CS 211: Computer Architecture course wrapup: goodbye to cs211!

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Recall from Course Intro. . . Perspective

- Computer architecture design is directly linked to underlying technology
  - Semiconductor
  - Compiler technology
  - Computational models
- Goal of software designers is to run an application program efficiently on the architecture
  - Compiler plays a key role
  - what is the interplay between architecture features and application program properties
  - Bottom line is performance of application

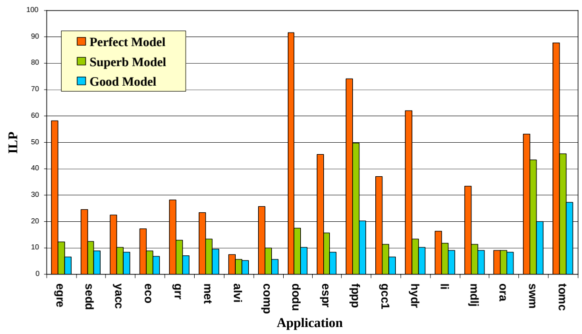
Trends In Technology, Applications,Architectures

Emerging trends in Semiconductor Technology: Recall from Week 1 !

- What's the trend in Semiconductor technology and its impact on new types of processor architectures ?
  - some aspects to consider:
    - Delay: switching time of transistor – impacts clock cycle
    - Feature size: size of transistor – impacts amount of logic in processor
    - Interconnect delay: clock cycle/delay in sending signal across the interconnect lines on a chip

Available instruction-level parallelism

[Wall'93, DECWRL]



To summarize...

- Lots of hardware parallelism available
  - can accommodate approx. 50 pentiums on one die in few years

However,

- Conventional architectures and compilation
  - cannot expose enough parallelism in applications
  - even the "superb" model yields an ILP < 10 on average
- Need for new architectures and compilation techniques!

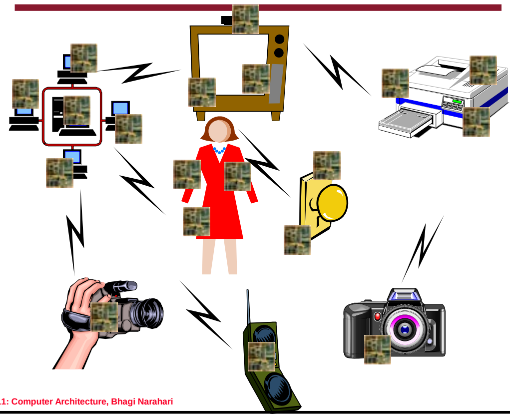
Emerging Architecture Directions

- ILP Architectures: This has been the focus of our discussions !
- ILP Wall leads to Multithreaded Processors
  - Multi-Core Processors
- Reconfigurable Processors—better for special purpose applications
  - let compiler handle everything
  - no commitment to a particular architecture
  - compiler generates architecture and code for it
  - Example: FPGA based processors

What "applications" have we considered ?

- Focus has been on processor design for general purpose computing
- Problems encountered during design of processors for general purpose computing
  - Workstations, no power limitation, no size limitation…sometimes cost not an issue to begin with

What about Special Purpose computing – the embedded processor



Glimpse into alternate approaches

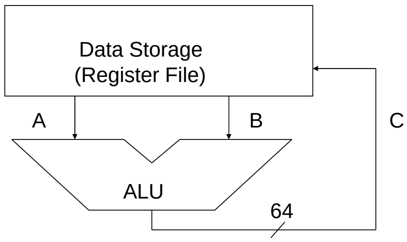
- Reconfigurable Architectures?
  - We have looked at fixed ISA and fixed datapath/logic processors..
  - Can we design architectures that can be reconfigured to meet the application requirements?
    - What new problems/challenges?
    - Embedded Systems: What ? Challenges
  - Field Programmable Gate Arrays (FPGA) as an example of reconfigurable architectures
- Embedded Systems
  - What?
  - Challenges in design
    - What do we need to do differently from what we have studied thus far

- overview of Reconfigurable computing and FPGAs
  - FPGAs are the enabling technology today
- Overview of embedded systems design issues
  - Want to learn more – take CS 297/CS 190

What is Reconfigurable Computing?

- Computation using hardware that can adapt at the logic level to solve specific problems
- Why is this interesting?
  - Some applications are poorly suited to microprocessor.
  - VLSI “explosion” provides increasing resources.
  - Hardware/Software codesign
  - Relatively new research area.

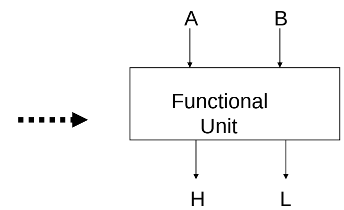
Microprocessor-based Systems



- Generalized to perform many functions well.
- Operates on fixed data sizes.
- Inherently sequential.

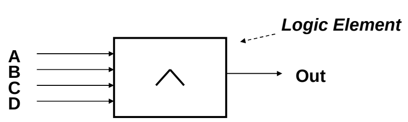
Reconfigurable Computing

```
If (A > B) {
  H = A;
  L = B;
}
Else {
  H = B;
  L = A;
}
```



- Create specialized hardware for each application.
- Functional units optimized to perform a special task.

Reconfigurable Hardware

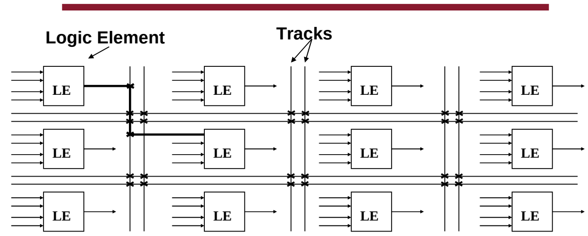


$A \wedge B \wedge C \wedge D = out$

- Each logic element operates on four one-bit inputs.
- Output is one data bit.
- Can perform <u>any</u> boolean function of four inputs

$2^{(2^4)}$ = 64K functions!

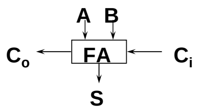
Field-Programmable Gate Array (FPGA)



- Each *logic element* outputs one data bit.
- Interconnect programmable between elements.
- Interconnect *tracks* grouped into channels.

Two Bit Adder

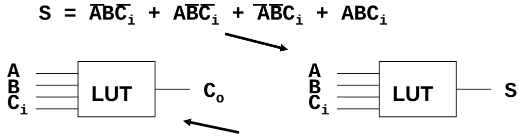
Made of Full Adders



A+B = D

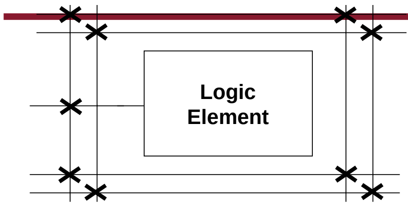
Logic synthesis tool reduces circuit to SOP form

$$S = \overline{A}B\overline{C}_i + A\overline{B}\overline{C}_i + \overline{A}\overline{B}C_i + ABC_i$$



$$C_o = \overline{A}BC_i + A\overline{B}C_i + AB\overline{C}_i + ABC_i$$

FPGA Architecture Issues

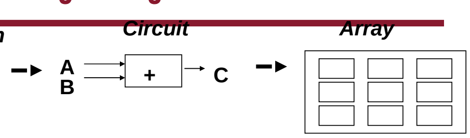


- Need to explore architectural issues.
- How much functionality should go in a logic element?
- How many routing tracks per channel?
- Switch "population"?
- Cost of reconfiguration

Translating a Design to an FPGA

C program

.
.
C = A+B
.



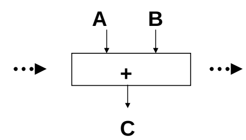
- CAD to translate circuit from text description to physical implementation well understood.
- CAD to translate from C program to circuit not well understood.
- Very difficult for application designers to successfully write high-performance applications

Need for design automation!

High-level Compilers

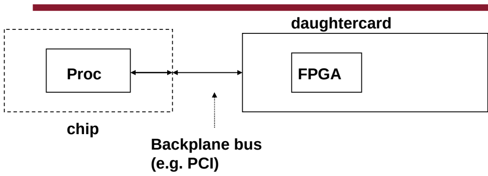
- Difficult to estimate hardware resources.
- Some parts of program more appropriate for processor (hardware/software codesign).
- Compiler must <u>parallelize</u> computation across many resources.
- Engineers like to write in C rather than pushing little blocks around.

C = A+B

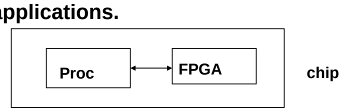



```
for (i = 0; i<n, i++)
{
  .
  .
}
```

Processor + FPGA Three possibilities



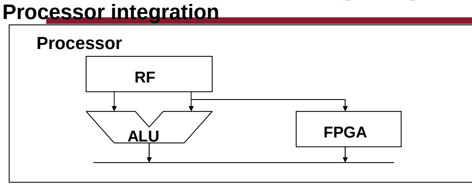
1. FPGA serves as coprocessor for data intensive applications.



2. FPGA serves as embedded computer for low latency transfer. *"Reconfigurable Functional Unit"*

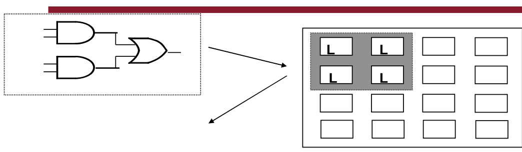
Processor + FPGA (cont..)

3. Processor integration



- **FPGA logic embedded inside processor.**
- **A number of problems with 2 and 3.**
  - **Process technology an issue.**
  - **ALU much faster than FPGA generally.**
  - **FPGA much faster than the entire processor.**

Dynamic Reconfiguration



- **What if I want to exchange part of the design in the device with another piece?**
- **Need to create architectures and software to incrementally change designs.**
- **Effectively a "configuration cache"**

Examples: encryption, filtering.

Dynamic Reconfiguration: Challenges ?

- Ability to change the configuration/functionality at run-time
  - Different local configurations can be thought of as instructions
  - Minimizing the number and size of instructions a key to successfully achieving efficient design
- Resources must be directed to do different things at different times through instructions.
- What is the overhead of reconfiguration ?
  - Is it worth it ?
- Do we reconfigure during run-time or statically ?
- Partial reconfigurability: reconfigure part of the logic while keeping the rest running
  - Emerging designs will support this model ?
- What applications benefit from this dynamic reconfigurability ?
- What software challenges are presented ?

Definition – Hardware/Software Co-Design

A design methodology supporting the cooperative and concurrent development of hardware and software (co-specification, co-development, and co-verification) in order to achieve shared functionality and performance goals for a combined system[1].

+ economic goals

1. Gupta, R. and De Micheli, G., "Hardware-Software Cosynthesis for Digital Systems," *IEEE Design & Test of Computers*, September 1993, pp. 29-41.

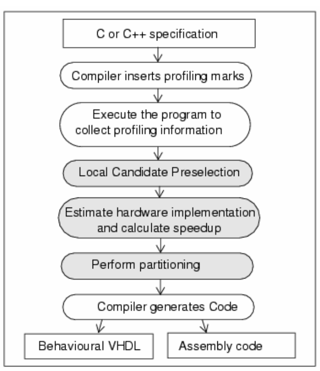
Objective

The target is to develop a methodology for performing hardware and software development, fabrication and support cost modeling concurrent with hardware/software co-design.

- •not possible to put everything into hardware due to resource limitations
- •Some things done better in hardware if we can get hardware configured to the application

Partitioning Analysis

- **Result of compilation is synthesizable HDL and assembly code for the processor**
- **Compiler profiler determines dependence and rough performance estimates**



Embedded Systems

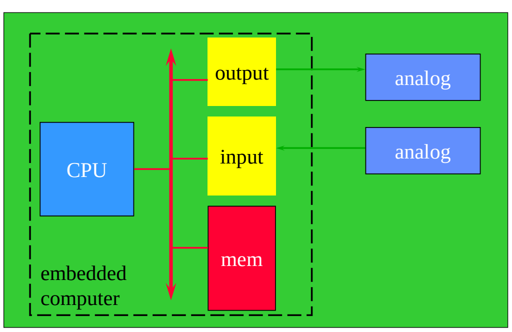
Definition: Embedded System

- **Embedded system**: any device that includes a programmable computer but is not itself a general-purpose computer.
- Take advantage of application characteristics to optimize the design:
  - don't need all the general-purpose bells and whistles.
  - Constrained system resources
  - Minimized human-machine interface (if at all)
  - Singly-focused application that runs when power is applied and terminates when power source is turned off or depleted.

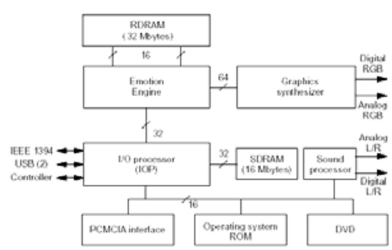
Modern Embedded Systems

- Personal digital assistant (PDA).
- Consumer electronics (e.g. digital cameras and household appliances)
- Cell phone
- Automobile engines, fuel control, etc.
- Global Positioning System (GPS) units
- Printers
- Home automation systems
- Manufacturing plants – process control

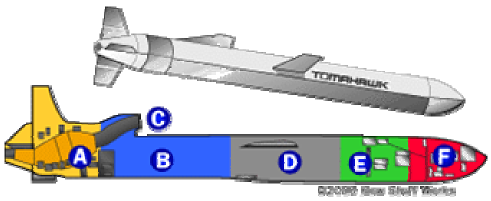
Embedding a computer



Recognize This System?



Cruise Missile Guidance



Examples: Minimized Human-Machine Interface

Singly-Focused Application

- This Global Positioning System (GPS) module receives a signal from a satellite and calculates its geographic position.
- It may be used as a component in a larger embedded system application.
- Notice…no on/off switches!!

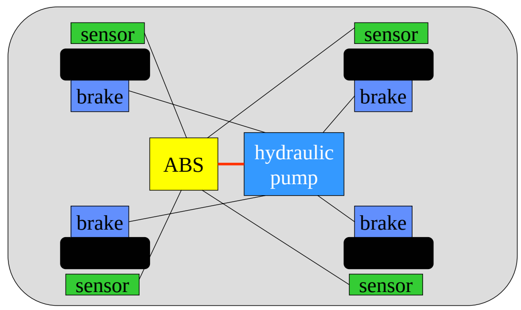
A little history

- Automobiles used microprocessor-based engine controllers starting in 1970's.
  - Control fuel/air mixture, engine timing, etc.
  - Multiple modes of operation: warm-up, cruise, hill climbing, etc.
  - Provides lower emissions, better fuel efficiency.
- First microprocessor was Intel 4004 in early 1970's
- What types of processors account for over 95% of all processors sold today ?

BMW 850i brake and stability control system

- Anti-lock brake system (ABS): pumps brakes to reduce skidding.
- Automatic stability control (ASC+T): controls engine to improve stability.
- ABS and ASC+T communicate.
  - ABS was introduced first---needed to interface to existing ABS module.
- Action based on data collected in real-time from sensors
  - Note need to integrate sensors into your system!

BMW 850i, cont'd.



Characteristics of embedded systems

- Sophisticated functionality
  - Often run complex algorithms; eg. cell phones
- Real-time operation.
  - Hard real-time constraints = system fails if time deadlines are not met…(ABS)
- Low manufacturing cost – mass market items
  - Simple processors; small memory, microcontrollers, DSPs
- Low power.
  - Battery powered devices; battery size
- Designed to tight deadlines by small teams.

Challenges in embedded system design

- How much hardware do we need?
  - How big is the CPU? Memory?
- How do we meet our deadlines?
  - Faster hardware or smarter software?
- How do we minimize power?
  - Turn off unnecessary logic? Reduce memory accesses?

Program design and analysis for Embedded Systems

- Optimizing for execution time.
- Optimizing for energy/power.
- Optimizing for program size.

Energy/power optimization

- **Energy**: ability to do work.
  - Most important in battery-powered systems.
- **Power**: energy per unit time.
  - Important even in wall-plug systems---power becomes heat.

Power Equation

$$P_{AVG} = \tfrac{1}{2} N_G f_{clk} C_L V_{DD}^2$$

- P_{AVG} - the average power consumed by the gates
- N_G - the number of gates that transition
- f_{clk} - the frequency of the system clock
- C_L - the average capacitive load per gate
- V_{DD} - the supply voltage

Considerations

- Which techniques are appropriate for incorporation into a compiler?
  - Code Optimization
  - Clock Gating
  - Voltage Scaling
  - Bit Correlation
  - Memory power consumption
- What other benefits can be derived from these techniques?
  - Heat and component reliability
  - EMI noise reduction

Issues in Compiling for Embedded Systems

- Code Generation for Specialized Architecture
- Code size
  - Using techniques for performance optimizations, such as loop unrolling etc., can increase code size
- Timing requirements
  - To get precise timing may need to use assembly language
  - Not always "fast as you can" – may need minimum time, and duration
- Energy/Power optimization
  - Can we control power through software??
  - Instruction power – use of low power instructions
  - Dynamic voltage scaling
  - Memory power optimization
    - Placement of data
    - Dynamic power control of memory modules
    - For i=1 to N A[i]=A[i}*2; For j=1 to N B[i]=B[i]+10;

Key Insights: Literature

- Do all type of ALU instructions consume same amount of power ?
  - Run different type of instructions and collect power numbers
  - Observed that add/sub take much less than multiply
  - Try to replace multiply instructions with series of additions and shifts (strength reduction)
  - However, care must be taken since ***time penalty incurred can offset savings in energy***!

Key Insights: Memory

- Do number of accesses to memory matter
  - Major impact on timing and therefore energy
- Does location in memory play a role ?
  - Effect on number of memory modules that need to be "active"
  - **Placing data into memory can be used to switch memory modules on or off and have big savings in power** -- *Levy, Crilly, Narahari, 2000*

Optimizing for program size

- Goal:
  - reduce hardware cost of memory;
  - reduce power consumption of memory units.
- Two opportunities:
  - data;
  - instructions.

Data size minimization

- Reuse constants, variables, data buffers in different parts of code.
  - Requires careful verification of correctness.
- Generate data using instructions.
- May need to limit amount of optimization
  - Example of loop unrolling

Reducing code size

- Avoid function inlining.
- Choose CPU with compact instructions.
- Use specialized instructions where possible.

Adding logic to a board

- Programmable logic devices (PLDs) provide low/medium density logic.
- Field-programmable gate arrays (FPGAs) provide more logic and multi-level logic.
- Application-specific integrated circuits (ASICs) are manufactured for a single purpose.

What is an SoC?

- A System on a Chip is a collection of components that are designed as a system and implemented in a fashion similar to that of an Application Specific Integrated Circuit (ASIC)
- The goal is to pack as much functionality into a single die as possible

Summary

- **Embedded computers are all around us.**
  - Many systems have complex embedded hardware and software.
- **Embedded systems pose many design challenges: design time, deadlines, power, etc.**
- **Relevance to Software designers?**
  - Trend is towards software development environments
    - May no longer need sophisticated hardware designers to build embedded systems
- **More on Embedded Systems – take CS297 in Spring 2009**

Goodbye to CS 211

- Computer Architecture: key components and interplay between hardware and software
- Performance of application in terms of architecture features
- Improving performance via new classes of processors
  - Instruction level parallelism (ILP)
    - Superscalar and EPIC
  - ILP Wall leads to Multi-Core Processors
    - Multiprocessing on a chip
- Impact of memory organization on program performance
- Role of compiler
- Conclusions ??
  - Many parameters to choose from; application characteristics need to be taken into account

Course Trivia...

- Project 2 due this week
- Exam 2 next Tuesday
  - Focus on material after mid-term
    - But need to remember enough from first part of the course
  - Similar format to Exam 1
    - Multiple choice, short answers, and some detailed analysis
- Project 3 due December 9th
  - One set of experiments per team
  - Each team member writes their own report
    - Yes, you can reach different conclusions with the same data!