

EFFECTIVE DSP LABORATORY COURSE DESIGN

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ABSTRACT

The multi-disciplinary nature of a DSP laboratory course makes it depend more heavily on the surrounding curriculum than most other courses. We argue that the most effective DSP laboratory courses are tailored to their specific curricula. Based on almost 15 years of experience in designing DSP laboratory courses for three different ECE curricula at two different institutions, we present a general philosophy for designing DSP laboratory courses and evaluate our previous course designs as case studies. We close with a speculative course design for a hypothetical curriculum and some resulting conclusions regarding supporting materials such as textbooks and laboratory tools and equipment.

1. INTRODUCTION

A DSP laboratory course, by the intrinsic nature of the material, is very multidisciplinary; it necessarily involves mathematical material in system theory and signal processing, computer programming, elements of computer engineering, at least one application, and usually other topics as well. Such a course thus depends more heavily on the curriculum of which it is part, as well as on its place in that curriculum, than most other courses. For example, a DSP laboratory course taught before a DSP theory course will necessarily require a much different instructional approach and content than one following a solid theoretical grounding in signal processing techniques. Similarly, in a curriculum lacking a required assembly-language programming course, a laboratory based on assembly-level programming of DSP microprocessors requires extensive “remedial” instruction in this art and clearly should have a different syllabus than a course at an institution in which this expertise can be assumed.

The design of any course should also reflect the educational goals of the instructor, the curriculum, and

the institution. The following is a partial list of important educational topics or goals which could be wholly or partially accomplished through the vehicle of a DSP laboratory course:

- DSP theory
- Reinforce and expand DSP understanding
- Real-time DSP
- Advanced DSP algorithms
- Fixed-point/quantization in DSP
- DSP applications
- Digital control systems
- Real-time embedded systems
- Microprocessor systems
- Matlab programming
- Assembly language programming
- Software design/development
- Hardware design/development
- Research experience
- Capstone design experience
- Industrially relevant experience
- Design project management
- Writing skills
- Oral presentation skills
- Teamwork

This is not intended as a fanciful list; most of these items should appear somewhere in any Electrical or Computer Engineering curriculum, and a DSP lab course is a viable, and often ideal, place for introducing them. Faculty will recognize some of these items, such as the capstone design experience, as ABET requirements which must be included in an accredited curriculum, and others, such as writing and teamwork skills, as issues identified by industry as key areas in which they perceive educational programs should focus more attention. Note that the majority of these items are not explicitly DSP-related. In today's tightly packed curricula, a well-designed course will serve as a primary or secondary locus for several of these non-DSP-specific themes, thereby substantially enhancing its value both to the students and in the curriculum.

We contend that the topics included in a well-designed DSP laboratory course extend well beyond DSP, depend greatly on its place in a specific curriculum, and should be matched to the overall curricular needs. We explore these points through a case study of laboratory courses designed for three different curricula at two different universities, and compare and contrast the resulting course designs. We close with a speculative course design for a hypothetical curriculum and some resulting conclusions regarding supporting materials such as textbooks and laboratory tools and equipment.

2. A TALE OF THREE COURSES

In the past fifteen years, we have designed laboratory courses for three different curricula at two different universities. The level ranged from an advanced graduate-level DSP course with a research emphasis to a senior-level laboratory immediately following the first DSP theory course.

2.1. Elec 696: a graduate-level course with a DSP laboratory

In the Spring semester of 1985, Professor Tom Parks, then at Rice University, offered a new version of Elec 696, which is essentially an advanced graduate-level topics-in-DSP course. Texas Instruments donated several Evaluation Modules based on the then-new TMS32010 DSP microprocessor, along with supporting equipment and software allowing the construction of a real-time DSP instructional laboratory. I was the teaching assistant for this course, with the responsibility of setting up the equipment and creating a series of laboratory exercises. As an additional resource, Professor Hans Schuessler from the University of Erlangen-Nuremberg, one of the world's foremost experts on

finite-precision hardware implementation of DSP, was on sabbatical at Rice for the semester and interested in working with students on these issues using this then-revolutionary new technology.

The position of Elec 696 in a graduate curriculum with relatively advanced graduate students enrolled in the course greatly influenced its design. As an "advanced topics in DSP" course, a key role was to study issues of current research interest. At that time (especially at Rice and with Professor Schuessler's presence), such topics included efficient DSP algorithms, quantization issues, and algorithm implementation on DSP microprocessors. Additional important educational goals at the graduate level included giving students a taste of practical, industrially relevant knowledge to counterbalance the traditional academic emphasis on theory. Providing research experience was another key goal which graduate courses often address through a modest research project. Finally, improving writing and presentation skills was an important secondary goal.

Introducing a TMS32010-based laboratory component to Elec 696 offered a very promising way to achieve many of these goals. A substantial lecture component, with multiple lectures per week on advanced DSP algorithms and quantization effects, was included, as this was regarded as the most effective way to introduce new theoretical material. The DSP laboratory was designed to maximize the achievement of key educational goals in minimum time. The laboratory sessions met once per week for several weeks in the semester. Four laboratory exercises and programming assignments were designed to rapidly introduce DSP assembly-language programming, sampling and quantization effects, and real-time implementation of FIR and IIR filters. This portion of the course efficiently achieved the goal of modest exposure to practical or industrially oriented issues in signal processing. A substantial research project related to DSP algorithms was performed by each student to achieve the goals mentioned earlier. Some of these projects involved DSP microprocessors and the laboratory. A substantial written report and oral presentation of the project results addressed the key communication-skills objectives.

In our estimation, the course was quite successful in achieving its intended goals. Several of the research projects led to significant contributions which later appeared in technical reports, conference papers, and future standard implementations of IIR filters on the TMS32010; this clearly shows that these students learned the advanced algorithm theory, performed successful research, developed practical implementations, and comprehensibly presented these results. The mate-

rials developed for the initial labs evolved into an early DSP laboratory textbook [1].

2.2. ECE 320: A senior-level DSP laboratory

In the spring semester of 1989, the Electrical and Computer Engineering department at the University of Illinois at Urbana-Champaign offered an experimental course which evolved into the two-credit-hour senior-level elective ECE 320: Digital Signal Processing Laboratory. ECE 320 was explicitly created to fill several perceived needs in the existing electrical and computer engineering DSP curriculum:

- Additional undergraduate DSP elective option
- Deepen and reinforce understanding of DSP concepts
- Teach real-time DSP
- Industrially relevant DSP experience
- DSP applications

In addition, several other educational goals were part of my “hidden agenda” for the course. In the extant curriculum, the capstone design experience was, in my opinion, relatively limited, and ECE 320 was designed in part to remedy this perceived deficiency. Few opportunities elsewhere in the curriculum for developing writing and oral communication skills and experience in teamwork, and we sought a course design which exercised these skills. In the initial offering of the course, we discovered (to our surprise) that very few of the students had any real understanding of microprocessor systems or assembly language programming. As I regard a basic understanding of computer-based systems essential for almost all modern electrical engineers, offering a remedial education in computer system architecture, microprocessor systems, and assembly language programming became a key objective of the course.

Overall curricular credit-hour constraints recommended a two-hour stand-alone DSP laboratory course. The design of ECE 320 reflects this hourly constraint and the key explicit and implicit educational goals. ECE 320 was introduced as a senior-level elective lab with ECE 310: Introduction to Digital Signal Processing, an “Oppenheim and Schaffer”-level DSP theory course [2], as a prerequisite. To simultaneously achieve the central goals of deepening the understanding of theoretical DSP concepts, teaching microprocessor systems, and exploring real-time DSP implementation (which is also industrially relevant), a series of weekly laboratory assignments were created. They

successively introduced the microprocessor system and interface software, basic DSP assembly programming, real-time sampling and sampling theory review, FIR and IIR filter design and implementation, and FFT-based spectral analysis. A final “challenge” laboratory assignment emphasized efficient coding of an important DSP function such as a DCT. This portion of the course took approximately half of the semester. The second half was devoted to a real-time DSP project of the students’ choice. This segment provided a solid “capstone” open-ended design experience, in-depth exposure to a DSP application, and additional practice with DSP theory, real-time microprocessor system programming and implementation, and industrially relevant project experience. In the project phase, students were required to write project proposals, progress reports, a final report, and to orally present their project. They were strongly encouraged to work in groups. These elements were deliberately introduced to emphasize communication and teamwork skills.

To maximize the course’s effectiveness in achieving its primary goals, an unconventional structure was adopted. The laboratory experience, culminating in the project, was made the focal point of the course. The laboratory met weekly every week of the semester, and considerable additional lab time was required to complete the assignments and the project. The course included a weekly lecture, but its role was subordinated to the in-laboratory activities. The lectures primarily reviewed key elements of DSP theory and microprocessor system architecture and programming in support of the weekly laboratory assignments in the first portion of the course, and overviewed several important DSP applications during the project phase. All graded assignments were laboratory-based. All quizzes and evaluation of the weekly assignments were conducted as 15-minute oral examinations. This was done to allow a personalized examination of each student’s understanding of the theoretical and practical principles of signal processing and to provide instant feedback and instruction to fill the gaps in the student’s knowledge. We found this to be an extremely effective and efficient (for the students!) way to deepen and reinforce their comprehension of DSP principles and their practical application. As a secondary benefit, it provided the students additional experience in oral communication.

In the project phase of the course, the instructor and teaching assistants adopted a “senior colleague” or “consultant” role in which they provided advice, suggestions, and pointers to the literature. We believe this created a guided (and therefore relatively efficient), yet open-ended and student-driven project experience which somewhat reflected the character of a profes-

sional work environment. Carefully critiqued and corrected written and oral project presentations developed communication skills.

We found ECE 320 to be a very effective course which achieved its design goals very well. Our students' understanding of DSP theory and practice was greatly enhanced, they became competent at DSP and microprocessor system development, gained critical experience in open-ended projects and engineering system design, and were highly sought after in industry. Even students with mediocre performance in the course itself have been very successful in their early careers, and we received many compliments on the quality of our former students from their superiors and colleagues. The enrollment rose steadily from under 30 per year to a capped level of 60 per year.

2.3. ECE 320, Version 2.0

In 1995, the Electrical and Computer Engineering Department at the University of Illinois at Urbana-Champaign adopted a major revision of its Electrical Engineering curriculum. Among many changes, perhaps the most significant was eliminating the traditional sophomore circuits course and the junior signals and systems course and replacing them with a required sophomore-level course ECE 210: Analog Signal Processing and a modified, semi-required ECE 310: Introduction to Digital Signal Processing, which is typically taken in the junior year. More substantial computer and hardware experience is required in the new curriculum. The change in the curriculum, particularly in the signal processing component, has had a major impact on the enrollment in ECE 320. The demand has skyrocketed due to the increased pool of students completing the DSP theory course earlier in their studies, the increased awareness of DSP as a promising career specialty, and the popular reputation of the course among students. Due to this demand, we recently began offering the course every semester, with a cap of 60 students per semester. To put this in perspective, each year approximately 110 students, or one-third of our ECE undergraduates, complete ECE 320.

In addition to enrollment trends, alterations in the curriculum as a whole called for at least some redesign of ECE 320 to maximize its efficiency and effectiveness. We are now engaged in an on-going process of evolving its design to better fit the new curriculum. Among other changes, the new curriculum includes elsewhere a much more substantial written communication component and an improved capstone design experience. This somewhat reduces the need for extensive practice in written communication and open-ended design in ECE 320. Some of the effort previously invested in

these areas may be more productively directed toward other goals. Accordingly, we have slightly increased the number of weekly labs (and decreased the project time accordingly) to add more extensive coverage of DSP theory and applications, and have delayed the due-date of the final report to the end of the course, thereby recovering some project time at the expense of providing better feedback on the written report. The sophomore Analog Signal Processing course includes basic filtering and AM radio; we leverage and extend this background (and address the greatly expanded role of DSP in modern communications) with two week-long communications-related assignments. Somewhat improved computer skills allow slightly faster progress through the microprocessor system and DSP assembly programming training. We are now evaluating whether our educational goals can be better met by adopting a TMS320C54x-based platform with a modern software development environment. As should be clear from the discussion above, the ultimate decision depends on a complex interaction between the new curriculum, the students' backgrounds, our detailed educational goals, and industrial trends.

3. PERSPECTIVE

All courses must reside in a larger curriculum. By virtue of its multi-disciplinary nature, a digital signal processing laboratory draws upon, and can contribute to, a greater range of topics and educational goals than many other courses. A well-designed DSP laboratory course provides a significant new component to the total signal processing education available to the students. Just as important (or perhaps even more important!), an effective course also addresses several other, non-DSP-specific, educational components of an overall curriculum. Given the differences in curricula, courses, personnel, and educational objectives between programs, DSP laboratory classes in every department and university should be different.

We advocate designing DSP laboratory courses by carefully studying the surrounding curriculum, by identifying in detail the educational goals for both the discipline and the total curriculum, by selecting the most important goals which the course will address, and by carefully crafting a course design, assignments, and grading mechanisms which best achieve these goals. As a thought-experiment in course design, consider a hypothetical curriculum at an undergraduate-focused institution with a strong hands-on, laboratory-centric program. Assume that, through several courses and design projects, students have intimate knowledge of microprocessor systems, assembly language program-

ming, and instrumentation, extensive open-ended design experience, and considerable skill at learning through hands-on experiments. Assume as well that their mathematical and theoretical background may be less emphasized and developed than that of undergraduate students at a research-oriented university.

In the hypothesized educational environment, students' primary needs may be in learning DSP concepts and theory, and more generally in relating abstract mathematical concepts to applied engineering. A project-oriented laboratory like those described earlier probably offers little value-added over the extensive project experience already obtained elsewhere in the curriculum. On the other hand, such students would require almost negligible ramp-up time to implement and explore DSP concepts with DSP microprocessor systems in the laboratory. In this context, tightly integrating a DSP laboratory component with a DSP theory course could greatly enhance understanding of the mathematical concepts. A series of short laboratory exercises which illuminate the theoretical concepts under study at the time and which provide skilled hands-on learners with tangible applications of this theory should greatly enhance understanding with little additional time-investment while also addressing some weaknesses of the overall curriculum. This course looks very different from any of the DSP laboratory courses described in Section 2, yet it is likely to better serve the target curriculum.

We have argued here that a well-designed DSP laboratory course is carefully crafted for its unique situation and goals, and thus that every DSP laboratory course should be unique. Indeed, we note that DSP laboratory courses are in fact different at almost every institution, and we contend that this is not merely due to the strong individualistic tendencies of college professors, but due to differing needs. However, this near-infinite proliferation of different course models creates major challenges for potential authors of textbooks for such courses, and for corporations such as Texas Instruments which wish to provide equipment, materials, and support for educational programs. To such authors and institutions, perhaps the following advice is useful: offer flexibility, modularity, and support for homegrown initiatives. While every course is different in detail, many specific components may be virtually identical at many institutions. Modular resources, which allow the educator to pick-and-choose, and mix-and-match, the components which best fit their particular needs, may serve many different courses. Flexible resources which can be used in different ways to achieve different goals may also serve a broader spectrum of courses. Finally, do not attempt to second-guess the exact needs of

professional educators with their intimate knowledge of their particular curricula, students, and goals; rather, serve as enablers to support instructors in constructing the unique course which best serves their students. This will best leverage the particular strengths and expertise of both faculty and industry to produce better educated students who will accelerate the progress of signal processing.

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