RISC, CISC, and ISA Variations

Prof. Hakim Weatherspoon
CS 3410, Spring 2015
Computer Science
Cornell University

See P&H Appendix 2.16 – 2.18, and 2.21
Announcements

There is a Lab Section this week, C-Lab2

Project1 (PA1) is due next Monday, March 9th

Prelim today

Starts at **7:30pm** sharp

Go to location based on netid

[a-g]* → MRS146: Morrison Hall 146
[h-l]* → RRB125: Riley-Robb Hall 125
[m-n]* → RRB105: Riley-Robb Hall 105
[o-s]* → MVRG71: M Van Rensselaer Hall G71
[t-z]* → MVRG73: M Van Rensselaer Hall G73
Announcements

Prelim1 today:

- Time: We will start at 7:30pm sharp, so come early
- Location: on previous slide
- Closed Book
  - Cannot use electronic device or outside material
- Practice prelims are online in CMS

Material covered everything up to end of this week

- Everything up to and including data hazards
- Appendix B (logic, gates, FSMs, memory, ALUs)
- Chapter 4 (pipelined [and non] MIPS processor with hazards)
- Chapters 2 (Numbers / Arithmetic, simple MIPS instructions)
- Chapter 1 (Performance)
- HW1, Lab0, Lab1, Lab2, C-Lab0, C-Lab1
Big Picture: Where are we now?

- **IF/ID**
  - Instruction Fetch
  - New pc
  - Inst

- **ID/EX**
  - Instruction Decode
  - Extend
  - Detect hazard
  - Control

- **EX/MEM**
  - Forward unit
  - Execute
  - Compute jump/branch targets

- **MEM/WB**
  - Write-Back
  - Memory
  - Addr
  - D
  - M

- **alu**
  - Compute jump/branch targets
  - Forward unit

- **register file**
  - Extend
  - Instruction Decode

- **memory**
  - New pc
  - Inst
  - Instruction Fetch
Big Picture: Where are we going?

```
int x = 10;
x = 2 * x + 15;
```

```
addi r5, r0, 10  \Rightarrow r5 = r0 + 10
muli r5, r5, 2  \Rightarrow r5 = r5 << 1 #r5 = r5 * 2
addi r5, r5, 15  \Rightarrow r5 = r15 + 15
```

```
00100000000001010000000000001010
00000000000001010010100001000000
00100001010010100000000000001111
```

```
op = addi r0 r5 10
```

```
op = addi r5 r5 15
```

```
op = r-type r5 r5 shamt=1 func=sll
```

C

compiler

MIPS

assembly

assembler

machine

code

CPU

Circuits

Gates

Transistors

Silicon
int x = 10;
x = 2 * x + 15;

C compiler

MIPS assembly

C

addi r5, r0, 10
muli r5, r5, 2
addi r5, r5, 15

MIPS assembly

machine code

00100000000001010000000000001010
00000000000001010010100001000000
00100000101001010000000000001111

C

High Level Languages

assembly

Instruction Set Architecture (ISA)

C compiler

MIPS assembly

C

addi r5, r0, 10
muli r5, r5, 2
addi r5, r5, 15

MIPS assembly

machine code

00100000000001010000000000001010
00000000000001010010100001000000
00100000101001010000000000001111

C

High Level Languages

assembly

Instruction Set Architecture (ISA)
Goals for Today

Instruction Set Architectures
• ISA Variations, and CISC vs RISC

Next Time
• Program Structure and Calling Conventions
Is MIPS the only possible instruction set architecture (ISA)?
What are the alternatives?
Instruction Set Architecture Variations

ISA defines the permissible instructions
Accumulators

- Early stored-program computers had **one** register!
- One register is two registers short of a MIPS instruction!
- Requires a memory-based operand-addressing mode
  - Example Instructions: `add 200`
    - Add the accumulator to the word in memory at address 200
    - Place the sum back in the accumulator

Intel 8008 in 1972 was an accumulator

EDSAC (Electronic Delay Storage Automatic Calculator) in 1949
Next step, more registers...

- Dedicated registers
  - E.g. indices for array references in data transfer instructions, separate accumulators for multiply or divide instructions, top-of-stack pointer.

- Extended Accumulator
  - One operand may be in memory (like previous accumulators).
  - Or, all the operands may be registers (like MIPS).

Intel 8086
“extended accumulator”
Processor for IBM PCs
Next step, more registers...

- General-purpose registers
  - Registers can be used for any purpose
  - E.g. MIPS, ARM, x86

- Register-memory architectures
  - One operand may be in memory (e.g. accumulators)
  - E.g. x86 (i.e. 80386 processors)

- Register-register architectures (aka load-store)
  - All operands must be in registers
  - E.g. MIPS, ARM
The number of available registers greatly influenced the instruction set architecture (ISA)

<table>
<thead>
<tr>
<th>Machine</th>
<th>Num General Purpose Registers</th>
<th>Architectural Style</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDSAC</td>
<td>1</td>
<td>Accumulator</td>
<td>1949</td>
</tr>
<tr>
<td>IBM 701</td>
<td>1</td>
<td>Accumulator</td>
<td>1953</td>
</tr>
<tr>
<td>CDC 6600</td>
<td>8</td>
<td>Load-Store</td>
<td>1963</td>
</tr>
<tr>
<td>IBM 360</td>
<td>18</td>
<td>Register-Memory</td>
<td>1964</td>
</tr>
<tr>
<td>DEC PDP-8</td>
<td>1</td>
<td>Accumulator</td>
<td>1965</td>
</tr>
<tr>
<td>DEC PDP-11</td>
<td>8</td>
<td>Register-Memory</td>
<td>1970</td>
</tr>
<tr>
<td>Intel 8008</td>
<td>1</td>
<td>Accumulator</td>
<td>1972</td>
</tr>
<tr>
<td>Motorola 6800</td>
<td>2</td>
<td>Accumulator</td>
<td>1974</td>
</tr>
<tr>
<td>DEC VAX</td>
<td>16</td>
<td>Register-Memory, Memory-Memory</td>
<td>1977</td>
</tr>
<tr>
<td>Intel 8086</td>
<td>1</td>
<td>Extended Accumulator</td>
<td>1978</td>
</tr>
<tr>
<td>Motorola 6800</td>
<td>16</td>
<td>Register-Memory</td>
<td>1980</td>
</tr>
<tr>
<td>Intel 80386</td>
<td>8</td>
<td>Register-Memory</td>
<td>1985</td>
</tr>
<tr>
<td>ARM</td>
<td>16</td>
<td>Load-Store</td>
<td>1985</td>
</tr>
<tr>
<td>MIPS</td>
<td>32</td>
<td>Load-Store</td>
<td>1985</td>
</tr>
<tr>
<td>HP PA-RISC</td>
<td>32</td>
<td>Load-Store</td>
<td>1986</td>
</tr>
<tr>
<td>SPARC</td>
<td>32</td>
<td>Load-Store</td>
<td>1987</td>
</tr>
<tr>
<td>PowerPC</td>
<td>32</td>
<td>Load-Store</td>
<td>1992</td>
</tr>
<tr>
<td>DEC Alpha</td>
<td>32</td>
<td>Load-Store</td>
<td>1992</td>
</tr>
<tr>
<td>HP/Intel IA-64</td>
<td>128</td>
<td>Load-Store</td>
<td>2001</td>
</tr>
<tr>
<td>AMD64 (EMT64)</td>
<td>16</td>
<td>Register-Memory</td>
<td>2003</td>
</tr>
</tbody>
</table>
The number of available registers greatly influenced the instruction set architecture (ISA)

<table>
<thead>
<tr>
<th>Machine</th>
<th>Number of general-purpose registers</th>
<th>Architectural style</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDSAC</td>
<td>1</td>
<td>Accumulator</td>
<td>1949</td>
</tr>
<tr>
<td>IBM 701</td>
<td>1</td>
<td>Accumulator</td>
<td>1953</td>
</tr>
<tr>
<td>CDC 6600</td>
<td>8</td>
<td>Load-store</td>
<td>1963</td>
</tr>
<tr>
<td>IBM 360</td>
<td>16</td>
<td>Register-memory</td>
<td>1964</td>
</tr>
<tr>
<td>DEC PDP-8</td>
<td>1</td>
<td>Accumulator</td>
<td>1965</td>
</tr>
<tr>
<td>DEC PDP-11</td>
<td>8</td>
<td>Register-memory</td>
<td>1970</td>
</tr>
<tr>
<td>Intel 8008</td>
<td>1</td>
<td>Accumulator</td>
<td>1972</td>
</tr>
<tr>
<td>Motorola 6800</td>
<td>2</td>
<td>Accumulator</td>
<td>1974</td>
</tr>
<tr>
<td>DEC VAX</td>
<td>16</td>
<td>Register-memory, memory-memory</td>
<td>1977</td>
</tr>
<tr>
<td>Intel 8086</td>
<td>1</td>
<td>Extended accumulator</td>
<td>1978</td>
</tr>
<tr>
<td>Motorola 68000</td>
<td>16</td>
<td>Register-memory</td>
<td>1980</td>
</tr>
<tr>
<td>Intel 80386</td>
<td>8</td>
<td>Register-memory</td>
<td>1985</td>
</tr>
<tr>
<td>ARM</td>
<td>16</td>
<td>Load-store</td>
<td>1985</td>
</tr>
<tr>
<td>MIPS</td>
<td>32</td>
<td>Load-store</td>
<td>1985</td>
</tr>
<tr>
<td>HP PA-RISC</td>
<td>32</td>
<td>Load-store</td>
<td>1986</td>
</tr>
<tr>
<td>SPARC</td>
<td>32</td>
<td>Load-store</td>
<td>1987</td>
</tr>
<tr>
<td>PowerPC</td>
<td>32</td>
<td>Load-store</td>
<td>1992</td>
</tr>
<tr>
<td>DEC Alpha</td>
<td>32</td>
<td>Load-store</td>
<td>1992</td>
</tr>
<tr>
<td>HP/Intel IA-64</td>
<td>128</td>
<td>Load-store</td>
<td>2001</td>
</tr>
<tr>
<td>AMD64 (EMT64)</td>
<td>16</td>
<td>Register-memory</td>
<td>2003</td>
</tr>
</tbody>
</table>
Next Goal

How to compute with limited resources?

i.e. how do you design your ISA if you have limited resources?
People programmed in assembly and machine code!

- Needed as many addressing modes as possible
- Memory was (and still is) slow

CPUs had relatively few registers

- Register’s were more “expensive” than external mem
- Large number of registers requires many bits to index

Memories were small

- Encouraged highly encoded microcodes as instructions
- Variable length instructions, load/store, conditions, etc
People programmed in assembly and machine code!

E.g. x86
- > 1000 instructions!
  - 1 to 15 bytes each
  - E.g. dozens of add instructions
- operands in dedicated registers, general purpose registers, memory, on stack, ...
  - can be 1, 2, 4, 8 bytes, signed or unsigned
- 10s of addressing modes
  - e.g. Mem[segment + reg + reg*scale + offset]

E.g. VAX
- Like x86, arithmetic on memory or registers, but also on strings, polynomial evaluation, stacks/queues, ...
Complex Instruction Set Computers (CISC)
The number of available registers greatly influenced the instruction set architecture (ISA)

*Complex Instruction Set Computers* were very complex

- Necessary to reduce the number of instructions required to fit a program into memory.
- However, also greatly increased the complexity of the ISA as well.
Next Goal

How do we reduce the complexity of the ISA while maintaining or increasing performance?
Reduced Instruction Set Computer (RISC)

John Cock

- IBM 801, 1980 (started in 1975)
- Name 801 came from the bldg that housed the project
- Idea: Possible to make a very small and very fast core
- Influences: Known as “the father of RISC Architecture”. Turing Award Recipient and National Medal of Science.
Reduced Instruction Set Computer (RISC)

Dave Patterson

- RISC Project, 1982
- UC Berkeley
- RISC-I: $\frac{1}{2}$ transistors & 3x faster
- Influences: Sun SPARC, namesake of industry

John L. Hennessy

- MIPS, 1981
- Stanford
- Simple pipelining, keep full
- Influences: MIPS computer system, PlayStation, Nintendo
MIPS Design Principles

Simplicity favors regularity
  • 32 bit instructions

Smaller is faster
  • Small register file

Make the common case fast
  • Include support for constants

Good design demands good compromises
  • Support for different type of interpretations/classes
MIPS = Reduced Instruction Set Computer (RISC)
- ≈ 200 instructions, 32 bits each, 3 formats
- all operands in registers
  - almost all are 32 bits each
- ≈ 1 addressing mode: Mem[reg + imm]

x86 = Complex Instruction Set Computer (CISC)
- > 1000 instructions, 1 to 15 bytes each
- operands in dedicated registers, general purpose registers, memory, on stack, ...
  - can be 1, 2, 4, 8 bytes, signed or unsigned
- 10s of addressing modes
  - e.g. Mem[segment + reg + reg*scale + offset]
<table>
<thead>
<tr>
<th>RISC vs CISC</th>
<th>RISC Philosophy</th>
<th>CISC Rebuttal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regularity &amp; simplicity</td>
<td>Leaner means faster</td>
<td>Compilers can be smart</td>
</tr>
<tr>
<td>Optimize the common case</td>
<td></td>
<td>Transistors are plentiful</td>
</tr>
<tr>
<td>Energy efficiency</td>
<td></td>
<td>Legacy is important</td>
</tr>
<tr>
<td>Embedded Systems</td>
<td></td>
<td>Code size counts</td>
</tr>
<tr>
<td>Phones/Tablets</td>
<td></td>
<td>Micro-code!</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Desktops/Servers</td>
</tr>
</tbody>
</table>
ARM Droid vs WinTel

- Android OS on ARM processor
- Windows OS on Intel (x86) processor
The number of available registers greatly influenced the instruction set architecture (ISA)

Complex Instruction Set Computers were very complex
- Necessary to reduce the number of instructions required to fit a program into memory.
- However, also greatly increased the complexity of the ISA as well.

Back in the day... CISC was necessary because everybody programmed in assembly and machine code! Today, CISC ISA’s are still dominant due to the prevalence of x86 ISA processors. However, RISC ISA’s today such as ARM have an ever increasing market share (of our everyday life!). ARM borrows a bit from both RISC and CISC.
How does MIPS and ARM compare to each other?
### MIPS instruction formats

All MIPS instructions are 32 bits long, have 3 formats:

- **R-type**
  - op
  - rs
  - rt
  - rd
  - shamt
  - func
  - 6 bits
  - 5 bits
  - 5 bits
  - 5 bits
  - 5 bits
  - 6 bits

- **I-type**
  - op
  - rs
  - rt
  - immediate
  - 6 bits
  - 5 bits
  - 5 bits
  - 16 bits

- **J-type**
  - op
  - immediate (target address)
  - 6 bits
  - 26 bits
All ARMv7 instructions are 32 bits long, has 3 formats:

**R-type**

<table>
<thead>
<tr>
<th>Field</th>
<th>Bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>opx</td>
<td>4</td>
</tr>
<tr>
<td>op</td>
<td>8</td>
</tr>
<tr>
<td>rs</td>
<td>4</td>
</tr>
<tr>
<td>rd</td>
<td>4</td>
</tr>
<tr>
<td>opx</td>
<td>8</td>
</tr>
<tr>
<td>rt</td>
<td>4</td>
</tr>
</tbody>
</table>

**I-type**

<table>
<thead>
<tr>
<th>Field</th>
<th>Bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>opx</td>
<td>4</td>
</tr>
<tr>
<td>op</td>
<td>8</td>
</tr>
<tr>
<td>rs</td>
<td>4</td>
</tr>
<tr>
<td>rd</td>
<td>4</td>
</tr>
<tr>
<td>immediate</td>
<td>12</td>
</tr>
</tbody>
</table>

**J-type**

<table>
<thead>
<tr>
<th>Field</th>
<th>Bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>opx</td>
<td>4</td>
</tr>
<tr>
<td>op</td>
<td>4</td>
</tr>
<tr>
<td>immediate (target address)</td>
<td>24</td>
</tr>
</tbody>
</table>
ARMv7 Conditional Instructions

- while(i != j) {
  - if (i > j)
    - i -= j;
  - else
    - j -= i;
- }

Loop: BEQ Ri, Rj, End // if "NE" (not equal), then stay in loop

SLT Rd, Rj, Ri // "GT" if (i > j),

BNE Rd, R0, Else // ...

SUB Ri, Ri, Rj // if "GT" (greater than), i = i-j;

J Loop

Else: SUB Rj, Rj, Ri // or "LT" if (i < j)

J Loop // if "LT" (less than), j = j-i;

End:

In MIPS, performance will be slow if code has a lot of branches
while(i != j) {
    if (i > j)
        i -= j;
    else
        j -= i;
}

LOOP: CMP Ri, Rj // set condition "NE" if (i != j)
    // "GT" if (i > j),
    // or "LT" if (i < j)

= ≠ < >  SUBGT Ri, Ri, Rj // if "GT" (greater than), i = i-j;

1 0 1 0  SUBLE Rj, Rj, Ri // if "LE" (less than or equal), j = j-i;

0 1 0 0  BNE loop // if "NE" (not equal), then loop

In ARM, can avoid delay due to Branches with conditional instructions.
ARMv7: Other Cool operations

Shift one register (e.g. Rc) any amount
Add to another register (e.g. Rb)
Store result in a different register (e.g. Ra)

ADD Ra, Rb, Rc LSL #4
Ra = Rb + Rc<<4
Ra = Rb + Rc x 16
ARMv7 Instruction Set Architecture

All ARMv7 instructions are 32 bits long, has 3 formats

Reduced Instruction Set Computer (RISC) properties

- Only Load/Store instructions access memory
- Instructions operate on operands in processor registers
- 16 registers

Complex Instruction Set Computer (CISC) properties

- Autoincrement, autodecrement, PC-relative addressing
- Conditional execution
- Multiple words can be accessed from memory with a single instruction (SIMD: single instr multiple data)
ARMv8 (64-bit) Instruction Set Architecture

All ARMv8 instructions are 64 bits long, has 3 formats

Reduced Instruction Set Computer (RISC) properties

• Only Load/Store instructions access memory
• Instructions operate on operands in processor registers
• 32 registers and r0 is always 0

NO MORE Complex Instruction Set Computer (CISC) properties

• NO Conditional execution
• NO Multiple words can be accessed from memory with a single instruction (SIMD: single instr multiple data)
Instruction Set Architecture Variations

ISA defines the permissible instructions

- **MIPS**: load/store, arithmetic, control flow, ...
- **ARMv7**: similar to MIPS, but more shift, memory, & conditional ops
- **ARMv8 (64-bit)**: even closer to MIPS, no conditional ops
- **VAX**: arithmetic on memory or registers, strings, polynomial evaluation, stacks/queues, ...
- **Cray**: vector operations, ...
- **x86**: a little of everything
Next time

How do we coordinate use of registers?
  Calling Conventions!

PA1 due next Tuesday