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A Mixed Instructional Methods Approach to Teaching a Circuits and Instrumentation Course

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Abstract

The circuits and instrumentation course at James Madison University provides students with foundational knowledge in DC, transient, and AC circuit design and analysis. The 4-credit course is comprised of three weekly lectures and one weekly laboratory session. Given the breadth of content and desired level of technical analysis required of this junior level course offering, numerous methods for extending learning beyond the classroom and encouraging student engagement with the material have been explored. Over the past five years, active learning instructional techniques inspired by the Process Oriented Guided Inquiry Learning (POGIL) approach and project based laboratory learning have been intermixed with traditional lectures and the flipped classroom method in an attempt to improve student learning.

This paper reports on the variety of methods used, how each instructional method is integrated into the classroom environment, the rationale behind implementing the various techniques, and the observations and impacts on student outcomes. Quantitative assessments, based on embedded measures throughout the past five years as well as and concept inventory performance, are used to evaluate the effectiveness of the methods and changes implemented. Qualitative assessment of the instructional methods from post-course student evaluation comments are used to understand students' response to the instructional methods described.

Introduction

The engineering program at James Madison University (JMU) was established in 2008. From the beginning, the program was intentionally developed as a non-discipline specific engineering program. It was created with the intention of producing versatile engineers, possessing qualities of the Engineer of 2020[1,2]. In addition to the technical training, the program emphasizes engineering design, systems thinking, and sustainability[3,4,5].

The engineering program curriculum is represented graphically in Figure 1. This program integrates a liberal arts general education core with courses in mathematics, engineering science, engineering design, business, systems analysis, and sustainability. Skill development, beginning in the freshman year, is blended with engineering design theory and engineering science concepts throughout the program. A design curriculum, comprised of six courses, is included throughout years two through four of the program, providing students with opportunities to apply science, management, and liberal arts education to a variety of complex, ill-defined problems that incorporate customer needs alongside technical constraints. The engineering science courses are intended to provide both theory and application exposure to support these design projects as well as prepare students for the NCEES Fundamentals of Engineering Exam.

YEAR 1	Calculus 1	Liberal Arts Core	Liberal Arts Core	Liberal Arts Core	Physics 1
	Calculus 2	Liberal Arts Core	Introduction to Engineering	Liberal Arts Core	Physics 2
YEAR 2	Calculus 3	Liberal Arts Core	Engineering Design 1	Liberal Arts Core	Chemistry 1
	Linear Algebra & Different Eq.	Statics & Dynamics	Engineering Design 2	Engineering Management 1	Chemistry 2
YEAR 3	Thermal-Fluids 1	Instrumentation & Circuits	Engineering Design 3	Engineering Management 2	Liberal Arts Core
	Thermal-Fluids 2	Materials & Mechanics	Engineering Design 4	Liberal Arts Core	Liberal Arts Core
YEAR 4	Sustainability Fundamentals	Systems Analysis	Engineering Design 5	Technical Elective	Liberal Arts Core
	Sustainability & Design (LCA)	Technical Elective	Engineering Design 6	Technical Elective	Liberal Arts Core

Figure 1 – Schematic representing the courses comprising the engineering curriculum at James Madison University, illustrating the incorporation of liberal arts education with training in engineering science, design, management, systems analysis, and sustainability[4].

The Circuits and Instrumentation course at JMU is intended to present junior level engineering students with the fundamentals of DC and AC circuit analysis techniques, the relevance of these concepts to instrumentation and measurement, and exposure to common electronics components and laboratory equipment. The primary learning objectives of this four-credit hours (five-contact hours), semester long course, including an integrated laboratory component, are:

- O1. Understand and use statistical methods to perform calibrations, quantify measurement uncertainties, and propagate uncertainties through systems.
- O2. Apply the basic laws, analysis techniques, and circuit theorems to fully analyze the steady state behavior of D.C. circuits.
- O3. Understand and predict the behavior of basic semiconductor components (e.g., diodes, transistors, operational amplifiers, solar cells, etc.).
- O4. Use differential equations to model the transient behavior of first and second order dynamic systems comprised of resistive, capacitive, and inductive elements.
- O5. Apply the basic laws, analysis techniques, and circuit theorems to analyze the steady state input and output behavior of A.C. circuits
- O6. Define and use instrumentation and measurement terminology and signal conditioning circuits.
- O7. Use computer software, mathematical modeling techniques, and common laboratory equipment to design, prototype, and test circuits.

As seen in Figure 1, students entering the Circuits and Instrumentation course are required to complete four semesters of calculus, including linear algebra and differential equations, as well as a second university physics course, which covers introductory electricity and magnetism concepts. With this foundation, an expectation of the course is to challenge students to integrate prior coursework into developing an understanding of circuits and instrumentation, as well as a broader context of systems analysis that can be applied to dynamic systems outside of the course.

To provide such an experience to upper division students, the instructors developed this course using a variety of pedagogical techniques intended to challenge, motivate, and engage students in the learning process. Recognizing the need to accommodate a variety of learning styles[6] and learner strategies[7,8], a combination of active learning strategies[9], laboratory exercise, and projects were incorporated with traditional lecture based approaches. This paper provides a description of the course development and evolution during a five-year period during which the author was the primary instructor for the course. Throughout this time, different instructional strategies were employed to encourage skill and knowledge development and retention. Results of these different approaches on the learning objectives for the course are examined using embedded assessment measurements, semester end concept inventory results, and qualitative student feedback and comments.

Circuits and Instrumentation Course Evolution

This section describes the evolution of the Circuits and Instrumentation Course through the initial course offerings in the 2010-2011 academic years through the Fall 2014 offering.

Initial Year (AY 2010-2011)

The initial course offering provided a blank-slate opportunity for the instructors to consider the course structure. For this initial delivery, due to the broad nature of the curriculum, it was decided that a strong emphasis would be placed on problem solving and applicability of the content to a breadth of engineering applications. The use of analogies to applications traditionally considered to be outside of electrical engineering applications were to be used to reinforce the generalities of the mathematical modeling and instrumentation concepts within the course.

To encourage cooperative learning and to scaffold student knowledge from prior coursework, a guided inquiry based approach was selected as the primary method for content delivery. Structured worksheets to be completed by student groups during class, inspired by the Process Oriented Guided Inquiry Learning (POGIL) approach[10,11], were developed for this purpose. While the majority of topics were covered using this approach, the instructors found it difficult to develop inquiry based learning mechanisms for all topics. In particular, it was decided that direct instruction on complex impedance and phasor analysis would be required initially, as students had not yet been exposed to using complex algebra in this manner. Similarly, as noted from Figure 1, students in the program had no required coursework in statistics prior to this course; therefore, direct instruction with in-class and homework exercises were used to deliver this content. Table 1 lists the topics, primary delivery method(s) used, and corresponding laboratory topics for each week for the first course deliveries.

Table 1 – List of topics and methods of instruction for the first course delivery.

Week	Topic(s)	Method(s)	Laboratory Topic	Method
1	Kirchoff's Laws	Direct Instruction	Resistors and Laboratory Equipment	Procedural
2	Resistive Circuit Analysis	Guided Inquiry	Diodes	Procedural
3	Strain Gauges	Guided Inquiry	Strain Gauge Mounting	Procedural
4	Equivalent Circuits	Guided Inquiry	Bridge Circuits	Experimental
5	Capacitors and Inductors	Guided Inquiry	Function Generators and Oscilloscopes	Direct Instruction
6	First Order Circuits	Guided Inquiry	RC Circuits	Experimental
7	Second Order Circuits, Free Response	Direct Instruction	Thermocouples	Experimental
8	Second Order Circuits, Step Response	Guided Inquiry	Mechanical Second Order System	Experimental
9	Complex Impedance	Direct Instruction	RLC Frequency Response	Experimental
10	Op-Amps and Semiconductor Devices	Direct Instruction	Op-Amp Circuits	Procedural
11	Instrumentation Concepts	Direct Instruction	A/D Sampling and Nyquist Theorem	Experimental
12	Calibration and Uncertainty	Direct Instruction	Design/Build Project	Problem-based
13	AC Power	Direct Instruction	Design/Build Project	Problem-based
14	AC Power and Power Factor	Guided Inquiry	Design/Build Project	Problem-based

For this first delivery, a mixture of direct instruction and guided inquiry was used for content delivery. The laboratory portion of the course focused on equipment usage through directed procedures (i.e., provided laboratory procedures), while concept reinforcement was attempted through experimental approaches, where questions were posed but a well-structured procedure was not provided. The laboratory component of the course concluded with a problem-based project, wherein student groups were required to select and address a problem of their choosing with the development of an analog circuit.

Student progress was evaluated and grades were administered based on homework assignments, three examinations, laboratory reports, and final project deliverables. Weekly homework assignments were comprised of two different question sets. The first set focused on the basic understanding and application of concepts covered in class while the second set posed more challenging concept integration questions. Often, the second question set was framed around consumer and industrial applications in an attempt to engage students with the relevance of the material. Similarly, the examinations were comprised of an in-class examination portion, testing conceptual understanding and basic computations, and a take-home portion, focusing on integration of concepts and application to more complex problems. Homework and examination questions were selected as embedded measures of student learning objective attainment (O1-O7) and have been administered throughout subsequent course deliveries.

At the conclusion of the each 14-week course delivery, the Circuits Concept Inventory[12] (CCI) was administered to all students in addition to an end-of-semester course survey to solicit feedback about the course. While minor modifications of the course were made between the Fall 2010 and Spring 2011 deliveries, the course structure and delivery methods remained fundamentally the same.

Second Year (AY 2011-2012)

Based on results, feedback, and instructor observations from the first course deliveries, as will be discussed in the Results section of this paper, the schedule of topics and delivery methods were slightly altered. A revised topic schedule is shown in Table 2. During the first deliveries of the course, it was noted that the instrumentation concepts of linear calibration and measurement uncertainty could be carried throughout the course if instruction was provided earlier in the semester. As a result, the direct instruction module was moved to the beginning of the class. An initial concern was the potential lack of engagement with instruction in statistical methods for calibration and error estimation. Therefore, direct instruction was supplemented with in-class problem-solving exercises derived from the instructor's industrial experiences. Additional time was also devoted to first and second order systems modeling through problem solving sessions. Although students had received prior instruction with differential equations and solutions, the first delivery of the course indicated that they lacked experience with applying these mathematical concepts to physical systems.

The laboratory component of the course was also modified. The strain gauge mounting laboratory, while providing a valuable experience, was not closely coupled to the outcomes for the course. Therefore, pre-installed strain gauges were supplied to students for the bridge-circuit laboratory and an additional laboratory related to solar cell i-v curves was implemented. Noting difficulties with the concept of diodes in the prior year, this additional laboratory experience was intended to provide additional exposure to the concepts of non-linear devices and equivalent circuits.

Table 2 – List of topics and methods of instruction for the second year of course delivery.

Week	**Topic(s)**	**Method(s)**	**Laboratory Topic**	**Method**
1	Calibration and Uncertainty, Instrumentation Concepts	Direct Instruction and Problem Solving	Resistors and Laboratory Equipment	Procedural
2	Kirchoff's Laws	Direct Instruction	Diodes	Procedural
3	Resistive Circuit Analysis	Guided Inquiry	Solar Cell i-v Curves	Experimental
4	Strain Gauges, Equivalent Circuits	Guided Inquiry	Bridge Circuits	Experimental
5	Equivalent Circuits, Capacitors and Inductors	Guided Inquiry	RC Circuits	Experimental
6	First Order Circuits	Guided Inquiry	Thermocouples	Experimental
7	Second Order Circuits, Free Response	Direct Instruction	Mechanical Second Order System	Experimental
8	Second Order Circuits, Step Response	Guided Inquiry	Function Generators and Oscilloscopes	Direct Instruction
9	Second Order Circuits, Problem Solving	Problem Solving	A/D Sampling and Nyquist Theorem	Experimental
10	Op-Amps and Semiconductor Devices	Direct Instruction	Op-Amp Circuits	Procedural
11	Complex Impedance	Direct Instruction	RLC Frequency Response	Experimental
12	Complex Impedance and Introduction to AC Power	Direct Instruction and Problem Solving	Design/Build Project	Problem-based
13	AC Power	Direct Instruction	Design/Build Project	Problem-based
14	AC Power	Guided Inquiry	Design/Build Project	Problem-based

Third Year (AY 2012-2013)

The third year course deliveries were conducted using a similar topic schedule as the previous year (Table 2). The early introduction of linear calibration and uncertainty allowed for continual, repeated questioning and application of such concepts throughout the course, particularly in relation to experimental observations and conclusions; therefore, it was considered to be an essential up-front component of the course.

Although the topics remained the same, the primary methods of delivery were modified somewhat. Based on student feedback and evidence from the embedded measures, it was apparent that, although students possessed conceptual understanding of the material, they had difficulties with executing problem solving strategies to arrive at correct analytical solutions. While the guided inquiry and problem solving approaches allowed students to build understanding based on prior conceptual understanding, students desired more modeling of problem solving processes that direct instruction provided. A particular request was to spend more class time with instructor modeled problem solutions. However, this request was in conflict with the time required to cover the fundamental topics within the course.

To address this, a modified flipped-classroom methodology was employed[13,14]. Basic concept introductions, that would have been provided prior to the guided inquiry exercises, were developed into brief video lectures administered online. Students were required to watch the videos prior to class and instructed to begin the guided inquiry activities immediately upon entering class. Through observation and questioning, the instructor was able to identify students who had not watched video lectures. Peer learning groups provided additional pressure for individual students to prepare for class.

In addition to the pre-class introduction videos, the instructor provided videos of solutions to the guided worksheet and problem solving session problems. Such a video delivery method provided students the opportunity to view the instructor’s problem solving approach, provided the final solution to the problems, and allowed for repeated viewing by students during study time outside of class. Additionally, as common questions arose in class and office hours, the instructor added videos addressing common misconceptions to the video library. While this proved a significant initial effort, it addressed many of the common concerns of students and provided an outlet for additional content delivery suited to the needs of some students. Finally, at the request of eager and engaged students, additional extension videos exploring topics more in-depth (such as semiconductor device fundamentals) were eventually added to the library to further stimulate engagement from high achieving students.

Another area of concern noted from prior deliveries was encouraging students to “keep pace” with content. Often, after completing in-class exercises and collaborating on homework assignments, individual students believed that they understood and could apply the concepts on their own, only to find out in a testing situation that this was not the case. To encourage self-evaluation and pacing, a series of summative and formative quizzes were implemented most weeks of the semester. A brief (5 to 10 minute), multiple choice quiz comprised of short conceptual and computation questions was delivered at the beginning of class on Wednesdays. This first assessment was formative and was not integrated into the grading structure of the course. On Friday of the same week, students were to expect a second, summative quiz covering the same topics. The results of these summative quizzes were included in the course grade. As described in the results and discussion section of this paper, it is believed that that the integration of these quizzes significantly encouraged students to keep pace with the material presented in the course and recognize when they did not fully grasp content.

Due to equipment constraints and the necessity for laboratory work to be performed in small groups, some students were not gaining the desired experience with laboratory equipment usage and were relying on lab partners to complete assignments. To encourage all students to acquire the basic laboratory skills desired, a series of laboratory skills tests were administered in the laboratory period to each individual student. While this method provided encouraging results, it was ultimately found to be too burdensome for the individual faculty member to manage and was removed from subsequent course offerings.

Of final note, for the third delivery cycle, the final laboratory design and build project was modified to allow students to select a project challenge from a list of approximately ten different design challenges. While the independent selection of a project of interest was engaging for the students, it was realized that students were selecting oversimplified projects, projects that were too complicated for the allotted time, or projects that did not fully exercise content from the course by relying on specialized integrated circuits and not fundamental understandings of circuits. By providing numerous project concepts (e.g., design a light controlled switching circuit, design a circuit to deliver a specified current impulse, etc.), the student teams were required to utilize concepts from the course in the design and prototyping while meeting a specified set of criteria. The variety of projects also provided opportunities for peer learning and sharing of different accomplishments.

Fourth Year (AY 2013-2014)

In the fourth year of course delivery, refinements on the processes and procedures employed previously were made. Additional lecture, worked example, and supplementary instruction videos were developed. Summative and formative quizzes were implemented using an online course management system, thus providing automated grading, immediate feedback to students, and removing the necessity to occupy class time for administration. Similarly, the conceptual and “simple” calculation questions from the homework assignments were administered through the online course management system, again providing automated grading and immediate student feedback. Further, this automation allowed for variability to be programmed within these questions, thus reducing peer copying and encouraging process (rather than result) collaboration amongst the students. To address the concerns about laboratory experience due to overreliance on laboratory partners, student laboratory partners were randomized throughout the semester. This was observed to have the added benefit of encouraging students to work with peers with whom they were not familiar prior to the class, thereby encouraging community development.

The most significant change in the course during this time was the removal of some directed or procedural laboratory experiences, which were then replaced with a less structured laboratory project, as indicated in Table 3. This additional project was added to provide a circuit design and prototyping experience related directly to D.C. circuits and linear calibration. It replaced the strain gauge and bridge circuit laboratories of previous course deliveries, opting to require students to research and develop an independent understanding of bridge circuits for the project. For this year, student teams were provided with a cantilever beam with a pre-mounted strain gauge. The objective of the project assignment was to use common instrumentation circuits (i.e., a Wheatstone bridge circuit) and amplification to design an instrument that would report the weight of an object hung from the end of the beam. This challenge also required students to calibrate the device and estimate the uncertainty in the device's measurement of weight. By adding this D.C. circuits focused project, the second course project was modified to a design challenge that focused on A.C. signals and filter design.

To accommodate this change, the order of topics was rearranged slightly. Operational amplifiers and semiconductor devices (diodes, transistors, and FETs) were presented immediately following the concepts of equivalent circuits and just prior to the first design and build project.

Table 3 – List of topics and methods of instruction for the fourth year of course delivery.

Week	Topic(s)	Method(s)	Laboratory Topic	Method
1	Calibration and Uncertainty, Instrumentation Concepts	Video Lectures, Problem Solving	Resistors and Laboratory Equipment	Procedural
2	Kirchoff's Laws	Direct Instruction and Guided Inquiry	Diodes	Procedural
3	Resistive Circuit Analysis	Guided Inquiry, Video Examples	Solar Cell i-v Curves	Experimental
4	Equivalent Circuits, Op-Amps	Guided Inquiry, Video Lectures and Examples	Op-Amps	Procedural
5	Op-Amps and Semiconductor Devices	Direct Instruction, Video Lectures	Design/Build Project 1	Problem-based
6	Equivalent Circuits, Capacitors and Inductors	Guided Inquiry, Video Examples	Design/Build Project 1	Problem-based
7	First Order Circuits	Guided Inquiry, Video Lectures	Design/Build Project 1	Problem-based
8	Second Order Circuits, Free Response	Direct Instruction, Video Lectures	Mechanical Second Order System	Experimental
9	Second Order Circuits, Step Response	Guided Inquiry, Video Examples	Function Generators and Oscilloscopes	Direct Instruction
10	Second Order Circuits, Problem Solving	Problem Solving, Video Examples	RLC Frequency Response	Experimental
11	Complex Impedance	Direct Instruction, Video Examples	Design/Build Project 2	Problem-based
12	Complex Impedance and Introduction to AC Power	Direct Instruction, Video Examples	Design/Build Project 2	Problem-based
13	AC Power	Direct Instruction, Video Examples	Design/Build Project 2	Problem-based
14	AC Power	Problem Solving, Video Examples	Design/Build Project 2	Problem-based

Fifth Year (Fall 2014)

The fifth year delivery of the course largely followed the same instructional format as the previous year. During this year, the course was taught in a technology enabled classroom wherein students were seated around desks that had video connectivity capabilities. Therefore, in-class activities this semester incorporated more circuit simulations and demonstrations using CircuitLab.com and LabView. The course projects for this delivery were modified slightly to emphasize modular design and understanding of subsystem input-output relationships.

Analysis

The effects of the described course evolution and the impact on the mixed pedagogical methods employed throughout the course were evaluated from longitudinal data. The quantitative data was derived for all five years from embedded questions from homework, quiz, examination, and laboratory exercises. The embedded measure questions were grouped for each course objective (O1-O7). A variety of concept, computation, and difficulty level questions were selected for each course objective. For each student, embedded measure questions were tracked and averaged for the entire course. Here, the average score of all students, along with the standard deviation of these scores, are presented on a semester basis for questions corresponding to the course outcomes.

Additionally, the Circuits Concept Inventory (CCI) was administered at the end of each semester to all students. The average score on this concept inventory by semester is presented. Course grades and course evaluations are also used as indicators of the effectiveness of the pedagogical strategies used.

Results

Table 4 provides an overview of the student demographics for each semester considered in this study, including the number of class and laboratory sections, the gender distribution.

Table 4 – Student demographics for each semester of the longitudinal study.

Semester	Number of Sections	Total Number of Students	Number of Males	Number of Females
Fall 2010	2	25	20	5
Spring 2011	1	15	15	0
Fall 2011	3	41	29	12
Spring 2012	1	17	17	0
Fall 2012	2	37	28	9
Spring 2013	1	21	16	5
Fall 2013	2	45	38	7
Spring 2014	2	39	28	11
Fall 2014	1	24	14	10

Figure 2 graphically presents the average scores (on a scale of 0 – 100%) obtained by students, per semester, on the embedded question sets (a-d), the end-of-semester Circuits Concept Inventory results (e), and the overall course grade scores. An analysis of the observed trends from these results, coupled to the course evolution follows. It should be noted that the standard deviations of each indicator score, represented as bars on the graphs in Figure 2, was large. Therefore, the differences in the mean scores between semesters are not statistically significant. Nonetheless, due to the small sample sizes and modifications made throughout, small changes in these average indicator scores may provide trend information related to the methods and approaches used.

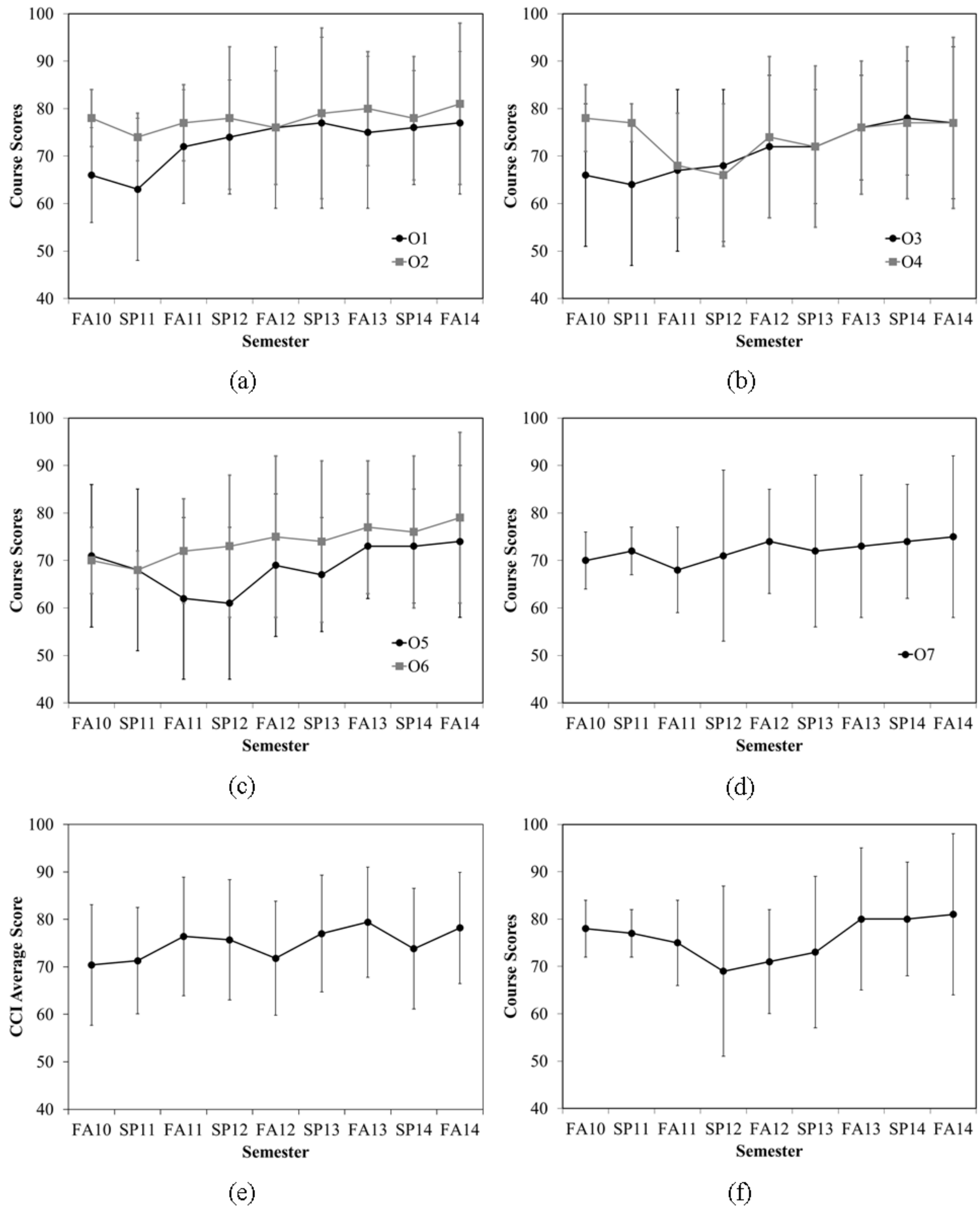

Figure 2 – Graphical representation of results from the longitudinal analysis of embedded question scores for objectives O1-O2 (a), O3-O4 (b), O5-O6 (c), O7 (d), concept inventory scores (e), and overall course grades (f).

Objective 1 – Statistics, Measurements, and Uncertainty

From Figure 2a, it is observed that students in the first iteration of the course did not perform as well as students in later course iterations on questions involving statistics, calibration, and uncertainty. Improvement on such concept and computation questions was improved with the second delivery of the course (beginning the Fall 2011 semester). During this semester, the instrumentation and statistics content of the course was introduced at the beginning of the semester. This allowed for continual reinforcement of these measurement uncertainty concepts throughout homework and laboratory content. It is thus believed that this modification to the content ordering was responsible for the indicator improvements observed.

Objective 2 – D.C. Circuit Analysis

From the results presented in Figure 2a for this objective (O2), a large change in the average performance on indicators related to D.C. circuit analysis and design concepts was not noticed. Although a slight upward trend may be observed, the average performance between the initial and final course deliveries differed by three percentage points. Guided inquiry learning was used to deliver this content throughout all course deliveries, suggesting this as a robust content delivery method. The addition of video content and example problems for this material did not significantly alter indicator question performance. A significant change in the variability of scores about the mean was noticed following the first course iteration, beginning in the Fall 2011 semester and continuing through the Fall 2014 semester. In fact, this increased performance indicator variability following the Fall 2011 semester is noted for all data sets.

Objective 3 – Semiconductor Devices

A gradual improvement in the understanding of and ability to design with semiconductor devices (O3, Figure 2b) is noted. Following the initial course deliveries, greater emphasis was placed on the understanding of diodes, transistors, and operational amplifiers. In particular, the instructor emphasized practical uses and guided students to increased usage of such devices for projects. Beginning in the Fall 2012 semester additional video lectures and problem solutions about semiconductor devices were made available to students. Additionally, summative and formative quiz questions focused on diode, transistor, and op-amp circuits were added to encourage students to learn the material shortly after it was presented. In the Fall 2014 semester, the additional laboratory project was incorporated into the class structure and the semiconductor device concepts were introduced earlier into the class.

Objective 4 – Transient Behavior (First and Second Order Systems)

The embedded question scores related to student understanding of first and second order systems (O4, Figure 2b), including differential equation modeling and step response behavior, indicated an average 78% competency score in the first course delivery. However, this attainment dropped by nearly 10% points in the second offering. This drop in attainment resulted in the implementation of video example problems as well as the summative and formative quiz cycle previously described. It was noted by the instructor that the first cohort of students exhibited high levels of mathematical competency, whereas subsequent cohorts required additional scaffolding to incorporate the differential equations concepts learned from mathematics courses into the transient system behavior analysis of the course. Following implementation of the video problem solving, additional time with first and second order system problem solving, and periodic quizzing beginning in the Fall 2012 semester, the competency attainment increased in subsequent course deliveries.

Objective 5 – A.C. Circuit Analysis

The concepts of A.C. circuit analysis and phasor representation (O5, Figure 2c) exhibited a pattern similar to that of the O4 results, with a noticeable decrease in attainment during the second year course deliveries. Here, however, the inclusion of video lectures, video example solutions, and formative quizzes rapidly increased the performance on this indicator in subsequent deliveries. Feedback from students indicated that they appreciated seeing how to apply and interpret the results of the phasor mathematics in the lecture videos but also appreciated the in-class lectures and activities that related the concepts to the complex algebra – a construct that they, prior to this class, did not realize could provide physical insights.

Objective 6 – Instrumentation and Measurement Concepts

Following the first course delivery, instrumentation and measurement terminology was introduced earlier in the semester along with the statistical calibration and uncertainty quantification module (O6, Figure 2c). Student attainments of these concepts remained similar, or increased slightly with subsequent offerings. This is believed to be due to the constant reinforcement of such concepts and, due to the early presentation of the material, requirement for students to demonstrate use of these concepts on laboratory, project, and homework assignments. However, the implementation of the second D.C. instrument design project in the Fall 2013 and subsequent semesters did not have a noticeable impact on the attainment in this objective.

Objective 7 – Software and Laboratory Equipment Use

Students were trained to use LabVIEW™ for data acquisition, SPICE based circuit simulation tools, and common laboratory and electronics prototyping tools. Results from objective indicators (O7, Figure 2e), which also included instructor observation, indicated similar student performance in the first two delivery years. A modest, approximately 3% point average increase was observed in the indicator following the third year implementation (Fall 2012). During this semester, laboratory groups were randomized for each procedural and experiment based lab, thus reducing individual student reliance on set laboratory partners. During this academic year, graded laboratory skills demonstrations were required of all students. This required skills demonstration was removed from the course in subsequent deliveries, due to instructor loading and time constraints. Instead, during the Fall 2013 semester, the second design and prototype laboratory project was introduced. The modest sustained increase in attainment after this time may suggest that the introduction of the second laboratory project had a similar effect to that of required laboratory skills demonstrations. For each project, student groups were required to meet with the instructor to explain and demonstrate the circuit. It is believed that this type of student-instructor interaction emphasized the importance of competency amongst all team members.

CCI Results

Circuit concept inventory results (Figure 2e) over the longitudinal study period show high variability and a modest increase in average attainment of core concepts. However, the inclusion of summative and formative quizzes in the Fall of 2012, which often mimicked questions similar to those on the FE exam and the concept inventory, did not significantly alter the concept inventory results, as was originally expected. A potential limitation of the CCI is that students, recognizing that the inventory would not have bearing on their grades, did not maximize efforts on this indicator.

Course Grades

Finally, average course scores are presented in Figure 2f. Of note is the decrease in course grades during the first two years. Following the implementation of video lectures and problem solving videos, as well as the formative and summative quizzes, scores gradually increased with time. A particularly interesting trend that can be observed is the marked increase in the course score variability (standard deviation error bars) beginning with the Spring 2012 semester delivery. From this point on, the grade variability remained high, due primarily to bimodality in the score distributions. Instead of a normal distribution of scores, the student scores were distributed about two modes – "high scores" with an average of approximately 85%, and "low scores" with a grouping near 65% and gradual "tail" of much lower scores.

It is unclear why this bimodality developed. One possible explanation, as seen from course evaluation comments, is the rigor and time demands of the course. Upon the addition of weekly summative and formative quizzes and additional video content, some students indicated being overwhelmed with the content and pacing of the course. Instead of utilizing the resources available, there was a perception of being "left behind" in terms of course content. This attitude may have resulted in behaviors (e.g., failure to complete assignments, "giving up", etc.) that ultimately resulted in lower course grades, despite the concept inventory indication of understanding.

Course Evaluation Results

Course evaluation comments were used to evaluate the effectiveness of the methods used in the course. Table 5 shows a tally, by semester, of the number of positive or negative comments written reflecting the teaching methods used in the course.

Table 5 – Tally of positive and negative comments from student evaluations related to teaching methods employed.

Method		**FA10**	**SP11**	**FA11**	**SP12**	**FA12**	**SP13**	**FA13**	**SP14**	**FA14**
Guided Inquiry	Positive	6	5	3	5	7	6	3	2	3
	Negative	1	2	1	1	1	1	0	0	0
Challenging Homework	Positive	5	3	2	4	3	2	0	0	0
	Negative	2	2	3	4	3	2	2	1	2
Workload and Pacing	Positive	2	3	2	1	0	0	0	0	0
	Negative	1	1	2	2	3	4	3	4	2
Lab Exercises	Positive	3	2	4	3	2	1	0	0	0
	Negative	0	0	0	0	0	0	0	0	0
Lab Projects	Positive	7	8	10	8	7	8	7	5	7
	Negative	0	0	1	0	0	0	1	1	1
Video Lectures	Positive					8	7	6	8	5
	Negative					0	0	0	0	0
Summative Quizzes	Positive					1	2	2	1	0
	Negative					0	0	0	0	0

Initially, students thought highly of the guided inquiry approach; however, as the course continued in this manner, it appears that this became the expected medium of delivery. This is most likely the result of “word of mouth” and student expectations coming into the course. This, over the time of this study, fewer positive or negative comments were made about this approach as it became the “norm”. It is also interesting to note that challenging homework and workload initially received positive reviews. Student comments, while admitting that this required significant time, also admitted that it resulted in them learning the material. Over time, such positive comments were replaced with negative perceptions of time and effort requirements.

Laboratory exercises and, in particular, projects continually receive positive comments. Students reflect upon the challenging design projects and recognize the importance of applying course knowledge to solve practical problems within specified constraints. Negative comments about the projects primarily stem from student group dynamics and time requirements.

Finally, the inclusion of video lectures and video problem solutions received significantly positive student reception. Comments indicated that students appreciated the ability afforded by the videos to review material at their own pace and to gain insights into how the instructor approached analytical problem solving.

Instructor Observations

For all of the assessment information presented, it is noted that the student indicator scores decreased from the first cohort (Fall 2010 – Spring 2011 semesters) scores. This first student group through the course was also the first cohort through the program. Thus, the group exhibited a mindset and drive unique from subsequent cohorts in the program. In particular, they possessed tenacity and motivation to build upon prior physics and mathematics experiences. Additionally, these two semesters represent the instructor’s first course development and delivery attempts; thus, comparison to this first cohort may not be suitable.

From an instructor’s standpoint, the described changes were implemented in an attempt to address multiple learning styles and reach a broader audience of students. The process oriented learning worksheets approach was well suited to the instructor’s teaching philosophy and Socratic style of content delivery. By observation and frequent interaction with the students, the instructor believes that this approach resulted in greater conceptual understanding of content, as opposed to rote memorization of procedures. Video lecture and problem solving content was added to address class time constraints and commonly repeated student questions and to provide a mechanism to model the analytical problem solving process applied to circuits and instrumentation concepts. Similarly, the formative and summative quizzes were added to encourage students to “keep pace” with material delivery.

While these additions were shown to be effective for the author, they may not be suited to all teaching styles and comfort levels. As an example, a colleague utilized the guided inquiry worksheet approach in the same class, but did not enjoy the approach or find it effective. As a consequence, students did not attain as well as when the delivery approach was chosen to meet the style of the instructor.

Conclusions and Recommendations

Based on the overview of the longitudinal data presented, no one instructional approach was identified as a providing a significant increase in student course outcome attainment. Rather, a variety of approaches within a single Circuits and Instrumentation course appears to provide a robust experience that complements a variety of learning styles. A guided inquiry approach to learning did not significantly improve student performance over time, but was not a hindrance to learning. In particular, such an approach anecdotally leads to improved conceptual understanding, if not procedural and computational efficiency. To address these concerns, provide analytical problem solving examples, and reduce classroom time constraints, the "flipped classroom" method of content and example problem solution delivery was employed. This supplementary method was met with student approval as well as a modest improvement in student outcomes. Finally, the instructor and students agreed that the inclusion of at least one open-ended, ill-structured, and minimal guidance electronics design project in the laboratory setting was essential to integrating course concepts with practice.

Thus, it is demonstrated that multiple instructional methods can, and perhaps should, be included within introductory electronics courses to appeal to a variety of learning styles and teaching methods. Anecdotal evidence suggests, however, that the mix of strategies used here may not be well suited to all instructors. While this is an opportunity for an additional avenue of inquiry, it is recommended that individual instructors consider how their personal content delivery mechanisms can be extended to accommodate a variety of different learners.

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