VLSI Design Curriculum

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Abstract—The Intel Foundation has funded a project at the University of Michigan to develop, document, and disseminate a world-class VLSI curriculum. This paper, which is the first presentation of the project, describes the overall curriculum at a high level, with more focus on the VLSI courses. Curriculum details (lecture content, text, references, projects, sample assignments and exams, computing environment and CAD tools) for sixteen undergraduate and graduate courses will be disseminated through a web site maintained by Intel Corp., and on CDs available from Intel.

I. Background

In the spring of 2003, the Intel University Relations office published a request for proposals (RFP) to develop and disseminate a "world-class" university-level VLSI Design curriculum in an effort to "develop a highly skilled, international workforce that can support the continued growth of the computing industry."[1] The RFP listed as justification for Intel's investment, deficiencies in VLSI curricula in the specific areas of logic design, circuit design, microarchitecture, validation, design methodology and tools, and mask-level design. It notes that teaching VLSI is challenging because it requires both depth and considerable breadth. As stated in the RFP, Intel would like to see students with stronger software skills, analog circuit expertise, experience in high speed and/or low power circuit design, exposure to modern submicron semiconductor processes, and considerably more hands-on experience designing integrated circuits.

The philosophy of the University of Michigan VLSI curriculum has been to give students a broad background in fundamental topics, combined with project-oriented VLSI courses that rely on modern design flows, professional CAD tools, and current process technologies. The courses cover topics ranging from semiconductor device physics to computer architecture. This program has produced graduates who are productive almost immediately when they begin work, and who have the broad and deep background that makes them flexible as technologies and design styles change throughout their careers. The proposal reviewers at Intel were convinced that this program meets their objectives, so the task at hand was to document and disseminate the curriculum.

II. Computing and CAD Environment

All VLSI programs are dependent upon their computing and design tool environments. In 1986, the University of Michigan Electrical Engineering and Computer Science Department procured commercial electronic design automation tools with the goal of replacing the fragmentary collection of software packages used in the Department with a consistent set of tools that would satisfy its instructional and research needs. The acquisition of commercial CAD tools was facilitated at UM by its leadership in distributed computing; at that time, it had 200 Apollo workstations in the College of Engineering. (Since then, HP and SUN workstations, now numbering more than 1600, have been employed to run the design tools. A full IC design flow is now available that runs on PCs under Linux.) Early "university programs" were established as major vendors accepted UM's proposals to donate their software and charge only modest maintenance fees. Our undergraduate circuit and computer courses were being reviewed at that time, and were restructured to use the commercial design automation software. Since that first major donation, professional CAD tools have been used throughout Michigan's undergraduate and graduate curricula.

Many universities have used the University of Michigan as a model for updating curricula to include electronic design automation.[2] The number of electronic CAD tools available to our students has continued to grow. The current list includes virtually all of the Cadence, Synopsys, and Mentor tools, as well as Prolific, Magma, and others.[3] Artisan is our primary source for cell libraries in research; we have developed automated cell generation tools for novel circuits and advanced processes for which commercial libraries are not available. A full-time staff person maintains the electronic CAD environment, and staff members support the computers and networks in the College of Engineering Computer-Aided Engineering Network and in the EECS Department. We use an HP82000 IC tester with 360 high-speed channels for chip testing, along with a full complement of other test, packaging and repair equipment, including a focused ion beam workstation, which are available to classes and research projects.

III. Curriculum Philosophy

From the beginning of VLSI activity at UM, the undergraduate program has been characterized by giving students a broad background in the fundamentals (including logic design, computer architecture, programming, device physics, circuit fundamentals, and large- and small-signal transistor circuits), and project-oriented VLSI courses. The graduate program has also required a great deal of breadth, including circuit fabrication in the Solid-State Electronics Lab, compilers and operating systems, computer architecture, CAD, digital testing, in-depth courses on advanced device technology, a theoretical course on logic circuit synthesis and optimization, and a VLSI experience with large projects designed by small teams, focused on design trade-offs.

One indication of the effectiveness of this program is our students' performance in VLSI competitions. The Student Design Contest sponsored by the Design Automation Conference (DAC) and the International Solid-State Circuits Conference (ISSCC) has entries from top universities around the world, including the leading US institutions. The winners receive cash prizes and have their expenses paid to attend DAC and ISSCC, where they present their designs and are honored at awards ceremonies. This contest has two categories, *conceptual* and *operational*. In the first year of this contest (2000), UM students took first prize in *operational* and both first and second prize in *conceptual*, as well as best paper. In 2001, UM students took first prize in *operational* and first, second and third prizes in *conceptual*, as well as best paper. In 2002, UM students won third place in the *operational* category, first place in the *conceptual* category, and overall best paper award. In 2003, with more than 45 entries, UM students were awarded first and second prizes in the conceptual category. For VLSI students, receiving these awards is like winning the Rose Bowl. An even better indication of the efficacy of UM's program is the graduates' performance in industry and graduate school.

III. Curriculum Overview

The University of Michigan EECS Department implemented new curricula for its three undergraduate degree programs, EE, CE (computer engineering), and CS, Fall term 2001. VLSI students come from both EE and CE backgrounds. These modern engineering curricula build on the foundation of math, physics, chemistry, English, humanities and social science required of all College of Engineering freshmen, and provide a solid background in the basic courses for each of the three areas of study as shown in Fig. 1. There is considerable overlap in these basic requirements because the degrees are closely related. Students are allowed to use credit for those basic courses lying outside of their own major, thereby encouraging them to take courses that will add breadth to their studies.

After taking the basic courses, students have the flexibility to select among core courses which extend their knowledge beyond the basics. CE majors are required to take at least two of -the four core courses listed in the right column of Table 1, while EE students are required to take two of the six courses listed in the left column of this table. Most students will take more of these core courses than the minimum. Obviously, EE VLSI students will choose to take the logic design and digital integrated circuits courses, which are prerequisites to the introductory VLSI course. Most courses are 4 credit hours. Students have 38 credit hours of technical and

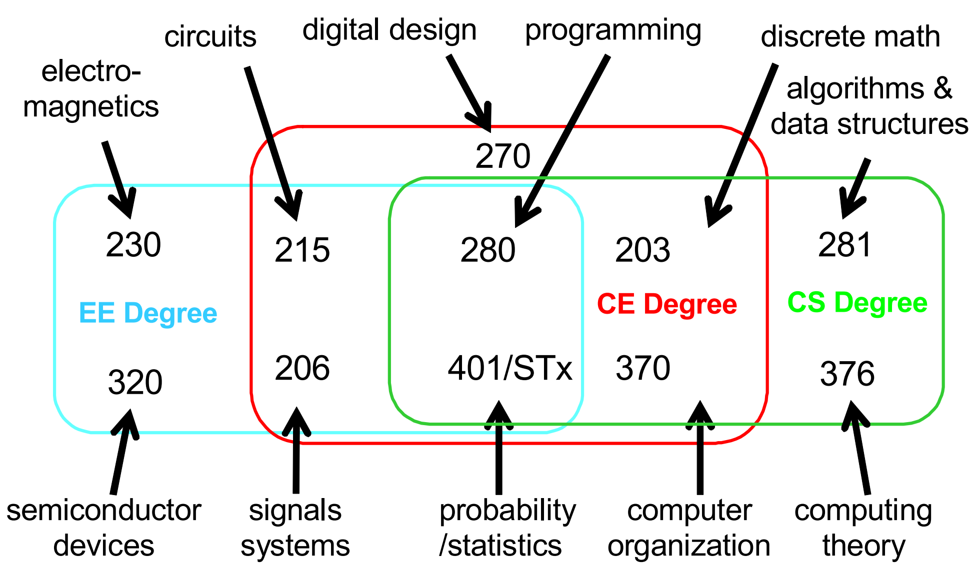

Fig. 1. Basic course requirements for University of Michigan EE, CE and CS undergraduate degree programs.

Table 1: Core course requirements for EE and CE students.

EE Core Courses (select 2 of 6)	CE Core Courses (select 2 of 4)
270: Introduction to Logic Design	281: Algorithms and Data Structures
306: Signals and Systems II	306: Signals and Systems II
311: Analog Electronic Circuits	
312: Digital Integrated Circuits	312: Digital Integrated Circuits
330: Electromagnetics II	
370: Introduction to Computer Organization	373: Microprocessor-Based Systems

Table 2: Technical electives typically taken by VLSI undergraduates.

427: VLSI Design I	452: DSP Design Lab	461: Embedded Control Systems
470: Computer Architecture	473: Digital System Design	478: Logic Synthesis
482: Operating Systems	483: Compilers	489: Computer Networks

Table 3: Graduate VLSI requirements.

427:VLSI Design I		
470: Computer Architecture	OR	478: Logic Synthesis and Optimization
522: Analog Integrated Circuits	OR	523: Digital Integrated Circuit Technology
627: VLSI Design II		

Table 4: VLSI graduate kernel courses.

413: Monolithic Amplifier Circuits	483: Compiler Construction
423: Solid-State Devices Laboratory	522: Analog Integrated Circuits
425: Integrated Circuits Laboratory	523: Digital Integrated Circuit Technology
470: Computer Architecture	527: Layout Synthesis and Optimization
478: Logic Synthesis and Optimization	578: Computer-Aided Design Verification
482: Introduction to Operating Systems	579: Digital System Testing

free electives in which they will take the introductory digital VLSI course, EECS427, and other courses from Table 2.

The graduate VLSI program requires students to take the courses specified in Table 3. Master's students must take at least three 500-level or higher courses in EECS. Ph.D. students must have at least four 500-level or higher EECS courses, one of which must be from Table 4, the VLSI

Table 5: Recommended VLSI graduate courses.

VLSI	Architecture/Testing
411: Microwave Circuits	570: Parallel Computer Architecture
512: Amorphous & Microcrystalline Dev.	571: Principles of Real-Time Computing
524: Microwave Monolithic ICs	573: Microarchitecture
525: Adv. Solid-State Microwave Circuits	577: Reliable Computing Systems
526: Dyn. Device Models and Circuits	670: Spec. Topics in Computer Architecture
534: Microwave Devices and Circuits	
Solid State	**CAD/Software**
420: Introduction to Quantum Electronics	477: Introductions to Algorithms
421: Properties of Transistors	481: Software Engineering
514: Adv. MEMS Devices & Technologies	574: Theoretical Computer Science
520: Elect. and Optical Prop. of Semicond.	575: Advanced Cryptography
521: High-Speed Transistors	581: Software Engineering Tools
528: Microelectronic Process Technology	582: Advanced Operating Systems
540: Applied Quantum Mechanics I	583: Advanced Compilers
541: Applied Quantum Mechanics II	586: Design and Analysis of Algorithms

kernel courses, or Table 5, the list of recommended VLSI courses. Master's students must earn a total of 30 credit hours, of which 24 must be technical courses. Ph.D. students must have 36 course credit hours, plus research hours. Other restrictions on course selection apply, as well.[4]

As can be seen in both the undergraduate and graduate programs, a student has ample opportunity, under the direction of a faculty advisor, to customize his/her course of study to achieve personal objectives. The students have responded very favorably to this flexibility.

IV. VLSI Curriculum

As seen from the courses listed above, the University of Michigan has a rich VLSI curriculum with many elective courses. These courses are continuously tuned to keep them current with technology, tools, and teaching methods, and to keep them correlated with each other. In the Intel Curriculum project, we have documented the 16 courses shown in the prerequisite tree of Fig. 2; these are the courses considered most relevant to the graduate and undergraduate VLSI program. It will be noted that some of these courses fall into the basic EE and CE course requirements (Fig. 1), and others are from the core undergraduate courses (Table 1), undergraduate technical electives (Table 2), or required, kernel and recommended graduate courses (Tables 3-5). The full content of these courses cannot be deduced from just their titles,

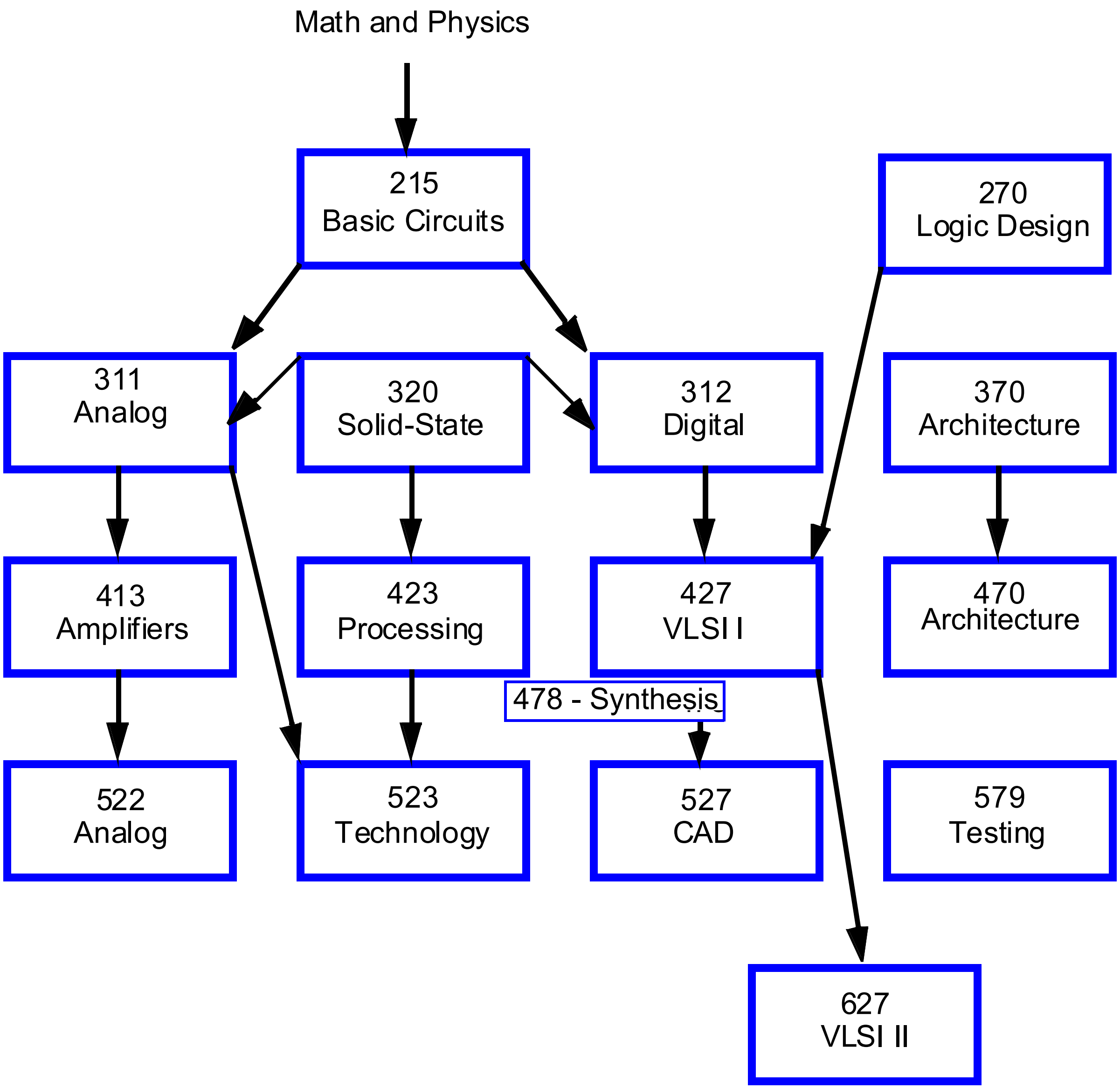

Fig. 2. Prerequisite chart for VLSI courses documented in the Intel VLSI Curriculum project.

but this set of courses encompasses the breadth of VLSI design. A solid foundation in digital and analog circuits, device physics and computer architecture is built upon with advanced courses on these topics, plus a hands-on fabrication course, courses on CAD, advanced technology, testing, and VLSI courses which cover mask-level layout through synthesis of large circuits.

In VLSI I (EECS 427), students form groups of four to design 16-bit RISC processors.[5] They are given a baseline architecture, but they choose an application for their microcontroller and modify the instruction set, peripherals, memory, etc. to suit their machine's intended use. The datapath is designed full-custom; students lay out and tile every cell, sizing transistors, pitch-matching cells, distributing power and clocks, and building up the core of their processor hierarchically. Control circuits and peripherals are synthesized from Verilog, and memories are produced by SRAM generators. Students employ circuit- and cell-level simulators, static timing analysis, electrical rule checking, design rule checks (DRCs), and layout versus schematic (LVS) checks. They choose a package for their chip and verify its operation by running test code. Many of them write application code for their chips, and those who have adequately verified their designs and will be able to test their chips are encouraged to have them fabricated through MOSIS.

Students gain maturity in VLSI II (EECS 627) as they are exposed to advanced VLSI topics in lectures, and have a realistic design experience. As in the introductory course, most 627 students work in small teams. In a weekly recitation section, detailed presentations are given on design methodology. Students start with high-level modeling of their target system, build a 'golden brick' model, and begin verification, which continues throughout the term, moving from focused tests to use of a random code generator, and in some cases, application code. Most projects in this course use Verilog design entry (which is employed throughout our curriculum) and synthesis of most of the logic. This course continues to evolve to include current topics in VLSI and the latest CAD capabilities.

V. Documentation

Little curriculum development was needed to meet the goals of the Intel VLSI Curriculum project, but documenting these 16 courses at a level of detail which would enable others to replicate them, involved a considerable amount of work. The courses were divided among the four faculty co-PIs so that to the extent possible, each had responsibility for the courses closest to his area. Permission to document courses not developed by the principles was sought and received. To assure uniformity and completeness, a template was developed and used as the starting point for all of the course documentation. Students (teaching assistants or top students in the respective courses) and staff members intimately involved in specific courses were employed to generate the raw documentation, which was then edited by the appropriate faculty member. For each of the 16 VLSI-related courses, the following information is provided on the web site (http://www.intel.com/education) and CD:

- A syllabus with an overview of the course and specific learning objectives.
- A recommended text with reading assignments correlated to each lecture.
- Instructor notes, with an outline of the topics to be covered in each lecture.
- Supplemental materials such as papers, graphs, and other slides to support lectures as needed.
- Lab descriptions including equipment recommendations and assignments.
- Software and design tool recommendations where appropriate.
- Sample homework assignments.
- Sample exams.

Two courses had significant revisions as part of this effort: the senior/beginning graduate analog circuit course, EECS 413, and the introductory VLSI course, EECS 427. The content of EECS 413 was modified to put more emphasis on MOSFET circuits, and to include in the term project the physical layout of the amplifier which students design to meet certain specifications. In EECS 427, lectures were modified to assume students have the background provided by EECS 312 (a course developed a year earlier), and to move from 0.5 μm to 0.25 μm technology. This technology change spawned a great deal of work in design kit and CAD support.

The web site and CDs include recommendations for computers, system software, CAD tools and other equipment, with contact information to university program directors for the various vendors. It should be mentioned that a number of different solutions is possible in each of these areas. Each school should evaluate their own situation and develop their computing and CAD environment appropriate to their resources and needs.

One might wonder, in these days of web-distribution of courses, why we did not propose to deliver sets of powerpoint slides for each lecture. There were several reasons: 1) transfering this level of detail could be seen as a conflict of commitment for the faculty involved, violating our employment agreement with the University of Michigan, 2) other faculty whose courses were included might have felt uncomfortable to have their courses published in full, 3) we believe that while slides have a place in teaching, lecturing exclusively from slides is among the worst ways to teach, and we would not want to foster this style of teaching, 4) a set of slides can facilitate teaching by one who has not invested the time to really understand the subject matter, and 5) courses tend to become stagnant over time if they are committed entirely to slides. Instead, we included all of the information one needs to prepare lectures that will be animated and engaging. We encourage the use of a variety of presentation methods, ranging from the tried-and-true chalk and blackboard, to computer projection and hands-on experiments.

VI. Summary

Leading educators who have extensive experience in VLSI research and in industrial design of integrated circuits, have developed and documented the University of Michigan VLSI curriculum. The dissemination of this curriculum begins with the publication of this paper. All are invited to use the information provided in the paper, to receive the VLSI curriculum documentation through the Intel web site or CDs that can be requested from the Intel University Relations Office, and to provide feedback to the authors on both the format and content of the curriculum.

This project would have taken much more time had the curriculum not been essentially developed before the project began. As mentioned above, the courses are routinely tuned and updated. The comprehensive evaluation of the VLSI curriculum prompted by this project led to more adjustments than usual, as the authors prepared to disseminate the curriculum to others.

Integrated circuit design, on which so much of high technology depends, is a challenge to teach because it requires hands-on experience in time-consuming projects; it calls for extensive computing facilities and complex CAD tools; and it requires depth in VLSI topics and breadth extending to device physics, circuits, computer architecture, and software.

This project may serve as a model for other organizations interested in disseminating best-of-class curricula in various engineering areas.

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Biographies

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Richard Brown received BS (with Highest Honors) and MS degrees from Brigham Young University in 1976, and after working in industry, his Ph.D. from the University of Utah in 1985, all in electrical engineering. He is currently a professor in the Electrical Engineering and Computer Science Dept. at the University of Michigan, and will become Dean of Engineering at the University of Utah July 1, 2004.

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Gordon Carichner received BS and MS degrees in electrical engineering from the University of Michigan, Ann Arbor, in 1989 and 1991, respectively. From 1991 through 1998 he was a VLSI designer in Motorola's DSP division in Austin, TX. He has since returned to the University of Michigan where he teaches and supports EDA software in the Department of Electrical Engineering and Computer Science.

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Catharine June received the Ph.D. degree in Musicology from the University of Michigan in 1991. She has worked for Prof. Brown as a staff member in the Department of Electrical Engineering and Computer Science at the University of Michigan since 1994. She has been involved in a variety of activities, including web design and maintenance, technical communication, and editing.