COMP1521 26T1

Week 4 Lecture 2

Bitwise Operators

Announcements

- **Week 3 Test** **Due Tomorrow**: Thursday 9pm
  - Many people have not done it yet!
  - Topic: MIPS Basics and MIPS Control
- Week 4 Test Out Tomorrow
  - Topic: MIPS Basics, Control and 1D Arrays
- **Census Date** : Tomorrow Thursday **12th March**
- Assignment 1 Due: Week 5 Friday (next week) at 6pm
- See Help Sessions Schedule
  - It is starting to get busy so get in now…

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Get help from the right places

- ○ Staff in lectures, tuts, labs
- ○ Forum, Help sessions
- ○ Do not get 'help' or submit code from external sources like:
    - ■ ChatGPT, external tutors, other people's code etc
- We run plagiarism checking on all submissions

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Today's Lecture

- Integers Recap Exercises
- End of last lecture
  - Loading in MIPS
- Bitwise Operators

I'll drink 5 ^ 6 beers today

Software developers:

Mathematicians:

Recap: Bit and Bytes

What does this represent in C?

1011011011110001101101011110110

Recap: Bit and Bytes
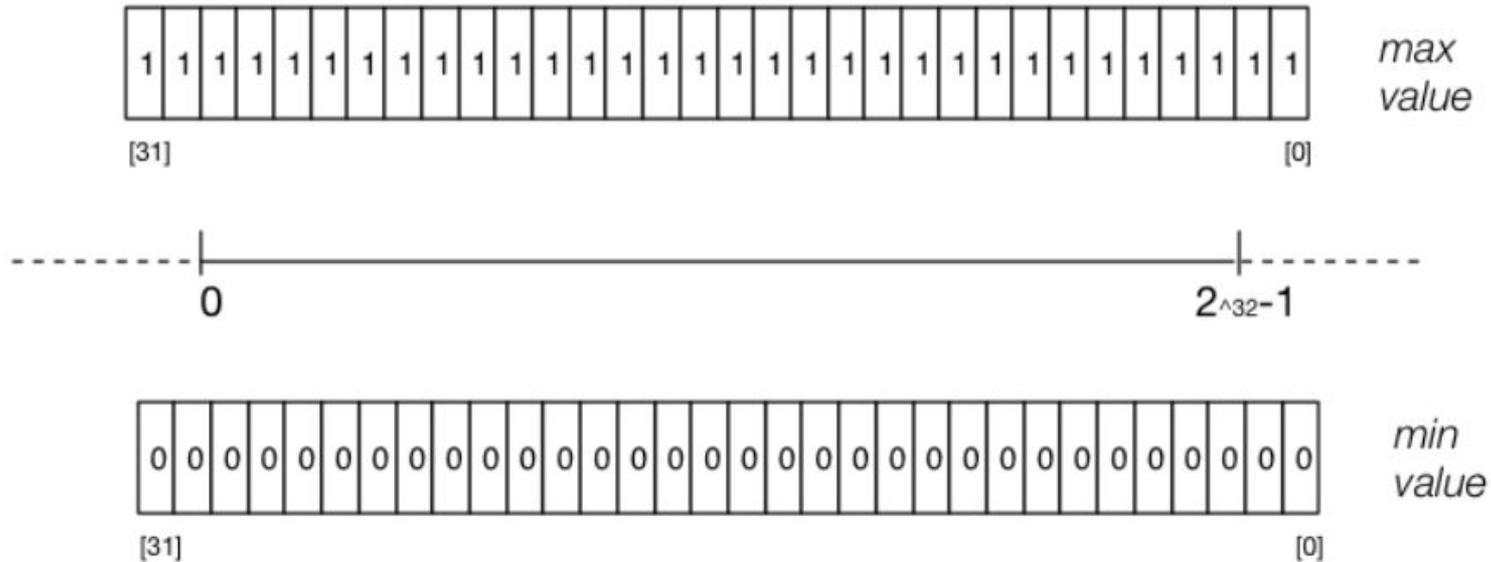
What does this represent in C?

1011011011111000111011010110110

We can't know without knowing its type!
Is it: int, unsigned int, float, unicode character, MIPS instruction?

Unsigned integers

- In C the `unsigned int` data type is 4 bytes on our system

 - means we can store values from the range 0 .. $2^{32}-1$

What do signed binary numbers look like?

- Modern computers use **two's complement** for integers

- Positive integers and zero represented as normal

- Negative integers represented in a way to make maths ✨easy✨ for the computer (not humans)

  - For an n-bit binary number, the number $-b$ is $2^n - b$

  - E.g. 8-bit number "-5" is represented as $2^8 - 5 = 251 = 1111\ 1011_2$

  - Conversely, $1111\ 1011_2$ represents "−5" because $251 − 2^8 = −5$.

Signed integers

- In C the `int` data type is 4 bytes on our system

  - we can store values from the range $-2^{31} .. 2^{31}-1$
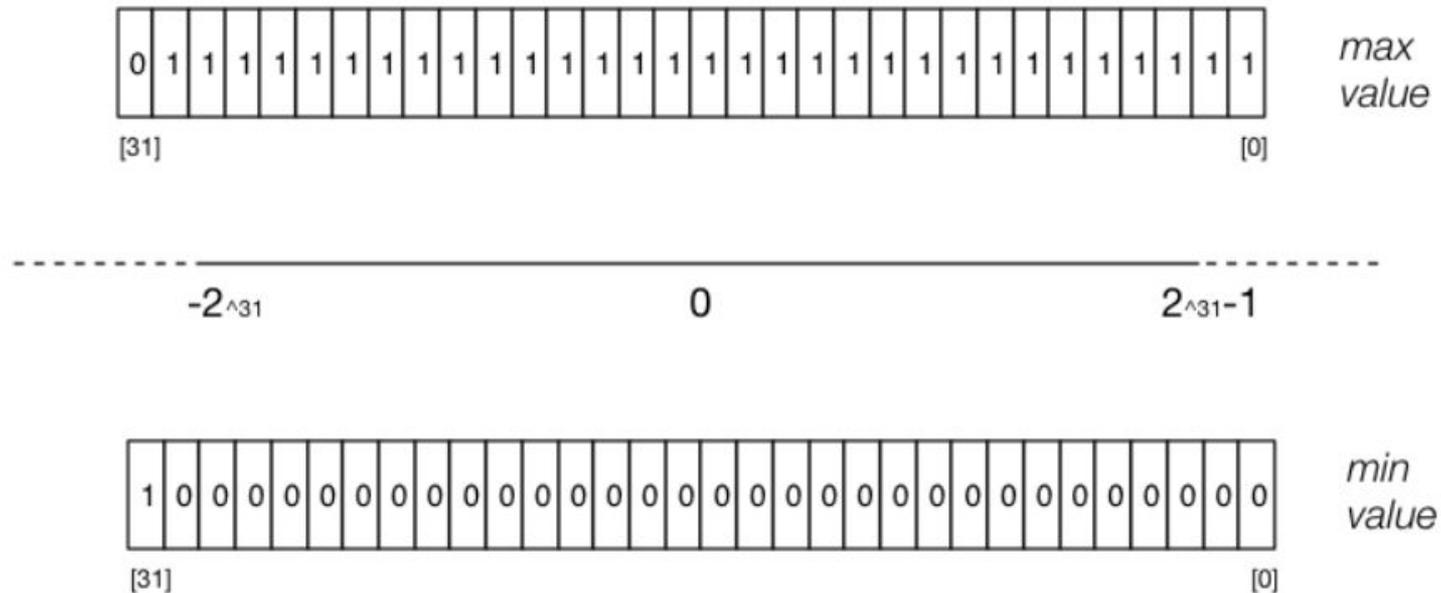
Signed vs Unsigned types

What do these bit patterns represent:

01000011

11000011

in decimal if the type is:

- uint8_t
- int8_t

Signed vs Unsigned types

What do these bit patterns represent:
01000011
11000011
in decimal if the type is:

- uint8_t
  - $01000011 = 2^6 + 2^1 + 2^0 = 64 + 2 + 1 = 67$

- int8_t

Signed vs Unsigned types

What do these bit patterns represent:

01000011

11000011

in decimal if the type is:

- uint8_t
  - $01000011 = 2^6 + 2^1 + 2^0 = 64 + 2 + 1 = 67$
  - $11000011 = 2^7 + 2^6 + 2^1 + 2^0 = 128 + 64 + 2 + 1 =$ **195**
- int8_t

Signed vs Unsigned types

What do these bit patterns represent:

01000011

11000011

in decimal if the type is:

- uint8_t
  - $01000011 = 2^6 + 2^1 + 2^0 = 64 + 2 + 1 = 67$
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- int8_t
  - $01000011 = 2^6 + 2^1 + 2^0 = 64 + 2 + 1 = 67$

Signed vs Unsigned types
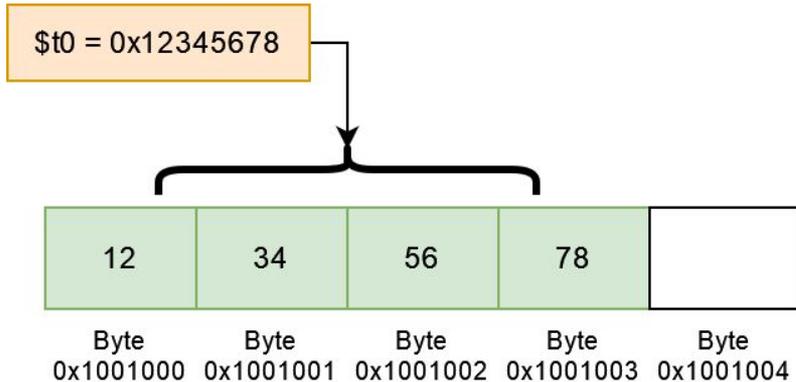
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in decimal if the type is:

- uint8_t
  - $01000011 = 2^6 + 2^1 + 2^0 = 64 + 2 + 1 = 67$
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- int8_t
  - $01000011 = 2^6 + 2^1 + 2^0 = 64 + 2 + 1 = 67$
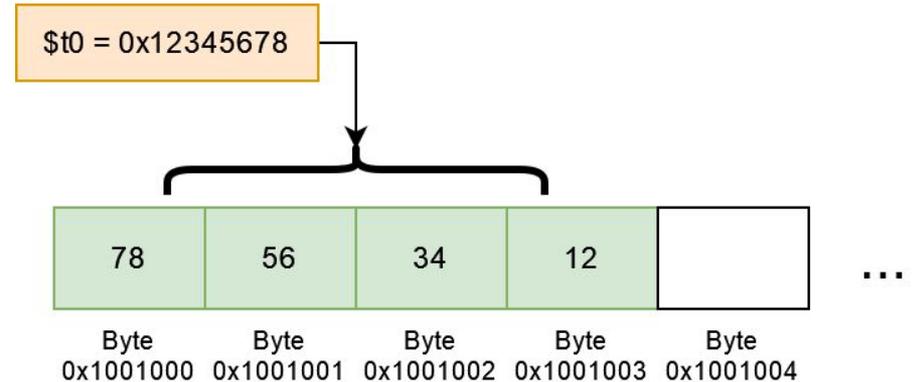 - $11000011 = $ **195** $ - 2^8 = 195 - 256 = -61$

New concept: Endian-ness

- "What order to put things in" is a hard question to answer
- Two schools of thought:
  - **Big**-endian: MSB at the "low address" - big bits "first!"
  - **Little**-endian: LSB at the "low address" - little bits "first!"

BIG: **LITTLE**:

$t0 = 0x12345678

| 12 | 34 | 56 | 78 | | ...
|---|---|---|---|---|

Byte	Byte	Byte	Byte	Byte
0x1001000	0x1001001	0x1001002	0x1001003	0x1001004

$t0 = 0x12345678

| 78 | 56 | 34 | 12 | | ...
|---|---|---|---|---|

Byte	Byte	Byte	Byte	Byte
0x1001000	0x1001001	0x1001002	0x1001003	0x1001004

Code example

- Mipsy-web is **little-endian**

```
        .text
main:

        li $t0, 0x12345678
        sw $t0, my_word


        .data
my_word:

        .space 4
```
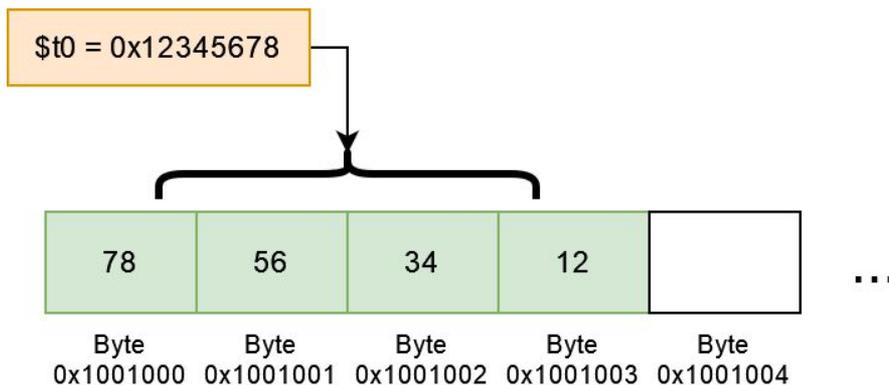
Loading bytes, half-words

The results of these will depend on endianness:
- `lh/lb` assume the loaded byte/halfword is signed
- `lhu/lbu` for doing the same thing, but unsigned

- What might we need to do differently if we are loading a signed vs unsigned number?
- Why did we not need 2 versions for lw?

Loading bytes, half-words

- Consider storing 0x80 in a 4 byte (32 bit register) register
- This only takes up 1 byte (8 bits)
- What do we store in the rest of the register?
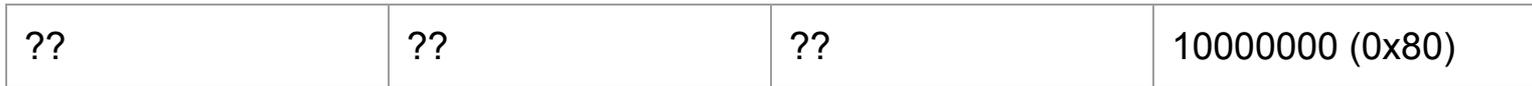
??	??	??	10000000 (0x80)

Loading bytes, half-words

- Consider storing 0x80 in a 4 byte (32 bit register) register
- This only takes up 1 byte (8 bits)
- What do we store in the rest of the register?

00000000 (0x00)	00000000 (0x00)	00000000 (0x00)	10000000 (0x80)

If we set them all the 0s, what happens if 0x80 is meant to be treated as a signed value?

Loading bytes, half-words

- Consider storing 0x80 in a 4 byte (32 bit register) register
- This only takes up 1 byte (8 bits)
- What do we store in the rest of the register?

11111111 (0xFF)	11111111 (0xFF)	11111111 (0xFF)	10000000 (0x80)

If our value is meant to be signed we extend the sign bit. For a negative value this means extending with 1

Loading Examples: lb

```
.text

main:

        lb $t0, my_label

.data

my_label:

        .word 0x12345678
```


$t0 = 0x00000078

78	56	34	12		...

Byte 0x1001000 Byte 0x1001001 Byte 0x1001002 Byte 0x1001003 Byte 0x1001004
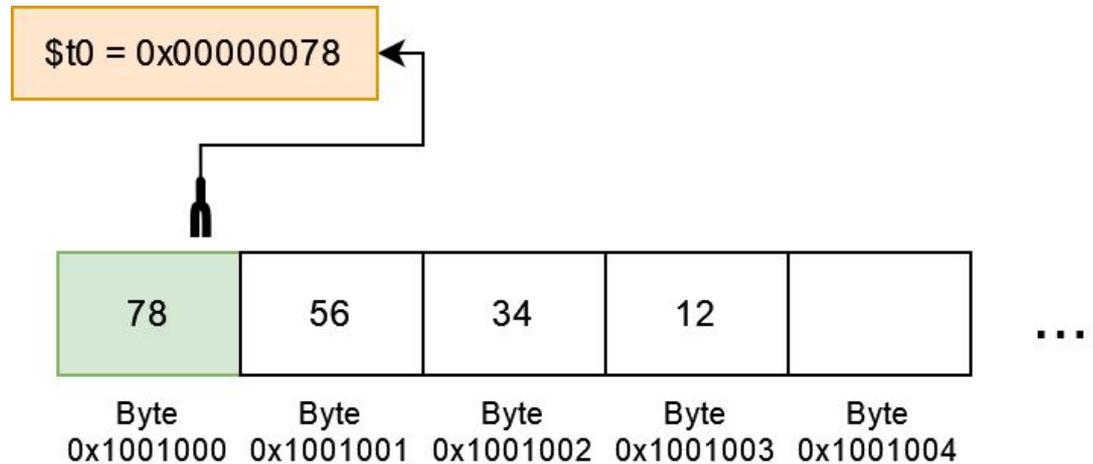
Loading Examples: lh

```
.text

main:

        lh $t0, my_label

.data

my_label:

        .word 0x12345678
```


$t0 = 0x00005678

78	56	34	12		...
Byte 0x1001000	Byte 0x1001001	Byte 0x1001002	Byte 0x1001003	Byte 0x1001004	
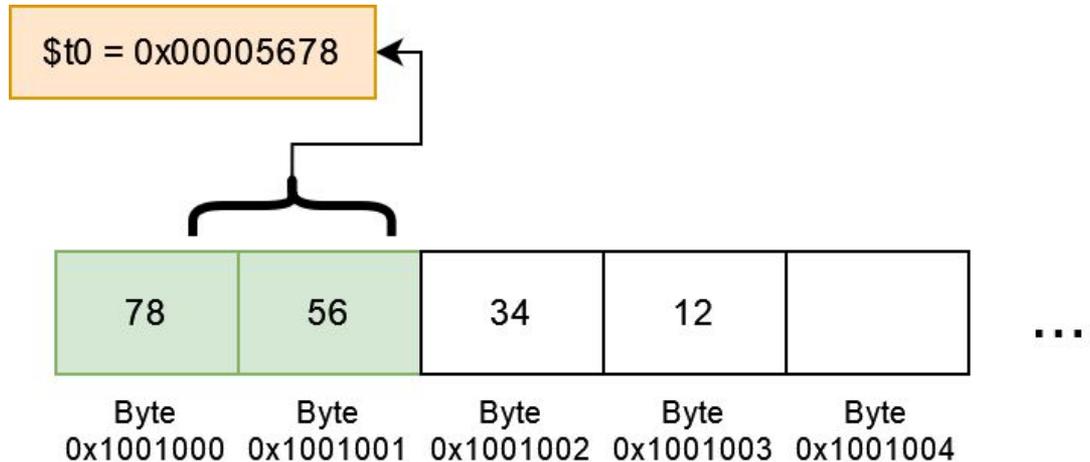
Loading Examples Negative: lb

```
.text

main:

        lb $t0, my_label

.data

my_label:

        .word 0x1234ABCD
```


$t0 = 0xFFFFFFCD

CD	56	34	12		...

Byte
0x1001000

Byte
0x1001001

Byte
0x1001002

Byte
0x1001003

Byte
0x1001004
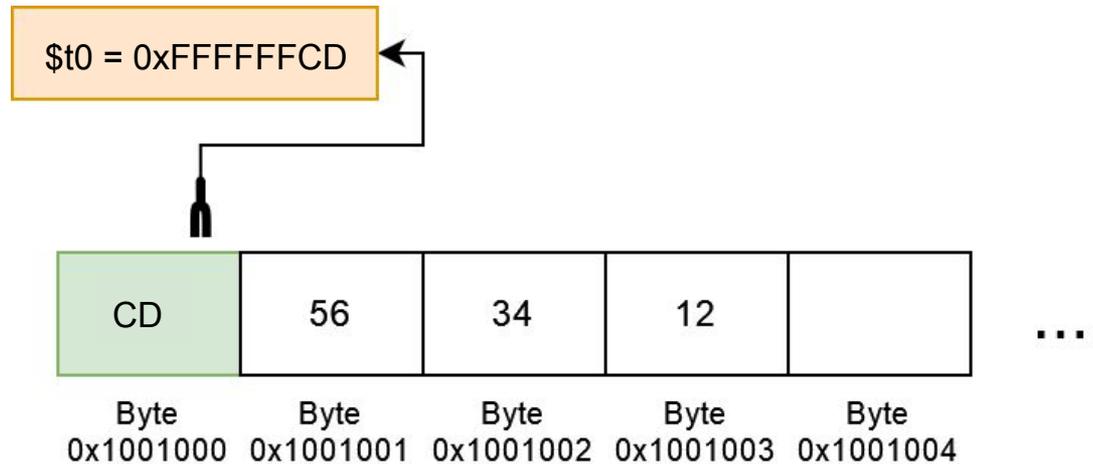
Loading Examples Negative: lh

```
.text

main:

        lh $t0, my_label

.data

my_label:

        .word 0x1234ABCD
```


$t0 = 0xFFFFABCD

CD	AB	34	12		...
Byte 0x1001000	Byte 0x1001001	Byte 0x1001002	Byte 0x1001003	Byte 0x1001004	
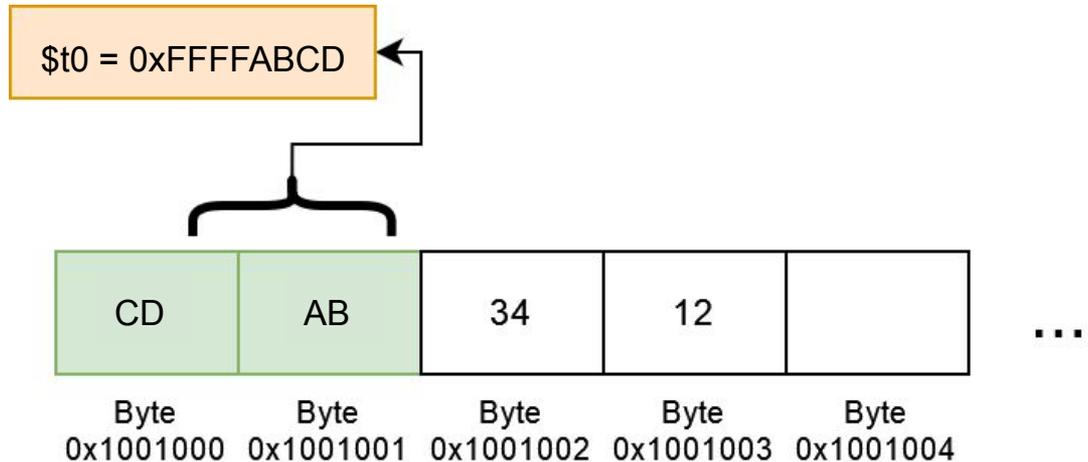
Loading Examples: lbu

```
.text

main:

        lbu $t0, my_label

.data

my_label:

        .word 0x1234ABCD
```

$t0 = 0x000000CD

CD	AB	34	12	

| Byte | Byte | Byte | Byte | Byte |
| 0x1001000 | 0x1001001 | 0x1001002 | 0x1001003 | 0x1001004 |

...
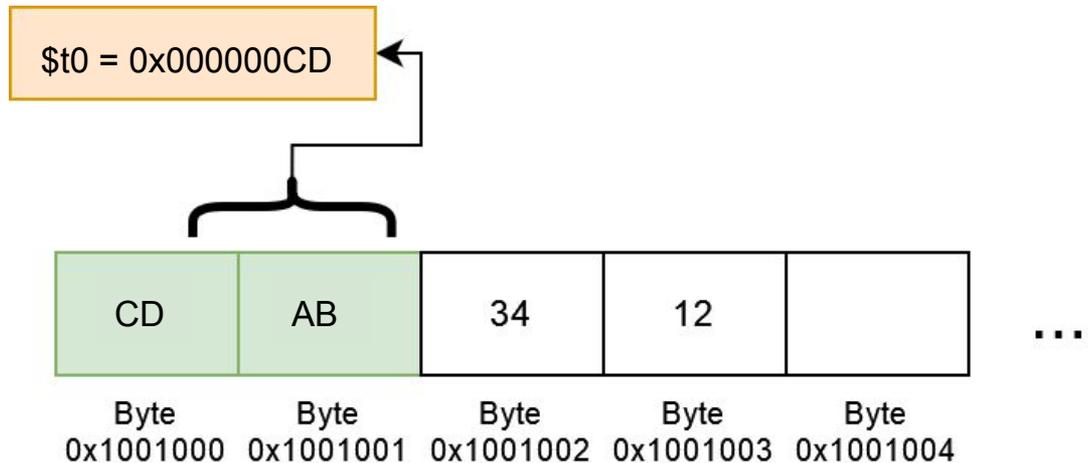
Loading Examples Negative: lhu

```
.text

main:

        lhu $t0, my_label

.data

my_label:

        .word 0x1234ABCD
```

$t0 = 0x0000ABCD

CD	AB	34	12	
Byte 0x1001000	Byte 0x1001001	Byte 0x1001002	Byte 0x1001003	Byte 0x1001004

...
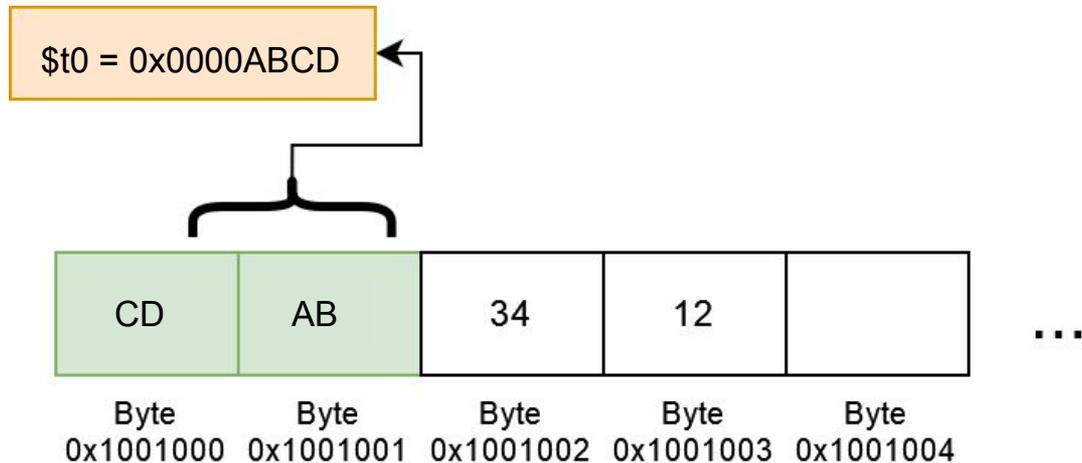
What MIPS instruction is this?

```
0x01288820  =
```

What MIPS instruction is this?

`0x01288820 =`

`0000 0001 0010 1000 1000 1000 0010 0000`

This is the bit pattern, but we need to know more about the MIPS instruction formats to work out what it represents.

What do MIPS instructions look like?

- 32 bits long
- Specify:
  - An operation
    - (The thing to do)
  - 0 or more operands
    - (The thing to do it over)
- For example:

OPCODE	R1	R2	R3	R4	OPCODE	R-type

6 bits — 5 bits — 5 bits — 5 bits — 5 bits — 6 bits

OPCODE	R1	R2	Memory Address Constant Value	I-type

6 bits — 5 bits — 5 bits — 16 bits

OPCODE	R1	Memory Address Constant Value	J-type

6 bits — 5 bits — 21 bits

```
00100001000010010000000000001100

addi $t1, $t0, 12
```

What MIPS instruction is this?

`0x01288820` =

`000000` `01001` `01000` `10001` `00000100000`

What MIPS instruction is this?

`0x01288820 =`

`000000 01001 01000 10001 00000100000`

add

What MIPS instruction is this?

`0x01288820 =`

`000000 01001 01000 10001 00000100000`

add $17

What MIPS instruction is this?

`0x01288820 =`

`000000 01001 01000 10001 00000100000`

`add $17, $9`

What MIPS instruction is this?

`0x01288820 =`

`000000 01001 01000 10001 00000100000`

`add $17, $9, $8`

What MIPS instruction is this?

`0x01288820 =`

`000000 01001 01000 10001 00000100000`

add $17, $9, $8

add $s1, $t1, $t0

Let's type it into mipsy web to check!

Bitwise Operators

Why Learn Bitwise Operators

Used extensively in this course and also:

- Optimisation
- Embedded Systems
- Data compression
- Security and Cryptography
- Graphics
- Computer Networks

Bitwise Operations

- CPUs provide instructions which implement bitwise operations

  - Provide us ways to manipulating the individual bits of a value.

  - MIPS provides 13 bit manipulation instructions

  - C provides 6 bitwise operators

    ```
    &  bitwise AND
    |  bitwise OR
    ^  bitwise XOR (eXclusive OR)
    ~  bitwise NOT
    << left shift
    >> right shift
    ```

Logical AND(&&) vs Bitwise AND (&)

- && works on whole values

  - We usually use it in conditions like:

    - if (x > 10 && x < 20)

- & works on every individual bit in each value

  - We use it to modify and/or extract bit information from values

Bitwise AND (&)

- takes two values (eg. **a & b**) and performs a logical AND between pairs of corresponding bits

  - resulting bits are set to 1 if **both** the original bits in that column are 1

Example:

	128	64	32	16	8	4	2	1
	0	0	1	0	0	1	1	1
&	1	1	1	0	0	0	1	1
	0	0	1	0	0	0	1	1

&	0	1
0	0	0
1	0	1

Used for eg. checking if a particular bit is set (that is, set to 1)

Exercise: &

For any given bit value, x what is:

x & 0 = ?
x & 1 = ?

Exercise: &

For any given bit value, x what is:

x & 0 = 0

x & 1 = x

Bit Masks

We can create bit patterns to help us isolate the bits we are interested in! We call these masks!

For example:
int8_t x = 0x13;   //00010011
int8_t mask = 0x7;   //00000111 &
int8_t result = x & mask;

Bit Masks

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For example:
int8_t x = 0x13;   //00010011
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Bit Masks

We can create bit patterns to help us isolate the bits we are interested in! We call these masks!

For example:
int8_t x = 0x13;   //00010011
int8_t mask = 0x7;   //00000111 &
int8_t result = x & mask;   //00000011

bit_ops_and.c

Checking if a number is odd

The obvious way to check if a number is odd in C:

```c
int is_odd(int n) {
    return n % 2 != 0;
}
```

Checking if a number is odd

Decimal	Binary
0	000
1	001
2	010
3	011
4	100
5	101
6	110
7	111

What pattern do you see in the binary representation of odd numbers?

Checking if a number is odd

Decimal	Binary
0	000
1	00**1**
2	010
3	01**1**
4	100
5	10**1**
6	110
7	11**1**

What pattern do you see in the binary representation of odd numbers?

They all have a 1 as the least significant bit.

We can check that bit to see if it is 1.
If it is it is odd!

Checking if a number is odd

An odd value must have a 1 bit in the 1s place:

128	64	32	16	8	4	2	1
0	0	1	0	0	1	1	1

We can use bitwise AND to check if the last bit is set .

Checking if a number is odd

```c
int is_odd(int n) {
    return n & 1;
}
```

If the value is **ODD** (eg 39):

If the value is **EVEN** (eg 38):

Bitwise OR (|)

- takes two values (eg. **a | b**) and performs a logical OR between pairs of corresponding bits

  - resulting bits are set to 1 if **at least** one of the original bits are 1

Example:

0	0	1	0	0	1	1	1
1	1	1	0	0	0	1	1
1	1	1	0	0	1	1	1

|	0	1
0	0	1
1	1	1

Used for eg. setting particular bits (ie set to 1)

Bit Masks with |

For any given bit value, x what is:

x | 0 = ?
x | 1 = ?

Bit Masks with |

For any given bit value, x what is:

x | 0 = x
x | 1 = 1

Bit Masks with |

For any given bit value, x what is:

x | 0 = x

x | 1 = 1

For example:

uint8_t x = 0x13;   //00010011

uint8_t mask = 0x7;   //00000111

uint8_t result = x | mask;   //00010111

Bitwise Negation (~)

- takes a single value (eg. ~**a**) and performs a logical negation on each bit

Example:

```
~  0  0  0  1  0  1  1  0
   ─────────────────────
   1  1  1  0  1  0  0  1
```

~	0	1
	1	0

Note: This does NOT mean making a number negative!

Bit Masks with ~

We can have a mask we can use to both set bits and unset bits
- Example:
  - mask 0x7 with | to set the least significant 3 bits
  - negate that mask and use it with **&** to unset the least significant 3 bits

Bit Masks with ~

We can have a mask we can use to both set bits and unset bits
- Example:
  - mask 0x7 with | to set the least significant 3 bits
  - negate that mask and use it with **&** to unset the least significant 3 bits

For example:

uint8_t x = 0x13;   //00010011

uint8_t mask = ~0x7;   //11111000

uint8_t result = x & mask; //00010000

Bitwise XOR (^)

- takes two values (eg. **a ^ b**) and performs an exclusive OR between pairs of corresponding bits

  - resulting bits are set to 1 if **exactly** one of the original bits are 1

Example:

```
    0  0  1  0  0  1  1  1
^   1  1  1  0  0  0  1  1
   ─────────────────────────
    1  1  0  0  0  1  0  0
```

^	0	1
0	0	1
1	1	0

Used for eg. cryptography, flipping a bit, checking for bits that don't match

Bit Masks with ^

For any given bit value, x what is:

x ^ 0 = ?

x ^ 1 = ?

Bit Masks with ^

For any given bit value, x what is:

x ^ 0 = x
x ^ 1 = ~x (flips the bit)

Bit Masks with ^

For any given bit value, x what is:

x ^ 0 = x

x ^ 1 = ~x (flips the bit)

For example:

uint8_t x = 0x13;   //00010011

uint8_t mask = 0x7;   //00000111

uint8_t result = x ^ mask;   //00010100

Bit Masks with ^

For any given bit value, x what is:

x ^ 0 = x

x ^ 1 = ~x (flips the bit)

For example:

uint8_t x = 0x13;   //00010011

uint8_t mask = 0x7;   //00000111

uint8_t result = x ^ mask;   //00010100

  What happens if I apply the mask again?

Exercise 1:

- Evaluate the following:

  - 5 && 6

  - 5 & 6

- How many beers did the software developer drink? i.e. What is 5^6

- Code Example: xor.c

I'll drink 5 ^ 6 beers today

Software developers:

Mathematicians:

Left Shift (<<)

- takes a value and a small positive integer x (eg. a << x)
- shifts each bit x positions to the left
  - any bits that fall off the left vanish
  - new 0 bits are inserted on the right
  - result contains the same number of bits as the input
- Example:

```
1  1  1  0  0  0  1  1  << 2
1  0  0  0  1  1  0  0
```

Implications of left shift

What does this mean mathematically?

Implications of left shift

What does this mean mathematically?

Expression	Result Binary	Result Decimal
00000001 << 1	00000010	2
00000001 << 2	00000100	4
00000001 << 3	00001000	8
00000001 << 4	00010000	16

Implications of left shift

What does this mean mathematically? Multiplies by powers of 2!

Expression	Result Binary	Result Decimal
00000001 << 1	00000010	2
00000001 << 2	00000100	4
00000001 << 3	00001000	8
00000001 << 4	00010000	16

Demo: shift_as_multiply.c

Right Shift (>>)

- takes a value and a small positive integer *x* (eg. `a >> x`)
- shifts each bit *x* positions to the right

    - any bits that fall off the right vanish

    - new 0 bits are inserted on the left (for unsigned types)

    - result contains the same number of bits as the input
- Example:

1	1	1	0	0	0	1	1	>> 2
0	0	1	1	1	0	0	0	

Used for eg looping through 1 bit at a time

Implications of right shift for unsigned values

What does this mean mathematically?

Implications of right shift

What does this mean mathematically? 16_{10} == 00010000_2

Expression	Result Binary	Result Decimal
00010000 >> 1	00001000	8
00010000 >> 2	00000100	4
00010000 >> 3	00000010	2
00010000 >> 4	00000001	1

Implications of right shift for unsigned values

What does this mean mathematically? 16_{10} == 00010000_2

Expression	Result Binary	Result Decimal
00010000 >> 1	00001000	8
00010000 >> 2	00000100	4
00010000 >> 3	00000010	2
00010000 >> 4	00000001	1

Divides by powers of 2

Implications of right shift for unsigned values

But what about situations like this? We lose some bits!

0111 >> 1   == 0011

This is the same as 7/2 == 3 with integer division!

Issues with shifting

- Shifts involving negative values may not be portable, and can vary across different implementations
- Common source of bugs in COMP1521 (and elsewhere)
- Always use unsigned values/variables when shifting to be safe/portable

Demo: shift_bug.c

Exercise

Given the following declarations:

```c
// a signed 8-bit value
uint8_t x = 0x55;

uint8_t y = 0xAA;
```

What is the value of each of these expressions?

```c
uint8_t a = x & y;

uint8_t b = x ^ y;

uint8_t c = x << 1;

uint8_t d = y << 2;
```

```c
uint8_t e = x >> 1;

uint8_t f = y >> 2;

uint8_t g = x | y;
```

Code Demo

- get_nth_bit.c

MIPS - Bit manipulation instructions

assembly	meaning	bit pattern
and r_d, r_s, r_t	$r_d = r_s \mathbin{\&} r_t$	`000000ssssstttttddddd00000100100`
or r_d, r_s, r_t	$r_d = r_s \mathbin{\vert} r_t$	`000000ssssstttttddddd00000100101`
xor r_d, r_s, r_t	$r_d = r_s \mathbin{\char`\^} r_t$	`000000ssssstttttddddd00000100110`
nor r_d, r_s, r_t	$r_d = \sim (r_s \mathbin{\vert} r_t)$	`000000ssssstttttddddd00000100111`
andi $r_t, r_s, \mathtt{I}$	$r_t = r_s \mathbin{\&} \mathtt{I}$	`001100ssssstttttIIIIIIIIIIIIIIII`
ori $r_t, r_s, \mathtt{I}$	$r_t = r_s \mathbin{\vert} \mathtt{I}$	`001101ssssstttttIIIIIIIIIIIIIIII`
xori $r_t, r_s, \mathtt{I}$	$r_t = r_s \mathbin{\char`\^} \mathtt{I}$	`001110ssssstttttIIIIIIIIIIIIIIII`
not r_d, r_s	$r_d = \sim r_s$	pseudo-instruction

MIPS - Shift instructions

assembly	meaning	bit pattern
sllv r_d, r_t, r_s	$r_d = r_t \ll r_s$	000000ssssstttttddddd00000000100
srlv r_d, r_t, r_s	$r_d = r_t \gg r_s$	000000ssssstttttddddd00000000110
srav r_d, r_t, r_s	$r_d = r_t \gg r_s$	000000ssssstttttddddd00000000111
sll r_d, r_t, I	$r_d = r_t \ll \mathrm{I}$	00000000000tttttdddddIIIII000000
srl r_d, r_t, I	$r_d = r_t \gg \mathrm{I}$	00000000000tttttdddddIIIII000010
sra r_d, r_t, I	$r_d = r_t \gg \mathrm{I}$	00000000000tttttdddddIIIII000011

- **srl** and **srlv** shift zeroes into most-significant bit

  - This matches shift in C of unsigned values
- **sra** and **srav** propagate most-significant bit

  - This ensures the sign is maintained

MIPS Code Demos

- odd_even.s
- mips_bits.s
- mips_negative_shifts.s

What did we learn today?

- Integer representation recap
- Bitwise Operators
- Next lecture:
  - Finish Bitwise
  - Floating Point Data

Feedback Please!

Your feedback is valuable!

If you have any feedback from today's lecture, please follow the link below or use the QR Code.

Please remember to keep your feedback constructive, so I can action it and improve your learning experience.

https://forms.office.com/r/NKVTwTXixC

Reach Out

Content Related Questions:

Forum

Admin related Questions email:

cs1521@cse.unsw.edu.au

Student Support | I Need Help With…

My Feelings and Mental Health Managing Low Mood, Unusual Feelings & Depression	Mental Health Connect Telehealth	student.unsw.edu.au/**counselling**	In Australia Call Afterhours UNSW Mental Health Support Line	1300 787 026 5pm-9am
	Mind HUB Online Self-Help Resources	student.unsw.edu.au/**mind-hub**	Outside Australia Afterhours 24-hour Medibank Hotline	+61 (2) 8905 0307

Uni and Life Pressures Stress, Financial, Visas, Accommodation & More	Student Support Indigenous Student Support	student.unsw.edu.au/**advisors**
Reporting Sexual Assault/Harassment	Equity Diversity and Inclusion (EDI)	edi.unsw.edu.au/**sexual-misconduct**
Educational Adjustments To Manage my Studies and Disability / Health Condition	Equitable Learning Service (ELS)	student.unsw.edu.au/**els**
Academic and Study Skills	Academic Language Skills	student.unsw.edu.au/**skills**
Special Consideration Because Life Impacts our Studies and Exams	Special Consideration	student.unsw.edu.au/**special-consideration**