CS 61C: Great Ideas in Computer Architecture (Machine Structures)

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Agenda

- Review
- Overflow and Real Numbers
- Administrivia
- Technology Break
- Instructions as Numbers
- Assembly Language to Machine Language
- Summary

Review from Last Lecture

- Registers selectively saved/restored on call
  - Saved registers \$s0-\$s7; temporary regs \$t0-\$t9 not saved
- C splits memory into text, static, heap, stack, with registers dedicated to support: \$gp, \$sp, \$fp
- Program can interpret binary number as unsigned integer, two's complement signed integer, floating point number, ASCII characters, Unicode characters, …
- Integers have largest positive and largest negative numbers, but represent all in between
  - Two's comp. wierdness is one extra negative num

What if result of operation doesn't fit in 32 bits?

- Called *overflow*: calculate too big a number to represent within a word
- Unsigned numbers: 1 + 4,294,967,295 (2^{32}-1)
- Signed numbers: 1 + 2,147,483,647 (2^{31}-1)

Answer Depends on Language

- C unsigned number arithmetic ignores overflow (arithmetic modulo 2^{32})
  1 + 4,294,967,295 =
- C signed number arithmetic also ignores overflow
  1 + 2,147,483,647 (2^{31}-1) =
- Other languages want overflow signal on signed numbers (e.g., Fortran)
- What's a computer architect to do?

MIPS Solution: offer both

- Instructions that overflow:
  – add, sub, mult, div, addi, multi, divi
- Instructions that don't overflow called "unsigned" (but really means no overflow):
  – addu, subu, multu, divu, addiu, multiu, diviu
- Given semantics of C, always use unsigned versions
- Note: slt and slti do signed comparisons, while sltu and sltiu do unsigned comparisons
  – Nothing to do with overflow
  – When would get different answer for slt vs. sltu?

What about Real Numbers?

- Normalized scientific notation (aka standard form or exponential notation):
  - $r \times E^i$, *E* is where exponent (usually 10), *i* is a positive or negative integer, *r* is a real number ≥ 1.0, < 10
  - Normalized => No leading 0s
  - 61 is 6.10×10^2, 0.000061 is 6.10×10^{-5}
- Computers version of normalized scientific notation called *Floating Point* notation
- $r \times E^i$, *E* where is exponent (2), *i* is a positive or negative integer, *r* is a real number ≥ 1.0, < 2

Floating Point Numbers

- 32-bit word has 2^{32} patterns, so must be approximation of real numbers ≥ 1.0, < 2
- IEEE 754 Floating Point Standard:
  - 1 bit for *sign (s)* of floating point number
  - 8 bits for *exponent (E)*
  - 23 bits for *fraction (F)* (get 1 extra bit of precision if leading 1 is implicit)

$(-1)^s \times (1 + F) \times 2^E$

- Can represent from 2.0×10^{-38} to 2.0×10^{38}

Floating Point Numbers

- What about bigger or smaller numbers?
- IEEE 754 Floating Point Standard: *Double Precision* (64 bits)
  - 1 bit for *sign (s)* of floating point number
  - 11 bits for *exponent (E)*
  - 52 bits for *fraction (F)* (get 1 extra bit of precision if leading 1 is implicit)

$(-1)^s \times (1 + F) \times 2^E$

- Can represent from 2.0×10^{-308} to 2.0×10^{308}
- 32 bit format called *Single Precision*

More Floating Point

- What about 0?
  - Bit pattern all 0s means 0, so no implicit leading 1
- What if divide 1 by 0?
  - Can get infinity symbols $+\infty$, $-\infty$
  - Sign bit 0 or 1, largest exponent, 0 in fraction
- What if do something stupid? ($\infty - \infty$, $0 \div 0$)
  - Can get special symbols NaN for Not-a-Number
  - Sign bit 0 or 1, largest exponent, not zero in fraction
- What if result is too big? ($2\text{x}10^{308} \times 2\text{x}10^2$)
  - Get *overflow* in exponent, alert programmer!
- What if result is too small? ($2\text{x}10^{-308} \div 2\text{x}10^2$)
  - Get *underflow* in exponent, alert programmer!

MIPS Floating Point Instructions

- C, Java has single precision (**`float`**) and double precision (**`double`**) types
- MIPS instructions: .s for single, .d for double
  - Fl. Pt. Addition single precision:
    Fl. Pt. Addition double precision:
  - Fl. Pt. Subtraction single precision:
    Fl. Pt. Subtraction double precision:
  - Fl. Pt. Multiplication single precision:
    Fl. Pt. Multiplication double precision:
  - Fl. Pt. Divide single precision:
    Fl. Pt. Divide double precision:

MIPS Floating Point Instructions

- C, Java has single precision (**`float`**) and double precision (**`double`**) types
- MIPS instructions: .s for single, .d for double
  - Fl. Pt. Comparison single precision:
    Fl. Pt. Comparison double precision:
  - Fl. Pt. branch:
- Since rarely mix integers and Fl. Pt., MIPS has separate registers for floating-point operations: $f0, $f1, …, $f31
  - Double precision uses adjacent even-odd pairs of registers:
  - $f0 and $f1, $f2 and $f3, $f4 and $f5, …, $f30 and $f31
- Need data transfer instructions for these new registers
  - lwc1 (load word), swc1 (store word)
  - Double precision uses two lwc1 instructions, two swc1 instructions

Peer Instruction

Suppose Big, Tiny, and BigNegative are floats in C, with Big initialized to a big number (e.g., age of universe in seconds or 4.32 x 10^{17}), Tiny to a small number (e.g., seconds/femtosecond or 1.0 x 10^{-15}), BigNegative = - Big.
Here are two conditionals about associativity:

I. (Big * Tiny) * BigNegative == (Big * BigNegative) * Tiny

II. (Big + Tiny) + BigNegative == (Big + BigNegative) + Tiny

Which statement below is correct?

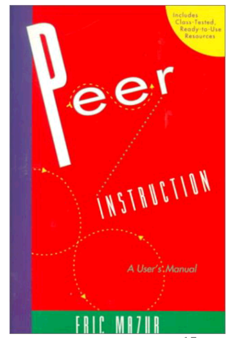
A. I. is false and II. is false
B. I. is false and II. is true
C. I. is true and II. is false
D. I. is true and II. is true

Pitfall

- Floating point addition is NOT associative
- Some optimizations can change order of floating point computations, which can change results
- Need to ensure that floating point algorithm is correct even with optimizations

Peer Instruction

- Increase real-time learning in lecture, test understanding of concepts vs. details
  mazur-www.harvard.edu/education/pi.phtml
- As complete a "segment" ask multiple choice question
  - 1-2 minutes: decide yourself, vote
  - 2-3 minutes: discuss in pairs, then team vote; flash cards
    - Try to convince partner; learn by teaching



Instructions as Numbers

- Instructions are kept as binary numbers in memory too
  - Stored program concept
  - As easy to change programs as it is to change data
- Saw mapping of register names to numbers
- Need to map instruction operation to a part of number

Instructions as Numbers

- addu $t0,$s1,$s2
  – Destination register $t0 is register 8
  – Source register $s1 is register 17
  – Source register $s2 is register 18
  – Add unsigned instruction encoded as number 33

0	17	18	8	0	33
000000	10001	10010	01000	00000	100001
6 bits	5 bits	5 bits	5 bits	5 bits	6 bits

- Groups of bits call *fields* (unused field default is 0)
- Layout called *instruction format*
- Binary version called *machine instruction*

Instructions as Numbers

- sll $zero,$zero,0
  – $zero is register 0
  – Shift amount 0 is 0
  – Shift left logical instruction encoded as number 0

0	0	0	0	0	0
000000	00000	00000	00000	00000	000000
6 bits	5 bits	5 bits	5 bits	5 bits	6 bits

- Can also represent machine code as base 16 or base 8 number: $0000\ 0000_{hex}$, 0000000000_{oct}

Everything in a computer is just a Binary Number

- Up to program to decide what data means
- Example 32-bit data shown as binary number:

$0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000_{two}$

What does it mean if its treated as

1. Signed integer
2. Unsigned integer
3. Floating point
4. ASCII characters
5. Unicode characters
6. MIPS instruction

Implications of everything is a number?

- *Stored program concept*
  - Invented about 1947 (many claim invention)
- As easy to change programs as to change data!
- Implications?

Names of MIPS fields

op	rs	rt	rd	shamt	funct
6 bits	5 bits	5 bits	5 bits	5 bits	6 bits

- *op*: Basic operation of instruction, or *opcode*
- *rs*: 1st register source operand
- *rt*: 2nd register source operand.
- *rd*: register destination operand (result of operation)
- *shamt*: Shift amount.
- *funct*: Function. This field, often called *function code*, selects the specific variant of the operation in the op field

What about load, store, immediate, branches, jumps?

- Fields for constants only 5 bits (-16 to +15)
  - Too small for many common cases
- #1 Simplicity favors regularity (all instructions use one format) vs. #3 Make common case fast (multiple instruction formats)?
- 4th Design Principle: *Good design demands good compromises*
- Better to have multiple instruction formats and keep all MIPS instructions same *size*
  - All MIPS instructions are 32 bits or 4 bytes

Names of MIPS fields in I-type

op	rs	rt	address or constant
6 bits	5 bits	5 bits	16 bits

- *op*: Basic operation of instruction, or *opcode*
- *rs*: 1st register source operand
- *rt*: 2nd register source operand for branches but register destination operand for lw, sw, and immediate operations
- *Address/constant*: 16-bit two's complement number
  - Note: equal in size of rd, shamt, funct fields

Register (R), Immediate (I), Jump (J) Instruction Formats

R-type

op	rs	rt	rd	shamt	funct
6 bits	5 bits	5 bits	5 bits	5 bits	6 bits

I-type

op	rs	rt	address or constant
6 bits	5 bits	5 bits	16 bits

- Now loads, stores, branches, and immediates can have 16-bit two's complement address or constant: -32,768 (-2^{15}) to +32,767 ($2^{15}-1$)
- What about jump, jump and link?

J-type

op	address
6 bits	26 bits

Encoding of MIPS Instructions: Must Be Unique!

Instruction	Format	op	rs	rt	rd	shamt	funct	address
addu	R	0	reg	reg	reg	0	33_{ten}	*n.a.*
subu	R	0	reg	reg	reg	0	35_{ten}	*n.a.*
sltu	R	0	reg	reg	reg	0	43_{ten}	*n.a.*
sll	R	0	reg	*n.a*	reg	constant	0_{ten}	*n.a.*
addi unsigned	I	9_{ten}	reg	reg	*n.a.*	*n.a.*	*n.a.*	constant
lw (load word)	I	35_{ten}	reg	reg	*n.a.*	*n.a.*	*n.a.*	address
sw (store word)	I	43_{ten}	reg	reg	*n.a.*	*n.a.*	*n.a.*	address
beq	I	4_{ten}	reg	reg	*n.a.*	*n.a.*	*n.a.*	address
bne	I	5_{ten}	reg	reg	*n.a.*	*n.a.*	*n.a.*	address
j (jump)	J	2_{ten}	*n.a.*	*n.a.*	*n.a.*	*n.a.*	*n.a.*	address
jal	J	3_{ten}	*n.a.*	*n.a.*	*n.a.*	*n.a.*	*n.a.*	address
jr (jump reg)	R	0	reg	reg	reg	0	8_{ten}	*n.a.*

Summary

- Integer and floating point operations can lead to results too big to store within their representations: overflow/ underflow
- Floating point is an approximation of reals
- Everything is a (binary) number in a computer
  - Instructions and data; stored program concept
- MIPS ISA guided by 4 design principles:
  1. Simplicity favors regularity
  2. Smaller is faster
  3. Make the common case fast
  4. Good design demands good compromises
  - MIPS has 3 instruction formats, but all instructions 32 bits