# Industry-Oriented Laboratory Development for Mixed-Signal IC Test Education

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***Abstract*—The semiconductor industry is lacking qualified integrated circuit (IC) test engineers to serve in the field of mixed-signal electronics. The absence of mixed-signal IC test education at the collegiate level is cited as one of the main sources for this problem. In response to this situation, the Department of Electrical and Computer Engineering at the Ohio State University, Columbus, has partnered with Texas Instruments to establish an IC test-engineering-oriented course. The course objectives are to familiarize students with industrial testing techniques and to help students obtain the fundamental skill sets required to be competent mixed-signal IC test engineers. A novel laboratory pedagogy is developed to achieve these objectives. The results of the classroom assignments and the feedback provided by students, faculty, and industry representatives indicate that the approach has successfully achieved these goals.**

***Index Terms*—Industry-oriented, integrated circuits (ICs), laboratory development, mixed-signal IC test, test engineering.**

## I. Introduction

MIXED-SIGNAL integrated circuits (ICs) have become increasingly prevalent lately, as both analog and digital circuits are being integrated in a single System-on-Chip (SoC) for increased functionality and reduced cost. However, the increase in functionality also leads to an increase in complexity, which makes mixed-signal ICs more challenging to test than their purely analog or digital counterparts. This is particularly true in high volume, low-cost chip sets such as the ones in wireless devices (e.g., Bluetooth, Wi-Fi, multimode cellular, and so on), multimedia, and embedded systems. The increasing challenge in mixed-signal IC testing demands highly skilled and better trained test engineers, who have been and still are in short supply due to the lack of university programs and courses on the subject [1].

To break the imbalance between the supply and the demand of qualified test personnel, the Department of Electrical and Computer Engineering (ECE) at the Ohio State University (OSU), Columbus, has collaborated with Texas Instruments (TI) in opening a new course: ECE 694I: Mixed-Signal IC Test and Measurement. The course aims to introduce mixed-signal IC test to students and to help them obtain the fundamental skill sets required in order to be competent test engineers.

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A laboratory is a very important component in engineering education. It is even more so for this new course due to its subject matter; students cannot learn how to test circuits without going to a laboratory, just as human beings cannot learn how to swim without diving into the water. However, conventional engineering laboratory strategies are not sufficient to meet our course objectives. Therefore, a new industry-oriented "extract-and-match" approach is proposed.

The paper is organized as follows. Section II describes the need for the new course in mixed-signal IC testing. Section III discusses the curriculum context and the overall course objectives. Section IV states the proposed laboratory pedagogy. Section V outlines the laboratory activities. Section VI presents the feedback and assessment data collected from students, faculty, and industrial sources. Finally, Section VII concludes the paper.

## II. The Need for the New Course

There has been a striking imbalance in recent times [1]–[5] between the rising demand for mixed-signal IC test engineers and the lack of college graduates with the skills required. As a result, "most test professionals came to this business (mixed-signal IC test) by accident," as an industrial expert has pointed out. "The question we must ask ourselves (the semiconductor industry) is this: 'How much more effective could they be if they were intentionally directed here?'" [2]. A new course that introduces college students to mixed-signal IC testing and helps them obtain the skills to be proficient can effectively solve these problems.

The demand for qualified mixed-signal test engineers has been growing in the semiconductor industry for at least three reasons. First, mixed-signal ICs are increasingly dominant in today's market. They are widely used in applications like hard disk drives, smartphones, laptops, and portable multimedia devices. For example, a third-generation (3G) iPhone has nearly a dozen mixed-signal IC chips built in, from multistandard (GSM/EDGE/3G) wireless transceiver ICs to analog-to-digital converters (ADCs) and digital signal processors, all of which have surpassed the functionality of conventional purely analog or digital ICs.

Second, the ever-increasing complexity of modern mixed-signal ICs requires more tests to be done. The increase in the number of tests is a direct consequence of the increase in functionality, but it is also due to the continual device feature size scaling from micrometer to nanometer—for example, from 1 or 2 $\mu$m to 90 [6] and 65 nm [7]. As a result, more transistors and circuits are integrated on the same chip, all of which need to be verified and tested.

TABLE I
COMPARISON OF EXISTING COURSES ON TESTING

| | [3] | [4] | [8] | [5] | this course |
|---|---|---|---|---|---|
| year | 2001 | 2006 | 2008 | 2009 | 2009 |
| location | Europe | Asia | Canada | US | US |
| level | professional | BS | BS, MS, PhD | BS, MS | BS, MS, PhD |
| subject | industrial test | digital IC test | mixed-signal IC test | product test | mixed-signal IC test |
| DUT | 74ACT299 | varies | TL084CN, CY8C29466 | generic opamp | ADC1158 |
| ATE | Agilent 83000 | Teradyne J750 | Teradyne A567 | N/A | N/A |
| bench test | N/A | N/A | In-lab: bread-board | Given actual data from industry | To-go: evaluation module with USB 2.0 to PC/laptop |
| Feedback | Industry, students | Students | N/A | Students | Industry, students, faculty |

Third, the rising test costs for mixed-signal ICs call for more qualified test engineers with the expertise to develop new test methodologies. Verification and production test represents up to 50%–60% of the total time and cost in making very large scale integrated (VLSI) chips, making it the biggest single expense of the chip fabrication process [4]. It was also predicted by the Semiconductor Industry Association in 2003 that by 2014, the cost of testing a transistor would exceed the cost of its manufacturing [3].

The supply of qualified mixed-signal IC test engineers is scarce since most universities do not have any test-related courses. Meanwhile, recent college graduates do not recognize mixed-signal IC test as a viable and important engineering career path. As a result, they do not apply for those test positions, which further contributes to the shortage of qualified test personnel.

This shortage has encouraged companies to work with universities to incorporate test-engineering programs in their curricula. For example, Agilent Technology joined five European institutions in creating the Eu-NICE-Test (European Network for Initial and Continuing Education in VLSI/SOC Testing) project [3], FreeScale Semiconductor teamed up with Monash University of Malaysia to create an undergraduate course in Electronic Test Technology [4], Texas Instruments cooperated with McGill University in Montreal, QC, Canada [8], and Rose-Hulman Institute of Technology (RHIT) [5] in Terre Haute, IN, to offer mixed-signal IC test and product test courses. A brief comparison of these courses is listed in Table I.

However, the solutions reported in [3], [4], and [8] are not practical for all institutions since they developed their laboratories around the rather costly automatic test equipment (ATE), a set of automatic devices often used during IC production to test high-volume chips quickly. ATE consists of a test head, a workstation, and a mainframe with all the measurement instruments, but access to an ATE for an average university is limited by both economics and logistics. For example, Teradyne J750 ATE used in [8] costs as much as $1.7 million. Students in [4] rely on off-hour access to industrial ATE at nearby semiconductor manufacturing facilities. Thus, the advent of a new course that creatively develops methods for teaching mixed-signal IC testing and provides hands-on experience without the need for a nearby semiconductor site or expensive ATE could not be more opportune.

## III. Curriculum Context and Course Objectives

### A. Level and Prerequisites

This course targets undergraduate students (especially juniors and seniors) with basic electrical engineering knowledge, as well as graduate students at all levels. Specifically, the prerequisites of the course are:

1) Electronic Circuits: Overview of basic analog and digital signals, multistage transistor amplifiers, models for switches, digital circuits, and introduction to analog-to-digital (A/D) and digital-to-analog (D/A) conversion. At OSU, these topics are covered in ECE 301 and ECE 323, both of which are three-credit-hour core ECE courses required for all who are accepted into the ECE major.
2) Linear Systems: Overview of linear systems and models, time responses using convolution, Fourier series and transform, Laplace transform, frequency response, Bode plots, Z-transforms, state variables, state equations, and computer-aided analysis. At OSU, these topics are covered in ECE 351 and ECE 352, both of which are three credit hours, and they form a two-quarter series of courses on linear systems.

In addition, knowledge of sampling theory and digital signal processing (DSP) would be very helpful. A new approach known as DSP-based testing [1] has been widely adopted in mixed-signal ICs to test ac parameters. It is a powerful methodology that allows faster, more accurate, more repeatable measurement than traditional ac measurements using RMS voltmeters. In fact, the evaluation module (EVM) used in the laboratory for this course adopts the DSP-based test method (see Section V). However, this knowledge is not required because it will be briefly reviewed during the course lectures. Meanwhile, graduate students at all levels, M.S. or Ph.D., could take this course without any prerequisite. This is based on the fact that many OSU graduate students have already taken those courses or equivalents either at this institution or at other institutions where they received their Bachelor's degree.

### B. Course Objectives and Structure

There are three major objectives of this course according to the syllabus [9]: 1) students will learn industrial techniques for mixed-signal IC test, which include dc measurement, frequency response, harmonic and intermodulation distortion, and noise behavior; 2) students will apply these techniques to analog, sampled-data mixed-signal, RF, and high-speed digital channels; 3) students will understand mixed-signal IC test concepts, such as testability, design-for-test (DfT), and built-in-self-test (BIST).

With these objectives, three major components—namely, goals, activities, and assessments—are designed based on

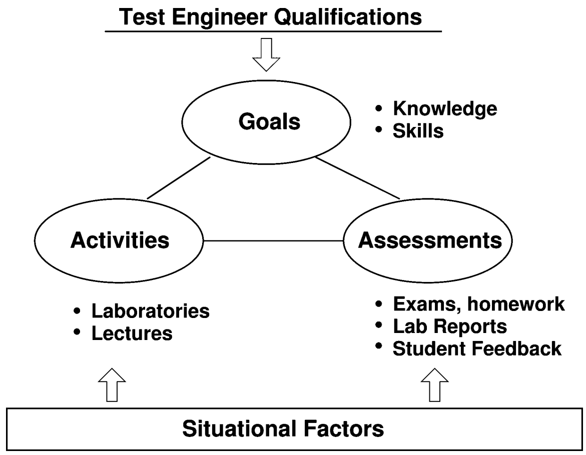


Fig. 1. Integrated Course Components.

Fink's method in creating significant learning experiences [10]. They form a three-ring structure as shown in Fig. 1. The advantage of this structure is the integration of all three components in that each goal warrants a type of activity, which is later assessed to determine whether the original goal has been met. As seen in Fig. 1, test engineer qualifications determine the course goals, while classroom activities and assessments reflect the unique situational factors in a university, such as the specific context of teaching and learning. Some of the most important situational factors are:

1) *Student Background*. There is a mixture of undergraduate and graduate students in this class (48.1% undergraduates and 51.9% graduate students in Spring 2009). They typically have fundamental ECE knowledge, but lack sufficient, if any, industrial experience.
2) *Curriculum Context*. Students have basic circuit (ECE 301, 323) and system (ECE 351, 352) courses as prerequisites. No IC design knowledge is assumed.
3) *Time Limit*. OSU is on a quarter system with only 10 weeks per quarter. For a three-credit-hour course, students meet three times a week, each time for only 48 min, which puts an upper limit of 30 h for all class materials.
4) *Resource Constraint*. Unlike industrial companies, universities generally have limited or no access to ATE, which constrains the complexity of laboratory exercises.

## IV. Laboratory Pedagogy

Laboratories have had a central role in the education of engineers [11]. Laboratory activities are added to the curricula for various reasons [12] and differ in methods and approaches. Traditional mixed-signal IC laboratory strategies, such as in [13] and [14], do not meet the objectives of this new course because they do not emphasize testing. Therefore, a novel "extract-and-match" method is proposed, which extracts core laboratory goals from industrial requirements, includes different laboratory types, and matches each type of laboratory to a specific goal.

### A. Extract Goals

A laboratory can serve different purposes. Some common goals of laboratories in engineering courses include seeking higher retention of students [16], assisting the understanding of theory [17], improving exam performances [18], enhancing learning effectiveness [19], [20], and improving the quality of experience [21], [22]. This laboratory, however, is intended to help students obtain the skills of a test engineer (T.E.). Since the complete list of test engineer skills is long [15] and impossible to fully cover in a single course, five major duties that a proficient mixed-signal T.E.'s should be able to perform have been extracted from Texas Instruments test requirements (see [15]) to serve as the laboratory goals. They are listed in Table II and explained in detail here:

TABLE II
Skills Required for Test Engineering [15]

| | Skills |
|---|---|
| 1 | Decide on the test method |
| 2 | Develop the test plan |
| 3 | Design the test hardware and software |
| 4 | Debug the test solutions |
| 5 | Determine the test outcome |

1) *Decide on the test method*, such as describing the test purpose, selecting test equipment, and determining what will be tested in what sequence and in what operational mode.
2) *Develop the test plan*, such as developing a complete test plan for a specific product from its data sheet and other engineering documents.
3) *Design the test hardware and software*, such as creating the interface board to the device under test (DUT) and writing automated test programs.
4) *Debug the test solutions*, such as detecting abnormalities and collaborating with designers to solve any technical problems related to the test.
5) *Determine the test outcome*, such as deciding whether the device has passed or failed the test and identifying the root cause for every failure.

### B. Laboratory Category

Over the years, a number of laboratory methods have been reported for effective laboratory education, such as the remote lab [18], [22], virtual lab [20], and lab using information technology (IT) [16], [21], commercial software[17], [19], and customized pedagogical tools [23]. These methods can be classified into several categories as shown in Table III [12].

TABLE III
Laboratory Categories [12]

| Type | Purpose |
|---|---|
| Skills Lab | Achieve proficiency with basic tools and techniques |
| Methodology Lab | Learn methodology for problem solving |
| Reinforcement Lab | Increase retention of concepts |
| Comparison Lab | Develop comparative skills |
| Improvement Lab | Cultivate critical thinking and creativity |
| Discovery Lab | Broaden curriculum |

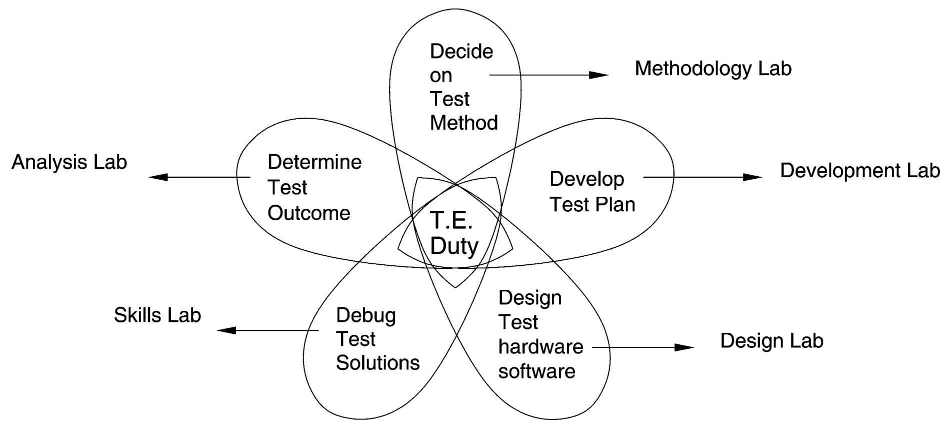


Fig. 2. Extract-and-match laboratory pedagogy.

### C. Matching

The key principle is to match different laboratory categories and exercises with the five goals extracted. Two of the five goals could be addressed by incorporating some of the major laboratory categories listed in Table III. The other three goals, however, require customized laboratory exercises. The resultant matching of lab types and goals is shown in Fig. 2 and explained as follows:

1) *Methodology Lab*. The goal that students could identify the appropriate test method is addressed by having students self-check their bench connections without the help from the teaching assistant (TA) before data collection. Students are also required to judge their own test methods based on the results they have obtained.
2) *Development Lab*. The goal that students will learn to develop test plans is met by asking students to develop a test list based on a commercial IC data sheet.
3) *Design Lab*. The goal related to hardware and software development is hard to meet directly due to the time and resource limitations. Instead, students are asked to explain the pros and cons of the alternative test methods and procedures used in the lab that are different from the industrial practices or ideals. This type of questions eventually takes up an eighth of the total laboratory questions.
4) *Skills Lab*. The goal that students could debug test solutions is addressed through encouraging students' independent debugging with limited TA intervention.
5) *Analysis Lab*. The goal that students will learn to determine test outcomes is satisfied through requiring students to predict test results before the test and interpret lab data after the measurement.

## V. Laboratory Activities

The laboratory portion of the course is intended to give students some practical experience to help solidify their understanding of the theoretical concepts covered in the course lectures. Additionally, students are able to observe and overcome technical problems related to the DUT as well as issues other than those foreseen by the instructor during the course planning, such as improper grounding and malfunctioning oscilloscopes, all of which are examples of what test engineers would encounter and have to deal with on a daily basis in the real world.

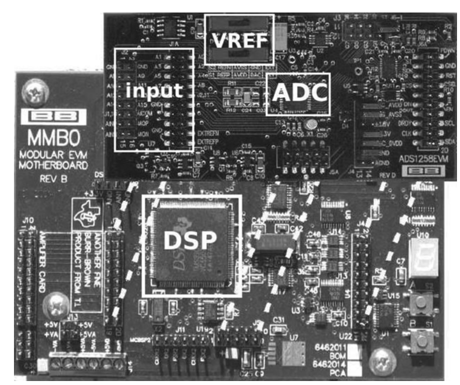


Fig. 3. Evaluation module: digital signal processor (DSP), analog-to-digital converter (ADC), voltage reference (VREF), and analog inputs (input).

### A. Laboratory Setup

Since automated test equipment is expensive and not widely available for university laboratory courses, the laboratory exercises focus on single-device bench tests using the ADS1158EVM [24]–[26] provided by Texas Instruments.

*1) Hardware:* The ADS1158 is a single-channel delta-sigma ADC capable of supplying a 16-bit sample at rates up to 125 kHz. It also includes a 16-channel analog multiplexer to allow different inputs to be selected for conversion [24]. It comes with an evaluation module (EVM) [25] and a digital motherboard that provides a digital signal processor (DSP), memory, and a USB interface in addition to power conditioning circuitry, as shown in Fig. 3.

*2) Software:* ADCPro is a modular software system for evaluating TI ADCs [26]. It allows students to easily configure the motherboard and converter as well as capture, display, and save data, as shown in the screen capture of Fig. 4.

*3) Bench:* The laboratory is conducted at a standard undergraduate lab bench outfitted with the equipment listed in Table IV as seen in Fig. 5. Students are able to install and run the ADCPro software on their own laptops, allowing easy analysis of collected data outside of the lab.

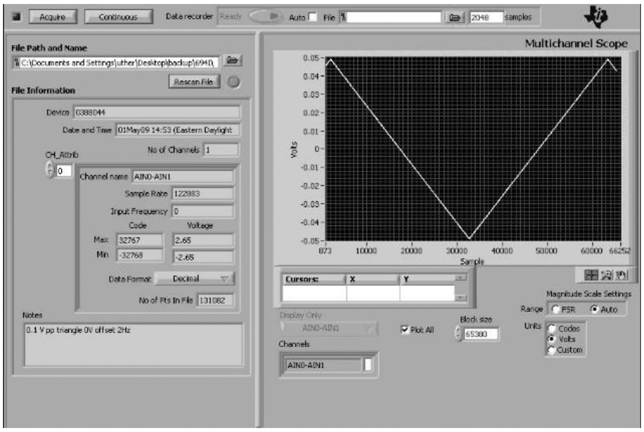


Fig. 4. ADCPro software from Texas Insturments.

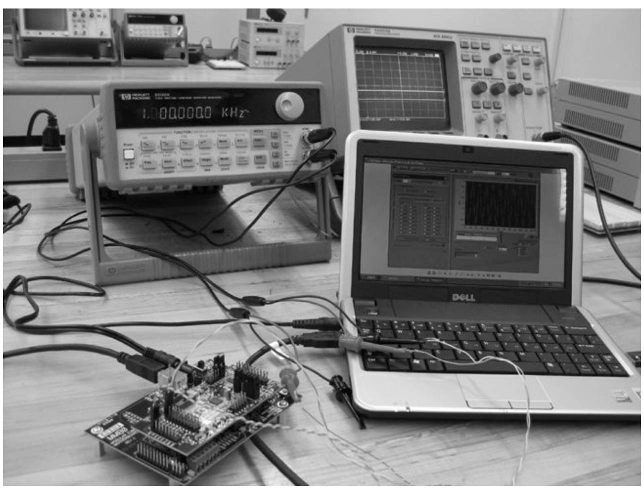


Fig. 5. Laboratory bench.

## B. Laboratory Organization

The laboratory portion of the course has three main sections: a pre-laboratory assignment, the actual laboratory experience, and a post-laboratory report. These three sections cover the five skill sets required in a test engineer position as outlined in Table V.

*1) Pre-Laboratory:* The pre-laboratory assignment is designed to familiarize the students with the ADS1158 data sheet and ensure that they possess a basic comprehension of the typical ac and dc tests commonly performed on ADCs and the methods used to perform such tests. The pre-laboratory exercises prompt students to consider methods of conducting the ac and dc tests as well as allowing them to plan their testing strategy.

*2) In-Laboratory Test:* The laboratory activities include several tests that can be run on the ADS1158EVM with an input from a signal generator. Students are asked to determine gain and offset error of the converter as well as code width, differential nonlinearity (DNL) error, integral nonlinearity (INL) error, signal-to-noise ratio (SNR), and frequency response and to verify that there are no missing codes. The ADCPro software, Fig. 4, provides a convenient interface for students to evaluate the converter. Using the MultiScope tool in the software, the students can observe the captured test waveforms and correct any setup errors before continuing. After collecting data in the lab, students are able to analyze the data using a variety of tools, including Matlab, the ADCPro evaluation software, and analysis scripts written in PERL.

TABLE IV
LABORATORY EQUIPMENT

| Equipment | Description |
|---|---|
| TI ADS1158 EVM | ADC Evaluation Module |
| TI ADCPro | Evaluation Module Software |
| HP 33120A | Signal Generator |
| HP 54603B | Oscilloscope |
| HP 3611E, HP 3630 | Bench Power Supply |

TABLE V
IMPLEMENTATION OF LAB TYPES

| Lab Method | Lab Application |
|---|---|
| Methodology Lab | Pre-laboratory assignment |
| Development Lab | Pre-laboratory assignment |
| Design Lab | Laboratory Setup |
| | Data Analysis |
| Skills Lab | Laboratory Testing |
| Analysis Lab | Data Analysis |
| | Laboratory Report |

*3) Post-Laboratory Report:* The final portion of the laboratory is a report detailing the exercises conducted in the laboratory and explaining the analysis and results. Students are asked to apply their theoretical knowledge, gained in the lecture component of the course, to the practical results gained in the laboratory. Reports show the analyses of the collected data to determine the requested performance parameters of the ADC as well as to detail any deviations from the typical test results provided by the device data sheet. The report exercise provides the students an opportunity to demonstrate and improve their ability to determine and report test outcomes, a critical skill for test engineers in industry.

## C. Technical Description

Resolution, which is the number of output bits, does not fully characterize the behavior of an ADC. A variety of performance parameters, such as gain, offset error, offset drift, nonlinearity, SNR, maximum data rate, and power consumption, need to be measured before using an ADC for a specific application. These parameters can be loosely divided into static and dynamic parameters, which could be measured through dc and ac tests, respectively.

*1) DC Tests of Static Parameters:* Most static parameters of an ADC, such as gain, offset error, INL, or DNL, can be derived from the ADC transfer curve, which is the relationship of the input voltage and the output code. Due to the statistical nature of an ADC, where the output codes generated by a real-world ADC are affected by noise from the input circuits, dc measurements could require multiple iterations.

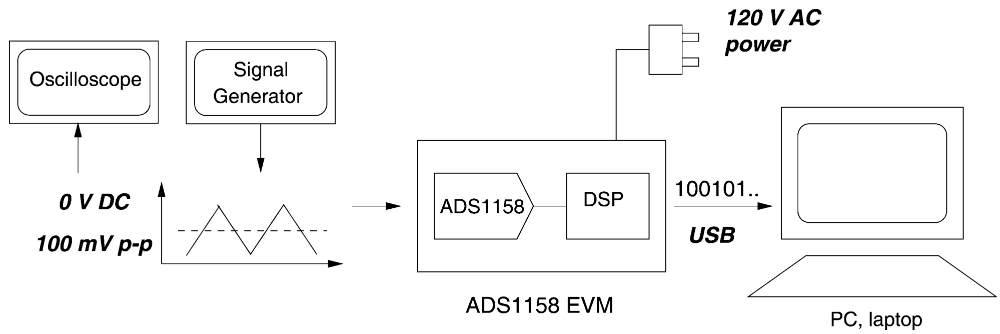


Fig. 6. DC test setup.

The dc tests of this lab adopt a simple rising or falling linear ramp method as illustrated in Fig. 6. A signal source generated a 0-V average, 100 mV$_{pp}$, $f = 2$ Hz triangular wave as an input to ADS1158. The frequency of the signal is chosen to be low enough to avoid any missing codes. ADS1158 is configured to sample the input at $f_s = 128$ kHz. The ADCPro software that runs on the evaluation module allows student to capture the ADC output codes and save them to a text file on their PCs. Students then run prewritten MATLAB and PERL scripts on their computers to analyze the data, plot the ADC transfer curve, and derive the rest of the static parameters. Students are also asked to compare their measurements to the data sheet [24].

*2) AC Tests of Dynamic Parameters:* The AC tests of the lab measure SNR, effective number of bits (ENOB), and frequency response, among other characteristics. Unlike the dc tests of the lab, where relatively detailed instructions are provided in the lab manual, the ac tests challenge students to develop their own test methods as much as possible.

For example, the frequency response measurement of the anti-aliasing filter requires students to design and "self-evaluate" their test methods before data collection. The anti-aliasing filter is a digital low-pass filter whose bandwidth is programmable by adjusting the amount of filtering. Tradeoffs can be made between resolution and data rate, thus filtering more for higher resolution, or filtering less for higher data rate. Students are free to choose their target data rates and methods to measure the filter response, but before they proceed to collect the data, they have to "self-evaluate" (without the help of the TA) whether they have set the control bits $\mathrm{DRATE}\,[1:0]$ correctly and whether their methods are feasible given only a signal generator and an oscilloscope.

Again, students are asked to compare their measurements to the data sheet [24], in which various frequency response diagrams for the programmable filter are listed. With different choices of the ADC data rate settings, different groups should be getting different frequency responses, and there is not a single right answer to the problem.

## VI. Feedback and Assessment

To provide a comprehensive assessment of the new course developed and the pedagogical issues addressed, three anonymous surveys were conducted among, respectively, students who took the new course, fellow ECE faculty members who have never taught it, and engineers in the semiconductor industry who will eventually benefit from the course.

### A. Student Survey

The goal of the student survey is to assess the effectiveness of the proposed pedagogy. Students enrolled in the class were asked to fill out an anonymous survey based on their experience in the lab and their opinion of the lectures. The survey instructs the students to read a series of statements and rate them on a scale from 1 to 5, with 5 indicating they strongly agree, and 1 indicating they strongly disagree with the statement. Out of 27 students enrolled, 24 returned the survey. Table VI shows the survey questions and their results. The results of Questions 1, 4, 6, 8, and 14, which demonstrate the students' perception of how successfully the five goals (as listed in Table II) have been met are shown in Fig. 7.

1) *Can the students decide on a test method?* Yes. According to Question 4, 91.6% of the students agreed or strongly agreed that the laboratory helped their ability to test an ADC. The pre-lab also served to introduce students to the test methodologies involved in testing an ADC, as 79.2% agreed with Question 1.
2) *Can the students develop a test plan?* Yes. According to Question 14, 81.8% of the students thought they understood all that is involved in creating a test plan after taking this class.
3) *Can the students design hardware and software?* Probably not to the full extent, since sometimes alternative methods were used. However, Question 7 indicates that 41.7% of the students agreed and 37.5% strongly agreed that they were more comfortable reading data sheets, which is an important technical document for test-related hardware and software development.
4) *Can the students debug test problems?* Yes. According to Question 6, 91.6% of the students believed that they had improved their ability to debug test problems as a result of this laboratory.
5) *Can the students determine the test outcomes?* Yes. When responding to Question 8, 87.5% of the students felt that the laboratory questions helped them understand the test outcomes.

### B. Faculty Survey

The goal of the faculty survey was to discover the level of interest this new course would generate in the faculty. Six ECE faculty members from different universities (OSU and Iowa State), different ECE fields [IC, electromagnetic (EM), power electronics (PWR), and biomedical engineering (BME)], and

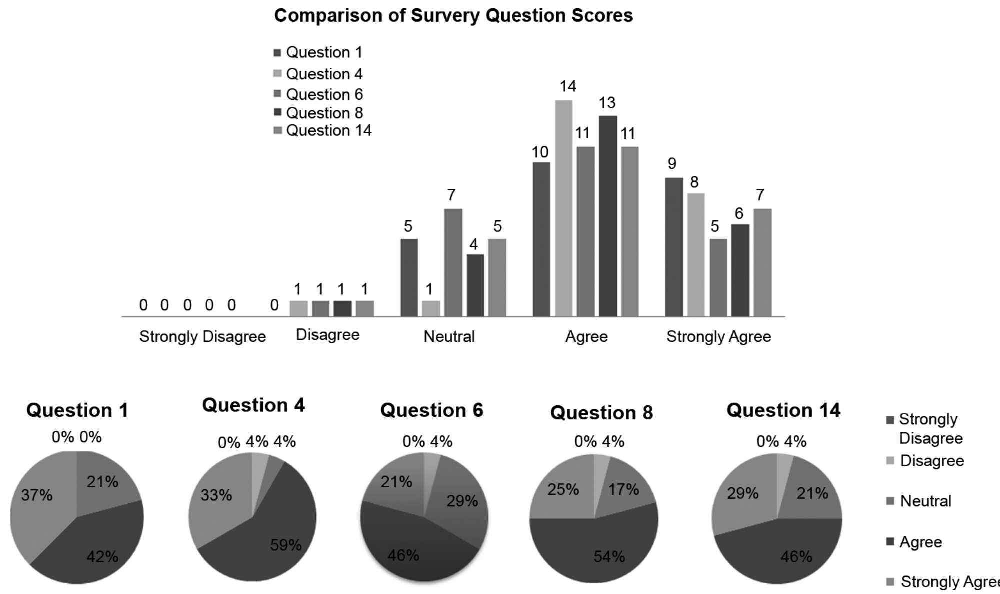


Fig. 7. Survey results: assessment of the five laboratory goals.

TABLE VI
STUDENT SURVEY QUESTIONS AND RESULTS

| | Question | 5 | 4 | 3 | 2 | 1 | Avg |
|---|---|---|---|---|---|---|---|
| 1 | The prelab helped prepare me for the laboratory. | 9 | 10 | 5 | 0 | 0 | 4.17 |
| 2 | The experience of this class will help strengthen my resume. | 10 | 10 | 4 | 0 | 0 | 4.25 |
| 3 | I enjoyed the laboratory experience. | 8 | 9 | 6 | 1 | 0 | 4.00 |
| 4 | The laboratory helped develop my ability to test an ADC. | 8 | 14 | 1 | 1 | 0 | 4.21 |
| 5 | Learning through teamwork was better than learning on my own. | 10 | 10 | 3 | 0 | 1 | 4.17 |
| 6 | The laboratory helped develop my ability to debug test problems. | 8 | 14 | 1 | 1 | 0 | 4.21 |
| 7 | I feel more comfortable reading data sheets as a result of this lab. | 9 | 10 | 4 | 0 | 1 | 4.08 |
| 8 | The laboratory questions helped me understand the test outcomes. | 6 | 13 | 4 | 1 | 0 | 4.00 |
| 9 | Observing the ADC response in the lab helped me to better understand the tests. | 7 | 11 | 5 | 1 | 0 | 4.00 |
| 10 | I feel this class has prepared me to interview for a position as a test engineer. | 7 | 9 | 7 | 1 | 0 | 3.92 |
| 11 | The laboratory increased my understanding of non-ideal ADCs. | 6 | 12 | 5 | 1 | 0 | 3.96 |
| 12 | I would prefer more time spent in lab and less time in lecture. | 5 | 13 | 5 | 1 | 0 | 3.92 |
| 13 | A regular laboratory section for this course would be rewarding. | 7 | 13 | 4 | 0 | 0 | 4.13 |
| 14 | After taking this class I understand the process of creating a test plan. | 7 | 11 | 5 | 1 | 0 | 4.00 |
| 15 | I am considering a career as a test engineer as a result of taking this class. | 3 | 9 | 8 | 4 | 0 | 3.46 |

different work experiences (whether or not they have worked in the semiconductor industry) participated in the survey, which includes two yes-or-no questions and optional brief explanations for their answers. The survey questions and the faculty profile are shown in Table VII.

There are two significant findings from Table VII. First, the benefits of industry–academia collaboration are acknowledged across different disciplines. For faculty members within the field of IC, the benefits include timely update of knowledge and materials; as faculty member D said, "For us (universities), it helps us to update what we teach and stay timely and relevant. For industry, it helps them train students with the required skill sets of the day. So it is a win–win mutually beneficial cooperation." For faculty members outside the specialization of IC, the views

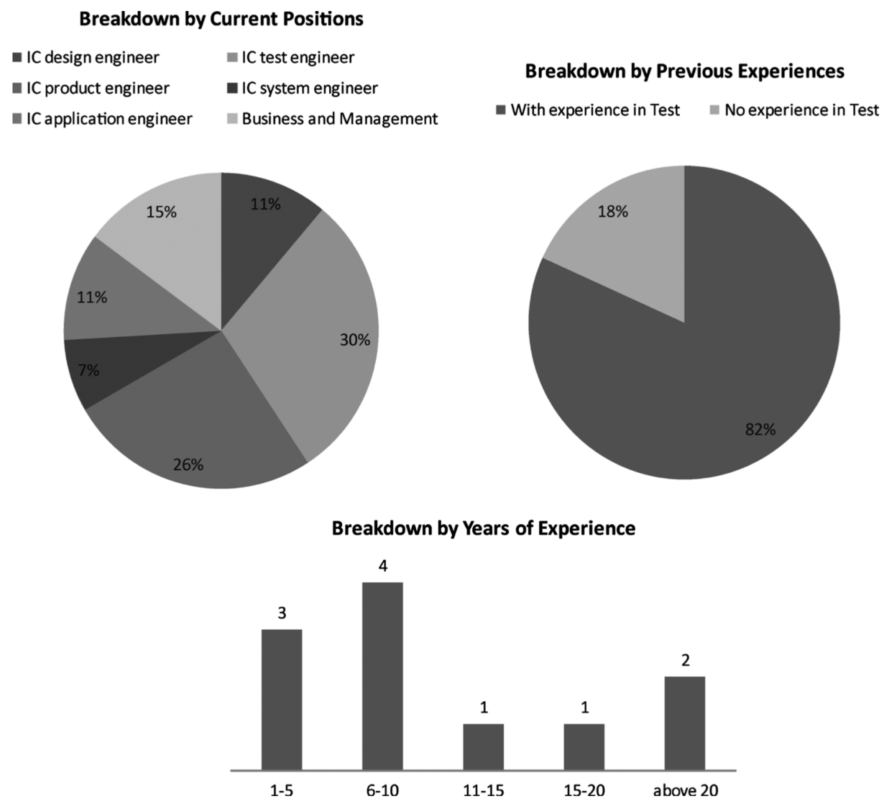


Fig. 8. Industrial respondents' background breakdown.

TABLE VII
FACULTY SURVEY AND RESULTS

| | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| Major area | EM | PWR | BME | IC | IC | IC |
| School | OSU | OSU | OSU | OSU | OSU | ISU |
| Teaching hours per week | 3 | 3 | 5 | 4 | 3 | 4 |
| Work experience in the IC industry? | N | N | N | N | Intel: 19 years | TI: 9 years |
| Collaborated with the IC industry? | N | N | N | Y | Y | Y |
| Q1: Is industry-academia collaboration beneficial? | Y | Y | Y | Y | Y | Y |
| Q2: Is this course only of interest as work-force training? | N | N | N | N | N | N |

TABLE VIII
INDUSTRIAL SURVEY QUESTIONS AND RESULTS

| | Question | 5 | 4 | 3 | 2 | 1 | Avg |
|---|---|---|---|---|---|---|---|
| 1 | Do you consider IC test an important role in industry? | 11 Y | | 0 N | | | 100% |
| 2 | Recent college graduates know too little about IC test compared to other fields (e.g., IC design). | 6 | 5 | 1 | 0 | 0 | 4.82 |
| 3 | It is very hard to find college graduates with IC testing skills. | 6 | 3 | 1 | 1 | 0 | 4.27 |
| 4 | Do you think there is a lack of instruction in the subject of testing in college? | 10 Y | | 1 N | | | 90.9% |
| 5 | Suppose two otherwise equally-competent college graduates A and B are interviewing for an IC testing position in your group. A has successfully completed an introductory course in IC testing. B has not taken any test-related courses. Who would you rather work with? (1-5: 5: A 3: No difference 1: B) | 7 | 2 | 2 | 0 | 0 | 4.45 |
| 6 | If I were on the industry advisory board for the EE/ECE department of another university, I would recommend a similar introductory IC test course. | 9 | 1 | 1 | 0 | 0 | 4.73 |
| 7 | (optional) What's your overall impression of this course?(1-5: 5: Excellent 3: Good 1: Dislike) | 0 | 6 | 3 | 0 | 0 | 3.67 |

in favor of this collaboration are due to a wide range of reasons. For example, faculty member A commented that this type of course "brings real life experience and problems to academia and broadens the ECE curriculum." Faculty member B said, "It is crucial for students and faculty members at all levels. It is easy for students and professors to overlook the connection between theory and practice. Without it, the university education and research will be out of touch."

Second, this new course shows a wide appeal. Not only is it attractive as workforce training, but it is also valuable for research universities. For example, faculty member C commented, "Though Ohio State is a public research university and many of our B.S. students would attend graduate schools for research, 75% of our graduates go directly to industry after graduation. Meeting the needs of industry might not be the most important goal, but it is certainly a crucial one, especially given the mission of a land-grant university like Ohio State."

### C. Industry Feedback

The goal of industry survey is to find out the value of this new course for the semiconductor industry. The survey consists of seven questions (as listed in Table VIII), where respondents are asked to rate the statements on a 1-to-5 scale, with 5 being strongly agree, 3 being neutral, and 1 being strongly disagree, unless noted otherwise. Eleven engineers from various business groups within Texas Instruments, including Battery Management Solutions (BMS), Battery Charge Management (BCM), Low Power Wireless (LPW), Mixed-Signal Automotive (MSA), High-Speed Interface (HSI), and Storage Products Group (SPG), responded to this request. A breakdown of the respondents by current positions, previous testing experiences, and total years of industrial experience in the semiconductor industry can be seen in Fig. 8.

At least three major conclusions can be drawn from the survey results shown in Table VIII. First, there is a huge need for IC testing education in college as indicated by the respondents. All of them either strongly agreed or agreed with the statement that recent college graduates know too little about testing compared to other fields according to Q2, which yielded the highest agreement index (4.82) among all statements. Second, almost all respondents (10 out of 11) agreed that there is a lack of instruction in the subject of testing (Q4), and they would recommend such a course to EE/ECE departments (Q6). Furthermore, this type of course could help increase the students' employability when they graduate. According to Q5, a majority of the respondents agreed that they would prefer working with a new hire who had received this type of education.

In addition, many of our respondents pointed out the skills that they felt the graduates of this course could be lacking. Among them, debugging skills came to the top of the list. One respondent said, "For this course I would suggest a bit more on the debugging skills, which is when you see xx output, what the likely causes could be. Being able to work from a problem to a root cause is a great skill to have." Another respondent commented, "It is the debugging skill, i.e., when something is not working as expected in the data or in the test procedure, how to narrow down the causes and find the problem in the least amount of time."

Finally, some respondents suggested ways to improve the course. For example, one engineer said, "This course is a good start. Please consider adding more to this course, such as economics of cost, production test, manufacturing environment, quality and reliability stressing. I would be very happy to contribute in these areas." These recommendations have been presented to the ECE Department at OSU as well as Texas Instruments management for full consideration.

## VII. Conclusion

A new course in mixed-signal IC test at the Ohio State University developed in conjunction with Texas Instruments has established a foundation for a curriculum on test engineering. The course has introduced the industrial techniques and their application for mixed-signal IC test. Students have also cultivated many skills required to be IC test engineers, which include deciding on a test method, developing a test plan, designing hardware and software for testing, debugging the test solution, and determining the validity of test outcomes.

The industry-oriented approach and the new laboratory pedagogy proposed in this paper have been successful as evidenced by feedback and assessment from students, faculty, and industry. It shows that industry–academia collaboration is a step in the right direction in addressing the test engineer shortage.

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## References

[1] M. Burns and G. W. Roberts*, An Introduction to Mixed-Signal IC Test and Measurement*. New York: Oxford Univ. Press, 2000.
[2] N. Konidaris, "Wanted: Test engineers!," *Eval. Eng.*, vol. 42, no. 2, pp. 34–39, Feb. 2003.
[3] F. Novak, A. Biasizzo, Y. Bertrand, M.-L. Flottes, L. Balado, J. Figueras, S. Di Carlo, P. Prinetto, N. Pricoli, H.-J. Wunderlich, and J.-P. Van Der Hayden, "Academic network for microelectronic test education," *Int. J. Eng. Educ.*, vol. 23, no. 6, pp. 1245–1253, Dec. 2007.
[4] S. Demidenko, V. Lai, and Z. Kassim, "Industry-academia collaboration in undergraduate test engineering unit development," in *Proc. 3rd IEEE DELTA*, 2006, pp. 116–122.
[5] T. Hudson and B. Copeland, "Working with industry to create a test and product engineering course," in *Proc. IEEE MSE*, 2009, pp. 130–133.
[6] K. Muhammad, Y.-C. Ho, T. Mayhugh, C.-M. Hung, T. Jung, I. Elahi, C. Lin, I. Deng, C. Fernando, J. Wallberg, S. Vemulapalli, S. Larson, T. Murphy, D. Leipold, P. Cruise, J. Jaehnig, M.-C. Lee, R. Staszewski, R. Staszewski, and K. Maggio, "The first fully integrated quad-band GSM/GPRS receiver in a 90-nm digital CMOS process," *IEEE J. Solid-State Circuits*, vol. 41, no. 6, pp. 1772–1783, Aug. 2006.
[7] M. Ito, K. Nitta, K. Ohno, M. Saigusa, M. Nishida, S. Yoshioka, T. Irita, T. Koike, T. Kamei, T. Komuro, T. Hattori, Y. Arai, and Y. Kodama, "A 65 nm single-chip application and dual-mode baseband processor with partial clock activation and IP-MMU," *IEEE J. Solid-State Circuits*, vol. 44, no. 1, pp. 83–89, Jan. 2009.
[8] "ECSE-435B: Introduction to mixed-signal test techniques," McGill University, 2008 [Online]. Available: http://www.ece.mcgill.ca/~grober4/ROBERTS/COURSES/EE435/ee435.html
[9] "ECE 694I course syllabus: Introduction to mixed-signal IC test and measurement," The Ohio State University [Online]. Available: http://www.ece.osu.edu/~hua/ECE694I.html
[10] L. D. Fink*, Creating Significant Learning Experiences: An Integrated Approach to Designing College Courses*. Hoboken, NJ: Jossey-Bass, 2003.
[11] L. D. Feisel and A. J. Rosa, "The role of the laboratory in undergraduate engineering education," *J. Eng. Educ.*, pp. 121–130, Jan. 2005.
[12] B. C. Parker and J. D. McGregor, "A goal-oriented approach to laboratory development and implementation," *SIGCSE Bull.*, vol. 27, no. 1, pp. 92–96, 1995.
[13] G. Mason, "A handheld data acquisition system for use in an undergraduate data acquisition course," *IEEE Trans. Educ.*, vol. 45, no. 4, pp. 388–393, Nov. 2002.
[14] R. DeLyser, R. Quine, P. Rullkoetter, and D. Armentrout, "A sophomore capstone course in measurement and automated data acquisition," *IEEE Trans. Educ.*, vol. 47, no. 4, pp. 453–458, Nov. 2004.
[15] B. Neidorff, R. Antley, and J. Coyne*, BA500: Role of Test in Design*. Dallas, TX: Texas Instruments, 2008.
[16] B. A. Wooley, "Utilizing a computing lab to improve retention and recruiting of computer science and computer information science students," *J. Comput. Small Coll.*, vol. 18, no. 3, pp. 228–234, Mar. 2003.
[17] T. Sansaloni, A. Perez-Pascual, V. Torres, V. Almenar, J. Toledo, and J. Valls, "FFT spectrum analyzer project for teaching digital signal processing with FPGA devices," *IEEE Trans. Educ.*, vol. 50, no. 3, pp. 229–235, Aug. 2007.
[18] E. Lindsay and M. Good, "Effects of laboratory access modes upon learning outcomes," *IEEE Trans. Educ.*, vol. 48, no. 4, pp. 619–631, Nov. 2005.
[19] Y. Zhu, T. Weng, and C.-K. Cheng, "Enhancing learning effectiveness in digital design courses through the use of programmable logic boards," *IEEE Trans. Educ.*, vol. 52, no. 1, pp. 151–156, Feb. 2009.

[20] M. Koretsky, D. Amatore, C. Barnes, and S. Kimura, "Enhancement of student learning in experimental design using a virtual laboratory," *IEEE Trans. Educ.*, vol. 51, no. 1, pp. 76–85, Feb. 2008.

[21] S. Li and A. Khan, "Applying it tools to a laboratory course for measurement, analysis, and design of electric and electronic circuits," *IEEE Trans. Educ.*, vol. 48, no. 3, pp. 520–530, Aug. 2005.

[22] S. R. Jernigan, Y. Fahmy, and G. D. Buckner, "Implementing a remote laboratory experience into a joint engineering degree program: Aerodynamic levitation of a beach ball," *IEEE Trans. Educ.*, vol. 52, no. 2, pp. 205–213, May 2009.

[23] B. Pueo, M. Roma, J. Escolano, and J. J. Lopez, "A pedagogical software for the analysis of loudspeaker systems," *IEEE Trans. Educ.*, vol. 52, no. 2, pp. 236–247, May 2009.

[24] *"16-Channel, 16-bit Analog-to-Digital Converter, ADS 1158,"* Texas Instruments, 2008 [Online]. Available: http://focus.ti.com/lit/ds/symlink/ads1158.pdf

[25] *"ADS1158EVM, ADS 1258EVM, ADS 1158EVM-PDK, and ADS1258EVM-PDK User's Guide,"* Texas Instruments, 2008 [Online]. Available: http://focus.ti.com/lit/ug/sbau126b/sbau126b.pdf, ADS 1158 Evaluation Module

[26] *"ADCPro User's Guide,"* Texas Instruments, 2009 [Online]. Available: http://focus.ti.com/lit/ug/sbau128b/sbau128b.pdf, ADCPro

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