University of Waterloo

CS241 - Winter 2024 - Course Notes

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Section 1: Lectures

Lecture 1

- Definition: A bit is a binary digit. That is, a 0 or 1 (off or on)
- Definition: A nibble is 4 bits.
  - Example: 1001
- Definition: A byte is 8 bits.
  - Example: 10011101
- in C/C++:
  - Char: 8 bits
  - Unsigned char: 8 bits
  - Short: 2 bytes/16 bits
  - int: 4 bytes
  - longlong: 16 bytes
- Definition: A word is a machine-specific grouping of bytes. For us, a word will be 4 bytes (32-bit architecture) though 8-byte (or 64-bit architectures) words are more common now.
- Definition (Hexadecimal Notation): The base-16 representation system is called the hexadecimal system. It consists of the numbers from 0 to 9 and the letters a, b, c, d, e, f (which convert to the numbers from 10 to 15 in decimal notation)
  - Sometimes we denote the base with a subscript like 10011101_2 and $9d_{16}$.
  - Also, for hexadecimal,you will routinely see the notation `0x9d`. (The `0x` denotes a hexadecimal representation in computer science).
  - Note that each hexadecimal character is a nibble (4 bits).
- Conversion Table
  - Note: upper case letters are also used for hexadecimal notation. Context should make things clear.

Binary	Decimal	Hex
0000	0	0
0001	1	1
0010	2	2
0011	3	3
0100	4	4
0101	5	5
0110	6	6
0111	7	7

Binary	Decimal	Hex
1000	8	8
1001	9	9
1010	10	a
1011	11	b
1100	12	c
1101	13	d
1110	14	e
1111	15	f

- Notation:
  - Binary: 0, 1
  - Decimal(Base 10): 0, ..., 9
  - Hexadecimal: 0, ..., 9, A(10), B(11), C(12), D(13), E(14), F(15)
- Examples:
  - 0000(base 2) -> 0x0(base 16)
  - 1111(base 2) -> 0xf(base 16)
- What do bytes represent?
  - Numbers
  - Characters
  - Garbage in memory
  - Instructions (Words, or 4 bytes, will correspond to a compute instruction in our computer system)
- Bytes as Binary Numbers
  - Unsigned (non-negative integers)
    - $b_7 ... b_0$ (base 2) = $b_7 \times 2^7 + ... + b_0 \times 2^0$ (base 10)
    - Example: $01010101 = 0 \times 2^7 + ... + 1 \times 2^0$
    - Converting to Binary:

- One way: Take the largest power of 2 less than the unsigned integer, subtract and repeat
- Another way is to constantly divide by 2, get the remainer for each division, reading *from the bottom to up* at the end, and that will be the binary representation of this unsigned integer
  - Example: 38

Number	Quotient	Remainder
38	19	0
19	9	1
9	4	1
4	2	0
2	1	0
1	0	1

  - Brief Explanation: Consider

$$N = b_0 + 2b_1 + 2^2 b_2 + \dots$$

The remainder when dividing N by 2 gives the b_0 value. After doing $\frac{N-b_0}{2}$, we end of with

$$\frac{N - b_0}{2} = b_1 + 2b_2 + 2^2 b_3 + \dots$$

and we can repeat the process. (This is why we have to read bottom-up as we get b_0 first, then b_1 ...)

- Signed integers
  - Attempt 1: make the first bit a signed bit. This is called the "sign-magnitude" representation
    - Problems:
      - Two representations of 0(wasteful and awkward)
      - Arithmetic is tricky. Is the sum of a positive number and a negative number positive or negative? It depends!
  - Attempt 2: Two's complement form
    - Similar to "sign-magnitude" representation in spirit, first bit is 0 if non-negative, 1 if negative
    - Negate a value by just subtracting from zero and *letting it overflow*.
    - Decimal to Two's Compliment:
      - A trick to the same thing of negating a value:
        - Take the complement of all bits (flip the 0 bits to 1 and 1 bits to 0)
        - Add 1
      - A slightly faster trick is to locate the rightmost 1 bit and flip all the bits to the left of it
        - Example: 11011010 Negating: 00100110 = 00100101 + 1
        - Note: Flipping the bits and adding 1 is the same as
          - subtracting 1 and flipping the bits for non-zero numbers
          - subtracting from 0
        - Example: compute -38_{10} using this notation in one byte of space:
          - Step 1: $38_{10} = 00100110_2$
          - Step 2: take the complment of all the bits: 11011001_2
          - Step 3: plus 1: 11011010_2
    - Two's Compliment to Decimal
      - Let's compute -38_{10} using one-byte Two's complement. First, write 38 in binary: 38_{10} = 00100110_2. Next, take the complement of all the bits 11011001_2. Finally, add 1: 11011010_2. This last value is -38_{10}.
      - To convert 11011010_2, a number in Two's complement representation, to decimal, one method is to flip the bits and add 1: 00100110_2 = $2^5 + 2^2 + 2^1 = 38$. Thus, the corresponding positive number is 38 and so the original number is -38.

- Another way to do this computation is to treat the original number 11011010_2 as an unsigned number, convert to decimal and subtract 2^8 from it (since we have 8 bits, and the first bit is a 1 meaning it should be a negative value). This also gives -38

$$\begin{aligned} 11011010_2 &= 2^7 + 2^6 + 2^4 + 2^3 + 2^1 - 2^8 \\ &= 128 + 64 + 16 + 8 + 2 - 256 \\ &= 218 - 256 \\ &= -38 \end{aligned}$$

- The idea behind [one byte] Two's Complement notation is based on the following observations:
  - The range for unsigned integers is 0 to 255. Recall that 255 is 11111111_2. If we add 1 to 255, then, after discarding overflow bits, we get the number 0.
  - Thus, let's treat 2^8 as 0, i.e., let's work modulo $2^8 = 256$. In this vein, we set up a correspondence between the positive integer k and the unsigned integer $2^8 - k$. Since we are working modulo 2^8, subtracting a positive integer k from 0 is the same as subtracting it from 2^8.
  - In this cse, note that $255 = 2^8 - 1 = 2^7 + 2^6 + 2^5 + 2^4 + 2^3 + 2^2 + 2^1 + 2^0$ and in general

$$2^n - 1 = \sum_{i=0}^{n-1} 2^i$$

  - As an explicit example (which can be generalized naturally) take a number, say $38_{10} = 00100110_2 = 2^5 + 2^2 + 2^1$. What should the corresponding negative number be? Well, note that we've said subtracting a positive integer k from 0 is the same as subtracting it from 2^8 :

$$\begin{aligned} 2^8 - 1 &= 2^7 + 2^6 + 2^5 + 2^4 + 2^3 + 2^2 + 2^1 + 2^0 \\ 2^8 - 1 &= 38 + 2^7 + 2^6 + 2^4 + 2^3 + 2^0 \\ 2^8 - 38 &= 2^7 + 2^6 + 2^4 + 2^3 + 2^0 + 1 && \text{(flip the bits and add 1)} \end{aligned}$$

  - We mentioned that another method of negating a two's complement number is to flip the bits to the left of the rightmost 1. Justify why this technique works.
    - Every bit to the right of the rightmost 1 is a 0. When we "flip the bits", these become 1s. When we "add 1", the carry propagates up until the position of the "rightmost 1" (the "rightmost 1" is 0 after flip and will stop propagating when the carry reaches this point, and everything on the left of the "rightmost 1" is flipped).

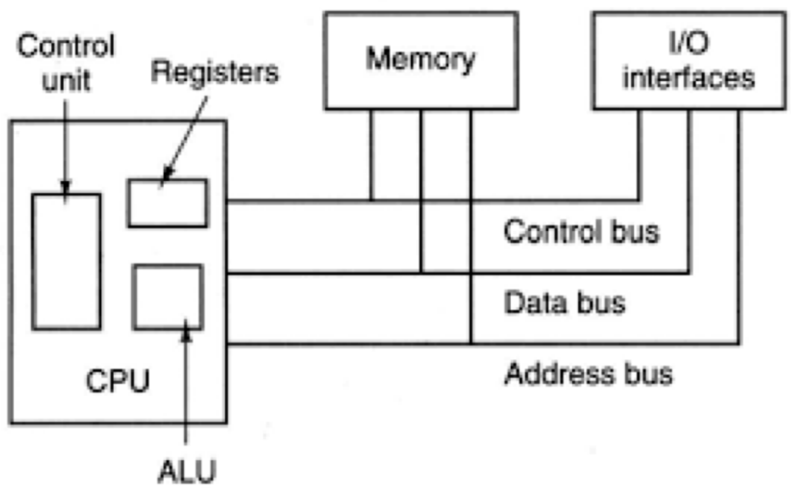
- The main difference between signed and unsigned binary arithmetic is that we are now working modulo 256 (or, more generally, 2n in the case of n-bit Two's complement numbers)
- When working in Two's complement, overflow occurs when adding numbers if the original two numbers have the same sign, but the result has a different sign.
- Arithmetic of Signed Integers
  - All of the arithmetic works by ignoring overflow precisely because arithmetic works in Z_{256}!
- What is the range of numbers expressible in one-byte Two's Complement notation?
  - $-128 \sim 127$
- Definitions: The Most Significant Bit (MSB) is the left- most bit (highest value/sign bit); The Least Significant Bit (LSB) is the right-most bit (lowest value).

Lecture 2

- ASCII (American Standard Code for Information Interchange) uses 7 bits to represent characters.

```
char c = '0';
printf("%c", c);
// stdout: 0
printf("%d", (int)c);
// stdout: 48
```

- Bit-Wise Operators
  - Example: suppose we have `unsigned char a=5, b=3;`, which means $a = 00000101, b = 00000011$
    - Bitwise not $\sim a$, for example $c =\sim a$; gives $c = 11111010$
    - Bitwise and $\boxed{\&}$, for example $\boxed{\text{c=a\&b;}}$ gives $c = 00000001$
    - Bitwise or $|$, for example $c = a|b$; gives $c = 00000111$
    - Bitwise exclusive ^(only true if the bit in a and b is different), for example $c = a\hat{}b$; gives $c = 00000110$
    - Bitwise shift right or left $>>$ and $<<$, for example
      - $c = a >> 2$; gives $c = 00000001$ and
      - $c = a << 3$; gives $c = 00101000$
    - $a << 1$ equivalent to $a * 2$
    - $a >> 1$ equivalent to $a/2$
    - These can even be combined with the assignment operator: `c &= 5;`



- CPU with Memory
- MIPS has 32 registers that are called "general purpose"
  - Some general-purpose registers are special:
    - `$0` is always 0
    - `$31` is for return address
    - `$30` is our stack pointer
    - `$29` is our frame pointer
- Problem: We only know from context what bits have what meaning, and in particular, which are instructions.
  - Solution: Convention is to set memory address 0 in RAM to be an instruction. `0x0: instruction i1`
- Problem: How does MIPS know what to do next?
  - Solution: Have a special register called the Program Counter (or PC for short) to tell us what instruction to do next.
- Problem: How do we put our program into RAM?
  - Solution: A program called a loader puts our program into memory and sets the PC to be the first address.
- Algorithm 1 Fetch-Execute Cycle

```
PC=0
while true do
    IR = MEM[PC]
    PC += 4
    Decode and execute instruction in IR
end while
```

- Write a program in MIPS that adds the values of registers `$8` and `$9` and stores the result in register `$3`.

```
add $d, $s, $t
0000 00ss ssst tttt dddd d000 0010 0000
```

- Why 5 bits for each? Because there are 32 registers `$0 - $31` and $2^5 = 32$
- Adds registers `$s` and `$t` and stores the sum in register `$d`. Important! The order of `$d`, `$s` and `$t` are shifted in the encoding.

Lecture 3

- **Putting values in registers** Load immediate and skip. This places the next value in RAM [an immediate] into $d and increments the program counter by 4 (it skips the next line which is usually not an instruction).

```
lis $d: 0000 0000 0000 0000 dddd d000 0001 0100
# What it really does is
$d = MEM[PC]
PC = PC + 4
```

- How do we get the value we care about into the next location in RAM?

```
.word i: iiii iiii iiii iiii iiii iiii iiii iiii
```

- The above is an assembler directive (not a MIPS instruction). The value i, as a two's complement integer, is placed in the correct memory location in RAM as it occurs in the code.
  - Can also use hexadecimal values: `0xi`
  - Decimal is also allowed.
- Example:

```
lis $1
.word 10
# At this moment, $1 = 10
add $1, $1, $0
```

- Example: Write a MIPS program that adds together 11 and 13 and stores the result in register $3.

```
lis $1
.word 11
list $2
.word 13
add $3, $1, $2
# Solution on the course notes
lis $8          0000 0000 0000 0000 0100 0000 0001 0100
.word 11        0000 0000 0000 0000 0000 0000 0000 1011
lis $9          0000 0000 0000 0000 0100 1000 0001 0100
.word 0xd       0000 0000 0000 0000 0000 0000 0000 1101
add $3,$8,$9    0000 0001 0000 1001 0001 1000 0010 0000
    # The code on the left is what we call Assembly Code.
    # The code on the right is what we call Machine Code.
```

- Jump Register. Sets the pc to be $s.

```
jr $s
0000 00ss sss0 0000 0000 0000 0000 1000
```

- For us, our return address will typically be in $31, so we will typically call the below. This command returns control to the loader.

```
jr $31
0000 0011 1110 0000 0000 0000 0000 1000
```

- So the complete example for the example is (so that the while loop will terminate)

```
lis $8          0000 0000 0000 0000 0100 0000 0001 0100
.word 11        0000 0000 0000 0000 0000 0000 0000 1011
lis $9          0000 0000 0000 0000 0100 1000 0001 0100
.word 0xd       0000 0000 0000 0000 0000 0000 0000 1101
add $3,$8,$9    0000 0001 0000 1001 0001 1000 0010 0000
jr $31          0000 0011 1110 0000 0000 0000 0000 1000
```

- To multiply two words, we need to use the two special registers `hi` and `lo`.
  - `hi` is most significant 4 bytes
  - `lo` is least significant 4 bytes

```
mult $s, $t
0000 00ss ssst tttt 0000 0000 0001 1000
```

- The above performs the multiplication and places the most significant word (largest 4 bytes) in `hi` and the least significant word in `lo`.
- `div $s, $t` performs integer division and places the quotient s/t in `lo` [lo quo] and the remainder st in `hi`. Note the sign of the remainder matches the sign of the divisor stored in $s.

```
div $s, $t
0000 00ss ssst tttt 0000 0000 0001 1010
```

- Multiplication and division happen on these special registers hi and lo. How can I access the data?
  - Move from register `hi` into register `$d`.

  ```
  mfhi $d
  0000 0000 0000 0000 dddd d000 0001 0000
  ```

  - Move from register `lo` into register `$d`.

  ```
  mflo $d
  0000 0000 0000 0000 dddd d000 0001 0010
  ```

- RAM
  - Large[r] amount of memory stored off the CPU.
  - RAM access is slower than register access (but is larger, as a tradeoff).
  - Data travels between RAM and the CPU via the bus.
  - Modern day RAM consists of in the neighbourhood of 10^{10} bytes.
  - Instructions occur in RAM starting with address 0 and increase by the word size (in our case 4).
    - But, this simplification will vanish later...
  - Each memory block in RAM has an address; say from 0 to $n-1$
  - Words occur every 4 bytes, starting with byte 0. Indexed by $0, 4, 8, ... n-4$.
  - Words are formed from consecutive, aligned (usually) bytes.
  - Cannot directly use the data in the RAM. Must transfer first to registers.
- Load word. Takes a word from RAM and places it into a register. Specifically, load the word in `MEM[$s + i]` and store in `$t`.

```
lw $t, i($s)
1000 11ss ssst tttt iiii iiii iiii iiii
# which is equivalent to
$t = MEM[$s + i]
# Example
lw $1, -4($30)
# which means
$1 <- MEM[$30 - 4]
```

- Store word. Takes a word from a register and stores it into RAM. Specifically, load the word in `$t` and store it in `MEM[$s + i]`.

```
sw $t, i($s)
1010 11ss ssst tttt iiii iiii iiii iiii
```

- Note that `i` must be an immediate, NOT another register! It is a 16-bit Two's complement immediate
- Example: Suppose that `$1` contains the address of an array of words, and `$2` takes the number of elements in this array (assume less than 220). Place the number 7 in the last possible spot in the array.

```
# First element in the array is arr, then the second element is arr + 4 ... the last element in the array is
arr + 4 * (length - 1)
lis $8 ; 7
.word 7
lis $9 ; 4
```

```
.word 4
mult $2, $9 ; length * 4
mflo $3 ; length * 4
add $3, $3, $1 ; arr + length 4
sw $8, -4($3) ; MEM[$3 - 4] = $8
jr $31
```

- Branch on equal.If `$s==$t` then `pc += i*4`. That is, skip ahead i many instructions if `$s` and `$t` are equal.

```
beq $s, $t, i
0001 00ss ssst tttt iiii iiii iiii iiii
# It is like
if ($s == $t) {
    PC += i*4
}
```

- Branch on not equal.If `$s!=$t` then `pc+=i*4`. That is, skip ahead i many instructions if `$s` and `$t` are not equal.

```
bne $s, $t, i
0001 01ss ssst tttt iiii iiii iiii iiii
# It is like
if ($t != $s) {
    PC += i*4
}
```

- Example:

```
beq $0, $0, 0 ; This executes the next instruction as PC has been updated to +4 already
beq $0, $0, 1 ; This executes the second next instruction
```

Lecture 4

- Write an assembly language MIPS program that places the value 3 in register `$2` if the signed number in register `$1` is odd and places the value 11 in register `$2` if the number is even.

```
lis $8 ; $8 = 2
.word 2
lis $9 ; $9 = 3
.word 3
lis $2 ; $2 = 11
.word 11
div $1, $8
mfhi $3
beq $3, $0, 1
add $2, $9, $0
jr $31
```

- Set Less Than. Sets the value of register `$d` to be 1 provided the value in register `$s` is less than the value in register `$t` and sets it to be 0 otherwise.

```
slt $d, $s, $t
0000 00ss ssst tttt dddd d000 0010 1010
# which basically means
if ($s < $t) {
    $d = 1 (true)
} else {
    $d = 0 (false)
}
```

- Example: Write an assembly language MIPS program that negates the value in register `$1` provided it is positive.

```
slt $2, $1, $0
bne $2, $0, 1
sub $1, $0, $1
jr $31
```

- Exercise: Write an assembly language MIPS program that places the absolute value of register $1 in register 2$.

```
add $2, $1, $0 ; $2 = $1
slt $3, $0, $1 ; 0 < $1
bne $3, $0, 1
sub $2, $0, $2 ; $2 = 0 - $2
jr $31
```

- Looping exmaple: Write an assembly language MIPS program that adds together all even numbers from 1 to 20 inclusive. Store the answer in register `$3`.
  - Note: semicolons for comments in MIPS assembly

```
lis $2
.word 20
lis $1
.word 2
add $3, $0, $0
add $3, $3, $2 ; line -3
sub $2, $2, $1 ; line -2
bne $2, $0, -3 ; line -1 from here
jr $31
```

- Labels aren't machine code, so don't take words. That means that for `beq` and `bne`, *labels don't have "line numbers" on their own*. A label at the end of code is allowed. It has the address of what would be the first instruction after the program.

```
label: operation commands
```

- Example: `sample` has the address $0x4$, which is the location of `add $1, $0, $0`.

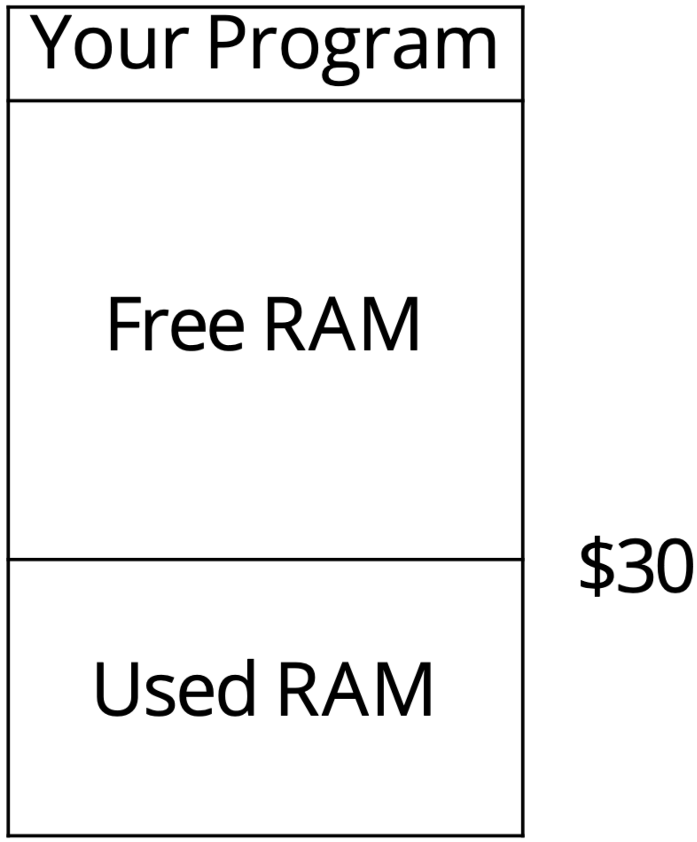
```
sub $3, $0, $0
sample:
add $1, $0, $0
```

- A better way to loop without hard-coding -3 in the previous example is (otherwise, if we were to, say, add a new instruction in between the lines specified by our branching, all our numbers would be incorrect.)
  - Note that top in bne is computed by the assembler to be the *difference between the program counter and top*. That is, here it computes $(top - PC)/4$ which is $(0\text{x}14 - 0\text{x}20)/4 = -3$
  - PC is the line number after the current line

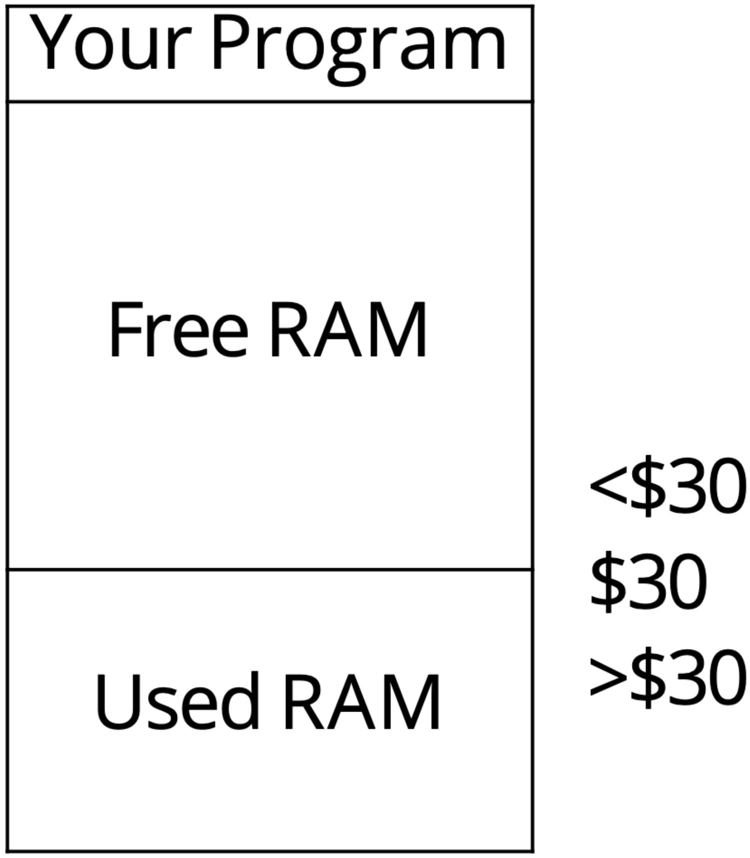
```
lis $2
.word 20
lis $1
.word 2
add $3, $0, $0
top:
    add $3, $3, $2
    sub $2, $2, $1
    bne $2, $0, top
jr $31
```

- RAM

- Register `$30` initially points to the very bottom of the free RAM. It can be used as a bookmark to separate the used and unused free RAM if we allocate from the one end, and push and pop things like a stack! In other words, we will use `$30` as a pointer to the top of a stack.
- Really, `$30` points to the top of the stack of memory in RAM.

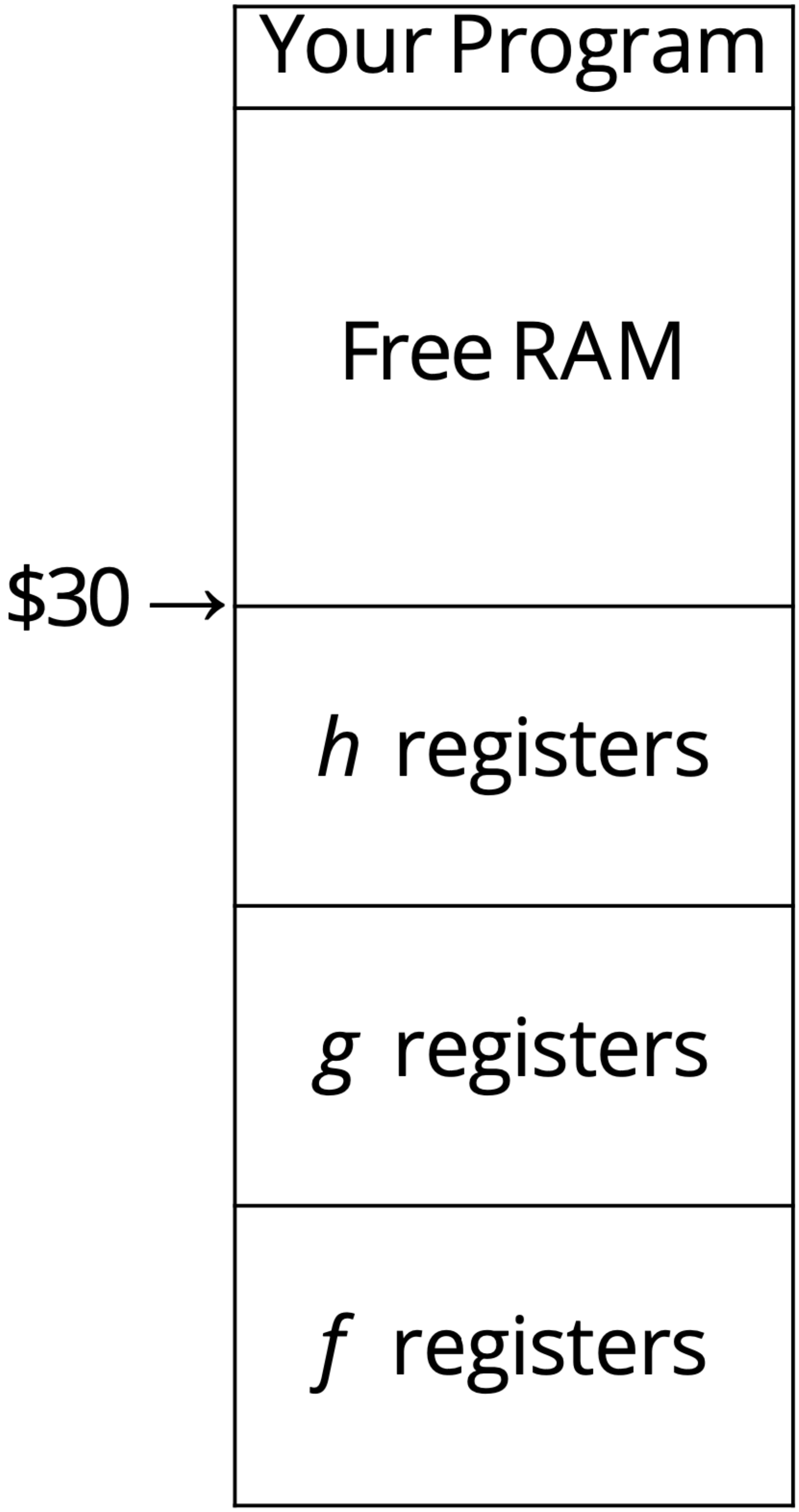


- Because our program is at zero, the stack grows from high memory to low memory, so pushing involves reducing the value of `$30`.



- Example: Suppose procedures f, g and h are such that:

```
f calls procedure g
    g calls procedure h
        h returns
    g returns
f returns.
```



- In the previous example:
  - Calling procedures pushes more registers onto the stack and returning pops them off.
  - This is a stack, and we call `$30` our **stack pointer**.
  - We can also use the stack for local storage if needed in procedures. Just reset `$30` before procedures return.
- Template for a procedure `f` that modifies registers `$1`and `$2`:

```
f:
sw $1, -4($30) ; Push registers we modify
sw $2, -8($30)
lis $2 ; Decrement stack pointer
.word 8
```

```
sub $30, $30, $2
    ; Insert procedure here
add $30, $30, $2 ; Assuming $2 is still 8
lw $2, -8($30) ; Pop = restore
lw $1, -4($30)
    ; Uh oh! How do we return?
```

- There is a problem with returning:

```
main:
lis $8
.word f ; Recall f is an address
jr $8 ; Jump to the first line of f
(NEXT LINE)
```

- Once f completes, we really want to jump back to the line labelled above as (NEXT LINE), i.e., set the program counter back to that line. How do we do that?
- Jump and Link Register. Sets `$31` to be the PC and then sets the PC to be `$s`. Accomplished by `temp = $s` then `$31 = PC` then `PC = temp`.

```
jalr $s
0000 00ss sss0 0000 0000 0000 0000 1001
```

- Main Changes

```
main:
    lis $8
    .word f
    sw $31, -4($30) ; Push $31 to stack
    lis $31 ; Use $31 since it's been saved .word 4
    sub $30, $30, $31
    jalr $8 ; Overwrites $31
    lis $31 ; Use $31 since we'll restore it .word 4
    add $30, $30, $31
    lw $31, -4($30) ; Pop $31 from stack
    jr $31 ; Return to loader
```

- Procedure Changes

```
f:
    sw $1, -4($30) ; Push registers we will modify
    sw $2, -8($30)
    lis $2
    .word 8
    sub $30, $30, $2 ; Decrement stack pointer
    ; Insert procedure here
    add $30, $30, $2 ; Assuming $2 is still 8
    lw $2, -8($30) ; Pop registers to restore
    lw $1, -4($30)
    jr $31 ; New line!
```

Lecture 5

Lecture 6

Lecture 7

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Section 2: Tutorials

Tutorial 1

- What is Binary?
  - Binary - ways our machines encode info, and $b \in 0, 1$
- Eg. what is 1000 be
  - $2^3 = 8$ unsigned magnitude
  - -8 2's complement
  - $[T, F, F, F]$ array of bools
  - "backspace char" in ASCII
  - **Representation matters**
- Unsigned binary: n-bit binary number is represented as $b_{n-1}, b_{n-2}, \ldots, b_0$, where $b \in 0, 1$
- To convert to decimal: $2^{n-1} \times b_{n-1} + \ldots + 2^0 \times b_0$
- Decimal to binary
  - Idea 1: take the highest powers of 2 from the decimal (inefficient)
  - Idea 2: Repeatedly divide the number by 2, tracking the quotient & remainder
  - Eg. Convert 23 to binary

Number	Quotient	Remainder
23/2	11	1
11/2	5	1

Number	Quotient	Remainder
5/2	2	1
2/2	1	0
1/2	0	1

    - and read from bottom to up, that will be $10111_2 = 23_{10}$
- 2's complement
  - Range of values for n-ary
    - Unsigned Binary $0 \sim 2^n - 1$
    - 2's complement $-2^{n-1} \sim 2^{n-1} - 1$
- Convert decimal to 2's complement
  - if number is ≥ 0: use the unsigned representation
  - if number is < 0:
    - Get the binary rep of the positive number
    - flip the bits
    - then add 1
- Convert from 2's complement to decimal
  - Method 1: if $b_{n-1} = 1$, then flip the bits, add 1 and negate the positive decimal
  - Method 2: Treat $b_{n-1} -> -2^{n-1} b_{n-1}$, and add the rest as unsigned representation
- Assembly
  - CS 241: MIPS
    - Runs programs $ stores its data all in MEM (RAM)
    - 32 bits system where instructions are encoded as 4 bytes (1 word)
    - Registers hold 1 word of info
    - Special registers
      - 0 = 0$, immutable
      - 31$, end address in RAM, `jr $31` means return address
      - 3, 29,30$
      - $iii\ldots$ <- 2's complement number
        - `divu, multu, addi ...` treats the register values as unsigned binary
  - **Programs live in the same sapce in MEM (RAM) as as the data they operate on**
    - PC cannot distinguish the two
  - Fetch-Execute Cycle

```
PC = 0x00
while True do:    // until PC = $31
    IR = MEM[PC]
    PC = PC + 4
    ... decode $ execute IR ...
done
```

  - Constant Values
    - Use the Load Immediate Skip command (`lis $s`) followed by an instruction to save into `$s`.
      - `lis $s` -> skip the next instruction -> store that instruction into `$s`
      - Use with `.word i` to store `i` into `$s`
      - Eg. Store 10 into `$5`

```
lis $5
.word 10
; the above two lines of commands skips the .word 10 & sets $5 = 10
```

    - Machine Code (based on the order of machine code horizontally for `lis $5`)
      - 000000 (operating code)
      - 00000 (`$s`)
      - 00000 (`$t`)
      - 00101 (`$d`)
      - 00000 (dead code, always be 0)

        - 010100 (function code)
    - Machine Code (`.word 10`)
        - `00000 ....... 000 001010`

Section 3: Reviews

Final Review