An Approach to Using RASP Tools in Analog Systems Education

Michelle Collins
School of Electrical and Computer Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332–0250
Email: michelle.collins@gatech.edu

Jennifer Hasler
School of Electrical and Computer Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332–0250
Email: jennifer.hasler@ece.gatech.edu

Sahil Shah
School of Electrical and Computer Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332–0250
Email: sshah389@gatech.edu

***Abstract*—This paper presents the assessment results of using Field Programmable Analog Arrays (FPAAs) and its concomitant design automation software, RASP Tools, in an analog graduate level course to integrate hands-on activities for learning. We describe our teaching methodology as well as experiments involving the FPAA SoC and its tool suite created for this course. We are evaluating the student satisfaction of using RASP Tools and FPAA SoCs for analog design and our blended approach to convey this material. Metrics considered are students' perception of hardware & software capabilities, self-efficacy in the core areas, and their assessment of the course methodology.**

I. Motivation & Education

Field Programmable Gate Arrays (FPGAs) are used by a diverse audience that vary in age, experience, and background. The widespread acceptance (e.g. academia and industry) of FPGAs and its supportive community has created a means to attract and encourage new users as well as retain them. One might presume that the analog domain shares equivalent mobility, however this assumption is far from accurate. There is a need for analogous analog hardware and software to garner the level of progress seen with FPGAs. Configurable analog hardware, namely FPAAs and its complementary tool suite, fill this void.

Georgia Tech has utilized FPAA devices in a classroom setting as a way of innovating teaching techniques for the past ten years [1]–[5]. We decided to incorporate assessment into our pedagogic strategy to measure the effectiveness of our methodology and technology. The culmination of refining our efforts will be a blueprint for implementing this technique elsewhere. For this discussion we present the evaluation of using this technology in the course ECE 6435: Neuromorphic Analog VLSI Circuits to promote experiential learning.

Our approach to assessing the impact of student's learning and acceptance of the technology is through pre- and post-surveys and discussions during the semester. This class uses a blended approach to facilitate learning through pre-recorded mini-lecture videos, portable laboratories, traditional lectures, classroom discussions, and in-class exercises as illustrated in Fig. 1. The technologies used during this course are FPAA system on chips (SoCs) [6] and its design synthesis software RASP Tools [7], which includes programming capability [8]. The assessment methodology employed is shown in Fig. 2.

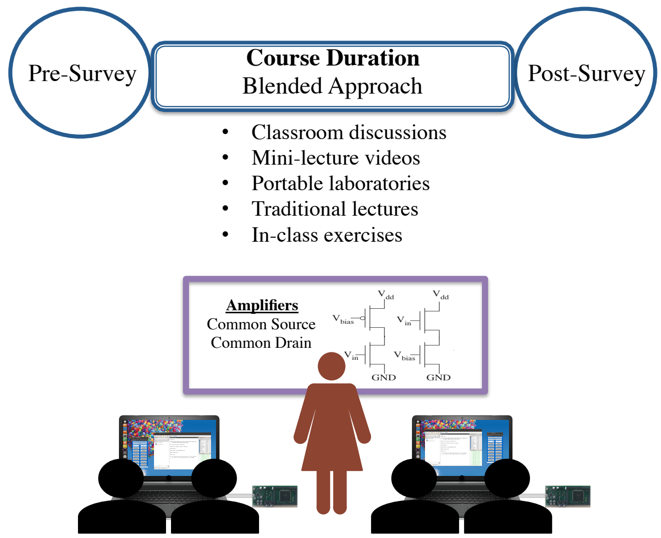

Fig. 1: Overview of approach to assess using technology in an analog course. Using hardware and software namely, FPAAs and RASP Tools, we created a blended course to facilitate learning through hands-on labs. This created an environment that promoted interactive class discussions. Pre- and post-surveys were given on the first and last day of class, respectively to evaluate the course.

II. Overview of FPAAs & Education Usage

The FPAA SoC is a programmable and configurable IC device that contains both analog and digital circuit elements [6]. The analog and digital components are situated within Computational Analog Block (CAB) and Computational Logic Block (CLB) arrays in the FPAA, respectively. This FPAA features an open-source MSP430 microprocessor that encourages codesign approaches for the user to explore and other on-chip structures including memory-mapped General Purpose (GP) I/Os, a ramp ADC, and several 7-bit signal DACs. FPAAs, with nearly 0.5 million parameters, enable a wide range of configurable and programmable SoC embedded system computing options. RASP Tools is an open-source high-level system design framework that permits users to create a flow-diagram of their circuit/system [7]. Its library consists of high-level block abstractions of CAB/CLB components. This toolset facilitates system designers in integrating useful systems. This tool enables circuit experts to develop creative and reusable

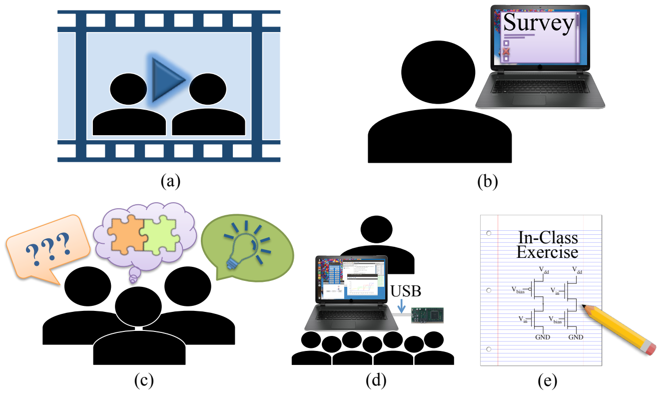

Fig. 2: Assessment techniques used to gauge students' comprehension of course material. (a) Five-minute video of laboratory project results, observations, analysis, and rationale. (b) Student self-reporting through pre- and post-surveys about their learning and interaction with FPAAs and RASP Tools. (c) Classroom discussions concerning analog and neuromorphic circuits driven by instructors and students. (d) Student demonstrations of working projects using two modes of data acquisition. (e) Non-evaluative quizzes of circuit concepts.

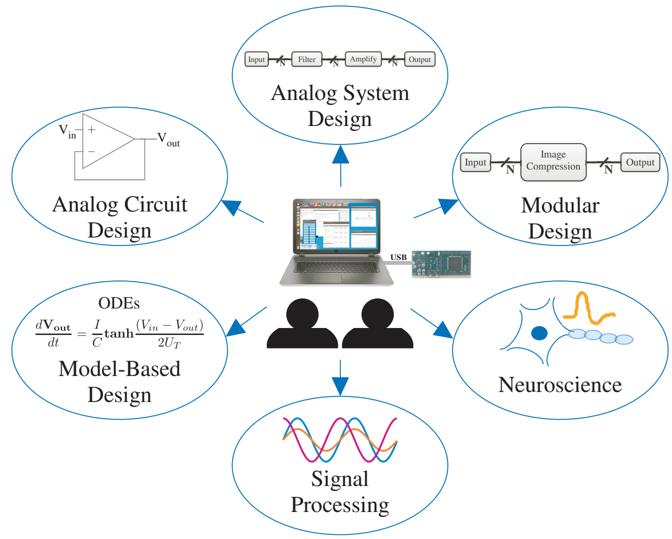

Fig. 3: FPAAs and RASP Tools are designed to allow students to focus on circuit operation using a single platform that enables them to revisit previous circuit designs while learning new material. Using this configurable hardware, educators have the ability to vary course content, build on foundational concepts, and explore system designs. In this course we were able to delve into multiple areas like analog circuit and system design, model-based and modular design, signal processing, and neuroscience.

designs. RASP Tools utilizes Scilab and Xcos [9] (open-source alternatives to MATLAB and Simulink, respectively) as the medium to convert information from the design environment to a single programming file for hardware.

FPAAs have been incorporated in an educational setting for several years to educate engineers to design for system applications [1]–[5], [10]. The evolution of this course has experienced a time prior to FPAAs when pre-fabricated chips were used for each assignment and bulky measuring equipment infrastructures were required [5]. FPAAs and RASP Tools has permitted the structure of this course to include flipped classroom approaches as students use their own laptops and the provided FPAA and software for activities. Remote testing is another feature of this toolset that provides an avenue for students to obtain data outside the classroom [11]. The maturation of the FPAA has caused the coverage of core analog concepts and more advanced topics to expand and give more freedom to the class to experiment with their own ideas.

III. Teaching Methodology

Figure 2 illustrates how we assessed the students' progress towards course goals throughout the semester via student videos, class conversations, circuit demonstrations, and in-class exercises. The measures presented in Fig. 2 were also used to evaluate our course approach effectiveness. Figure 3 shows core areas like analog circuit and system design, model-based and modular design, signal processing, and neuroscience that were covered in this course with intention. We paired in-class lectures, discussions, short videos, and experiments to create a blended course. The course objectives were defined as:

(a) Students will be able to design neuromorphic analog circuits/systems.
(b) Students will be able to analyze neuromorphic analog circuits/systems data from FPAA.
(c) Students will be able to recognize, relate, and verbalize analog concepts to phenomenon observed in data.
(d) Students will be able to use intuition to create novel implementations of neuromorphic analog circuits/systems in FPAA.
(e) Students will be able to model analog circuits that correspond to silicon data from FPAA.

The lectures were purposely interactive to encourage dialogue and create an environment of community. The discourse was sparked by students ideas, comments, and questions as well as instructor queries. Five to ten minutes lectures were made available to students at the beginning of the semester to allow students to preview future material and prepare for topics covered before coming to class. We promoted "learning by doing" in our laboratory experiments which are discussed further in section IV. We had students record project videos that were released to the class for review by next meeting time. In this course we gave students FPAAs and virtual machines with preloaded software, RASP Tools, to install on their computer. RASP Tools is the FPAA's design synthesis tool that enables simulation and experimental measurement.

Acknowledging the classroom is a place where student perception of material and the desire to pursue more knowledge can be influenced, we developed laboratories for this course to increase the students' familiarity of analog design concepts and experimental practice. Each group was assigned a FPAA board to use for the semester. Since each FPAA board has unique characteristics (transistor mismatch), we expected that students would not obtain identical values and graphs with the same parameters. Each group was expected to record a short five to seven minute video of their process, results, and analysis. The videos were uploaded for the groups to view each

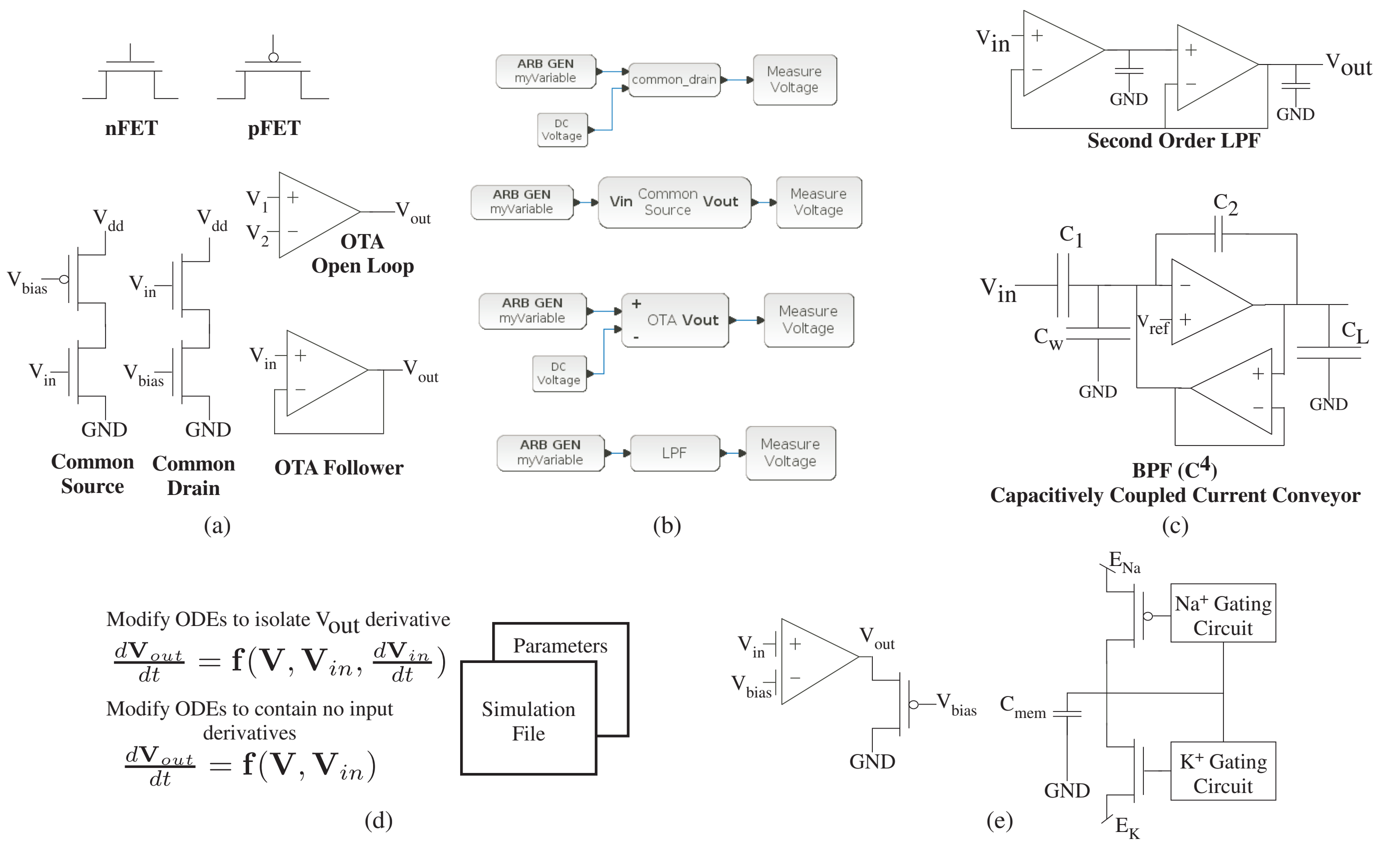

Fig. 4: (a) Lab 1: Circuit configuration of pFET & nFET transistors, common source & common drain amplifiers, and OTA open-loop & OTA follower (LPF). (b) RASP Tools implementation of circuits used for Lab 1. (c) Lab 2: Circuit configuration of a second order low pass filter (LPF) and band pass filter (BPF). (d) Lab 3: Determining the macromodels of circuits for the simulation function of blocks by deriving ODEs in the proper form. (e) Lab 4: The transistor channel model and Hodgkin–Huxley neuron circuits adapted for FPAA.

others work a day before class. This visual documentation of their procedure to solve problems and analyze data will be useful in the future for new cohorts. During the next class period we were able to discuss common issues, delve into other interesting technical topics, and even explore ideas outside the scope of the course. Students transitioned from merely stating their observations to analyzing their data more in-depth to account for non-idealities in their video for each lab. By the end of the semester, a student that did not have an analog background decided to expand their final project progress into the summer.

In a traditional classroom, students are lectured to for the duration of the class without formative assessment exposure or participating in active learning exercises. A course where students do not practice their comprehension of the material until they take a form of summative assessment, which may be the midterm, is not beneficial for students. By not addressing the topics that the class misinterprets, especially when material builds upon previous concepts, many students may become overwhelmed and discouraged from progressing further in their major. Attributes like these of a traditional classroom have been challenged for years [12], [13]. Alternative methodologies have been suggested to improve the learning experience of students so that they internalize more information through practice and hopefully real-world exposure [14]–[29]. Giving students a means to become aware of their conceptual acumen is important. Lectures alone do not provide students valuable feedback, which would allow each individual to assess their strengths and weaknesses. Consistent clarification of misconceptions through recitation sessions, group discussions, and in-class activities are viable options. Thus, educators have been introducing methods like in-class activities for individuals and groups such as problem solving, games, discussions, and other technology to supplement lectures [30]–[35].

IV. Laboratory Projects

Analog courses with laboratories typically have students obtain data for each assignment with different pre-fabricated boards or standalone ICs, wires, and solderless breadboards that can become convoluted. These laboratory activities require disassembling the previous project to create space and avoid confusion. In this analog course, we focus on giving the class hands-on project experience instead of only circuit simulation based problem sets. Students are exposed to working experimentally with fabricated hardware while designing and analyzing circuits. In this environment, students are able to observe and account for non-idealities that would not have to be considered if only solving equations and running a series of simulations. Over the course of the semester we had a total of six projects, where we separated the class into groups of two.

Lab 1: Transistors & Basic Amplifiers

In this lab, we had students take measurements with the remote system to verify their setup was installed and working properly. They showed a plot that compared remote and in-class measurement results. Afterwards, they investigated and regressed nFET and pFET transistor current measurements to determine key parameters such as kappa, U_T, and σ. These characteristics aid in combining two of these transistors to form amplifiers, namely common-drain (source-follower) and common-source. The students were able to observe and determine the gain of these amplifiers and mathematically prove their findings. Lastly, the class worked with an operational transconductance amplifier (OTA) where they used it in both its open-loop and follower topology, Fig. 4(a) & (b).

Lab 2: Low and Band Pass Filters

The next project sections focused on second-order section behavior, as shown in Fig. 4(c). The class analyzed a second order LPF that is composed of two OTAs. The students were able to view the increased linearity afforded. The FPAA board is equipped with audio ports, which enabled students to compile a bank of band-pass filter (BPF) blocks to selectively attenuate frequency bands from an audio input and hear the modified waveform.

Lab 3: Macromodeling Circuits

Macromodeling is the process of building blocks and their simulation files. These blocks represents circuits previously made or new ones, where students can confirm their understanding of non-idealities observed from compiled circuits working in silicon. The ODE models they create realize the behavior seen in such measurements, Fig. 4(d). By encouraging reuse of these blocks, which is a concept rarely at the forefront of discussion when talking about analog circuit and system design, students can share their ideas with each other to build interesting systems. Thus, promoting a community of designers to learn from another. Students successfully demonstrated analyzing a neuromorphic analog circuit by creating their own simulation mathematical model for a dendrite and verified it with hardware data.

Lab 4: Neuron

This project focuses on understanding and experimentally measuring the transistor channel model approach for handling passive and active channels. With the experience from the previous lab, students built more blocks concerned with building a Hodgkin–Huxley (HH) neuron. The HH neuron model takes into account the excitatory and inhibitory ion channels, sodium and potassium, that are necessary for an action potential to occur, Fig. 4(e).

Lab 5: VMM and Classifiers

In this project, the students focused on one type of classifier structure, the Vector-Matrix Multiplication (VMM) + Winner-Take-All (WTA) that elegantly compiles into our FPAA structure. The XOR function, which is a two layer neural network equivalent was implemented [6].

Lab 6: Dendrites and Diffusors

The focus of this project was to get a working dendritic line built from a diffusor circuit approach. After biasing approximated changes in a dendrite cable diameter, students combined multiple dendrites together to illustrate a dendritic-modeled neuron classifier.

V. FPAA and RASP Tools Immersion Assessment

Many features of RASP Tools were utilized by the students while completing their lab assignments. The class was able to manipulate existing design examples, view simulations, compile the design to FPAA hardware, and view experimental results. With this experience, students were able to create their own circuit blocks to create new designs. Their blocks contribute to the palette library of pre-tested block modules that translate to circuits on the FPAA board. Throughout the semester, students received feedback from instructors and peers on assignments to augment their learning. We were interested in determining the effectiveness of hardware & tools, the course environment, and the students' confidence of their mastery of course material and associated skills. Therefore, we planned to give two surveys that encompassed inquiries to assess the impact of our approach.

Previous Observations

We noticed former students preferred using the remote system to take project measurements throughout the semester. This occurrence was a surprise at the time because the class had access to FPAA boards and Diligent's Analog Discovery data acquisition boards that were either supplied or purchased individually. A considerable improvement was made in the software to include more documentation, measurement support, block modules, and utility features before this semester began. This semester we chose to not introduce the class to the Analog Discovery system to acquire experimental values. Instead, we had the class use the multiple FPAA internal measurements block modules that use on-chip DACs, on-chip ADCs, and compiled ADCs. We wondered if this switch in measurement systems would influence the students to continue choosing to use the remote system over the local FPAA boards or would there be a shift in preference. Our prediction was that the current cohort inclination would be in favor of the remote system. Our opinion was developed by weighing the flexibility the remote access gave the students to not physically be in the FPAA board storage area while obtaining the same results. We discovered the students preferred using the local boards over the remote system.

TABLE I
MEAN RESPONSE: HOW DO YOU CLASSIFY YOUR SKILLS IN WORKING WITH...?

Areas of Expertise	Before	After
CAD Tools	2.60	3.00
FPAAs	1.33	2.50
Scilab	1.73	2.50
Xcos	1.27	2.38
Embedded Systems	2.20	2.75
Hardware Debugging	2.87	3.00

NOTE: NOVICE (1), ADVANCED BEGINNER (2), COMPETENT (3), PROFICIENT (4), EXPERT (5)

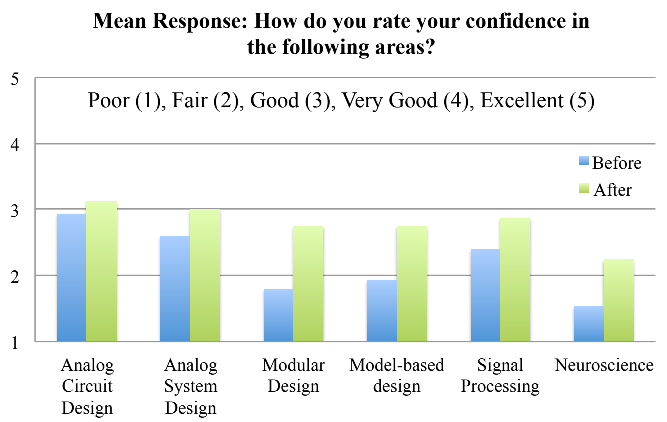

Fig. 5: Students were asked to rate their confidence in the core areas of the course. The course methodologies aimed to build up students expertise in the areas of analog circuit & system design, modular & model-baed design, signal processing, and neuroscience.

A. Pre-Survey

On the first day of class we had students take an anonymous online survey. We chose to give this survey on the first day because it guaranteed they had not interacted with the particular FPAA hardware or RASP Tools that we are assessing. Their initial evaluation of themselves, hardware & software, course structure, and personal preferences were polled. Our main reason for not collecting identifying information was to receive candid responses of these topics. Our belief was that the students would be assured their opinions would not be factored in or have an influence on their grade for the course. This survey has allowed us to gauge the previous knowledge, skills, and thoughts of this cohort to be contrasted to a follow-up survey given at the end of the semester.

This course uses analog circuits to mimic the building blocks for biological information manipulation and processing (e.g. brain and ears). Figure 5 shows that we probed the student's background knowledge of related topics by having them rate their confidence in analog/digital circuit design, analog system design, digital circuit design, digital system design, modular design, model-based design, signal processing, and neuroscience topics. Another question within this realm posed on the survey was familiarity in working with CAD tools, FPAAs, Scilab, Xcos, embedded systems, and hardware debugging, Table I.

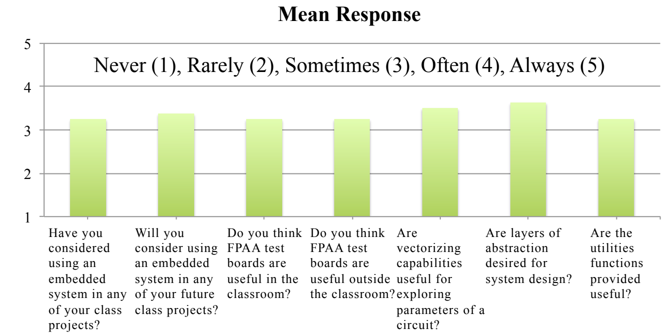

Fig. 6: Post-survey results of the students's response to being exposed to FPAAs and RASP Tools.

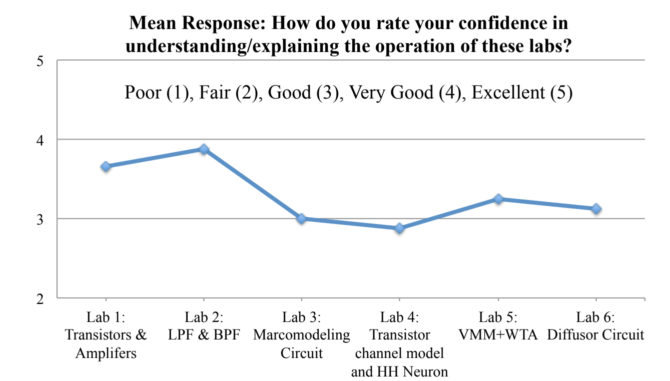

Fig. 7: We assessed the class to rate their confidence in each of the six semester laboratory projects.

B. Post-Survey

Final project oral presentation day marked the last day we would interact with the class and the best time to provide the link to a follow-up survey, similar to the former pre-survey with additional questions. This survey also did not acquire identifiable information for the reason mentioned earlier. Figures 5 & 6 and Table II depict the inclusion of more reflective questions in addition to accounting for the student's final opinion of their skills, the FPAA board & RASP Tools, assignments, and impression of useful features. Our results have provided insight for next steps in improving the tools to achieve our overarching aim and learning in this course.

As illustrated in Fig. 7, we felt it was essential to determine the effect that the lab projects had on the students. Several questions address this objective by allowing each student to evaluate their confidence in understanding and explaining the project material to another person. For example, students begin with transistor curves to discern its operation and extract parameters, then produced macromodel equations to show circuit behavior, and finally used a VMM+WTA to build classification hyperplanes. We then clarified the degree to which they believed that they had mastered procuring experimental measurements and interpreting collected data, which are two main skills that we desire for the students to strengthen. Other questions evaluated the remote system, measuring apparatuses, project effectiveness, embedded system use, and tool features.

TABLE II
MEAN RESPONSE: TO WHAT EXTENT DO YOU AGREE OR DISAGREE WITH THESE STATEMENTS...?

Statements	Rating
In-class demos improve your understanding of the subjects taught in class.	3.25
Having lab time spent in class improves your understanding of subjects taught.	3.25
Having lab time spent out of class improves your understanding of subjects taught	3.75
In-class demos help you complete labs.	3.38
Final projects are beneficial.	3.88
Graphical representations of circuits are easy to comprehend.	3.50
You prefer graphical representations of circuits over net lists.	3.75
The projects increased your learning.	3.50

NOTE: STRONGLY DISAGREE (1), DISAGREE (2), NEITHER AGREE OR DISAGREE (3), AGREE (4), STRONGLY AGREE (5)

We inquired to what extent FPAAs are useful, vectorization is appropriate for parameter coverage, and abstraction is desired for system design.

C. Comparison and Trends

We asked the students to classify their skills in the following hardware and tools at the beginning and at the end of course: CAD Tools, FPAAs, Scilab, and Xcos. The survey shows that the students had some familiarity with CAD tools before, but did not know about FPAAs or the tool Scilab. Table I shows that the students' competence increased in each of these areas by the end of the semester. If we look at Fig. 5, we are able to view the student's rating of their confidence in using hardware and software at the beginning and end of the course. We notice that the students are more comfortable using CAD Tools by the end of the course, which can be attributed to the number of labs given. Those who identified as advanced beginner and proficient increased their skills to a higher expertise category. A majority of the students had little confidence in interacting with FPAAs, Scilab, and Xcos at the beginning of class. We saw a transition from novice to advanced beginner and competent consistently across the FPAAs, Scilab, and Xcos graphs. Knowing that the group sizes were small and that members worked closely together could explain this trend of similar improvement. We want to note that by giving the first survey on day one of the class before the end of the add/drop period, the sample size differs from the final survey totaling in at fifteen and eight responses, respectively.

We polled the students to rate their confidence in: analog circuit & system design, modular & model based design, signal processing, and neuroscience. Students had some familiarity with analog design, but were not proficient in signal processing, modular design, and neuroscience. Figure 5 shows that the students' perception of their competence increased in each of these areas by the end of the semester, where no student assessed their ability as poor. The course was designed to cover aspects of each of these areas. Figure 5 portrays that everyone in the class felt they understood analog circuit and system design at least fairly; there is no major difference in the breakdown of the knowledge level across the categories. It was good to see that no one labeled their confidence as poor after completing the projects during the semester. Modular-based design is related to taking existing circuit block modules from the palette library to make a system, while model-based design can be mapped to the simulation models created and performed; the class gauged their confidence to be fair and good, which lends to the idea that if we were to give them an analog system to design they would know how to approach the problem. The signal processing data is related to the BPF lab where they were able to manipulate an incoming audio signal by tuning out particular frequency bands. The neuroscience concepts are related to the bank of filters used to mimic the ear as well as the neuron and dendrite labs that focused on the transfer of information. These labs had an impact because no response was in the poor confidence category. It is interesting to notice signal processing skills improved more than neuroscience. In Table II we depict the effectiveness of the teaching techniques implemented in class. We see that students appreciated in-class demos and labs and felt that they contributed to their success in the class. Students enjoyed working with graphical representations of circuits and it aided their learning of the subject material. The students appreciated in-class activities including designated lab time and liked that they were working with graphical representations of circuits and systems over net-lists.

Figure 6, depicts the opinions of students after interacting with the tools and hardware. The students considered two features of RASP Tools, abstraction and vectorization, to be desired and useful as well as other key integrated attributes. The FPAA hardware was deemed suitable for use inside and outside of the classroom. The laboratory projects that we had the class complete ranged from circuit basics to complex classification and neuromorphic circuits. We asked the students to reflect on their process of finishing these labs and to determine how much they learned. Figure 7, details the cohort's perception of their level of understanding and their ability to explain the topics of each lab to another individual. The graph depicts a mostly high student competence as a majority of the responses were in the good and very good categories. We soon learned that no one in the class thought they had a poor grasp of any lab material. We also became aware that some students considered themselves experts or very well-versed of some lab topics. The trend revealed from evaluating this data is that the majority of the students believe they have confidence in their expertise. These results were very encouraging and showed that these labs improved their overall understanding of the course content.

Tool and Assessment Incorporation

Throughout the semester we conversed with students to understand the concerns for the tools and the class. We became more aware that the block library in Xcos should be more extensive, that more examples that vary in complexity would be valued, and that various forms of formative assessment during the course like "Think-Pair-Share" and one minute papers would enhance the community we strive to cultivate. In the case of FPAAs, we can leverage the routing switches or resources because they are not to be considered dead-weight. VMMs are easily created in analog hardware through current summation of transistors in routing. VMMs are useful in various applications including audio signal processing as well as image convolution, and classification using bio-inspired circuits. As the size of the applications vary, so will the size of the VMM. Instead of having users choose from preset sizes, we want to improve the tools to build any sized VMMs.

VI. Conclusion: Initial FPAA and RASP Tools Positive Impact

We learned that students have a positive perception of the capabilities of FPAAs & RASP Tools, their self-efficacy in core areas improved, and their assessment of the course methodology was favorable. Our tool facilitated the completion of projects by providing essential features while aspiring to minimize negative experiences. The students' informal comments have been noted and will guide the inclusion of more features and block modules to enhance the software. The moderately affirmative impression the class had of the hardware and software can be attributed to the early state of this technology. We intended to provide the experience of a circuit/system design cycle, except for layout and fabrication exposure, using programmable and configurable hardware. The user interface for students was developed in Scilab, which called other custom and open source software. Since FPAAs do not have the limitations of pre-fabricated Application Specific Integrated Circuits (ASICs), students had the ability to create their own circuit and system ideas continually because the FPAA platform is configurable and programmable. All the groups were able to interact with the FPAA boards and get results, which spoke to the theory that individuals unfamiliar with FPAAs would reap benefits of having access to these low power signal processing resources. We are confident that the outcome of our assessment suggests to continue refining our approach as there is opportunity in the growth of this technology.

Our results show that lecture dominance in a course can be decreased by adopting portable, low-cost experiment modules, which is also consistent with researchers in this area [32], [34]. We are not alone in thinking that students need experience taking measurements from hardware and providing files with their results for further data analysis [30], [33]. We believe that a remote testing infrastructure gives students more flexibility to complete labs [11], [31], [36]. Similar to [15], our aim is to improve student learning by incorporating pedagogical methods such as learning in groups, through projects, and by doing experiments. Designing circuits to be manufactured in silicon and collecting data within a single semester is no easy feat [35]. Allowing students to test their designs in silicon helps solidify understanding of circuit concepts. The turn around fabrication time does not fit within a semester because the students have to learn the material, create a design, simulate for varying conditions, and then send their designs to the foundry to be manufactured. Testing, where most of the learning occurs, wound not be a part of the curriculum in the scenario described.

The maturation of our pioneering research has inspired our infrastructure's use in this course to augment instruction of analog concepts. In our opinion advocating the unity of innovative research and creative teaching bolsters progressive momentum in both. Thus, an eminent result of appreciating contemporary teaching techniques and concepts is the continuous improvement of FPAAs and RASP Tools. With an enhanced framework, we could explore intricate group dynamics of a team for an engineering project by emulating the methods described by [16]. Their assessment process was pre- and post-course surveys, weekly activity logs, and post-course semi-structured interviews. They analyzed correlation of self-efficacy, gender, and learning goals to task choices in a group setting. They found that goal setting had the desired effect in reducing gendered task choices as also proposed in [37]. They also found a correlation between time spent on tasks to pre-project learning goals [38]. Other researchers highlight the need for active engagement tools in a flipped/inverted class setting, which in his case was the use of an iClicker [18]. He concluded that the use of active tools helped students become active learners, with increased interaction with both their supervisor and peers.

We should stress that the infrastructure for this class is in the development phase, where the hardware and software are improved each semester which affects the teaching approach. This course has always involved an experimental piece that has evolved from pre-fabricated boards for each project and multiple software programs to the versatile FPAA and centralized software. Thus, it is hard to have a control case where experiments and class structure are the same every year. In fact we may have to consider outside factors that affected our course: other classes taken simultaneously, career work, and internships. Our tools are open source, not highly specific, and can be modified to be used with other ICs. This allows collaborators to explore our work and contribute because they have access to boards through our remote system to take experimental data. The base program Scilab and it sub-environment Xcos use flow graph to design, which is similar to MATLAB and Simulink. Students in this class will be familiar with analyzing data in a base program and manipulating parameters in its sub-environment. This tool experience is valuable for future projects that the students will do. To conclude, we emphasize that a blended teaching approach for circuits courses is very important and can be scaled to other electrical engineering courses as well.

VII. Acknowledgement

This material is based upon work partially supported by the National Science Foundation Graduate Research Fellowship under Grant No. DGE-1148903.

References

[1] C. M. Twigg and P. E. Hasler, "Incorporating large-scale FPAAs in analog design courses," in *IEEE International Conference on Microelectronics Systems Education (MSE)*, June 2007, pp. 171–172.

[2] ——, "Incorporating large-scale FPAAs into analog design and test courses," *IEEE Transactions on Education*, vol. 51, no. 3, pp. 319–324, 2008.

[3] P. Hasler, C. Scholttmann, and S. Koziol, "FPAA chips and tools as the center of an design-based analog systems education," in *IEEE International Conference on Microelectronics Systems Education (MSE)*. IEEE, 2011, pp. 47–51.

[4] M. Collins, J. Hasler, and S. George, "Analog systems education: An integrated toolset and FPAA SoC boards," in *IEEE International Conference on Microelectronics Systems Education (MSE)*. IEEE, 2015, pp. 32–35.

[5] J. Hasler, S. Kim, S. Shah, F. Adil, M. Collins, S. Koziol, and S. Nease, "Transforming mixed-signal circuits class through SoC FPAA IC, pcb, and toolset," in *European Workshop on Microelectronics Education (EWME)*, May 2016.

[6] S. George, S. Kim, S. Shah, J. Hasler, M. Collins, F. Adil, R. Wunderlich, S. Nease, and S. Ramakrishnan, "A programmable and configurable mixed-mode FPAA SoC," *IEEE Transactions on Very Large Scale Integration (VLSI) Systems*, vol. 24, no. 6, pp. 2253–2261, 2016.

[7] M. Collins, J. Hasler, and S. George, "An open-source tool set enabling analog-digital-software co-design," *Journal of Low-Power Electronics and Applications*, vol. 6, no. 1, p. 3, 2016.

[8] S. Kim, J. Hasler, and S. George, "Integrated floating-gate programming environment for system-level ICs," *IEEE Transactions on Very Large Scale Integration (VLSI) Systems*, 2015.

[9] Scilab-Enterprises, "Scilab: Free and open source software for numerical computation (version 5.5. 0)," 2014.

[10] P. Hasler, C. Scholttmann, and S. Koziol, "FPAA chips and tools as the center of an design-based analog systems education," in *IEEE International Conference on Microelectronics Systems Education (MSE)*. IEEE, 2011, pp. 47–51.

[11] S. Shah, J. Hasler, S. Kim, I. Lal, M. Kagle, and M. Collins, "Demonstration of a remote FPAA system for research and education," in *IEEE ISCAS*. IEEE, May 2016, pp. 319–324.

[12] R. Talbert, "Inverted classroom," *Colleagues*, vol. 9, no. 1, p. 7, 2012.

[13] J. L. Bishop and M. A. Verleger, "The flipped classroom: A survey of the research," in *ASEE National Conference Proceedings, Atlanta, GA*, vol. 30, no. 9, 2013.

[14] B. Ferri, W. Newstetter, and D. Majerich, "Instructor and graduate teaching assistant development and training for a blended linear circuits and electronics course," in *Frontiers in Education Conference (FIE)*. IEEE, 2015, pp. 1–4.

[15] J. P. Queiroz-Neto, D. C. Sales, H. S. Pinheiro, and B. O. Neto, "Using modern pedagogical tools to improve learning in technological contents," in *Frontiers in Education Conference (FIE)*. IEEE, 2015, pp. 1–8.

[16] L. Hirshfield and D. Chachra, "Task choice, group dynamics and learning goals: Understanding student activities in teams," in *Frontiers in Education Conference (FIE)*. IEEE, 2015, pp. 1–5.

[17] S. Huang and E. Pierce, "The impact of a peer learning strategy on student academic performance in a fundamental engineering course," in *Frontiers in Education Conference (FIE)*. IEEE, 2015, pp. 1–4.

[18] K. J. Shryock, "Engaging students inside the classroom to increase learning," in *Frontiers in Education Conference (FIE)*. IEEE, 2015, pp. 1–7.

[19] J. Bishop and M. Verleger, "Testing the flipped classroom with model-eliciting activities and video lectures in a mid-level undergraduate engineering course," in *IEEE Frontiers in Education Conference (FIE)*. IEEE, 2013, pp. 161–163.

[20] D. May, K. Lensing, A. E. Tekkaya, M. Grosch, U. Berbuir, and M. Petermann, "What students use: Results of a survey on media use among engineering students," in *IEEE Frontiers in Education Conference (FIE) Proceedings*. IEEE, 2014, pp. 1–6.

[21] J.-L. Lin, P. Imbertson, and T. Moore, "Classroom discourse development for" flipping classrooms": Theoretical concepts, practices, and joint efforts from engineering students and instructors," in *IEEE Frontiers in Education Conference (FIE) Proceedings*. IEEE, 2014, pp. 1–8.

[22] L. Hong, K. Qian, G. Quan, and K. Ma, "Low-cost and portable labware for computing curriculum using scalable mobile sensory platform," in *IEEE Frontiers in Education Conference (FIE)*. IEEE, 2013, pp. 200–202.

[23] K.-S. Ma, Y. Ma, Y. Wang, K. Qian, Q. Zheng, and L. Hong, "Innovative mobile tool for engineering embedded design and security educations," in *Frontiers in Education Conference (FIE)*. IEEE, 2015, pp. 1–4.

[24] B. Ferri, J. Harris, M. A. Weitnauer, and D. Majerich, "A feedback-based approach for evolving a blended class model for large enrollment, multiple section circuits courses," in *Frontiers in Education Conference (FIE)*. IEEE, 2015, pp. 1–8.

[25] L. Svensson and L. Peterson, "A system-level mixed-signal design course," in *IEEE International Conference on Microelectronics Systems Education (MSE)*. IEEE, 2015, pp. 44–47.

[26] T. Westerlund, P. Liljeberg, J. Plosila, and H. Tenhunen, "From traditional vlsi education to embedded electronics," in *IEEE International Conference on Microelectronics Systems Education (MSE)*. IEEE, 2013, pp. 32–35.

[27] G. Donzellini and D. Ponta, "A bottom-up approach to digital design with fpga," in *IEEE International Conference on Microelectronics Systems Education (MSE)*. IEEE, 2011, pp. 31–34.

[28] T. A. Hudson, B. Copeland, and D. Solomon, "Creating a mixed-signal test and product engineering course," in *IEEE International Conference on Microelectronics Systems Education (MSE)*. IEEE, 2011, pp. 56–59.

[29] M. Abdulwahed and Z. K. Nagy, "Applying kolb's experiential learning cycle for laboratory education," *Journal of Engineering Education*, vol. 98, no. 3, pp. 283–294, 2009.

[30] R. H. Caverly and V. Zlatkovic, "Analog microsystem design education via the world wide web," in *IEEE International Conference on Microelectronics Systems Education (MSE)*. IEEE, 1999, pp. 45–46.

[31] C. D. Knight and S. P. DeWeerth, "A shared remote testing environment for engineering education," in *Frontiers in Education Conference (FIE), 1996 IEEE*. IEEE, 1996, pp. 1003–1006.

[32] J. Auerbach and B. Ferri, "Work in progress: The costs and benefits of using alternative approaches in lecture-based courses: Experience in electrical engineering," in *Frontiers in Education Conference (FIE), 2010 IEEE*. IEEE, 2010, pp. T1E–1.

[33] R. H. Caverly, "A laboratory-oriented paradigm for undergraduate analog cmos microsystems design and education," in *University/Government/Industry Microelectronics Symposium, 1993., Proceedings of the Tenth Biennial*. IEEE, 1993, pp. 193–196.

[34] A. Lanterman, M. Giardino, B. Ferri, J. Michaels, W. Hunt, and A. Ferri, "Embedding low-cost, portable experiments into a lecture-based signals and systems course," in *American Control Conference (ACC), 2014*. IEEE, 2014, pp. 2543–2549.

[35] D. W. Parent, E. J. Basham, S. Ng, and P. B. Weil, "An analog leaf cell for analog circuit design," in *IEEE International Conference on Microelectronics Systems Education (MSE)*. IEEE, 2005, pp. 11–12.

[36] J. Hasler, S. Shah, S. Kim, I. Lal, and M. Collins, "Remote FPAA system setup enabling wide accessibility of configurable devices," *Journal of Low-Power Electronics and Applications*, June 2016.

[37] B. Linder, M. Somerville, Ö. Eris, and N. Tatar, "Work in progress–taking one for the team: Goal orientation and gender-correlated task division," in *IEEE Frontiers in Education Conference (FIE)*. IEEE, 2010, pp. F4H–1.

[38] B. J. Zimmerman, A. Bandura, and M. Martinez-Pons, "Self-motivation for academic attainment: The role of self-efficacy beliefs and personal goal setting," *American Educational Research Journal*, vol. 29, no. 3, pp. 663–676, 1992.