Project and Problem Based Learning for Circuits, Systems, VLSI and Digital Signal Processing Courses

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***Abstract*—Project-based and problem-based learning are widespread and proven pedagogical techniques to achieve a variety of learning outcomes. In this paper, several projects in the circuits, systems, VLSI and signal processing areas are described. The projects can be implemented using both project-based and problem-based learning and as part of an Electrical and Computer Engineering curriculum without the need for additional expensive resources. Learning outcomes in Science, Technology, Engineering and Mathematics (STEM) are emphasized such that students achieve analytical, design, software and communication skills. The VLSI design project also has an entrepreneurship component. Assessment results are provided.**

Keywords—project based learning, problem based learning, STEM outcomes, laboratory protocol, entrepreneurship, assessment

I. Introduction

The tasks posed to engineers can be characterized by a wide range of scope and complexity, and therefore require varied levels of mastery. The educational objectives within engineering courses can be designed to reflect this range of scope and complexity. One tool for characterizing educational objectives that is commonly applied in engineering education is Bloom's taxonomy [1]. The taxonomy proposes six levels for educational objectives in the cognitive domain: Knowledge, Comprehension, Application, Analysis, Synthesis and Evaluation. A revision of Bloom's taxonomy [2] again identifies six levels but replaces the use of nouns with verbs that characterize the specific activities undertaken by a learner: Remember, Understand, Apply, Analyze, Evaluate and Create. Traditional homework problems that consist of calculations and that have unique correct answers are commonly limited in scope to the three lower levels of the taxonomy ("Knowledge, Comprehension, Application" or "Remember, Understand, Apply"). Engineering courses frequently utilize design projects and/or open-ended problems as mechanisms for challenging students to act at the higher levels of Bloom's Taxonomy ("Analysis, Synthesis, Evaluation" or "Analyze, Evaluate, Create").

A distinction can be made between project-based learning and problem-based learning, both of which are frequently abbreviated PBL [3][4]. In project-based learning, students acquire knowledge in a classroom setting (for example, through lectures and/or active learning activities) and then apply that knowledge to the completion of open-ended projects. Thus, from the student's perspective, the emphasis of the project is typically on producing a high-quality deliverable. Depending upon the project, the deliverable could be a laboratory report that presents and analyzes data, a design report, or a completed prototype. Students are typically evaluated on the quality of the deliverable. Project-based learning can be implemented in any course, and is a routine feature of capstone design experiences, in which design projects are culminating experiences that require students to synthesize the content of several courses [3].

In contrast, in problem-based learning, students are presented with a problem, and the problem serves as a context for the acquisition of knowledge. Students examine the problem, recognize the additional knowledge that is required for successful completion of the problem, and devise a strategy for learning what is needed [5]. One of the primary differences between problem-based learning and project-based learning is with respect to course structure and agenda. In a traditional engineering course, the instructor prescribes the agenda for each class period, with respect to both the topics to be covered and the specific learning activities. Project-based learning is readily implemented within an instructor-driven agenda, with the instructor establishing expectations and deadlines for completion of the project. In problem-based learning, by contrast, the students set the agenda based upon what they perceive they need to learn in order to complete the problem, and the instructor acts as a facilitator. Another key difference is that in project-based learning, the primary goal of the project is on completing a high-quality deliverable, while in problem-based learning, the primary emphasis is on the acquisition of new knowledge. Hybrid approaches that blend elements of the problem-based and project-based approaches are also possible [5][6].

In summarizing the potential benefits of project-based and problem-based learning, Prince and Felder [6] note that "studies comparing project-based learning to conventional instruction have yielded results similar to those obtained for problem-based learning, including significant positive effects on problem-solving skills, conceptual understanding, and attitudes to learning, and comparable or better performance on tests of content knowledge." In [3], Woods provides an excellent summary of the benefits of problem-based learning, which also include higher knowledge retention, higher student motivation, and development of career skills such as communication, teaming, problem-solving and lifelong learning.

This paper presents a series of projects in the areas of circuits, VLSI and signal processing, all of which can be implemented as part of an Electrical and Computer Engineering (ECE) curriculum. The approaches are both project-based and problem-based and can be implemented in a hybrid fashion. The paper will focus on technical aspects of the projects and provide assessment results.

The outline of the paper is as follows. Section 2 gives the learning outcomes. Sections 3 to 6 provide the descriptions of each project. Section 7 gives the summary and conclusions.

II. LEARNING OUTCOMES

Although the projects are in different areas of Electrical and Computer Engineering, they share common learning outcomes [7] as given below. These outcomes are significant for undergraduate students moving on to graduate school or entering the job market.

1. Enhanced mathematical skills and how these skills are important in engineering.
2. Enhanced software implementation skills.
3. Enhanced design skills especially from a systems perspective.
4. Enhanced written communication skills.
5. Enhanced comprehension and appreciation of how concepts are related from one course to another to form a unified knowledge base.

III. PROJECT 1: ANALOG AND DIGITAL FILTER DESIGN

This project, briefly described in [8], has three parts and can be carried out in any junior level Signals and Systems Course. Both analytical work and software design are covered. The deliverable is a formal written laboratory report.

A. *Part 1: Design of Analog Lowpass Butterworth Filters*

The objectives are:

1. To understand the concepts of a transfer function and frequency response.
2. To understand the concepts of passband, stopband, cutoff frequency and filter specifications.
3. To understand the Butterworth approximation problem [9][10] both from a theoretical point of view and from the point of view of carrying out a MATLAB design from filter specifications.
4. To be able to realize Butterworth filters as active and passive analog circuits.

The theory of analog filter design is taught during the lectures. The experimental protocol is as follows (note that Ω denoted the analog frequency variable):

1. Prove that the Butterworth magnitude response is monotonic decreasing.
2. The filter specifications for a lowpass filter are given by (i) Passband: $0.89125 \leq |H(j\Omega)| \leq 1$ for $0 \leq \Omega \leq 0.2\pi$ and (ii) Stopband: $|H(j\Omega)| \leq 0.17783$ for $\Omega \geq 0.3\pi$. Demonstrate your understanding of the Butterworth method by solving for N and Ω_c by hand and show all your steps and calculations. You should get N = 5.8857 and $\Omega_c = 0.70474$. The order N is rounded up to 6 and Ω_c is recalculated.
3. Write a MATLAB code to carry out this design. Verify that all poles are in the left half plane and that the radius of the poles is equal to the cutoff frequency. Plot the magnitude response of the filter. Verify on the plot that the attenuation is 3 dB at the cutoff frequency.
4. Find the transfer function H(s) by hand for N = 3 and $\Omega_c = 0.5$. Show all calculations. Realize the filter using operational amplifiers, resistors and capacitors (active circuit). A cascade connection of a first and second order section is recommended. Do another realization as a passive circuit (resistors, capacitors and inductors only in that no operational amplifiers are used).

B. *Part 2: Design of Digital Infinite Impulse Response (IIR) Filters Based on Analog Butterworth LowpassPrototypes*

The objectives are:

1. To understand the bilinear transformation and how it is used in designing a digital lowpass filter from an analog lowpass prototype.
2. To understand the concept of a frequency transformation to get a digital highpass filter from a digital lowpass filter.
3. To carry out the design of digital filters using MATLAB.
4. To be able to realize digital filters in Direct II form [10].

The concept of the bilinear transformation along with its application to digital filter design is taught during the lectures. The experimental protocol is as follows:

1. For using the bilinear transformation in digital filter design, the digital filter specifications are translated into analog filter specifications by the prewarping equation relating the analog frequency Ω and the digital frequency ω. The equation is $\Omega = \tan(\omega/2)$. Prove this equation.
2. The bilinear transformation maps the left-half s-plane to inside the unit circle in the z-plane, the imaginary axis to the unit circle and the right-half plane to outside the unit circle. Prove this mapping property. This property is important as it guarantees the stability of the digital transfer function H(z).
3. The filter specifications for a digital lowpass filter are given by (i) Passband: $0.85 \leq |H(e^{j\omega})| \leq 1$ for $0 \leq \omega \leq 0.25\pi$ and (ii) Stopband: $|H(e^{j\omega})| \leq 0.15$ for $0.4\pi \leq \omega \leq \pi$. Demonstrate your understanding of the prewarping technique by translating these specifications to analog lowpass filter specifications. Show all your steps and calculations.

4. Write a MATLAB code to carry out the design given in the previous item. What is the cutoff frequency of the filter? Verify that all poles are inside the unit circle. Plot the magnitude response of the filter. Verify on the plot that the attenuation is 3 dB at the cutoff frequency.
5. Realize the filter designed in item 4 as a direct form II structure.
6. Given a lowpass filter H(z), a z to –z transformation gives a highpass filter H(-z). If the cutoff frequency of the lowpass filter is ω_c, prove that the cutoff frequency of the highpass filter is $\pi - \omega_c$. Write a MATLAB code to get H(-z) from the H(z) obtained in item 4. Plot the magnitude response of H(-z) and verify the value of the cutoff frequency from the plot.

C. *Part 3: Design of Finite Impulse Response (FIR) Linear Phase Filters*

The objectives are:

1. To understand the concepts of linear phase and how it is achieved for FIR filters.
2. To understand and compare the window, Remez and least-squares methods [10] for designing linear phase FIR filters.
3. To accomplish the MATLAB design of linear phase FIR filters.

The protocol is:

1. Describe the theory of linear phase FIR filters that clearly demonstrates your understanding of all concepts.
2. Derive the formula for the impulse response of an ideal lowpass filter p(n) having a cutoff frequency ω_C. For a cutoff frequency of $\omega_C = 0.2\pi$, plot p(n) from n = -20 to 20.
3. The window method is to be used to approximate an ideal lowpass filter with a cutoff frequency of 0.3π. Use a rectangular and Hamming window to get an FIR filter with 41 coefficients. Compare and contrast the magnitude responses of both these filters. Repeat for an FIR filter with 81 coefficients. How do the filters with 81 coefficients compare with the filters with 41 coefficients in terms of the magnitude response? Use MATLAB to do the programming and plotting.
4. Consider a linear phase lowpass FIR filter with specifications: (i) $D(\omega) = 1$ in the passband $0 \le \omega \le 0.45\pi$ and (ii) $D(w) = 0$ in the stopband given by $0.6\pi \le \omega \le \pi$. Use MATLAB code to accomplish a minimax design using the Remez exchange algorithm and a least-squares design. Compare the resulting filters with respect to L_1 error, L_2 error and L_∞ error in both the passband and stopband.

D. *Assessment Results*

A survey was conducted by asking the students specific questions about the learning outcomes of the filter design project. A subset of the results given in Table I has been published in [8].

TABLE I: Filter Design Project Assessment Results

1 - Strongly Disagree, 2 – Disagree, 3 – Neutral, 4 – Agree, 5 – Strongly Agree		
Statement	Mean	Median
The methodology of analog filter design was demonstrated and learned.	4.14	4
Concepts on active and passive filter realization were reinforced.	3.71	4
The methods of IIR and FIR filter design were well demonstrated and learned.	3.93	4
The concept of linear phase was learned.	3.57	3.50
The concepts of transfer function and frequency response were learned.	3.86	4 4
Written communication skills were reinforced.	3.50	4
Design skills were reinforced.	3.64	3.50
MATLAB skills were reinforced.	4.36	5
Theoretical and analytical skills improved.	4.07	4

IV. PROJECT 2: QUADRATURE MIRROR FILTER BANK DESIGN

This project is on the mathematical analysis and software simulation of a two band quadrature mirror filter (QMF) bank [11] and can be implemented in a final year undergraduate digital signal processing course. It is briefly described in [8] with more detail given here. The software implementation includes both a MATLAB and VHDL component.

Figure 1 gives a block diagram. The analysis filters consist of a lowpass $A_0(z)$ and a highpass $A_1(z)$. Similarly, the synthesis filters $B_0(z)$ and $B_1(z)$ are lowpass and highpass respectively.

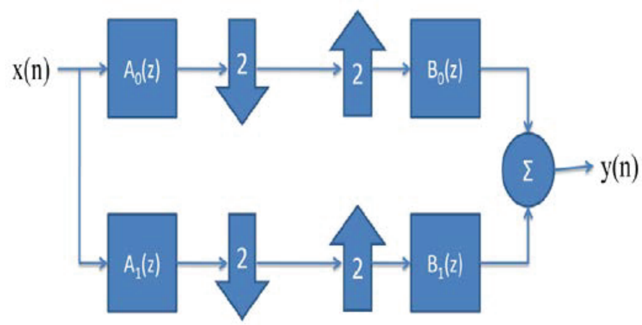


Figure 1: A Quadrature Mirror Filter Bank

The project protocol is as follows:

1. Derive Y(z) as a function of X(z) and the analysis and synthesis filters. State the conditions for perfect reconstruction of the input to within a scaling factor and delay.
2. If H(z) is a lowpass prototype, the analysis filters are given by $A_0(z) = H(z)$ and $A_1(z)) = z^{-1}H(-z)$. The synthesis filters are given by. $B_0(z) = z^{-1}H(z)$ and $B_1(z) = H(-z)$. Show that $Y(z) = z^{-1} [H^2(z) + H^2(-z)]$.
3. The aim is to design a lowpass H(z) such that $H^2(z) + H^2(-z) = cz^{-p}$ where c is a real number and p is an integer. An ideal lowpass frequency response $F(\omega)$ that satisfies this condition is known as the raised

cosine characteristic which is given by (i) $F(\omega) = 1$ for $|\omega| \leq \omega_c\ (1\text{-}\alpha)$, (ii) $F(\omega) = 0$ for $|\omega| \geq \omega_c\ (1+\alpha)$ and (iii)

$$F(\omega) = \frac{1}{2}\left[1 + \cos\left(\frac{\pi(\omega-\omega_c(1-\alpha))}{2\alpha\omega_c}\right)\right] \quad (1)$$

for $\omega_c\ (1\text{-}\alpha) < |\omega| < \omega_c\ (1+\alpha)$. The variable $0 \leq \alpha \leq 1$ is known as the roll-off factor and for a two-band system, $w_c = \pi/2$. Design a H(z) satisfying the above specifications using the Remez exchange algorithm. Adjust the number of filter taps to get a 40 dB stopband attenuation.

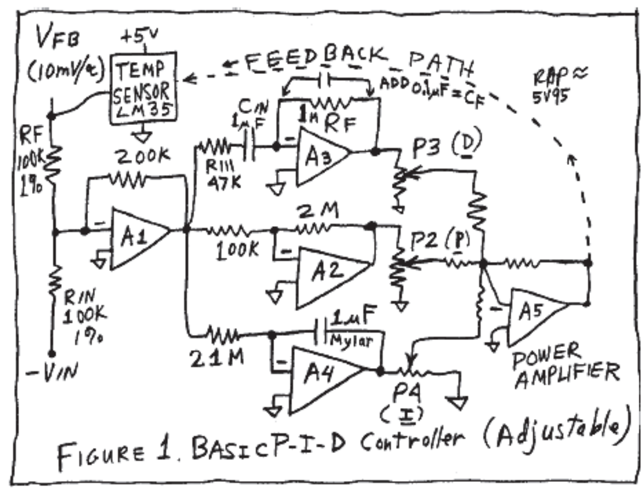
4. Implement the two band subband system using MATLAB. Use the lowpass prototype designed in the previous item. Use an impulse with an amplitude of 100 as an input to the system. Examine the magnitude responses of all intermediate signals and comment on your results. The intermediate signals include the inputs and outputs of all filters, subsamplers and upsamplers. Describe the output signal in the time and frequency domains and comment if perfect reconstruction has been achieved.
5. A speech file has been supplied. Use this as the input to the QMF system and comment if perfect reconstruction has been achieved. Listen to the input and output and comment if there is any difference in the perceptual quality of the input and output speech.
6. Write VHDL code to simulate the QMF system. Use IEEE 32-bit floating point arithmetic. Convert the speech input and the filter coefficients to IEEE 32-bit floating point format. Read these into your VHDL code and use Mentor Graphics for implementation. Compare the output of the QMF system to what was obtained using MATLAB.

The assessment results are based on student surveys and are given in [8]. The results indicated the improvement of theoretical and analytical skills, MATLAB skills and VHDL skills.

V. PROJECT 3: PID CONTROLLER DESIGN

A first course in systems provides students with an introduction to linear systems, systems modeling and controls. Extensive use is made of the Laplace Transform as the core analysis tool. In addition to the foundational systems concepts and tools, further opportunities present to integrate material from other courses as described earlier by Learning Outcome 5 (enhanced comprehension and appreciation of how concepts are related from one course to another to form a unified knowledge base). The design of analog proportional-integral-derivative (PID) controllers is such an example, providing a direct path to the electronics principles students have received in a previous class.

The project described is a PID design based on a circuit developed by Robert (Bob) Pease [12]. Bob Pease wrote a regular column, "Pease Porridge," in *Electronic Design*, which was always a source of insights into circuit behaviors ranging from the complex to sheer elegance. The article for the PID controller [12] is a crash course in practical control design and is a great introduction to the topic of PID. This circuit is shown in Figure 2 and realizes a parallel combination of a noninverting amplifier (proportional control), an active RC integrator circuit (integral control) and another active RC differentiator for derivative control. Potentiometers were used to adjust the gains of these three components. . The capacitors for the RC circuits can be selected easily to change the circuit time constants for the integrator and derivative stages. Students fabricated their PID controllers using solderless breadboards.



Supplement to Electronic Design August 4,1997

Figure 2: The PID Controller Circuit (taken from [12])

The PID is used as part of a closed loop control system with a thermal system as the plant. The lab protocol is as follows:

1. Starting with the Pease PID design, analyze the circuit qualitatively (give descriptive names to each part of the circuit) and quantitatively (e.g., the gain is X, the cut-off frequency is f_0, etc.) so that you have a thorough understanding of its theory and operation. This is your controller circuit $G_c(s)$.
2. Develop an electric analog for a 1st-order thermal system. That is, design an RC circuit (lowpass filter) that models the behavior of a simple heater circuit and its associated thermal mass. This is your plant G(s). Verify that the system behaves as you predicted—i.e., develop a Bode plot using Matlab.
3. Integrate the two subsystems together. That is, the output of the PID controller will be input to the G(s) plant and its output in turn will be fed back to the input summer of the PID controller. Note that since you are using an electrical analog, there will be no sensor required to make the temperature to voltage conversion.
4. Draw the block diagram of the overall control system and determine the overall transfer function.
5. Subject the system to a step input and compare the relative performance between various control strategies.

a. Proportional only. Set the derivative and integral gains to zero.
b. Proportional + Integral: Set the derivative gain to zero.
c. Proportional + Derivative: Set the integral gain to zero.

6. Interface your PID controller to a thermal system consisting of a power resistor mounted to a heatsink that has a temperature sensor.
7. Tune your PID system to achieve low static error.
8. For your write-up, include both simulation and empirical results and discuss.

VI. PROJECT 4: VLSI IMPLEMENTATION OF A 2-D DCT

This project is on the VLSI implementation of the two-dimensional (2-D) DCT [13]. More specifically, the Application Specific Integrated Circuit (ASIC) design is achieved. The project can be carried out in any VLSI/Signal Processing design course. Background material on the one-dimensional (1-D) and 2-D transforms is taught which include the concept of the unitary transform, fast computation and the energy compaction property. The separability of the 2-D transform and how it can be computed using the 1-D transform is also covered. Course content also includes the review of design options for digital components such as adders and multipliers. The ASIC implementation of a 2-D DCT enables students to develop a more thorough understanding of its implementation rather than simply seeing it as a MATLAB command.

For a given 2-D signal **X,** the 2-D DCT can be expressed as $\mathbf{Y} = \mathbf{C}\mathbf{X}\mathbf{C}^{\mathbf{T}}$ [13][14] where **C** is a cosine coefficient unitary matrix. It is this matrix version that is used to develop the ASIC format. Two simplifications are introduced. First, an 8 by 8 2-D DCT is calculated. Second, the **C** matrix of the cosine terms are calculated and entered into memory. Quantized DCT values are obtained by dividing each of the 64 2-D DCT coefficients by the corresponding quantization table values given by the MPEG2 standards for moving pictures [13][15].

Calculations reduce to a series of multiplications, summations and memory writes required for the matrix multiplications. The block diagram for the ASIC computation is given in Figure 3 (note that DCTQ refers to the quantized DCT).

This project has an excellent entrepreneurship component as students are introduced to VLSI design using a "corporate competition" model. The class is divided into three corporations each with a design team, a COO – Chief Operating Officer, responsible for assignment and coordination of tasks and a CEO – Chief Executive Officer, responsible for all reporting and presentations. The overall design competition involves the development of an ASIC to implement the 2-D DCTQ algorithm. Each corporation must develop a work plan, implement the ASIC in Verilog and simulate the design using Modelsim. The instructor serves as the "customer" working with each CEO to define specifications and monitor progress.

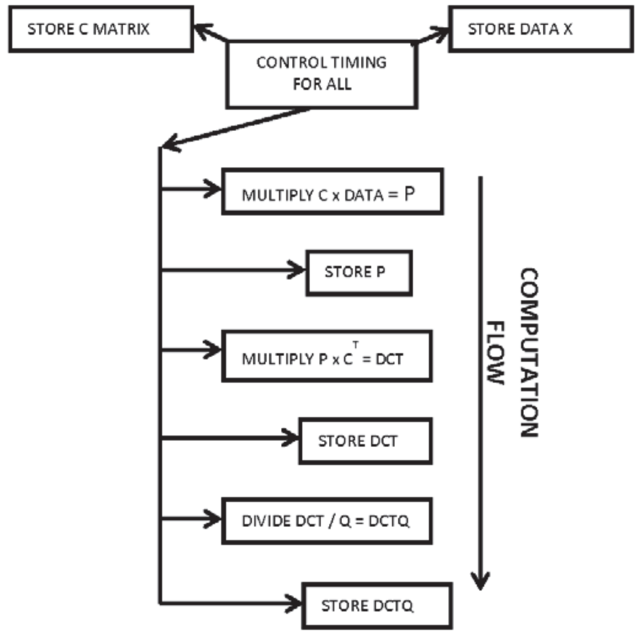


Figure 3: Block Diagram for the ASIC Computation

Once the project goals are communicated the "corporations" are challenged to develop a work plan. The designated CEO is empowered to make decisions regarding "staff" assignments for the team members. The COO is the technical expert for the team and the primary resource for the staff engineers. The COO implements the plan advocated by the CEO. At the completion of the semester each corporation presents their design to the instructor and to the other corporations with the goal of "selling" their design. The criteria for judging the designs were: efficient and innovative use of design techniques, speed, creativity in presentation of simulation, preparation of documentation, and professionalism of "sales pitch" (i.e. final presentation).

For the assessment, each staff engineer was required to evaluate their CEO and COO during the middle and end of semester. Each team of executives also evaluated their staff and each team of executives wrote a short narrative evaluation of their experience.

A. *Assessment of CEO and COO by Staff Engineers*

The staff engineers evaluated the CEO and COO based on six statements given below. The rating was based on a scale of 1 to 5 where five (5) is *"as good as I could have done"* and one (1) is *"could have done better here"*. The six statements are:

1. The executives assigned tasks that made the best use of personnel and built on the experience gained during the first half of the semester.
2. The executives provided guidance on individual assignments.
3. The executives set an appropriate schedule for completion of design effort.

4. The executives facilitated coordination of each module with control block and "nearest neighbor" modules.
5. The executives worked together effectively.
6. The executives dealt productively with any problems, issues, conflicts that arose.

Tables 2 gives the average evaluation scores of the team executives for teams 1, 2 and 3 separately.

TABLE II: Average Final Evaluation Scores of Team 1 Executives for Each Statement S1 to S6

Team	S1	S2	S3	S4	S5	S6
1	5.00	5.00	5.00	4.83	4.67	4.67
2	3.83	4.83	4.67	3.83	4.33	4.33
3	4.50	5.00	4.83	4.50	3.83	3.50

B. Narrative Written by Executives

One example of a narrative written by a team of executives is given below.

``In conclusion, the DCTQ was a success and is capable of producing the quantized transform coefficients of an image. The most important spectral domain information is represented by these coefficients. These coefficients can be used for various applications including the ability to compress an image. Each separate piece of the DCTQ had to be coded and tested separately. The final product came from combining all of these pieces together and making the small modifications necessary so they could link and calculate properly in a single program.''

``This project proved to be a great experience and we are sure it will be valued in the future when we are in a real-world working environment. In hindsight, our approach to this problem could have been improved upon. Our approach consisted of breaking up each individual piece of the DCTQ and assigning a different person (or group of two) to complete that piece. After all pieces were coded and tested individually, we then attempted to put them together. A better approach would have been to split the project up into sections (3 probably would have been best) and assign teams to put these sections together so that the full project would not have as many connections to check. Overall, the team worked well together and accomplished the goal of the project with a good understanding of the material.''

VII. SUMMARY AND CONCLUSIONS

Four projects that can be implemented as part of any circuits, systems, VLSI and/or digital signal processing courses in an ECE curriculum have been described. Assessment results have also been given and are encouraging. The projects accomplish a hybrid approach to project and problem based learning. In particular, the ASIC design of the 2-D DCT produced three excellent design reports and a learning experience that mirrored the corporate work environment for a group of senior students on the verge of graduation. The three CEOs and COOs both experienced and modeled the corporate "boss" role that the students will soon experience in their work place.

Acknowledgment

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