COMP-273
Instruction Representation

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Slides from Patterson's 61C

Review (1/2)

- Logical and Shift Instructions
  - Operate on bits individually, unlike arithmetic, which operate on entire word.
  - Use to isolate fields, either by masking or by shifting back and forth.
  - Use shift left logical, `sll`, for multiplication by powers of 2
  - shift right arithmetic, `sra`, close but wrong for divide by powers of 2 (negative numbers get wrong result: e.g., -5 sra 2 bits = -2 vs. $-5 / 2^2 = -5 / 4 = -1$)
- New Instructions:

`and,andi, or,ori, sll,srl,sra`

Review (2/2)

- MIPS Signed v. Unsigned is an "overloaded" term
  - Do/Don't sign extend (lb, lbu)
  - Don't overflow (addu, addiu, subu, multu, divu)
  - Do signed/unsigned compare (slt,slti/sltu,sltiu)

Overview

- Big idea: stored program
  - consequences of stored program
- MIPS instruction format for Add instructions
- MIPS instruction format for Immediate, Data transfer instructions

Big Idea: Stored-Program Concept

- Computers built on 2 key principles:
  1) Instructions are represented as numbers.
  2) Therefore, entire programs can be stored in memory to be read or written just like numbers (data).
- Simplifies SW/HW of computer systems:
  - Memory technology for data also used for programs

Consequence #1: Everything Addressed

- Since all instructions and data are stored in memory as numbers, everything has a memory address: instructions, data words
  - both branches and jumps use these
- C pointers are just memory addresses: they can point to anything in memory
  - Unconstrained use of addresses can lead to nasty bugs; up to you in C; limits in Java
- One register keeps address of instruction being executed: "Program Counter" (PC)
  - Basically a pointer to memory: Intel calls it Instruction Address Pointer, a better name

Consequence #2: Binary Compatibility

- Programs are distributed in binary form
  - Programs bound to specific instruction set
  - Different version for Macintosh and IBM PC
- New machines want to run old programs ("binaries") as well as programs compiled to new instructions
- Leads to instruction set evolving over time
- Selection of Intel 8086 in 1981 for 1st IBM PC is major reason latest PCs still use 80x86 instruction set (Pentium 4); could still run program from 1981 PC today

Instructions as Numbers (1/2)

- Currently all data we work with is in words (32-bit blocks):
  - Each register is a word.
  - `lw` and `sw` both access memory one word at a time.
- So how do we represent instructions?
  - Remember: Computer only understands 1s and 0s, so "`add $t0,$0,$0`" is meaningless.
  - MIPS wants simplicity: since data is in words, make instructions be words too

Instructions as Numbers (2/2)

- One word is 32 bits, so divide instruction word into “fields”.
- Each field tells computer something about instruction.
- We could define different fields for each instruction, but MIPS is based on simplicity, so define 3 basic types of instruction formats:
  - R-format
  - I-format
  - J-format (next lecture)

Instruction Formats

- I-format: used for instructions with immediates, `lw` and `sw` (since the offset counts as an immediate), and the branches (`beq` and `bne`),
  - (but not the shift instructions; later)
- J-format: used for `j` and `jal`
- R-format: used for all other instructions (stands for register format)
- It will soon become clear why the instructions have been partitioned in this way.

R-Format Instructions (1/5)

- Define "fields" of the following number of bits each: 6 + 5 + 5 + 5 + 5 + 6 = 32

6	5	5	5	5	6

- For simplicity, each field has a name:

opcode	rs	rt	rd	shamt	funct

- Important: On these slides and in book, each field is viewed as a 5- or 6-bit unsigned integer, not as part of a 32-bit integer.
  - Consequence: 5-bit fields can represent any number 0-31, while 6-bit fields can represent any number 0-63.

R-Format Instructions (2/5)

- What do these field integer values tell us?
  - `opcode`: partially specifies what instruction it is
    - Note: This number is equal to 0 for all R-Format instructions.
  - `funct`: combined with `opcode`, this number exactly specifies the instruction
  - Question: Why aren't `opcode` and `funct` a single 12-bit field?
    - Answer: We'll answer this later.

R-Format Instructions (3/5)

- More fields:
  - `rs` (Source Register): *generally* used to specify register containing first operand
  - `rt` (Target Register): *generally* used to specify register containing second operand (note that name is misleading)
  - `rd` (Destination Register): *generally* used to specify register which will receive result of computation

R-Format Instructions (4/5)

- Notes about register fields:
  - Each register field is exactly 5 bits, which means that it can specify any unsigned integer in the range 0-31. Each of these fields specifies one of the 32 registers by number.
  - The word "generally" was used because there are exceptions that we'll see later. E.g.,
    - `mult` and `div` have nothing important in the `rd` field since the dest registers are `hi` and `lo`
    - `mfhi` and `mflo` have nothing important in the `rs` and `rt` fields since the source is determined by the instruction

R-Format Instructions (5/5)

- Final field:
  - `shamt`: This field contains the amount a shift instruction will shift by. Shifting a 32-bit word by more than 31 is useless, so this field is only 5 bits (so it can represent the numbers 0-31).
  - This field is set to 0 in all but the shift instructions.
- For a detailed description of field usage for each instruction, see back cover of textbook.

R-Format Example (1/2)

- **MIPS Instruction:**

```
add    $8,$9,$10
```

`opcode` = 0 (look up in table)

`funct` = 32 (look up in table)

`rs` = 9 (first *operand*)

`rt` = 10 (second *operand*)

`rd` = 8 (destination)

`shamt` = 0 (not a shift)

R-Format Example (2/2)

- **MIPS Instruction:**

```
add   $8,$9,$10
```

Decimal/field representation:

0	9	10	8	0	32

Binary/field representation:

000000	01001	01010	01000	00000	100000

hex

hex representation: $012A\ 4020_{hex}$

decimal representation: $19{,}546{,}144_{ten}$

- **Called a Machine Language Instruction**

I-Format Instructions (1/5)

- What about instructions with immediates?
  - 5-bit field only represents numbers up to the value 31: immediates may be much larger than this
  - Ideally, MIPS would have only one instruction format (for simplicity): unfortunately, we need to compromise
- Define new instruction format that is partially consistent with R-format:
  - First notice that, if instruction has immediate, then it uses at most 2 registers.

I-Format Instructions (2/5)

- Define "fields" of the following number of bits each: 6 + 5 + 5 + 16 = 32 bits

6	5	5	16

- Again, each field has a name:

opcode	rs	rt	immediate

- Key Concept: Only one field is inconsistent with R-format. Most importantly, `opcode` is still in same location.

I-Format Instructions (3/5)

- What do these fields mean?
  - `opcode`: same as before except that, since there's no `funct` field, `opcode` uniquely specifies an instruction in I-format
  - This also answers question of why R-format has two 6-bit fields to identify instruction instead of a single 12-bit field: in order to be consistent with other formats.

I-Format Instructions (4/5)

- More fields:
  - `rs`: specifies the *only* register operand (if there is one)
  - `rt`: specifies register which will receive result of computation (this is why it's called the *target* register "rt")

I-Format Instructions (5/5)

- The Immediate Field:
  - `addi`, `slti`, `sltiu`, the immediate is sign-extended to 32 bits. Thus, it's treated as a signed integer.
  - 16 bits ➔ can be used to represent immediate up to 2^{16} different values
  - This is large enough to handle the offset in a typical `lw` or `sw`, plus a vast majority of values that will be used in the `slti` instruction.

I-Format Example (1/2)

- **MIPS Instruction:**

```
addi    $21,$22,-50
```

`opcode` = 8 (look up in table)

`rs` = 22 (register containing operand)

`rt` = 21 (target register)

`immediate` = -50 (by default, this is decimal)

I-Format Example (2/2)

- **MIPS Instruction:**

```
addi    $21,$22,-50
```

Decimal/field representation:

8	22	21	-50

Binary/field representation:

001000	10110	10101	1111111111001110

hexadecimal representation: 22D5 FFCE$_{hex}$

decimal representation: 584,449,998$_{ten}$

I-Format Problems (1/3)

- **Problem 1:**
  - **Chances are that `addi`, `lw`, `sw` and `slti` will use immediates small enough to fit in the immediate field.**
  - **What if too big?**
    - **We need a way to deal with a 32-bit immediate in *any* I-format instruction.**

I-Format Problems (2/3)

- Solution to Problem 1:
  - Handle it in software + new instruction
  - Don't change the current instructions: instead, add a new instruction to help out
- New instruction:

```
lui   register, immediate
```

  - stands for Load Upper Immediate
  - takes 16-bit immediate and puts these bits in the upper half (high order half) of the specified register
  - sets lower half to 0s

I-Format Problems (3/3)

- **Solution to Problem 1 (continued):**
  - **So how does `lui` help us?**
  - **Example:**

```
addi    $t0,$t0, 0xABABCDCD
```

becomes:

```
lui     $at, 0xABAB
ori     $at, $at, 0xCDCD
add     $t0,$t0,$at
```

  - **Now each I-format instruction has only a 16-bit immediate.**
  - **Wouldn't it be nice if the assembler would do this for us automatically?**
    - **Next lecture: pseudoinstructions**

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In conclusion, …

- Simplifying MIPS: Define instructions to be same size as data word (one word) so that they can use the same memory (compiler can use `lw` and `sw`).
- Machine Language Instruction: 32 bits representing a single instruction

R	opcode	rs	rt	rd	shamt	funct
I	opcode	rs	rt	immediate		

- Computer actually stores programs as a series of these 32-bit numbers.