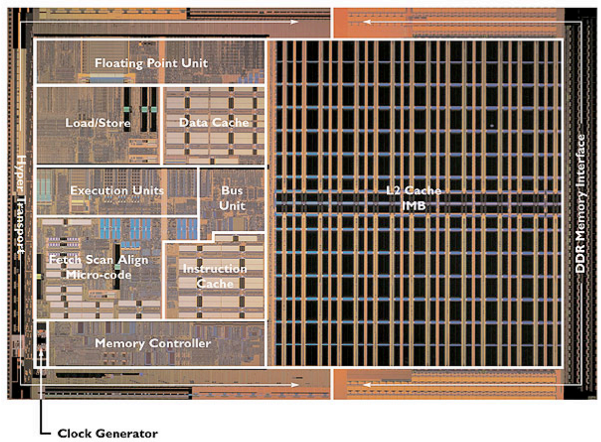
378: Machine Organization and Assembly Language

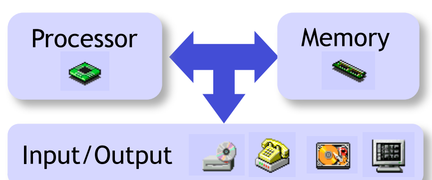
Fall 2007



Luis Ceze

What is computer architecture about?

- Computer architecture is the study of building computer systems.



- CSE378 is roughly split into three parts.
  — The first third discusses instruction set architectures—the bridge between hardware and software.
  — Next, we introduce more advanced processor implementations. The focus is on pipelining, which is one of the most important ways to improve performance.
  — Finally, we talk about memory systems, I/O, and how to connect it all together.

Why should you care?

- It is interesting.
  - — You will learn how a processor actually works!

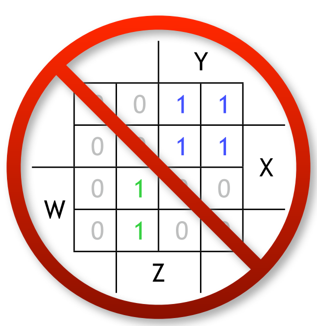
- It will help you be a better programmer.
  - Understanding how your program is translated to assembly code lets you reason about correctness and performance.
  - Demystify the seemingly arbitrary (*e.g.,* bus errors, segmentation faults)

- Many cool jobs require an understanding of computer architecture.
  - The cutting edge is often pushing computers to their limits.
  - Supercomputing, games, portable devices, etc.

- Computer architecture illustrates many fundamental ideas in computer science
  - Abstraction, caching, and indirection are CS staples

CSE370 vs. CSE378

- This class expands upon the computer architecture material from the last few weeks of CSE370, and we rely on many other ideas from CS370.
  - — Understanding binary, hexadecimal and two's-complement numbers is still important.
  - — Devices like multiplexers, registers and ALUs appear frequently. You should know what they do, but not necessarily how they work.
  - — Finite state machines and sequential circuits will appear again.
- We do *not* spend time with logic design topics like Karnaugh maps, Boolean algebra, latches and flip-flops.



Who we are

- *Lecturer*:
  Prof. Luis Ceze

- *Teaching Assistants, Lab Assistants*:
  Joseph Devietti (TA)
  Anindita Mitra (TA)
  Shen-Hui Lee (SLA)
  Colin Bayer (SLA)

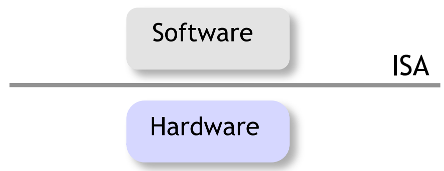
Administrivia

- The textbook provides the most comprehensive coverage
  — *Computer Organization and Design*, Patterson and Hennessy, 3rd Edition

- Lectures will present course material
- Sections will clarify course material and homeworks
- Grading:
  — lab assignments: 35%
  — homeworks: 20%
  — midterm: 15%
  — final: 25%
  — participation: 5%

- Getting in touch with us: cs378@cs, cse378-tas@cs, course Wiki
- Course webpage:
  http://www.cs.washington.edu/education/courses/378/07au/

Instruction set architectures



- Interface between hardware and software
  — abstraction: hide HW complexity from the software through a set of simple operations and devices

  `add, mul, and, lw, ...`

MIPS

- In this class, we'll use the MIPS instruction set architecture (ISA) to illustrate concepts in assembly language and machine organization
  – Of course, the concepts are not MIPS-specific
  – MIPS is just convenient because it is real, yet simple (unlike x86)

- The MIPS ISA is still used in many places today. Primarily in embedded systems, like:
  – Various routers from Cisco
  – Game machines like the Nintendo 64 and Sony Playstation 2

From C to Machine Language

High-level language (C)

`a = b + c;`

Compiler

Assembly Language (MIPS)

`add $16, $17, $18`

Assembler

Binary Machine Language (MIPS)

`0101011101010110 1...`

What you will need to learn soon

- You must become “fluent” in MIPS assembly:
  — Translate from C to MIPS and MIPS to C

- Example problem: Write a recursive function

  Here is a function pow that takes two arguments (n and m, both 32-bit numbers) and returns n^m (i.e., n raised to the m^{th} power).

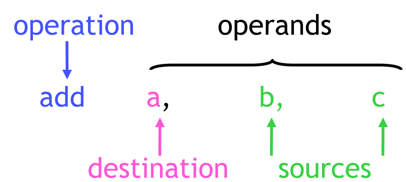
```
int
pow(int n, int m) {
  if (m == 1)
    return n;
  return n * pow(n, m-1);
}
```

  Translate this into a MIPS assembly language function.

MIPS: register-to-register, three address

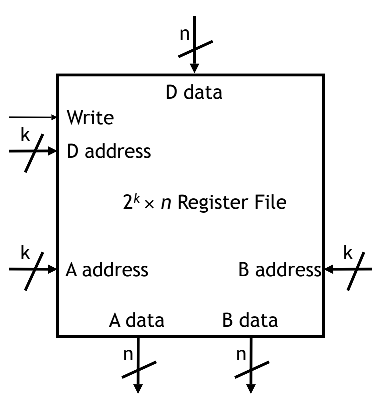
- MIPS is a register-to-register, or load/store, architecture.
  - The destination and sources must all be registers.
  - Special instructions, which we'll see soon, are needed to access main memory.

- MIPS uses three-address instructions for data manipulation.
  - Each ALU instruction contains a destination and two sources.
  - For example, an addition instruction (a = b + c) has the form:



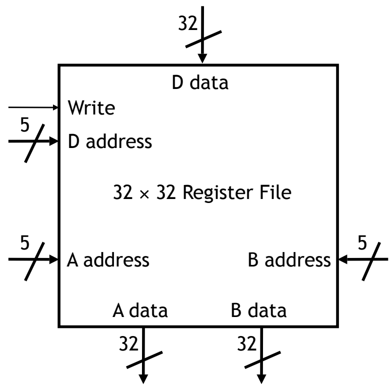
Register file review

- Here is a block symbol for a general $2^k \times n$ register file.
  - If Write = 1, then D data is stored into D address.
  - You can read from two registers at once, by supplying the A address and B address inputs. The outputs appear as A data and B data.
- Registers are clocked, sequential devices.
  - We can read from the register file at any time.
  - Data is written only on the positive edge of the clock.



MIPS register file

- MIPS processors have 32 registers, each of which holds a 32-bit value.
  - Register addresses are 5 bits long.
  - The data inputs and outputs are 32-bits wide.
- More registers might seem better, but there is a limit to the goodness.
  - It's more expensive, because of both the registers themselves as well as the decoders and muxes needed to select individual registers.
  - Instruction lengths may be affected, as we'll see in the future.



MIPS register names

- MIPS register names begin with a $. There are two naming conventions:
  - By number:

    $0 $1 $2   … $31

  - By (mostly) two-character names, such as:

    $a0-$a3 $s0-$s7 $t0-$t9 $sp $ra

- Not all of the registers are equivalent:
  - E.g., register $0 or $zero always contains the value 0
    - (go ahead, try to change it)
- Other registers have special uses, by convention:
  - E.g., register $sp is used to hold the "stack pointer"
- You have to be a little careful in picking registers for your programs.

Basic arithmetic and logic operations

- The basic integer arithmetic operations include the following:

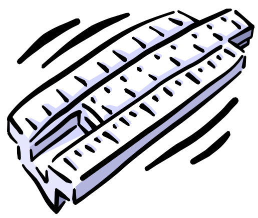
add sub mul div

- And here are a few logical operations:

and or xor

- Remember that these all require three register operands; for example:

```
add  $t0, $t1, $t2      # $t0 = $t1 + $t2
mul  $s1, $s1, $a0      # $s1 = $s1 x $a0
```



Larger expressions

- More complex arithmetic expressions may require multiple operations at the instruction set level.

$$t0 = (t1 + t2) \times (t3 - t4)$$

```
add  $t0, $t1, $t2     # $t0 contains $t1 + $t2
sub  $s0, $t3, $t4     # Temporary value $s0 = $t3 - $t4
mul  $t0, $t0, $s0     # $t0 contains the final product
```

- Temporary registers may be necessary, since each MIPS instructions can access only two source registers and one destination.
  - In this example, we could re-use $t3 instead of introducing $s0.
  - But be careful not to modify registers that are needed again later.

Immediate operands

- The ALU instructions we've seen so far expect register operands. How do you get data into registers in the first place?
  - Some MIPS instructions allow you to specify a signed constant, or "immediate" value, for the second source instead of a register. For example, here is the immediate add instruction, addi:

```
addi  $t0, $t1, 4        # $t0 = $t1 + 4
```

  - Immediate operands can be used in conjunction with the $zero register to write constants into registers:

```
addi  $t0, $0, 4         # $t0 = 4
```

- MIPS is still considered a load/store architecture, because arithmetic operands cannot be from arbitrary memory locations. They must either be registers or constants that are embedded in the instruction.

A more complete example

- What if we wanted to compute the following?

$$1 + 2 + 3 + 4$$

We need more space!

- Registers are fast and convenient, but we have only 32 of them, and each one is just 32-bits wide.
  - That's not enough to hold data structures like large arrays.
  - We also can't access data elements that are wider than 32 bits.
- We need to add some main memory to the system!
  - RAM is cheaper and denser than registers, so we can add lots of it.
  - But memory is also significantly slower, so registers should be used whenever possible.
- In the past, using registers wisely was the programmer's job.
  - For example, C has a keyword "register" that marks commonly-used variables which should be kept in the register file if possible.
  - However, modern compilers do a pretty good job of using registers intelligently and minimizing RAM accesses.

General hints to reach CSE378 nirvana

- **Remember the big picture.**
  What are we trying to accomplish, and why?
- **Read the textbook.**
  It's clear, well-organized, and well-written. The diagrams can be complex, but are worth studying. Work through the examples and try some exercises on your own. Read the "Real Stuff" and "Historical Perspective" sections.
- **Talk to each other.**
  You can learn a lot from other CSE378 students, both by asking and answering questions. Find some good partners for the homeworks/labs (but make sure you all understand what's going on).
- **Help us help you.**
  Come to lectures, sections and office hours. Send email or post on the mailing list/Wiki. Ask lots of questions! Check out the web page.