An Embedded Systems Curriculum Based upon the IEEE/ACM Model Curriculum

Selected for the 2009 IEEE Education Society Best Transactions Paper Award

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Southeastern Association of Electrical and Computer Engineering Department Heads (SECEDHA) Annual Meeting

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Agenda

• Introduction
  – Computer Engineering (CE) at the University of Alabama (UA)
  – Why Embedded Systems?
• Challenges with Embedded Systems Education
• The UA Curriculum Reform “Process”
  – The 2004 IEEE/ACM CE Model Curriculum
  – UA Curriculum Specifics
• Assessment
• Conclusions/Lessons Learned
CE at UA

• CE is an option within the EE program (is not a standalone degree program YET)

• CE is independently ABET accredited

• There are approximately 300 undergraduates in the ECE Dept. (approx. 125 are in the CE option)

• There are 16 faculty members in the ECE Dept. (5 in CE)
CE at UA (cont.)

• In 2002-2003, the UA ECE Dept. performed a self-assessment and decided to create 3 focus areas aligned with common research activities among the faculty
  – Electromechanical Systems
  – Devices and Materials
  – Embedded Systems (ES) (CE area)

• Motivation was improved resource utilization
What is an Embedded System?

• Any device that has a computing core that is not intended as a general-purpose computer

• Examples:
  – Consumer electronics (cell phones)
  – Home appliances
  – Medical devices
  – Automobiles
  – Aerospace vehicles
  – Etc.
Why Embedded Systems?

• “Currently, a dominant area within computer engineering is embedded systems, the development of devices that have software and hardware embedded in them. For example, devices such as cell phones, digital audio players, digital video recorders, alarm systems, x-ray machines, ... all require integration of hardware and embedded software and all are the result of computer engineering.” [19]

• Approximately 98% of all processors produced annually are used in embedded devices

• It is estimated that the amount of embedded software doubles every 10 months and will account for 90% of all software being written by the year 2010 [20]
Why Embedded Systems? (cont.)

• Embedded systems was/is a shared research area among UA CE faculty (facilitates collaboration among UA faculty members)

• The curriculum focus will help to meet workforce needs of local industry
Challenges for ES Education

• Breadth problem
  – Hardware concepts
  – Software concepts
  – Interfacing concepts

• Domain-specific information is also required

• This often leads to small subsets of ES topics being incorporated into a small number of courses
UA Curricular Reform Process

• UA goals:
  – To provide a well-rounded CE curriculum with an underlying emphasis on ES
  – To integrate a broad set of ES topics into a large set of courses
  – To minimize structural changes to the CE curriculum
• NOTE: the goal was not to overhaul the entire curriculum as much as it was to provide a common thread within the overall program
• This goal facilitates adoption of this technique by other institutions
UA Curricular Reform Process

• Visited/talked with several universities with established ES components in their curricula

• Reviewed various publications associated with ES curricula
  – Many smaller efforts focusing on a small subset of ES topics

• Identified several “models” for ES curricula
  – Models can tend to unify a field of study
  – The model of interest for UA was the 2004 IEEE/ACM Computer Engineering Model Curriculum
UA Curricular Reform Process

• This effort was/is unique due to:
  – Scale: A broad set of topics integrated across an entire CE curriculum with assessment of a large set of learning outcomes
  – Closely coupled with an entire “model”
2004 IEEE/ACM CE Model Curriculum

Knowledge Areas (18)

Knowledge Units

Topics

Learning Outcomes
Model CE Knowledge Areas

- Algorithms
- Computer Architecture and Organization
- Computer Systems Engineering
- Circuits and Signals
- Database Systems
- Digital Logic
- Digital Signal Processing
- Electronics
- Embedded Systems
- Human-Computer Interaction
- Computer Networks
- Operating Systems
- Programming Fundamentals
- Social and Professional Issues
- Software Engineering
- VLSI Design and Fabrication
- Discrete Structures
- Probability and Statistics
Model ES Knowledge Units

- ESY0 – History/Overview(1)
- ESY1 – Embedded Microcontrollers(6)
- ESY2 – Embedded Programs(3)
- ESY3 – Real-Time Operating Systems(3)
- ESY4 – Low-Power Computing(2)
- ESY5 – Reliable System Design(2)
- ESY6 – Design Methodologies(3)
- ESY7 – Tool Support
- ESY8 – Multiprocessors
- ESY9 – Networked Embedded Systems
- ESY10 – Interfacing and Mixed-Signal Systems

(#) Denotes min. coverage time for core topics; min = 20 hours
Breadth Problem Up Close

• Total of 18 Knowledge Areas

• For ES Knowledge Area Alone:
  – 11 Knowledge Units (7 core; 4 elective)
  – 63 topics (42 core; 21 elective)
  – 34 Learning Outcomes (24 core; 10 elective)
Department of Electrical and Computer Engineering

Computer Engineering Option -- for students starting their college careers Fall 2010 or later

Freshman Year
Fall - 16 cr  Spring - 15 cr
- CH 101 - 4 cr  General Chemistry
- Math 125 Calculus I  4 cr
- ENGR 111 Eng. For the Future  1 cr
- EN 101 English Composition  3 cr
- ECE 131 Fund. of ECE I  1 cr
- CS 160 - 1 cr  Computer Science Concepts
- ENGR 141 Eng. Con. & Des. I  1 cr
- ENGR 151 Fund. Eng. Graphics  1 cr

Sophomore Year
Fall - 15 cr  Spring - 16 cr
- PH 105 - 4 cr  General Physics with Calculus I
- MATH 126 Calculus II  4 cr
- MATH 227 Calculus III  4 cr
- ECE 121 Fund. of ECE I  1 cr
- ENGR 141 Eng. Con. & Des. II  1 cr
- ENGR 151 Fund. Eng. Graphics  1 cr
- CS 160 - 1 cr  Computer Science Concepts
- Math 237 Applied Matrix Theory
- ECE 131 Fund. of ECE II  1 cr
- Math 238 Applied Diff. Equations I  3 cr
- Math 301 Discrete Mathematics  3 cr
- Math 355 Theory of Probability  3 cr
- Math 331 Fund. of Comp. Sc.  3 cr
- Math 360 Found. of Comp. Sc.  3 cr
- Math 360 Found. of Comp. Sc.  3 cr

Junior Year
Fall - 16 cr  Spring - 16 cr
- PH 106 - 4 cr  General Physics with Calculus II
- Math 236 Electric Networks  3 cr
- Math 238 Applied Diff. Equations II  3 cr
- Math 355 Theory of Probability  3 cr
- Math 331 Fund. of Comp. Sc.  3 cr
- Math 360 Found. of Comp. Sc.  3 cr
- Math 360 Found. of Comp. Sc.  3 cr
- Math 360 Found. of Comp. Sc.  3 cr

Senior Year
Fall - 16 cr  Spring - 15 cr
- ECE 492 Capstone Design I  2 cr
- ECE 494 Capstone Design II  2 cr
- ECE 480 Digital Sys. Design  3 cr
- ECE 480 Digital Sys. Design  3 cr
- ECE 486 Embedded Systems  3 cr
- ECE 487 Embedded Systems Lab  1 cr
- ECE 481 Digital Sys. Design Lab  1 cr
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- ECE 481 Digital Sys. Design Lab  1 cr

Legend:
- Prerequisite
- Corequisite
- Prerequisite may be required, check Catalog
- Check Catalog for prerequisites, University Core and College Requirements

May 19, 2010

125 total credits
UA CE Core Course Sequence

ECE 285: Programming for ECE (3)
CS 160: Computer Science Concepts (1)

CS 260: Foundations of Computer Science (2)

ECE 380: Digital Logic (4)

CS 351: Programming III (2)

ECE 383: Microcomputers (4)

CS 360: Data Structures and Algorithms (4)

ECE 480: Digital System Design (3)
ECE 481: Digital System Design Laboratory (1)
ECE 484: Computer Architecture (3)
ECE 486: Embedded Systems (3)
ECE 487: Embedded Systems Laboratory (1)

ECE 492/494: Capstone Design (2)/(2)

OR
Integration into UA Courses

• ES topics are integrated into courses in three ways:
  – Lecture materials (L)
  – Written assignments (W)
  – Laboratory assignments (A)

• Overlapping content provides depth of knowledge

• Explicit forward/backward references among courses help to provide depth and breadth of knowledge
  – Establish solid relationships among courses
  – Promote design-for-reuse principles
  – Increase proficiency in the use of development tools
ECE 380 Digital Logic

• Summary of coverage areas:
• L = Lecture coverage; W = Written Assignment; A = Laboratory Assignment

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ECE 383 Microcomputers

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November 11, 2010
University of Alabama
20
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ECE 484 Computer Architecture

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ECE 492/494 Capstone Design

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Overlapping Content

• Example (ESY1 T1 and LO2):
  • ECE 383 introduces polled and interrupt-driven I/O using a microcontroller and assembly language

• ECE 484 investigates CPU design requirements to support interrupt processing

• ECE 486/487 covers system-level design specifically regarding when polling and interrupt-driven approaches are appropriate; assignments use a high-level language (C language)
Forward/Backward References

• Example:
  ECE 380 – Design an ALU using VHDL; download and demo using DE2 FPGA board

• ECE 484 – Use the ALU designed in ECE 380 for a MIPS CPU design

• ECE 480/481 – Use VHDL and the same FPGA tools used in previous courses (ECE 380)
Assessment

• Assessment goals:
  – Evaluate breadth and depth of student understanding of ES learning outcomes in model curriculum

• Assessment data was collected during 2005-2006 academic year

• Qualitative data
  – Student surveys (pre- and post-course)

• Quantitative data
  – Written and lab assignments
Assessment

• Summary of qualitative analysis:
  • Student perception improved across every ES knowledge unit
    – Supports the idea that a broad range of ES topics were integrated into the curriculum
  • Student perception improved for every learning outcome for each ES knowledge unit
    – Supports the idea that depth of understanding was also addressed
  • Improvement means:
    – Increased average values
    – Reduced number of “Strongly Disagree” and “Disagree” responses
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Assessment

• Summary of quantitative analysis:
• Data is not comprehensive
• No pre-curriculum change data for comparison
• Student performance was strong across the 8 ES knowledge units evaluated
  – Supports the idea that a broad range of topics were integrated into the curriculum
• Student performance was strong across all learning outcomes for ESY1
  – Supports the idea that depth of understanding was also addressed
### Quantitative Assessment Data

<table>
<thead>
<tr>
<th>Course</th>
<th>Knowledge Unit/LO</th>
<th>Quantitative Results</th>
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Conclusions/Lessons Learned

• Creation of a common thread within a curriculum is easier than a complete curriculum overhaul
• Having a small set of faculty involved makes curriculum reform, at any level, easier
• Basing reform on a well-respected curriculum model is preferred to those based upon custom/localized approaches
• A broad set of topics can be integrated into a curriculum without the need for significant structural changes
  – No need to “settle” on some subset of topics
• Breadth and depth of topical coverage must be addressed
• Use of an established model can facilitate ABET assessment
Questions?

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References


References (cont.)


References (cont.)


ESY0: History and Overview

Topics:
• T1 – Indicate some reasons for studying embedded systems
• T2 – Highlight some people that influenced or contributed to the area of embedded systems
• T3 – Indicate some important topic areas such as mapping between language and hardware, classifications, influence of software engineering, applications and techniques, and tool support
• T4 – Contrast between an embedded system and other computer systems
ESY0: History and Overview

• Topics:
• T5 – Mention the role of programming and its associated languages as applied to embedded systems
• T6 – Explore some additional resources associated with embedded systems
• T7 – Explain the purpose and role of embedded systems in computer engineering
ESY0: History and Overview

• Learning outcomes:
• LO1 – Identify some contributors to embedded systems and relate their achievements to the knowledge area
• LO2 – Describe the meaning of an embedded system
• LO3 – Explain the reasons for the importance of embedded systems
• LO4 – Describe the relationship between programming languages and embedded systems
• LO5 – Describe how computer engineering uses or benefits from embedded systems
Topics:

T1 – Structure of a basic computer system: CPU, memory, I/O devices on a bus
T2 – CPU families used in microcontrollers: 4-bit, 8-bit, 16-32-bit
T3 – Basic I/O devices: timers/counters, GPIO, A/D, D/A
T4 – Polled I/O vs. interrupt-driven I/O
T5 – Interrupt structures: vectored and prioritized interrupts
T6 – DMA transfers
T7 – Memory management units
T8 – Memory hierarchies and caches
ESY1: Embedded Microcontrollers

Learning outcomes:
- LO1 – Understand the CPU in the context of a complete system with I/O and memory
- LO2 – Understand how the CPU talks to the outside world through devices
- LO3 – Understand how memory system design (caches, memory management) affect program design and performance
ESY2: Embedded Programs

- Topics:
  - T1 – The program translation process: compilation, assembly, linking
  - T2 – Representations of programs: data flow and control flow
  - T3 – Fundamental concepts of assembly language and linking: labels, address management
  - T4 – Compilation tasks: mapping variables to memory, managing data structures, translating control structures, and translating expressions
  - T5 – What can and cannot be controlled through the compiler; when writing assembly language makes sense
ESY2: Embedded Programs

• Learning outcomes:
  • LO1 – Understand how high-level language programs convert into executable code
  • LO2 – Know the capabilities and limits of compilers
  • LO3 – Comprehend basic representations of programs used to manipulate programs either in a compiler or by hand
ESY3: Real-Time Operating Systems

- Topics:
  - T1 – Context switching mechanisms
  - T2 – Scheduling policies
  - T3 – Rate-monotonic scheduling: theory and practice
  - T4 – Priority inversion
  - T5 – Other scheduling policies such as EDF
  - T6 – Message-passing vs. shared memory communication
  - T7 – Interprocess communication styles such as mailbox and RPC
ESY3: Real-Time Operating Systems

• Learning outcomes:
• LO1 – Distinguish RTOSs from workstation/server OS
• LO2 – Distinguish real-time scheduling from traditional OS scheduling
• LO3 – Understand major real-time scheduling policies
• LO4 – Understand interprocess communication mechanisms
ESY4: Low-Power Computing

- Topics:
- T1 – Sources of energy consumption: toggling, leakage
- T2 – Instruction-level strategies for power management: function unit management
- T3 – Memory system power consumption: caches, off-chip memory
- T4 – Power consumption with multiple processes
- T5 – System-level power management: deterministic, probabilistic methods
ESY4: Low-Power Computing

- Learning outcomes:
  - LO1 – Understand why low-power computing is important
  - LO2 – Identify sources of energy consumption
  - LO3 – Identify possible remedies for energy consumption at various levels of design abstraction
ESY5: Reliable Systems Design

- Topics:
  - T1 – Transient vs. permanent failures in hardware
  - T2 – Sources of errors from software
  - T3 – The role of design verification in reliable system design
  - T4 – Fault-tolerance techniques
  - T5 – Famous failures of embedded computers
ESY5: Reliable System Design

- Learning outcomes:
  - LO1 – Understand the variety of sources of faults in embedded computing systems
  - LO2 – Identify strategies to find problems
  - LO3 – Identify strategies to minimize the effects of problems
ESY6: Design Methodologies

- Topics:
  - T1 – Multi-person design projects
  - T2 – Designing on-time and on-budget
  - T3 – Design reviews
  - T4 – Tracking error rates and sources
  - T5 – Change management
ESY6: Design Methodologies

• Learning outcomes:
  • LO1 – Understand why real-world projects are not the same as class projects
  • LO2 – Identify important goals of the methodology
  • LO3 – Understand the importance of design tracking and documentation
ESY7: Tool Support

• Topics:
• T1 – Compilers and programming environments
• T2 – Logic analyzers
• T3 – RTOS tools
• T4 – Power analysis
• T5 – Software management tools
• T6 – Project management tools
ESY7: Tool Support

• Learning outcomes:
  • LO1 – Understand role of hardware and software tools in system development
  • LO2 – Understand how to use tools to support the methodology
ESY8: Embedded Multiprocessors

- Topics:
  - T1 – Importance of multiprocessors as in performance, power, and cost
  - T2 – Hardware/software partitioning for single-bus systems
  - T3 – More general architectures
  - T4 – Platform FPGAs as multiprocessors
ESY8: Embedded Multiprocessors

• Learning outcomes:
  • LO1 – Understand the use of multiple processors in embedded systems
  • LO2 – Identify trade-offs between CPUs and hardwired logic in multiprocessors
  • LO3 – Understand basic design techniques
ESY9: Networked ES

- Topics:
  - T1 – Why networked embedded systems
  - T2 – Example networked embedded systems: automobiles, factory automation systems
  - T3 – The OSI reference model
  - T4 – Types of network fabrics
  - T5 – Network performance analysis
  - T6 – Basic principles of the Internet protocol
  - T7 – Internet-enabled embedded systems
ESY9: Networked ES

• Learning outcomes:
• LO1 – Understand why networks are components of embedded systems
• LO2 – Identify roles of hardware and software in networked embedded systems
• LO3 – Compare networks designed for embedded computing with Internet networking
ESY10: Interfacing/Mixed Sig. Sys.

- Topics:
  - T1 – Digital-to-analog conversion
  - T2 – Analog-to-digital conversion
  - T3 – How to partition analog/digital processing in interfaces
  - T4 – Digital processing and real-time considerations
Learning outcomes:
- LO1 – Understand pros and cons of digital and analog processing in interfaces
- LO2 – Understand fundamentals of A/D and D/A conversion
Representative Topics

• ESY1 Embedded Microcontrollers [core]

Topics:
T1. Structure of a basic computer system: CPU, memory, I/O devices on a bus
T2. CPU families used in microcontrollers: 4-bit, 8-bit, 16-32-bit
T3. Basic I/O devices: timers/counters, GPIO, A/D, D/A
T4. Polled I/O vs. interrupt-driven I/O
T5. Interrupt structures: vectored and prioritized interrupts
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Representative Learning Outcomes

- ESY1 Embedded Microcontrollers [core]

Learning outcomes:
LO1. Understand the CPU in the context of a complete system with I/O and memory
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