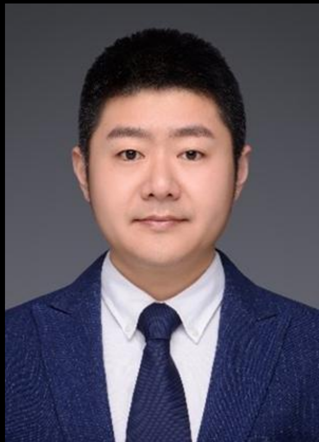

Computer Architecture
（计算机体系结构）

Lecture 5
Introduction to MIPS : Decisions II

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Germany Taking the Autobahn to Autonomy

Review

- Memory is byte-addressable, but **`lw`** and **`sw`** access one word at a time.
- A pointer (used by **`lw`** and **`sw`**) is just a memory address, so we can add to it or subtract from it (using offset).
- A Decision allows us to decide what to execute at run-time rather than compile-time.
- C Decisions are made using conditional statements within **`if`**, **`while`**, **`do while`**, **`for`**.
- MIPS Decision making instructions are the conditional branches: **`beq`** and **`bne`**.
- New Instructions:

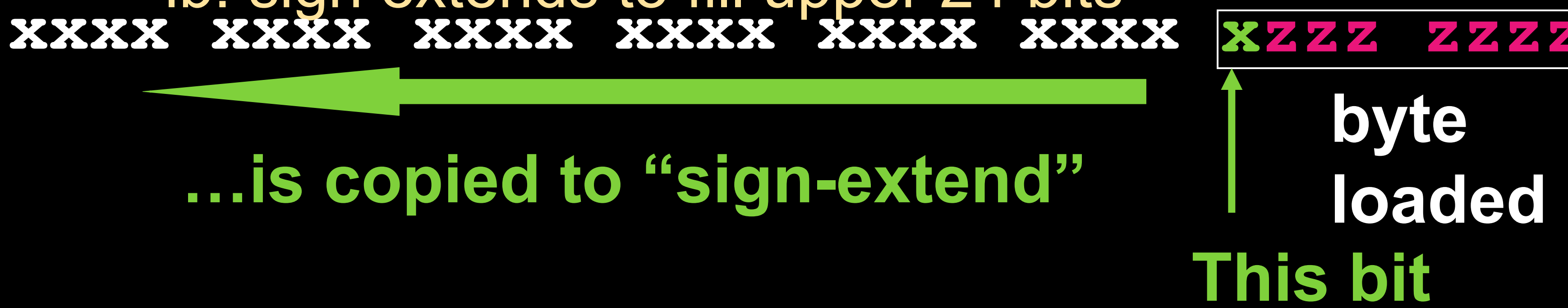
```
lw, sw, beq, bne, j
```

Last time: Loading, Storing bytes 1/2

- In addition to word data transfers (**`lw`**, **`sw`**), MIPS has byte data transfers:
  - load byte: **`lb`**
  - store byte: **`sb`**
- same format as `lw`, `sw`
- E.g., **`lb $s0, 3($s1)`**
  - *contents of memory location with address = sum of "3" + contents of register **`s1`** is copied to the low byte position of register **`s0`**.*

Loading, Storing bytes 2/2

- What do with other 24 bits in the 32 bit register?
  - lb: sign extends to fill upper 24 bits



- Normally don't want to sign extend chars
- MIPS instruction that doesn't sign extend when loading bytes:
  - load byte unsigned: `lbu`

Overflow in Arithmetic (1/2)

- Reminder: Overflow occurs when there is a mistake in arithmetic due to the limited precision in computers.
- Example (4-bit unsigned numbers):

```
  15        1111
+  3      + 0011
----      ------
  18       10010
```

  - But we don't have room for 5-bit solution, so the solution would be `0010`, which is **+2**, and wrong.

Overflow in Arithmetic (2/2)

- Some languages detect overflow (Ada), some don't (C)
- MIPS solution is 2 kinds of arithmetic instructs:
  - These cause overflow to be detected
    - add (`add`)
    - add immediate (`addi`)
    - subtract (`sub`)
  - These do not cause overflow detection
    - add unsigned (`addu`)
    - add immediate unsigned (`addiu`)
    - subtract unsigned (`subu`)
- Compiler selects appropriate arithmetic
  - MIPS C compilers produce `addu, addiu, subu`

Two “Logic” Instructions

- Here are 2 more new instructions
- Shift Left: `sll $s1,$s2,2` `#s1=s2<<2`
  - Store in `$s1` the value from `$s2` shifted 2 bits to the left (they fall off end), inserting 0’s on right; `<<` in C.
  - Before: `0000 0002` $_{hex}$
    `0000 0000 0000 0000 0000 0000 0000 0010` $_{two}$
  - After: `0000 0008` $_{hex}$
    `0000 0000 0000 0000 0000 0000 0000 1000` $_{two}$
  - What arithmetic effect does shift left have?
- Shift Right: `srl` is opposite shift; >>

Loops in C/Assembly (1/3)

- Simple loop in C; `A[]` is an array of `int`s

```
do {  g = g + A[i];
       i = i + j;
} while (i != h);
```

- Rewrite this as:

```
Loop: g = g + A[i];
      i = i + j;
      if (i != h) goto Loop;
```

- Use this mapping:

```
  g,   h,   i,   j, base of A
$s1, $s2, $s3, $s4, $s5
```

Loops in C/Assembly (2/3)

- Final compiled MIPS code:

```
Loop: sll  $t1,$s3,2      # $t1= 4*I
      addu $t1,$t1,$s5    # $t1=addr A+4i
      lw   $t1,0($t1)     # $t1=A[i]
      addu $s1,$s1,$t1    # g=g+A[i]
      addu $s3,$s3,$s4    # i=i+j
      bne  $s3,$s2,Loop   # goto Loop
                          # if i!=h
```

- Original code:

```
Loop: g = g + A[i];
      i = i + j;
      if (i != h) goto Loop;
```

Loops in C/Assembly (3/3)

- There are three types of loops in C:
  - **`while`**
  - **`do… while`**
  - **`for`**
- Each can be rewritten as either of the other two, so the method used in the previous example can be applied to these loops as well.
- Key Concept: Though there are multiple ways of writing a loop in MIPS, the key to decision-making is conditional branch

Inequalities in MIPS (1/4)

- Until now, we've only tested equalities (`==` and `!=` in C). General programs need to test < and > as well.
- Introduce MIPS Inequality Instruction:
  - "Set on Less Than"
  - Syntax: `slt reg1,reg2,reg3`
  - Meaning: `reg1 = (reg2 < reg3);`

```
if (reg2 < reg3)
    reg1 = 1;
else reg1 = 0;
```

Same thing…

"set" means "change to 1",
"reset" means "change to 0".

Inequalities in MIPS (2/4)

- How do we use this? Compile by hand:
  `if (g < h) goto Less; #g:$s0, h:$s1`
- Answer: compiled MIPS code…

```
slt $t0,$s0,$s1 # $t0 = 1 if g<h
bne $t0,$0,Less # goto Less
                # if $t0!=0
                # (if (g<h)) Less:
```

- Register `$0` always contains the value 0, so `bne` and `beq` often use it for comparison after an `slt` instruction.
- A `slt` ➔ `bne` pair means `if(… < …)goto…`

Inequalities in MIPS (3/4)

- Now we can implement <,
  but how do we implement >, ≤ and ≥ ?
- We could add 3 more instructions, but:
  - MIPS goal: Simpler is Better
- Can we implement ≤ in one or more instructions using just `slt` and branches?
  - What about >?
  - What about ≥?

Inequalities in MIPS (4/4)

```
# a:$s0, b:$s1
 slt $t0,$s0,$s1 # $t0 = 1 if a<b
 beq $t0,$0,skip # skip if a >= b
     <stuff>     # do if a<b
 skip:
```

Two independent variations possible:

- Use `slt $t0,$s1,$s0` instead of `slt $t0,$s0,$s1`
- Use `bne` instead of `beq`

Immediates in Inequalities

- There is also an immediate version of `slt` to test against constants: `slti`
  - Helpful in `for` loops

C

```
if (g >= 1) goto Loop
```

MIPS

```
Loop:    . . .

slti $t0,$s0,1      # $t0 = 1 if
                    # $s0<1  (g<1)
beq  $t0,$0,Loop    # goto Loop
                    # if $t0==0
                    # (if (g>=1))
```

An `slt` → `beq` pair means `if (… ≥ …) goto…`

What about unsigned numbers?

- Also unsigned inequality instructions:

  `sltu`, `sltiu`

…which sets result to `1` or `0` depending on unsigned comparisons

- What is value of `$t0`, `$t1`?

(`$s0 = FFFF FFFA`$_{hex}$, `$s1 = 0000 FFFA`$_{hex}$)

```
slt $t0, $s0, $s1
sltu $t1, $s0, $s1
```

MIPS Signed vs. Unsigned – diff meanings!

- MIPS terms Signed/Unsigned "overloaded":
  - Do/Don't sign extend
    - `(lb, lbu)`
  - Do/Don't overflow
    - `(add, addi, sub, mult, div)`
    - `(addu, addiu, subu, multu, divu)`
  - Do signed/unsigned compare
    - `(slt, slti/sltu, sltiu)`

Peer Instruction

```
Loop:addi $s0,$s0,-1     # i = i - 1
     slti $t0,$s1,2      # $t0 = (j < 2)
     beq  $t0,$0 ,Loop   # goto Loop if $t0 == 0
     slt  $t0,$s1,$s0    # $t0 = (j < i)
     bne  $t0,$0 ,Loop   # goto Loop if $t0 != 0
```

($s0=i, $s1=j)

What C code properly fills in the blank in loop below?

```
do {i--;} while(__);
```

```
a) j < 2 && j < i
a) j ≥ 2 && j < i
b) j < 2 && j ≥ i
b) j ≥ 2 && j ≥ i
c) j > 2 && j < i
c) j < 2 || j < i
d) j ≥ 2 || j < i
d) j < 2 || j ≥ i
e) j ≥ 2 || j ≥ i
e) j > 2 || j < i
```

"And in conclusion…"

- To help the conditional branches make decisions concerning inequalities, we introduce: "Set on Less Than" called `slt`, `slti`, `sltu`, `sltiu`
- One can store and load (signed and unsigned) bytes as well as words with `lb`, `lbu`
- Unsigned add/sub don't cause overflow
- New MIPS Instructions:

```
sll, srl, lb, lbu
slt, slti, sltu, sltiu
addu, addiu, subu
```

Bonus Slides

Example: The C Switch Statement (1/3)

- Choose among four alternatives depending on whether `k` has the value 0, 1, 2 or 3. Compile this C code:

```
switch (k) {
  case 0: f=i+j; break; /* k=0 */
  case 1: f=g+h; break; /* k=1 */
  case 2: f=g-h; break; /* k=2 */
  case 3: f=i-j; break; /* k=3 */
}
```

Example: The C Switch Statement (2/3)

- This is complicated, so simplify.
- Rewrite it as a chain of if-else statements, which we already know how to compile:

```
if(k==0) f=i+j;
   else if(k==1) f=g+h;
      else if(k==2) f=g-h;
         else if(k==3) f=i-j;
```

- Use this mapping:

```
f:$s0, g:$s1, h:$s2,
i:$s3, j:$s4, k:$s5
```

Example: The C Switch Statement (3/3)

- Final compiled MIPS code:

```
      bne  $s5,$0,L1     # branch k!=0
      add  $s0,$s3,$s4  #k==0 so f=i+j
      j    Exit         # end of case so Exit
L1:   addi $t0,$s5,-1   # $t0=k-1
      bne  $t0,$0,L2    # branch k!=1
      add  $s0,$s1,$s2  #k==1 so f=g+h
      j    Exit         # end of case so Exit
L2:   addi $t0,$s5,-2   # $t0=k-2
      bne  $t0,$0,L3    # branch k!=2
      sub  $s0,$s1,$s2  #k==2 so f=g-h
      j    Exit         # end of case so Exit
L3:   addi $t0,$s5,-3   # $t0=k-3
      bne  $t0,$0,Exit  # branch k!=3
      sub  $s0,$s3,$s4  # k==3 so f=i-j
Exit:
```