by external ones that students can understand and manipulate.

The developed tool exhibits a very simple design, solely based on Operational Amplifiers, gates and Flip Flops. This is not a drawback, but rather an important didactic advantage. In fact, students who have taken basic engineering courses such as Circuit Theory and Digital Electronics are able to comprehend the design in its totality. Of course, such a simple design of the external components cannot duplicate all the functions performed by the oscilloscope internal components. This is quite acceptable because the main goal of the external components is to capture the functionality principle of the internal counterparts.

The proposed teaching approach is highly effective. This conclusion is supported by the graph of Figure 9, where we can compare the distribution of students in the different rubrics for the cases a) without the Educational Oscilloscope (white) and b) with the Educational Oscilloscope (black). We can see that the student population mainly migrates from the lower rubric 2 to the higher rubrics 3 and 4. According to the definition of rubrics in Table 1, this means that an increased number of students become better at completely understanding the oscilloscope operation, or at least they are able to understand it well enough that they do not need assistance from the instructor.

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REFERENCES

[1] J.W. Pierre and R.F. Kubichek, "Investigating sampling and quantization using a digital storage oscilloscope," Transactions of the IEEE International Conference on Acoustics, Speech, and Signal Processing, (icassp), vol. 5, pp. 2725-2728, 2001.

[2] Kathleen Albertson, "Teaching Pronunciation with an Oscilloscope," Journal of the National Association of Learning Laboratory Directors, vol. 13, pp. 25-30, 1979.

[3] Thomas H. O'Delle, "Circuits for Electronic Instrumentation," Cmabridge University Press, 1991.

[4] Ian Hickman, "Oscilloscopes," 5th edition, Newnes (Elsevier), Burlington MA, 2000

[5] Walt Boyes et al, "Instrumentation Reference Book, 3rd edition, Elsevier Science, Burlington MA, 2002.

[6] R. Gianetti, "An analog oscilloscope simulator with Internet interaction capability for on-line teaching," IEEE Transactions on Education, vol. 41, issue 4, pp. 1-9, 1998.