CS/ECE 3810: Computer Organization

Lecture 4: MIPS instruction set

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Instruction Set

- Understanding the language of the hardware is key to understanding the hardware/software interface

- A program (in say, C) is compiled into an executable that is composed of machine instructions – this executable must also run on future machines – for example, each Intel processor reads in the same x86 instructions, but each processor handles instructions differently

- Java programs are converted into portable bytecode that is converted into machine instructions during execution (just-in-time compilation)

- What are important design principles when defining the instruction set architecture (ISA)?

Instruction Set

- Important design principles when defining the instruction set architecture (ISA):

  - keep the hardware simple – the chip must only implement basic primitives and run fast
  - keep the instructions regular – simplifies the decoding/scheduling of instructions

We will later discuss RISC vs CISC

A Basic MIPS Instruction

C code: a = b + c ;

Assembly code: (human-friendly machine instructions)

```
add   a, b, c      #  a is the sum of b and c
```

Machine code: (hardware-friendly machine instructions)

00000010001100100100000000100000

Translate the following C code into assembly code:

a = b + c + d + e;

Example

C code   a = b + c + d + e;

translates into the following assembly code:

```
add  a, b, c                add  a, b, c
add  a, a, d       or       add  f, d, e
add  a, a, e                add  a, a, f
```

- Instructions are simple: fixed number of operands (unlike C)
- A single line of C code is converted into multiple lines of assembly code
- Some sequences are better than others… the second sequence needs one more (temporary) variable f

Subtract Example

C code   f = (g + h) – (i + j);

Assembly code translation with only add and sub instructions:

Subtract Example

C code $f = (g + h) - (i + j);$

translates into the following assembly code:

```
add  t0, g, h              add  f, g, h
add  t1,  i, j       or    sub   f, f, i
sub  f,   t0, t1           sub   f, f, j
```

- Each version may produce a different result because floating-point operations are not necessarily associative and commutative… more on this later

Operands

- In C, each “variable” is a location in memory
- In hardware, each memory access is expensive – if variable *a* is accessed repeatedly, it helps to bring the variable into an on-chip scratchpad and operate on the scratchpad (registers)
- To simplify the instructions, we require that each instruction (add, sub) only operate on registers
- Note: the number of operands (variables) in a C program is very large; the number of operands in assembly is fixed… there can be only so many scratchpad registers

Registers

- The MIPS ISA has 32 registers (x86 has 8 registers) – Why not more? Why not less?
- Each register is 32 bits wide (modern 64-bit architectures have 64-bit wide registers)
- A 32-bit entity (4 bytes) is referred to as a word
- To make the code more readable, registers are partitioned as \$s0-\$s7 (C/Java variables), \$t0-\$t9 (temporary variables)…

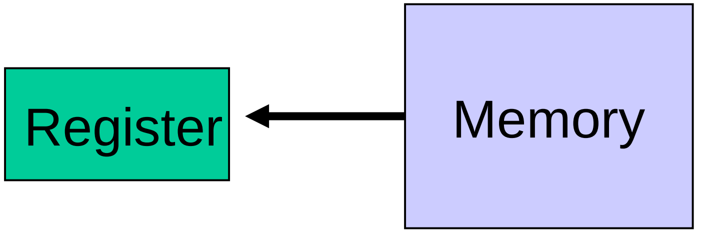
Binary Stuff

- 8 bits = 1 Byte, also written as 8b = 1B
- 1 word = 32 bits = 4B
- 1KB = 1024 B = 2^{10} B
- 1MB = 1024 x 1024 B = 2^{20} B
- 1GB = 1024 x 1024 x 1024 B = 2^{30} B
- A 32-bit memory address refers to a number between 0 and $2^{32} – 1$, i.e., it identifies a byte in a 4GB memory

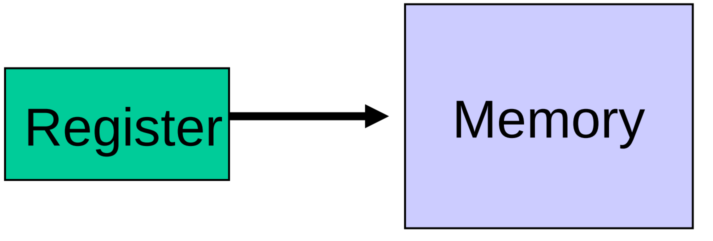
Memory Operands

- Values must be fetched from memory before (add and sub) instructions can operate on them

Load word
lw $t0, memory-address



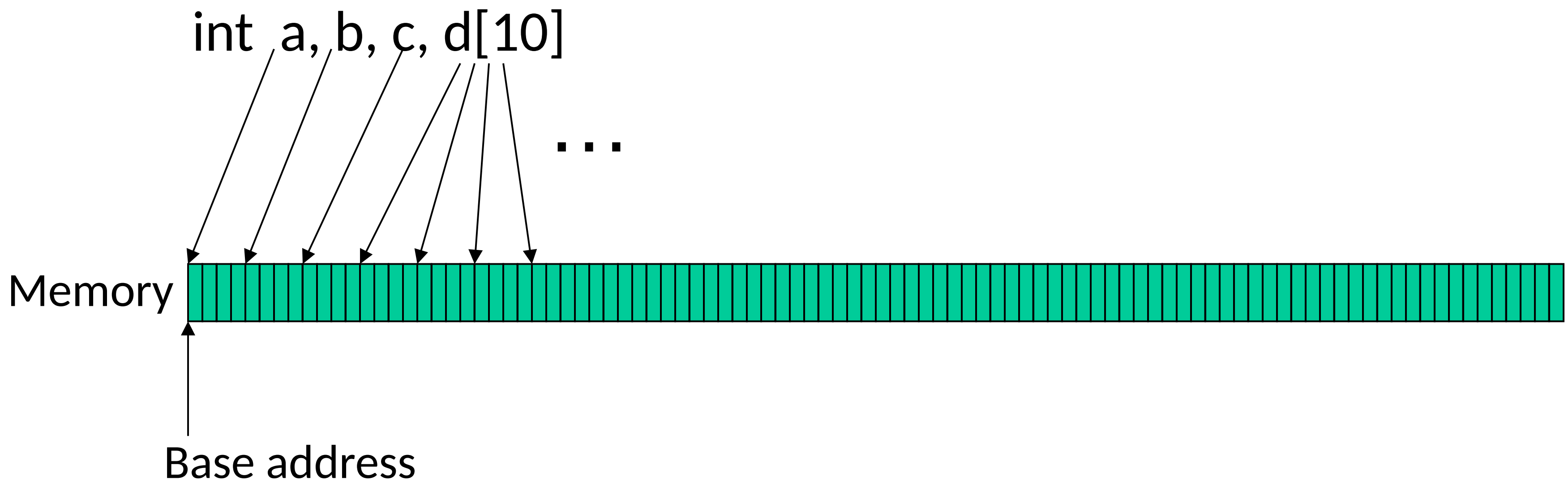
Store word
sw $t0, memory-address



How is memory-address determined?

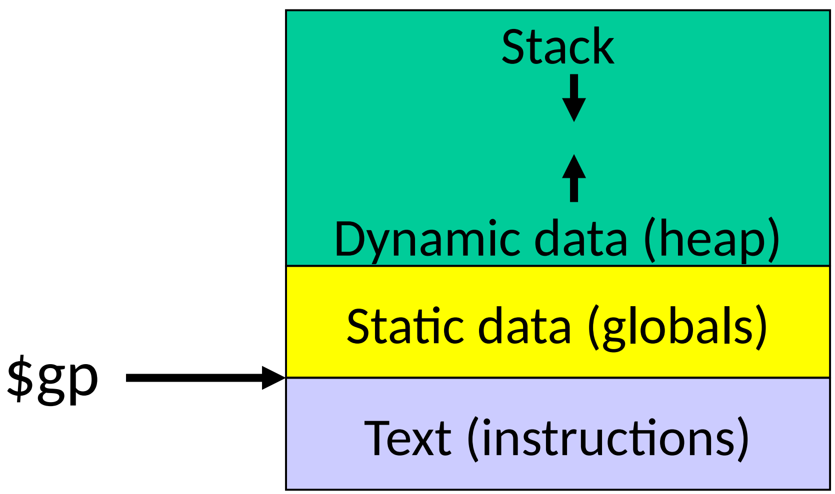
Memory Address

- The compiler organizes data in memory… it knows the location of every variable (saved in a table)… it can fill in the appropriate mem-address for load-store instructions



Memory Organization

$gp points to area in memory that saves global variables



Memory Instruction Format

- The format of a load instruction:

destination register

source address

lw $t0, 8($t3)

any register

a constant that is added to the register in parentheses

Memory Instruction Format

- The format of a store instruction:

source register

destination address

sw $t0, 8($t3)

any register

a constant that is added to the register in parentheses

Example

```
int a, b, c, d[10];


addi   $gp, $zero, 1000   # assume that data is stored at
                          # base address 1000; placed in $gp;
                          # $zero is a register that always
                          # equals zero
lw   $s1, 0($gp)          # brings value of a into register $s1
lw   $s2, 4($gp)          # brings value of b into register $s2
lw   $s3, 8($gp)          # brings value of c into register $s3
lw   $s4, 12($gp)         # brings value of d[0] into register $s4
lw   $s5, 16($gp)         # brings value of d[1] into register $s5
```

Example

Convert to assembly:

C code: d[3] = d[2] + a;

Example

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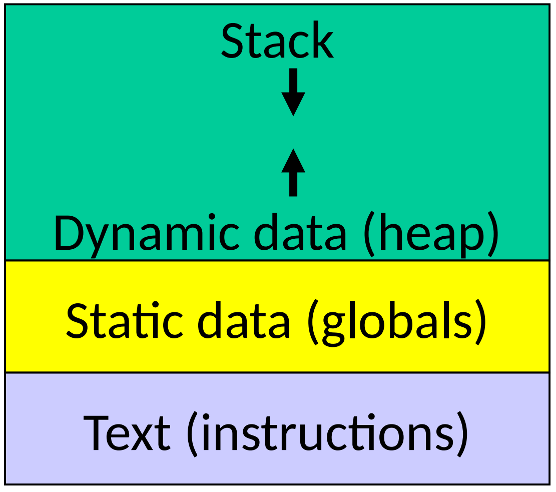
Assembly (same assumptions as previous example):

```
lw    $s0, 0($gp)     #  a is brought into $s0
lw    $s1, 20($gp)    #  d[2] is brought into $s1
add   $s2, $s0, $s1   #  the sum is in $s2
sw    $s2, 24($gp)    #  $s2 is stored into d[3]
```

Assembly version of the code continues to expand!

Memory Organization

- The space allocated on stack by a procedure is termed the activation record (includes saved values and data local to the procedure) – frame pointer points to the start of the record and stack pointer points to the end – variable addresses are specified relative to $fp as $sp may change during the execution of the procedure
- $gp points to area in memory that saves global variables
- Dynamically allocated storage (with malloc()) is placed on the heap



Binary Representation

- The binary number

01011000 00010101 00101110 11100111

Most significant bit

Least significant bit

represents the quantity

$0 \times 2^{31} + 1 \times 2^{30} + 0 \times 2^{29} + \ldots + 1 \times 2^{0}$

- A 32-bit word can represent 2^{32} numbers between 0 and 2^{32}-1

… this is known as the unsigned representation as we're assuming that numbers are always positive

Negative Numbers

32 bits can only represent 2^{32} numbers – if we wish to also represent negative numbers, we can represent 2^{31} positive numbers (incl zero) and 2^{31} negative numbers

$0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000_{two} = 0_{ten}$

$0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0001_{two} = 1_{ten}$

…

$0111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111_{two} = 2^{31}-1$

$1000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000_{two} = -2^{31}$

$1000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0001_{two} = -(2^{31} - 1)$

$1000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0010_{two} = -(2^{31} - 2)$

…

$1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1110_{two} = -2$

$1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111_{two} = -1$

2's Complement

$0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000_{two} = 0_{ten}$

$0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0001_{two} = 1_{ten}$

…

$0111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111_{two} = 2^{31}-1$

$1000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000_{two} = -2^{31}$

$1000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0001_{two} = -(2^{31} - 1)$

$1000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0010_{two} = -(2^{31} - 2)$

…

$1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1110_{two} = -2$

$1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111_{two} = -1$

Why is this representation favorable?

Consider the sum of 1 and -2 …. we get -1

Consider the sum of 2 and -1 …. we get +1

This format can directly undergo addition without any conversions!

Each number represents the quantity

$$x_{31}\ -2^{31} + x_{30}\ 2^{30} + x_{29}\ 2^{29} + \ldots + x_1\ 2^1 + x_0\ 2^0$$

2's Complement

$0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000_{two} = 0_{ten}$
$0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0001_{two} = 1_{ten}$
...
$0111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111_{two} = 2^{31}-1$

$1000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000_{two} = -2^{31}$
$1000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0001_{two} = -(2^{31} – 1)$
$1000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0010_{two} = -(2^{31} – 2)$
...
$1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1110_{two} = -2$
$1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111_{two} = -1$

Note that the sum of a number x and its inverted representation x' always equals a string of 1s (-1).

$x + x' = -1$
$x' + 1 = -x$ ... hence, can compute the negative of a number by
$-x = x' + 1$ inverting all bits and adding 1

Similarly, the sum of x and –x gives us all zeroes, with a carry of 1
In reality, $x + (-x) = 2^n$ ... hence the name 2's complement

Example

- Compute the 32-bit 2's complement representations for the following decimal numbers:
  5, -5, -6

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  5, -5, -6

 5:   0000 0000 0000 0000 0000 0000 0000 0101
-5:   1111 1111 1111 1111 1111 1111 1111 1011
-6:   1111 1111 1111 1111 1111 1111 1111 1010

Given -5, verify that negating and adding 1 yields the number 5

Signed / Unsigned

- The hardware recognizes two formats:

  unsigned (corresponding to the C declaration unsigned int)
  -- all numbers are positive, a 1 in the most significant bit
  just means it is a really large number

  signed (C declaration is signed int or just int)
  -- numbers can be +/- , a 1 in the MSB means the number
  is negative

This distinction enables us to represent twice as many numbers when we're sure that we don't need negatives

MIPS Instructions

Consider a comparison instruction:

    slt $t0, $t1, $zero

and $t1 contains the 32-bit number   1111 01…01

What gets stored in $t0?

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Consider a comparison instruction:

slt $t0, $t1, $zero

and $t1 contains the 32-bit number   1111 01…01

What gets stored in $t0?

The result depends on whether $t1 is a signed or unsigned number – the compiler/programmer must track this and accordingly use either slt or sltu

slt $t0, $t1, $zero   stores 1 in $t0

sltu $t0, $t1, $zero   stores 0 in $t0

Sign Extension

- Occasionally, 16-bit signed numbers must be converted into 32-bit signed numbers – for example, when doing an add with an immediate operand

- The conversion is simple: take the most significant bit and use it to fill up the additional bits on the left – known as sign extension

So 2_{10} goes from 0000 0000 0000 0010 to
0000 0000 0000 0000 0000 0000 0000 0010

and -2_{10} goes from 1111 1111 1111 1110 to
1111 1111 1111 1111 1111 1111 1111 1110

Alternative Representations

- The following two (intuitive) representations were discarded because they required additional conversion steps before arithmetic could be performed on the numbers

  - sign-and-magnitude: the most significant bit represents +/- and the remaining bits express the magnitude

  - one's complement: -x is represented by inverting all the bits of x

  Both representations above suffer from two zeroes