EE108B

Digital Systems II

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EE108B: Digital Systems II

• Part of the Digital Systems sequence of the new ugrad EE core
  – Revision of EE182 and EE183
    • Follow on to EE108A (Digital Systems I)
    • Prerequisite for courses like EE109, EE282, …
  – Should better match your interests
    • So give us feedback on what works and what doesn’t

• Class has TWO flavors
  – Take class with labs (for EE undergrads)
    • Prereq is EE108A
    • Lab enrollment is limited, so signup for lab section ASAP
  – Take lectures only (for CS undergrads, SCPD, grad students)
    • Do programming assignments instead of labs
What is EE108b About?

- Many different views:
  - How to build programmable digital systems
  - Introduction to processor architecture
  - Understanding why your programs sometimes run much more slowly than you expect or don’t run at all

- Bottom line:
  - Digital systems are ubiquitous
  - Processors are one of the common idioms in digital design
    - Can’t avoid them these days
    - They are in your computers, TV, car, phones, door locks, …
  - It pays to understand how they work
    - To understand what they can and can’t do

Major Topics

- Hardware-software interface
  - Machine language and assembly language programming

- Compiler optimizations and performance

- Processor design
  - Pipelined processor design

- Memory hierarchy

- Virtual memory & operating systems support

- I/O devices
Syllabus

• Please see Handout #1
  – Contact class staff with any questions

• Includes tentative schedule

• Assignment due dates & exams listed
  – Make sure you have time for everything before you sign up…
    • Especially if you are a SCPD student
  – If not, you should not take EE108b
    • Class offered again in Fall and Winter of 06-07 academic year

Course Information

• Instructor: Kunle Olukotun
  – E-mail: kunle@stanford.edu
  – Office: Gates 302
  – Office Hours: Tue-Thu 1:30-2:30pm or by appointment

• TAs
  – Yi Gu, Daxia Ge
  – E-mail: ee108b-fall0607-tas@lists.stanford.edu

• Course Support: Darlene Hadding
  – Office: Gates 408
  – Email: darlene@csl.stanford.edu
Lectures & Discussion Sessions

- **Lectures**
  - Tuesday/Thursday 11:00am -12:15pm, McCullough 115
    - Also on SCPD channel E4, but it’s best to come to class

- **Discussion Session**
  - Fridays 4.15pm – 5.05pm, TBD
  - Look at on-line schedule for specific sessions

- **You should actively participate in lectures**
  - Feel free to interrupt for Q&A, further thoughts on material, etc.
  - This is your way of setting the pace & quality of the class
  - Best way to get me to learn your name...

Prerequisites

- **Prerequisites**
  - EE undergrads: EE108A and CS106B
  - CS undergrads: E40 and CS106B

- **The problem with separate prerequisites**
  - EE students: know logic design but little about low level software
  - CS students: know software but no logic design
    - Many of you have taken CS107 and (perhaps) CS140

- **I’ll try to satisfy both sides but**
  - Need your feedback to make the best of this situation
    - Questions, answers, insightful comments
  - Help me teach your classmates for topics you know well
Other Course Info

- **Course Text**
  - *Computer Organization & Design, 3rd Edition*
    - By D. Patterson & J. Hennessy
    - CD includes manuals, appendices, simulators, CAD tools, …
  - “Green card” summarizes MIPS ISA

- **Website**
  - [http://eeclass.stanford.edu/ee108b](http://eeclass.stanford.edu/ee108b)
  - Check frequently
  - Will need to sign up with webpage once we enable it

- **Handouts**
  - Extras placed in cabinet on Gates 3rd floor
  - Print from class website

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**Grading**

- **Homework Sets** 15%
- **Programming Projects/Labs** 25%
- **Midterm** 25%
- **Final** 35%
Workload

• 5 Homework Sets
  – Work in groups of up to 2 (no more!)
  – Due at 5 PM
  – Submit in class or to outside Gates 408
  – One free problem set “late day” class period; NO more!
• 2 Programming Projects (for 3-unit option)
  – Complete individually
  – Will use spim simulator on the Leland systems
  – Electronic submission
  – One free project “late day” class period; NO more!
• 4 Laboratory Projects (for 4-unit option)
  – Work in groups of up to 2 (no more!)
  – Use Xilinx FPGA boards in Packard 129
  – Demo and short electronic report submission
  – One free project “late day” class period; NO more!

Class Exams

• Midterm: Tuesday October 24, 7pm – 10pm
  – Room TBD

• Final: Thursday December 7, 11am – 1pm
  – McCullough 115
  – Last day of class

• The rules
  – Open book, calculator
  – Local SCPD students expected to come to campus
  – Remote SCPD students must take exams on same date
Lecture 1

Introduction to Programmable Digital Systems

EE108b – Fall 2006
Stanford University
http://eeclass.stanford.edu/ee108b

Current State of the World

- Electronic systems dominate almost everything
  - And most of these systems use processors and memory

- Why?
  - Break this question into three questions
    - Why electronics
    - Why use ICs to build electronics
    - Why use processors in ICs

- Why use electronics
  - Electrons are easy to move / control
  - Easier than the current alternatives

- Result is that we move information / not real physical stuff
  - Think phone, email, fax, TV, WWW, etc.
Mechanical Alternative to Electronics

Picture of a version of the Babbage difference engine built by the Museum of Science UK

"The calculating section of Difference Engine No. 2, has 4,000 moving parts (excluding the printing mechanism) and weighs 2.6 tons. It is seven feet high, eleven feet long and eighteen inches in depth"

Electronics

- Building electronics:
  - Started with tubes, then miniature tubes
  - Transistors, then miniature transistors
  - Components were getting cheaper, more reliable but
    - There is a minimum cost of a component (storage, handling …)
    - Total system cost was proportional to complexity

- Integrated circuits changed that
  - Devices that integrate multiple transistors
  - Print a circuit, like you print a picture,
    - Create components in parallel
    - Cost no longer depended on # of devices
  - What happens as resolution goes up?
The Famous Moore’s Law

- Devices get smaller
  - Get more devices on a chip
  - Devices get faster

- Initial graph from 1965 paper
  - Prediction: 2x per year
  - Not too many data points

- Slowed down to 2x
  - Every 1.5 to 2 years?

- Is Moore’s Law really a Law?
- What does it say about performance?

Sense of Scale

- What fits on a chip today?

- Mainstream logic chip
  - 10mm on a side (100mm²)
  - 90nm drawn gate length
  - 210nm wire pitch
  - 10 wires levels

- For comparison
  - 32b RISC integer processor
    - 1K x 2K wire grids
    - 1100 processors
  - SRAM
    - About 4 x 4 grids / bit
    - 138 M SRAM cells
  - DRAM
    - 1 x 2 grids / bit
    - 1.1 B cells
Technology Scaling

- Chip density doubles every 3 years
  - What can you do with this?
  - More devices ⇒ harder to design

### The Complexity Problem

- Complexity is the limiting factor in modern chip design
  - Two problems
    1. How do you make use of all that space?
       - Uberappliance
         - Cellphone, PDA, iPod, mobile TV, video camera
         - Too many applications to cast all into hardware logic
         - Takes too long to finish the design
    2. How do you make sure it works?
       - Verification problem
       - How do you fix bugs?

- Only way to survive complexity:
  - Hide complexity in “general-purpose” components
  - Reuse components
Programmable Components
aka Processors

- An old approach to “solve” complexity problem
  - Build a generic device and customize with memory (program)
  - Best way to do this is with a general purpose processor

- Processor complexity grows with technology
  - But software model stays roughly the same
    - C, C++, Java, … run on Pentium 2, 3, and 4
    - True for sequential programs
  - This is getting much tougher to do
    - Recent hardware developments require software model changes
    - Multi-core processors

Microprocessor Complexity

- Model has hidden the scaling of technology
  - Efficiently transformed transistors to performance
  - 8080 – 3,500 transistors, and ran at 200kHz (1975)
  - Pentium4 – 42M transistors, runs at 3+GHz (2003)
  - Performance changed from 0.06MIPS to >1,000MIPS
### Key to Complexity: Nice Interfaces

- Use abstraction to hide complexity
  - Define an interface to allow people to use features without needing to understand all the implementation details
- Works for hardware and software
- Stable interfaces allows people to optimize below and above it

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<table>
<thead>
<tr>
<th>Applications</th>
<th>C, C++</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instruction Set Arch.</td>
<td>Functional Units</td>
</tr>
<tr>
<td>Logic Gates</td>
<td>Transistors</td>
</tr>
</tbody>
</table>

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### But I Never Want to Build Hardware

- Why should I care about how a computer works?
- And why should I have to learn about assembly code?
  - No one codes in assembly any more, right?
  - Unfortunately that is not correct
  - E.g. compilers, operating systems kernel
  - E.g. Embedded systems, video games

- It is still useful to look inside the box
  - Understand limitations of the programmers model
  - Understand strange performance issues
    - Efficiency and performance issues will become more important
  - Help you when things go wrong
Reality #1

*Int’s are not Integers, Float’s are not Reals*

- **Examples**
  - Is \(x^2 \geq 0\)?
    - **Float’s:** Yes!
    - **32b Int’s:**
      - \(40,000 \times 40,000 \rightarrow 1,600,000,000\)
      - \(50,000 \times 50,000 \rightarrow ??\)
  - Is \((x + y) + z = x + (y + z)\)?
    - **Unsigned & Signed Int’s:** Yes!
    - **Float’s:**
      - \((1e20 + -1e20) + 3.14 \rightarrow 3.14\)
      - \(1e20 + (-1e20 + 3.14) \rightarrow ??\)

Reality #2

*You’ve got to know assembly*

- **Chances are, you’ll never write program in assembly**
  - Compilers are much better & more patient than you are

- **Understanding assembly key to machine-level execution model**
  - **Behavior of programs in presence of bugs**
    - High-level language model breaks down
  - **Tuning program performance**
    - Understanding sources of program inefficiency
  - **Implementing system software**
    - Compiler has machine code as target
    - Operating systems must manage process state
Reality #3  
Memory Matters

- Memory is not unbounded  
  - It must be allocated and managed  
  - Many applications are memory dominated
- Memory referencing bugs especially pernicious  
  - Effects are distant in both time and space
- Memory performance is not uniform  
  - Cache and virtual memory can greatly affect program performance  
  - Adapting program to characteristics of memory system can lead to major speed improvements  
    - 10x to 100x in several cases

Class Goal

- Provide a better understanding of modern digital systems design  
  - These systems almost always have a programmable processor  
  - Processors are a good example of a complex system  
    - Pipelining and caches
- Tie the hardware with the software  
  - Most people use processors and don’t build them  
  - Interaction of HW and SW is fundamental to computer systems  
  - Write better software
- Provide a foundation for other classes in systems  
  - Networking, OS, Compilers, Embedded Systems, etc.  
  - Understand capabilities of Compilers, OS
What is a Computer System?

- Depends (a little) on what type of computer system
- We probably mostly think about PC systems

What is a Computer System?

- Actually most computers look like this…
5 components of any Computer

What is in a Computer System?

- Each system is different, but generally have similar parts:

  - Must have:
    - Processor, Memory
    - Interface to outside world (I/O)

  - Generally have:
    - Cache memory
    - System bus
    - Memory controller
    - I/O bus
Example Processor Based Systems

- MIPS processor board
- PC Board
- Digital cell phone
- Game console

MIPS Processor Board

- R3000 CPU (120K transistors)
- R3010 FPU
- 32 KB Instruction cache
- 32 KB Data cache
- 256 KB secondary cache
- Memory controller chips
PC System

- Pentium 4 2.66 GHz
  - 8KB Data cache, 12 KB Instruction cache
  - 512 KB L2 Cache
  - 533 MHz System Bus
  - 68 Watts
- Memory system
  - 4 DDR DIMM slots
  - Up to 4 GB
- I/O interfaces
  - Ethernet
  - USB
  - Serial ATA (disk)
  - Serial port
  - Parallel port
Digital Cell Phone (Nokia 8260)  
Front Side

- Battery 900 mAh
  - 3.5 hr talk ~ 1 W
  - 8 days standby ~ 1 mW

Digital Cell Phone (Nokia 8260)  
Back Side
Looking Forward

- EE108b is about understanding how to build & use such systems
  - From PCs to hi-tech refrigerators

- Starting in the next lecture
  - What is the hardware/software interface?
  - What is the functionality that the hardware must implement?