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# Active Analog Circuit Design: Laboratory Project and Assessment

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# ACTIVE ANALOG CIRCUIT DESIGN: LABORATORY PROJECT AND ASSESSMENT

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Ravi P. Ramachandran received the B. Eng degree (with great distinction) from Concordia University in 1984, the M. Eng degree from McGill University in 1986 and the Ph.D. degree from McGill University in 1990. From October 1990 to December 1992, he worked at the Speech Research Department at AT&T Bell Laboratories. From January 1993 to August 1997, he was a Research Assistant Professor at Rutgers University. He was also a Senior Speech Scientist at T-Netix from July 1996 to August 1997. Since September 1997, he is with the Department of Electrical and Computer Engineering at Rowan University where he has been a Professor since September 2006. He has served as a consultant to T-Netix, Avenir Inc., Motorola and Focalcool. From September 2002 to September 2005, he was an Associate Editor for the IEEE Transactions on Speech and Audio Processing and was on the Speech Technical Committee for the IEEE Signal Processing society. Since September 2000, he has been on the Editorial Board of the IEEE Circuits and Systems Magazine. Since May 2002, he has been on the Digital Signal Processing Technical Committee for the IEEE Circuits and Systems society. His research interests are in digital signal processing, speech processing, biometrics, pattern recognition and filter design.

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Ying Tang received the B.S. and M.S. degrees from the Northeastern University, P. R. China, in 1996 and 1998, respectively, and Ph. D degree from New Jersey Institute of Technology, Newark, NJ, in 2001. She is currently a Professor of Electrical and Computer Engineering (ECE) at Rowan University, Glassboro, NJ. Her research interests include virtual reality and augmented reality, artificial intelligence, and modeling and scheduling of computer-integrated systems. Dr. Tang is very active in adapting and developing pedagogical methods and materials to enhance engineering education. Her most recent educational research includes the collaboration with Tennessee State University and local high schools to infuse cyber-infrastructure learning experience into the pre-engineering and technology-based classrooms, the collaboration with community colleges to develop interactive games in empowering students with engineering literacy and problem-solving, the integration of system-on-chip concepts across two year Engineering Science and four year ECE curricula, and the implementation of an educational innovation that demonstrates science and engineering principles using an aquarium. Her work has resulted in over 90 journal and conference papers and book chapters.

**Dr. Steven H Chin, Rowan University**

Steven H. Chin is currently the Associate Dean of Engineering at Rowan University. He has been in this position since 1997, while serving as Interim Dean from 2010-2012. He has a Bachelor of Science in Electrical Engineering and Ph.D. from Rutgers University, and Masters of Science in Electrical Engineering from the Johns Hopkins University. His specialization areas are in signal processing and communication system. His current interests include STEM education, and academic partnerships.

# ACTIVE ANALOG CIRCUIT DESIGN: LABORATORY PROJECT AND ASSESSMENT


## ABSTRACT

It is very important that undergraduate teaching of analog circuits be rigorous, involve a laboratory component and stimulate student interest. This paper describes a three week module on active circuits that incorporates circuit design, analysis and testing. The lectures are integrated with the laboratory component and all appropriate concepts in mathematics are covered. Assessment results are based on running the project at three universities, namely, Rowan, Bucknell and Tennessee State. Quantitative results based on student surveys, a concept inventory test and faculty formulated rubrics demonstrate the accomplishment of the learning outcomes.

## INTRODUCTION AND MOTIVATION

A course on the principles of analog circuits is fundamental in the early part of an Electrical and Computer Engineering curriculum. A long standing debate is on how to get students more interested in circuit theory and simultaneously comprehend and apply the basic concepts [1][2]. Project-based learning has been shown to increase student interest, basic design skills [3] and comprehension of the concepts in basic engineering and mathematics through vertical integration [4][5]. Vertical integration is the principle of having a project or experiment in a course build upon concepts gained through experiments and/or projects performed in a parallel or previous course. Students will realize that the courses are part of a flow that contributes to a unified knowledge base.

This paper describes a project on active circuits that is performed at three universities, namely, Rowan, Bucknell and Tennessee State. The project has been formulated such that it can be taught at any university that has a course that covers the basic laws of circuit theory, introduces passive and active circuits, teaches the appropriate mathematical techniques and has a hands-on laboratory component. Specifically, the curriculum will include (but not limited to) mesh and nodal analysis, Thevenin equivalent, operational amplifier circuits, first and second order circuits, Laplace transform analysis, AC circuits, transformers and the frequency response of simple filters. The project reinforces circuit analysis, accomplishes simple design, involves the use of MATLAB and exposes the student to an operational amplifier chip. The project relies on concepts learned previously or concurrently like calculus and computer programming. It also leads into projects in follow-up courses like (1) building an audio amplifier or a power supply in an electronics course and (2) analog and digital filter design in a signals and systems course. Three different forms of assessment are carried out. They are based on student surveys, a concept inventory test and faculty formulated rubrics.

## LEARNING OUTCOMES

The student learning outcomes of the project include:

- Enhanced circuit design, analysis and testing skills.
- Enhanced awareness of the applications of operational amplifiers.
- Enhanced comprehension of concepts in circuit theory.
- Enhanced application of math skills.
- Enhanced written communication skills.
- Comprehension of the importance of vertical integration [4][5] in that students realize that their experiences are part of a curricular flow that contributes to a unified knowledge base.

**LABORATORY PROTOCOL**

The three week module incorporates circuit design, analysis and testing along with the concepts of a transfer function and frequency response. The lectures are integrated with the laboratory components with appropriate background in mathematics being covered.

*INVERTING AMPLIFIER*

Figure 1 shows an inverting amplifier circuit.

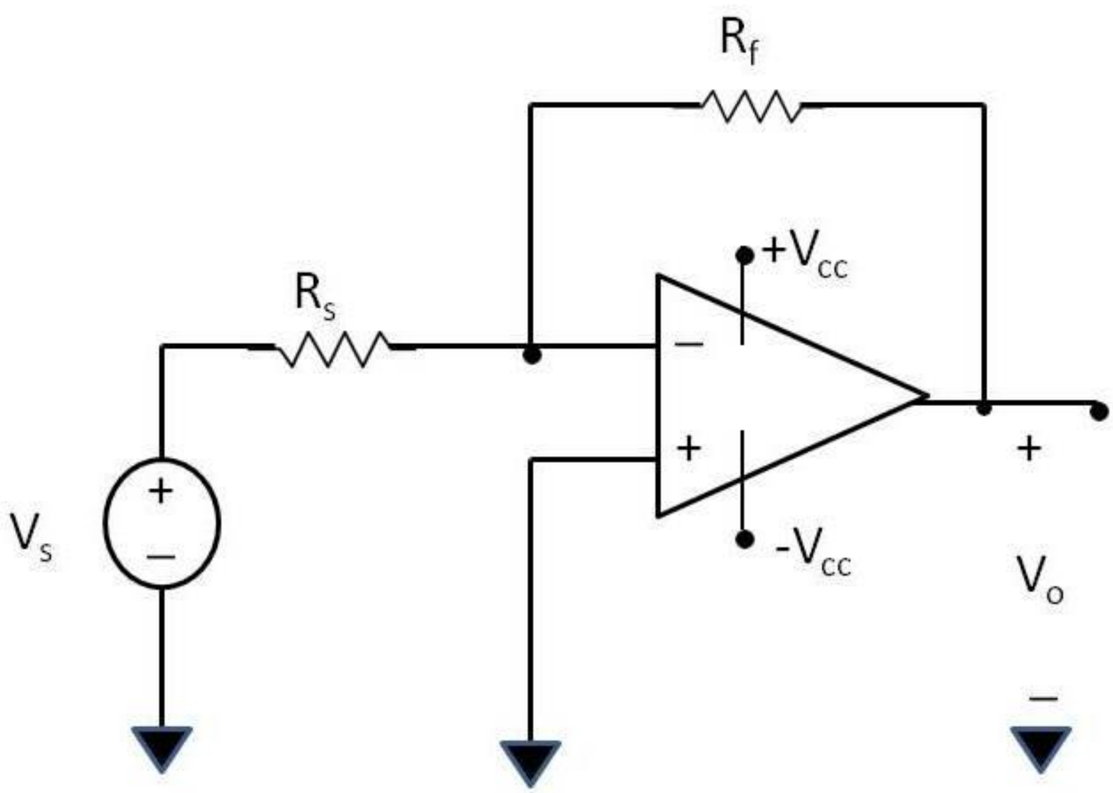


**Figure 1 – Inverting Amplifier Circuit**

Students do the following and visually observe clipping:

1. Derive the input-output relation: $V_o = f(V_s,R_s,R_f)$.
2. Use $V_{CC}$ = 15 V, use $V_s$ = 1 V, $R_s$ = 1 kΩ and $R_f$ = 10 kΩ. Measure $V_o$ and verify that the input-output relation is satisfied.
3. Continue to use $V_{CC}$ = 15 V, $V_s$ = 1 V and $R_s$ = 1 kΩ. Choose values for $R_f$ from 11 kΩ to 20 kΩ (in steps of 1 kΩ) and measure $V_o$. Discuss when the input-output relation is satisfied and when clipping occurs. Why does clipping occur for some values of $R_f$ ?

*NON-INVERTING AMPLIFIER*

Figure 2 shows a non-inverting amplifier circuit.

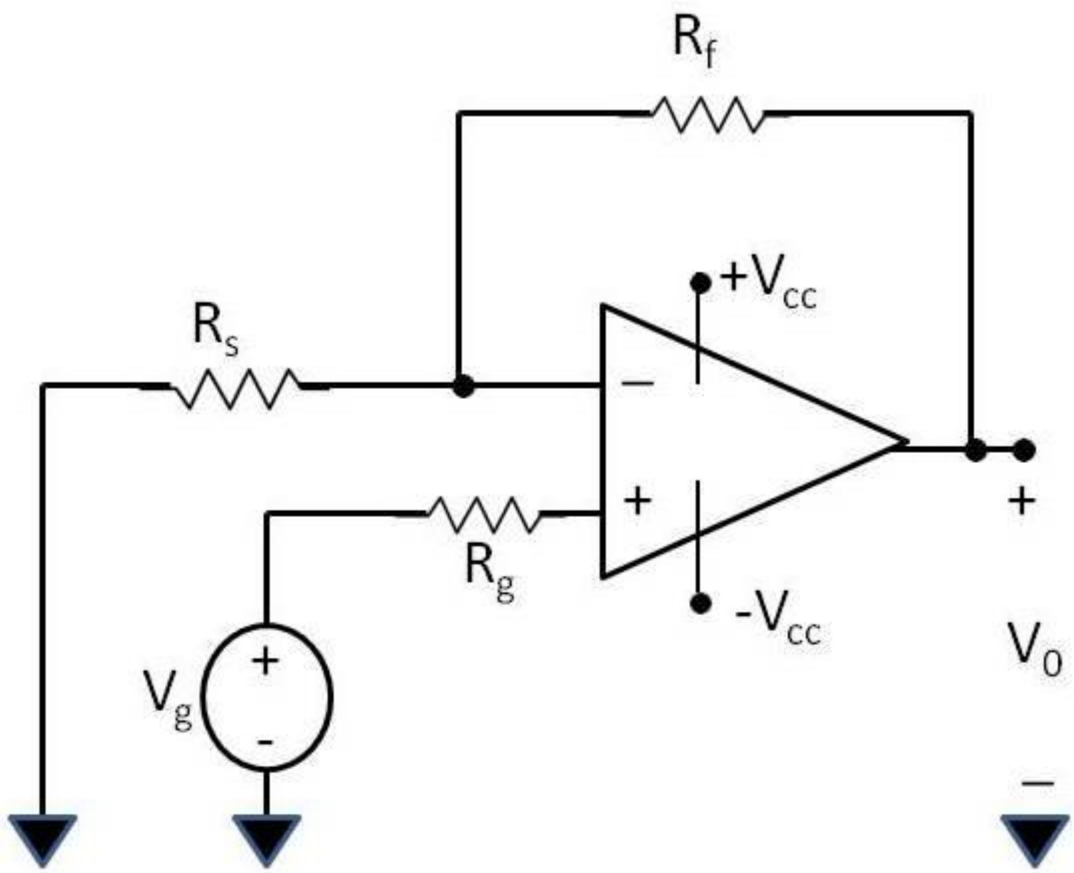


**Figure 2 – Non-inverting Amplifier Circuit**

Students accomplish a simple design and do the following:

1. Derive the input-output relation: $V_o = f(V_g, R_s, R_f, R_g)$.
2. Use $V_{CC}$ = 15 V, $V_g$ = 1 V and $R_g$ = 1 kΩ. Design a non-inverting amplifier (choose values of $R_s$ and $R_f$) with an output voltage of $V_o$ = 3 V such that the power dissipated in $R_s$ and $R_f$ is less than or equal to 0.003 W. Measure $V_o$ and verify that the input-output relation is satisfied. Show all your calculations.

*DIFFERENTIATOR*

Figure 3 shows a differentiator circuit. Students derive the input-output relation using Laplace transforms and explain why input noise is amplified at high frequencies. The concepts of frequency response and highpass filtering are introduced by examining the transfer function in the frequency domain.

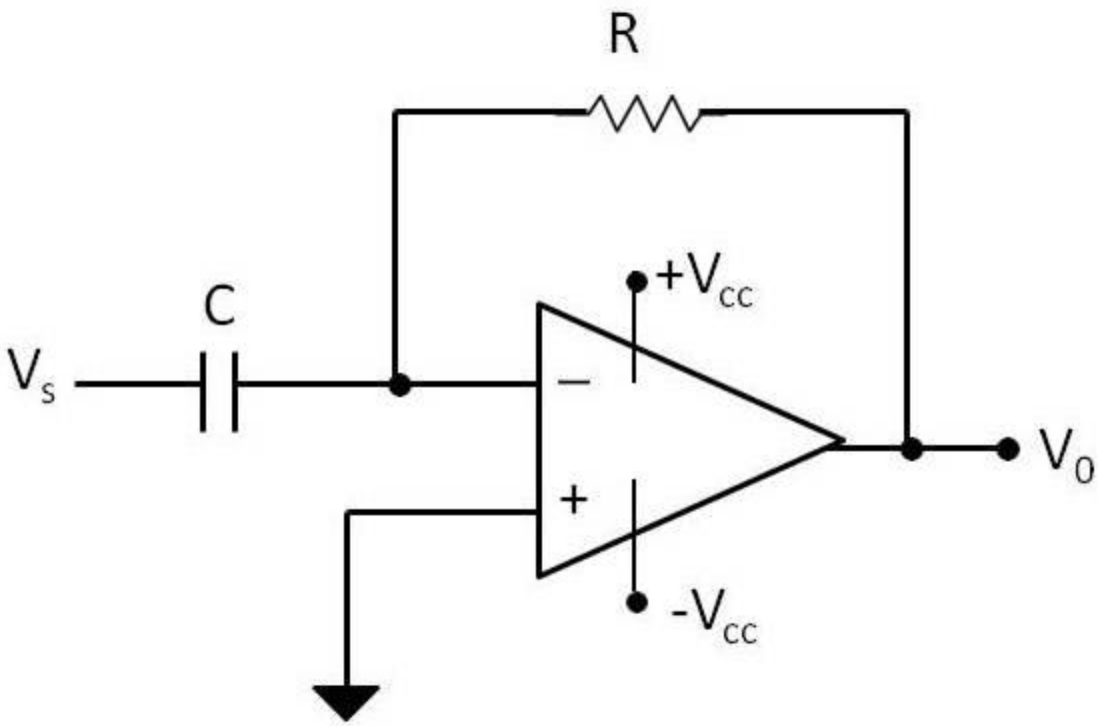


**Figure 3 – Differentiator Circuit**

*INTEGRATOR*

Figure 4 shows an integrator circuit. The output remains zero when the switch S remains closed. The integration starts (t = 0) when S opens. Students derive the input-output relation using Laplace transforms and explain why input noise is amplified at low frequencies. Students deduce that an integrator is a lowpass filter.

*PRACTICAL DIFFERENTIATOR*

To mitigate the problem of noise amplification at high frequencies, a differentiator used in practice is given in Figure 5. Differentiation of the input signal is accomplished over a bandwidth of low frequencies.

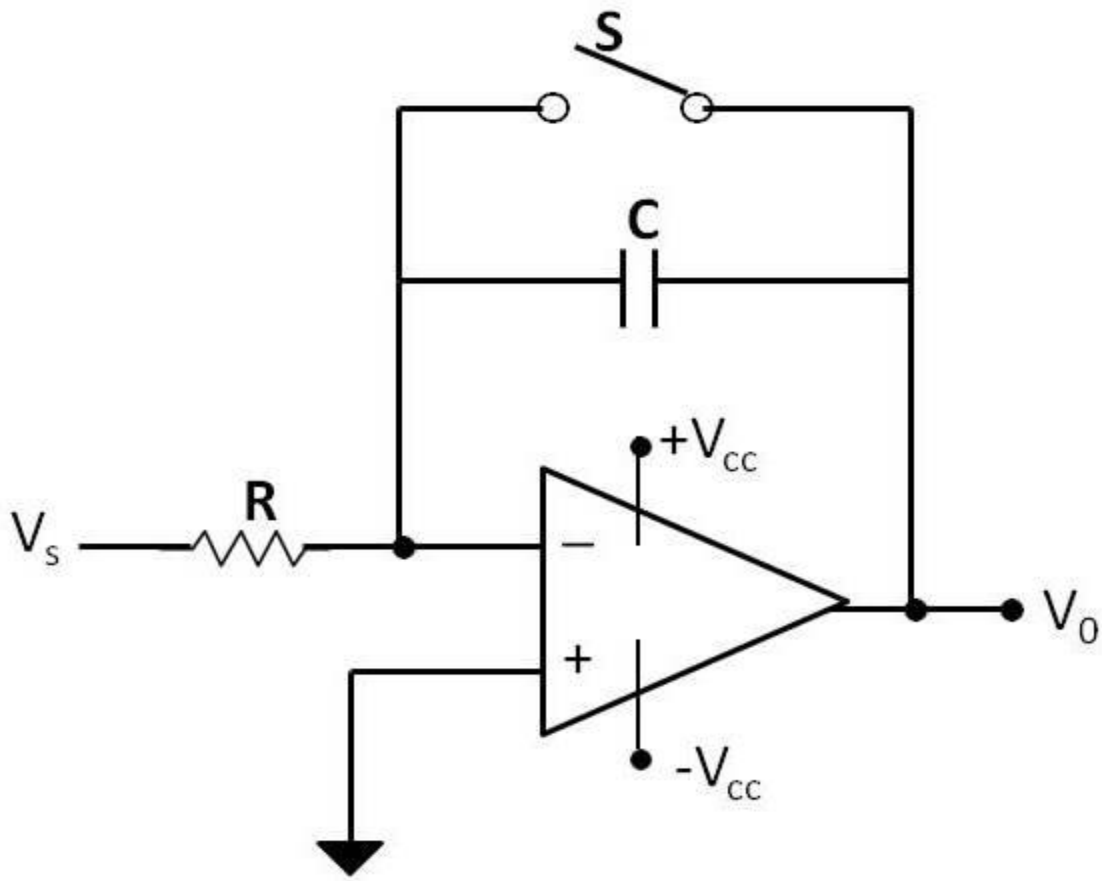


**Figure 4 – Integrator Circuit**

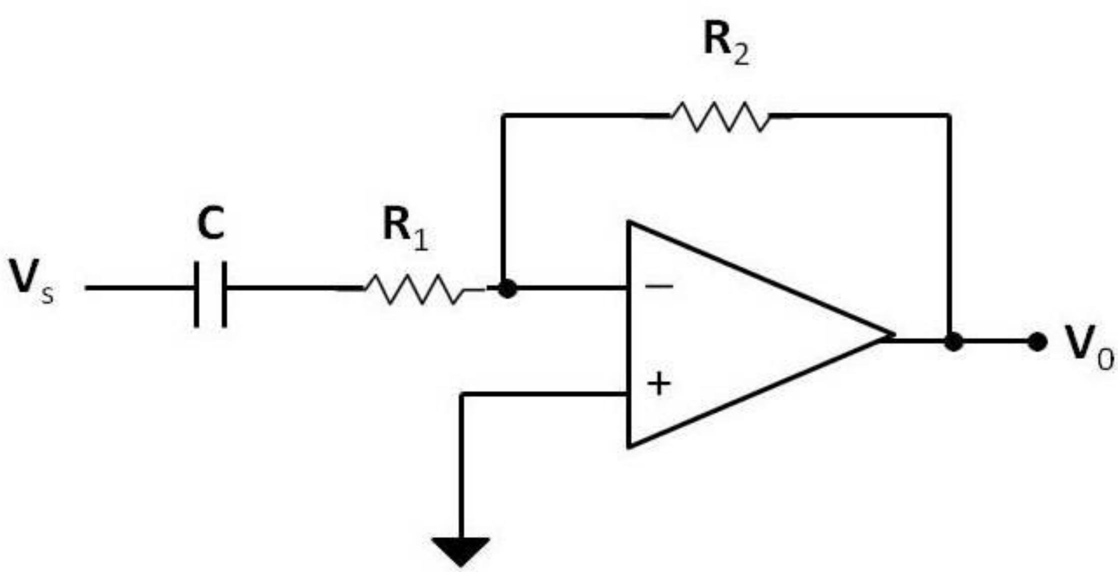


**Figure 5 – Practical Differentiator Circuit**

The student tasks are to:

1. Derive the transfer function in the Laplace transform domain. What type of filter does the circuit represent?
2. Write a well commented MATLAB function to calculate and plot the magnitude response of the circuit. The freqs command will be helpful. Generate a plot for R1 = 1.6 kΩ, R2 = 100 kΩ and C = 0.01 μF.
3. From the plot, deduce the bandwidth of frequencies for which differentiation is performed. For high frequencies, the circuit reduces to an inverting amplifier with absolute gain R2/R1. After about what frequency does this occur (deduce from the plot)?
4. Using the component values given above, build the circuit. Observe and explain the input and output waveforms on the oscilloscope. Use the following inputs:
    - A square wave (500 Hz fundamental) with a peak to peak voltage of 100 mV.
    - A triangular wave (500 Hz fundamental) with a peak to peak voltage of 100 mV.
    - A 500 Hz sine wave with a peak to peak voltage of 100 mV. Increase the frequency of the sine wave to 1000 Hz, 1500 Hz, 2000 Hz, 3000 Hz, 5000 Hz, 10000 Hz, 20000 Hz, 30000 Hz and 40000 Hz. Explain what you observe.

## ASSESSMENT RESULTS

### *Survey of Learning Outcomes and Vertical Integration*

A survey relating to the learning outcomes was given to the Rowan, Bucknell and Tennessee State students participating in the project. Table I gives the results. Statistical outliers diminish the mean score. The median score ignores these outliers and is a more robust indicator. Student perception of vertical integration was assessed by giving them a list of previously or concurrently taken courses and asking them whether the material learned in these courses had a connection with the circuits project. Calculus was selected by about 70% of the Rowan students and 90% of the Tennessee State students. Regarding the Bucknell students, about 86% selected Calculus and 97% selected the Foundations of Electrical Engineering course.

| Statement | Rowan (Mean, Median) | Bucknell (Mean, Median) | Tenessee State (Mean, Median) |
|---|---|---|---|
| The laboratory project as a whole helped reinforce circuit design and testing skills. | 3.93, 4 | 4.00, 4 | 3.80, 4 |
| The laboratory project as a whole helped reinforce circuit analysis skills. | 3.90, 4 | 3.90, 4 | 4.00, 4 |
| The laboratory project as a whole helped reinforce written communication skills. | 3.39, 3. | 3.00, 3 | 3.70, 3.5 |
| The laboratory project as a whole helped reinforce mathematical skills. | 3.61, 4 | 3.31, 3 | 3.70, 4 |
| The laboratory project helped me gain an appreciation of the applications of op-amps. | 3.76, 4 | 3.83, 4 | 4.00, 4 |

**Table 1 – Project Outcome Survey Results (1 - Strongly disagree, 2 - Disagree, 3 - Neutral, 4 - Agree, 5 - Strongly Agree)**

*Concept Inventory Test*

An assessment procedure in the form of a multiple choice concept inventory test was introduced in [6][7]. A 15 question test is given to the students at the beginning and end of the circuits course. This test evaluates concepts in mathematics, circuit theory and circuit analysis. Figure 6 shows a plot of the score of each student (out of 15) for the pre-test (beginning of the course) and post-test (end of the course). This plot includes the students from all three universities. Sixty six of the 72 students improved their score while the other 6 maintained the same score. Figure 7 shows a plot of the percentage of students that got each question correct for the pre-test and the post-test. There was a clear improvement for all questions.

For the results of both Figures 6 and 7, a one-tailed t-test with unequal variances was performed [8]. The post-test results are higher than the pre-test results (Figure 6) with statistical significance in that the p-value is 1.2e-24 (practically 0). With respect to the percentage of students getting each question correct (Figure 7), the post-test results are again higher than the pre-test results with statistical significance in that the p-value is 1.48e-4.

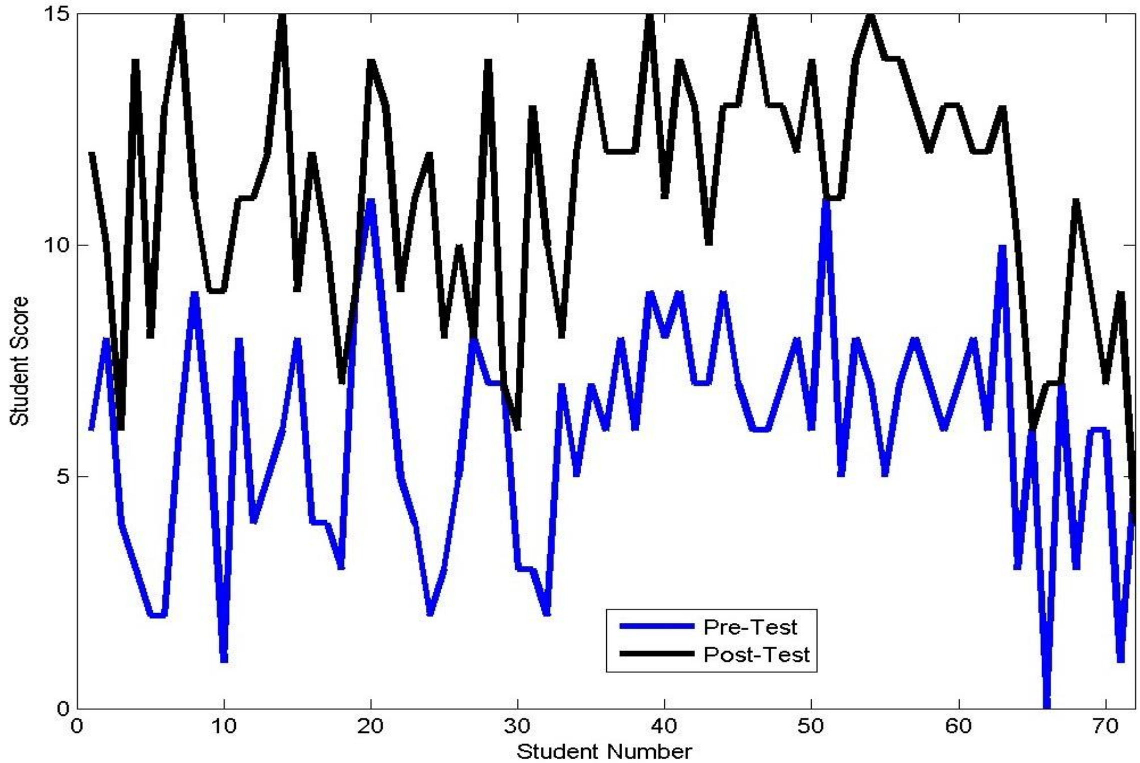


**Figure 6 – Student Score Out of 15**

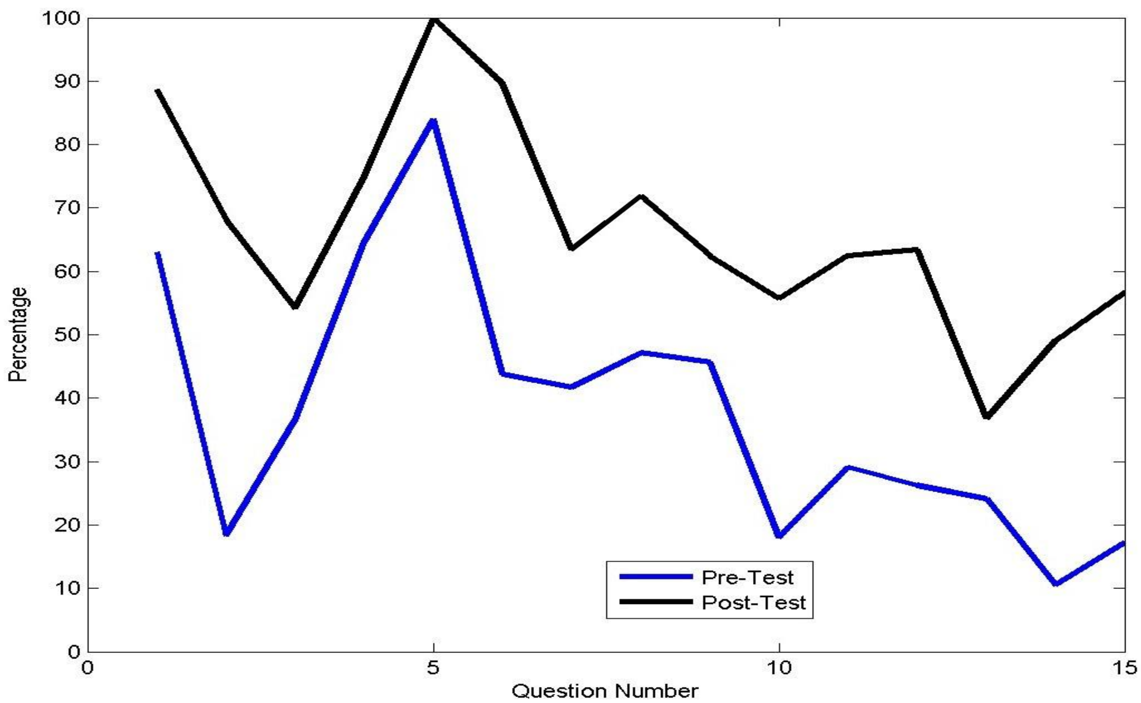


**Figure 7 – Percentage of Correct Responses For Each Question**

*Rubrics for Student Achievement*

Rubrics used to quantify student achievement of project instructional outcomes were developed. For each instructional outcome, four levels of achievement were designated. A score of 1 to 4 was given based on the project lab report. The advantages of using rubric based assessment are that it gives a quantitative judgment of student knowledge, requires little extra work in the grading process, requires no additional training for faculty to use, and avoids complete reliance on student self-reporting through surveys [9][10]. Table 2 gives the outcomes and levels of achievement for the circuits project. Table 3 gives the statistics.

| Indicator | 4 | 3 | 2 | 1 |
|---|---|---|---|---|
| Students are able to derive the input-output relations of all five circuits (inverting amplifier, non-inverting amplifier, differentiator, integrator and the practical differentiator). | All derivations are done correctly. | The derivations for the inverting and non-inverting amplifiers are done correctly. There are minor mistakes in the derivations for some or all of the other three circuits. | Only the derivations for the inverting and non-inverting amplifiers are done correctly. There are major mistakes in the derivations for some or all of the other three circuits. | The derivation for one circuit or none of the circuits is done correctly. |
| Non-inverting amplifier design: For a given input voltage, the students can calculate the values of the resistances to achieve a desired output voltage and a maximum power dissipation. | The design was carried out successfully. All calculations were well explained. | The design steps were well explained but calculation mistakes were noted. | The calculations were carried out but no reasoning was presented. | The calculations were inadequate and students could not carry out the design. |
| Practical differentiator: Students successfully ran the given MATLAB | Students ran the MATLAB code successfully | Students ran the MATLAB code successfully but made | Students ran the MATLAB code successfully but could not | Students could not run the MATLAB code and got no results. |

| | | | | |
|---|---|---|---|---|
| code, deduced the bandwidth for which differentiation is performed and identified the frequencies for which the circuit acts like an inverting amplifier. | and performed the required analysis. | minor errors in the interpretation of the magnitude response. | interpret the magnitude response. | |
| Practical differentiator: Students build the circuit and explain the output for sine wave inputs of 500, 1000, 1500, 2000, 3000, 5000, 10000, 20000, 30000 and 40000 Hz. | The explanations are completely correct. | There are minor flaws in the reasoning. | Students comprehend the circuit behavior for low or high frequencies but not both. | Students do not comprehend how the practical differentiator works for the various frequencies. |

**Table 2 – Rubrics for Circuits Project**

| Outcome | Rowan (Mean, Median) | Bucknell (Mean, Median) | Tenessee State (Mean, Median) |
|---|---|---|---|
| Transfer function | 4.00, 4 | 3.75, 4 | 3.90, 4 |
| Non-inverting amplifier design | 3.88, 4 | 3.56, 4 | 3.90, 4 |
| Practical differentiator: MATLAB code | 3.63, 4. | 3.38, 4 | 3.80, 4 |
| Practical differentiator: Circuit operation | 2.88, 3 | 3.38, 4 | 3.70, 4 |

**Table 3 – Rubric Statistics**

## SUMMARY AND CONCLUSIONS

The active circuits project has achieved many learning outcomes, contributed to STEM knowledge and given the students a perception of the usefulness of vertical integration. The fact that the project can be successfully disseminated anywhere is evident from it being performed at three universities. Students analyze and test different active circuits, do a simple design for a non-inverting amplifier, understand the concepts of a transfer function and frequency response and investigate input-output behavior of a practical differentiator. A variety of assessment instruments are used to show the success of students acquiring both STEM knowledge and specific skills.

**ACKNOWLEDGEMENT**

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**REFERENCES**

1. Y. Tsividis, “Turning students on to circuits”, it IEEE Circuits and Systems Magazine, pp. 58–63, First Quarter, 2009.
2. L. Trajkovic, “Teaching circuits to new generations of engineers”, IEEE Int. Symp. on Circuits and Systems, Rio de Janeiro, Brazil, pp. 1187–1190, May 2011.
3. P. Jansson, R. P. Ramachandran, J. L. Schmalzel and S. A. Mandayam, “Creating an agile ECE learning environment through engineering clinics”, IEEE Transactions on Education, Vol. 53, No. 3, pp. 455–462, August 2010.
4. C. Trullemans, L. De Vroey, S. Sobieski and F. Labrique, “From KCL to class D amplifier”, IEEE Circuits and Systems Magazine, pp. 63–74, First Quarter, 2009.
5. Y. Tang, L. M. Head, R. P. Ramachandran and L. M. Chatman, “Vertical integration of system-on-chip concepts in the digital design curriculum”, IEEE Transactions on Education, Vol. 54, No. 2, pp. 188–196, May 2011.
6. K. E. Wage, J. R. Buck, C. H. G. Wright and T. B. Welch, ``The Signals and Systems Concept Inventory”, IEEE Transactions on Education, Vol. 48, No. 3, pp. 448—461, August 2005.
7. J. R. Buck and K. E. Wage, ``Active and Cooperative Learning in Signal Processing Courses”, IEEE Signal Processing Magazine, Vol. 2, No. 2, pp. 76—81,March 2005.
8. R. D. Yates and D. J. Goodman, Probability and Stochastic Processes John Wiley, 1999.
9. J. A. Newell, H. L. Newell and K. D. Dahm, “Rubric Development and Inter-Rater Reliability Issues in Assessing Learning Outcomes”, Chemical Engineering Education, Summer 2002.
10. J. A. Newell, H. L. Newell and K. D. Dahm, “Rubric Development for Assessment of Undergraduate Research: Evaluating Multidisciplinary Team Projects”, Chemical Engineering Education,