COMP1521 25T2

Week 4 Lecture 2

Bitwise Operators

Adapted from Angela Finlayson, Hammond Pearce,
Andrew Taylor and John Shepherd's slides

Announcements

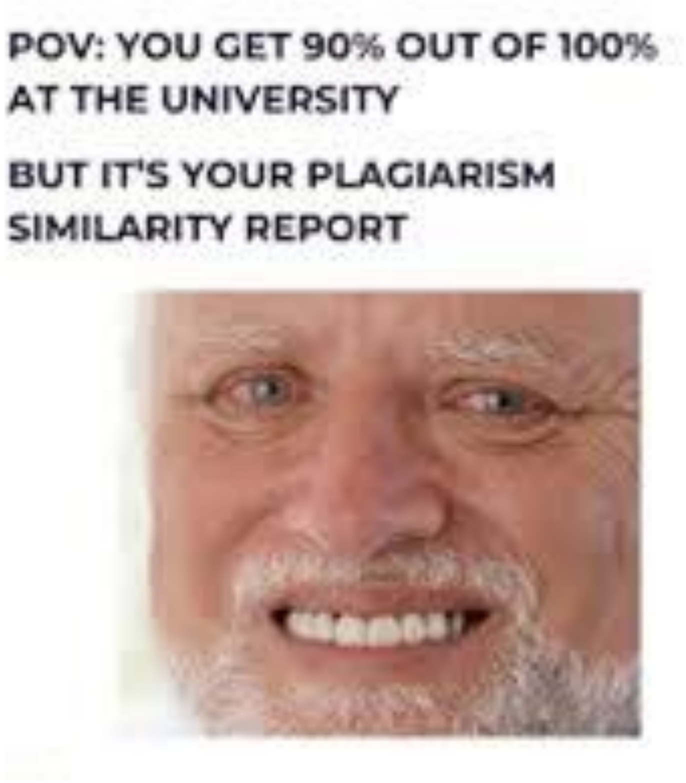
- Week 3 Test Due Tomorrow: Thursday 21:00:00.
- Census Date: Thursday 13th March
- Assignment 1 Due: Week 5 Friday (next week) at 6pm
- See Help Sessions Schedule

Plagiarism

Get help from the right places

- staff in lectures, tuts, labs
- forum, Help Sessions, Revision 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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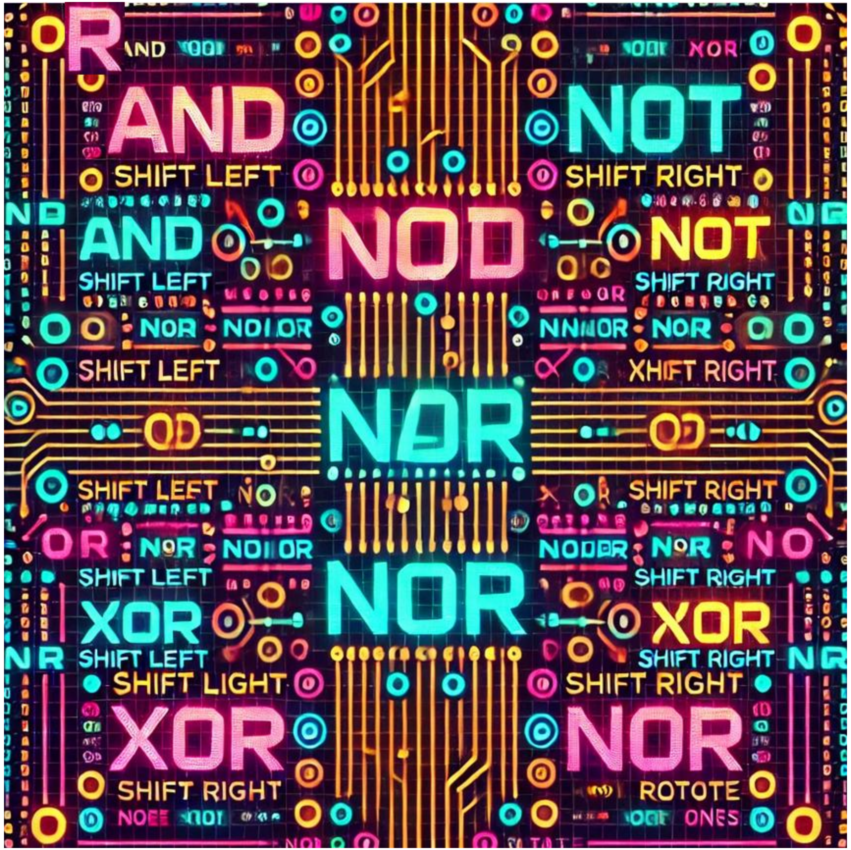
Today's Lecture

- Integers Recap Exercises
- Bitwise Operators



Base

10^3	10^2	10^1	10^0
1000_{10}	100_{10}	10_{10}	1_{10}

16^3	16^2	16^1	16^0
4096_{10}	256_{10}	16_{10}	1_{10}

4705_{10}

It is equivalent to: $4 * 10^3 + 7 * 10^2$

$$+ 0 * 10^1 + 5 * 10^0$$

$$= 4000 + 700 + 0 + 5$$

$3AF1_{16}$

Is equivalent to: $3 * 16^3 + 10 * 16^2$

$$+15 * 16^1 + 1 * 16^0$$

$$= 12288 + 256 + 240 + 1$$

$$= 15089_{10}$$

Recap: Bit and Bytes

What does this represent?

10110110111110001110110101110110

Recap: Bit and Bytes

What does this represent?

10110110111110001110110101110110

We can’t know without knowing its type!

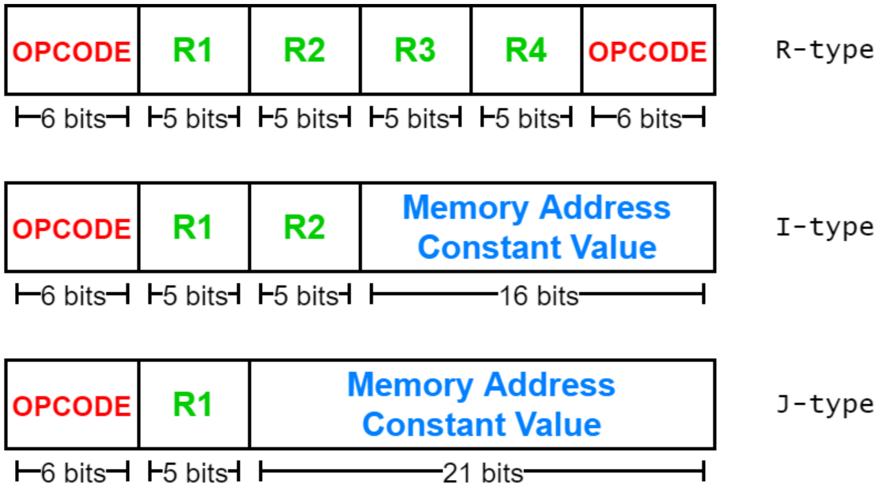
Is it: int, unsigned int, float, unicode character, MIPS instruction?

What MIPS instruction is this?

`0x01288820 =`

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:

`00100001000010010000000000001100`

`addi $t1, $t0, 12`

What MIPS instruction is this?

`0x01288820 =`

`0000 0001 0010 1000 1000 1000 0010 0000`

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`

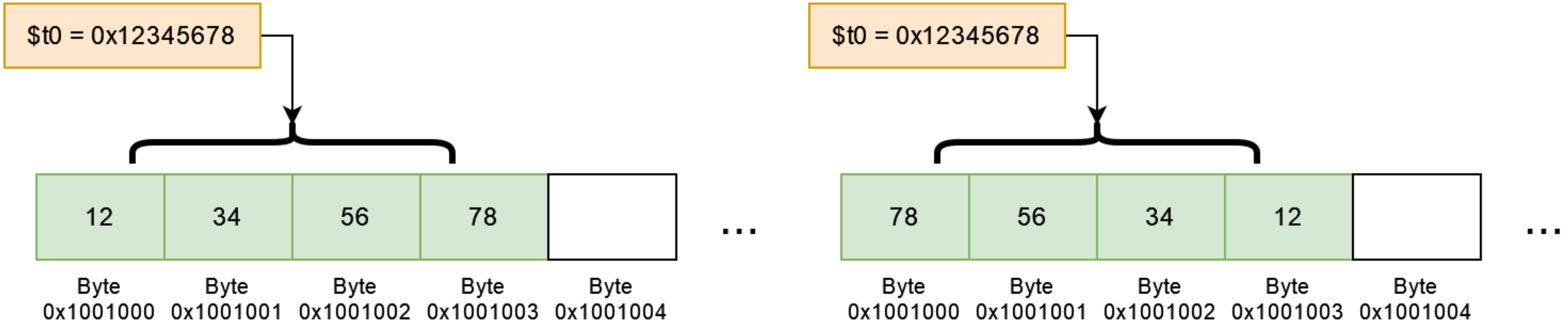
`add $s1, $t1, $t0`

Let’s type it into mipsy web to check!

Recap: 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:



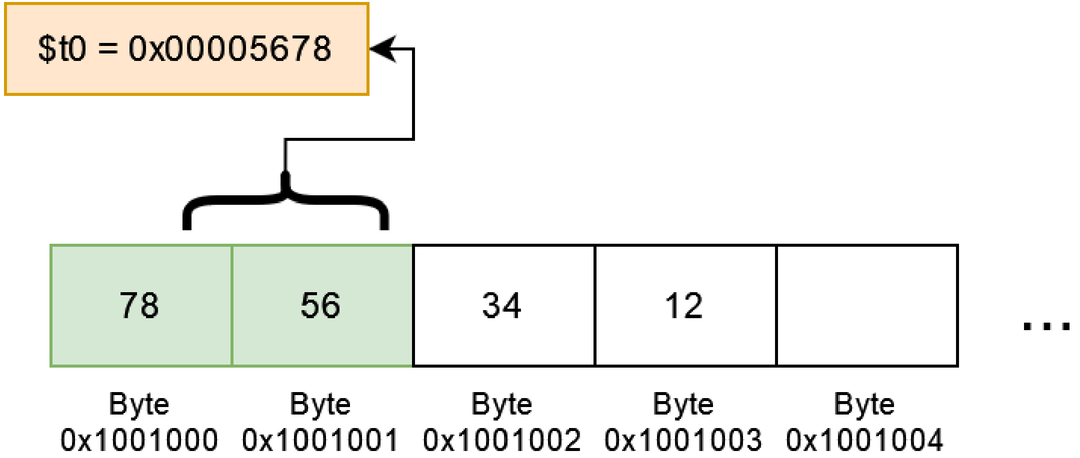
Loading bytes, half-words

The results of these will depend on endianness:

- `lh/lb` assume the loaded byte/halfword is signed
  - The destination register top bits are set to the sign bit
- `lhu/lbu` for doing the same thing, but unsigned

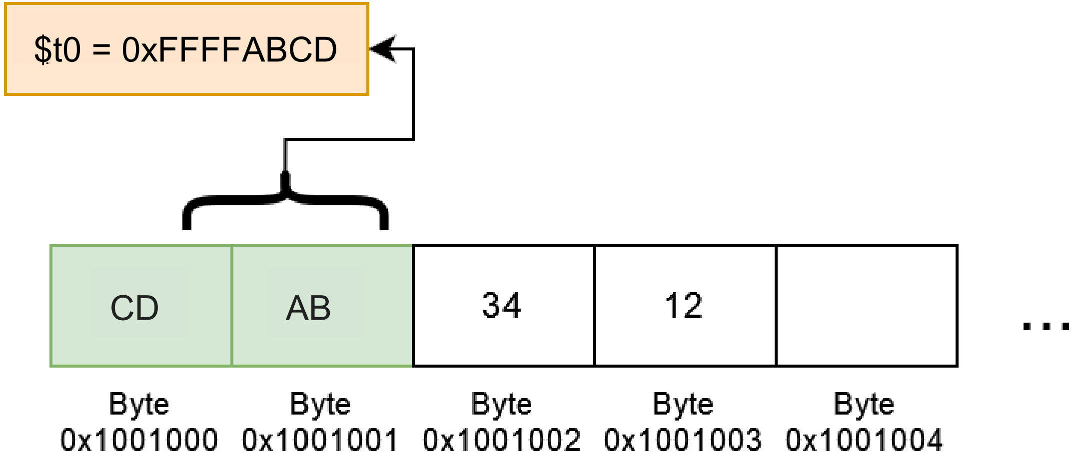
Loading Examples: lh

```
.text
main:
        lh $t0, my_label
.data
my_label:
        .word 0x12345678
```



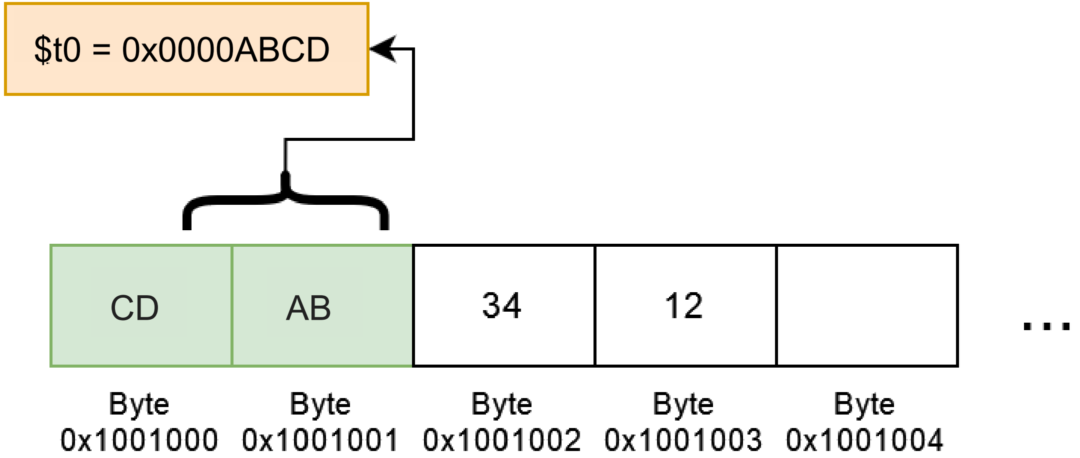
Loading Examples Negative: lh

```
.text
main:
        lh $t0, my_label
.data
my_label:
        .word 0x1234ABCD
```



Loading Examples Negative: lhu

```
.text
main:
        lhu $t0, my_label
.data
my_label:
        .word 0x1234ABCD
```



Fixed size integers

```c
#include <stdint.h>

int main(void) {

                 // range of values for type
                 //                minimum               maximum
    int8_t   i1; //                   -128                   127
    uint8_t  i2; //                      0                   255
    int16_t  i3; //                 -32768                 32767
    uint16_t i4; //                      0                 65535
    int32_t  i5; //            -2147483648            2147483647
    uint32_t i6; //                      0            4294967295
    int64_t  i7; // -9223372036854775808  9223372036854775807
    uint64_t i8; //                      0 18446744073709551615

    return 0;
}
```

```c
#include <limits.h>
```

```c
(char)CHAR_MIN,          (char)CHAR_MAX);

(char)CHAR_MIN,          (char)CHAR_MAX);


(signed char)SCHAR_MIN, (signed char)SCHAR_MAX)
(unsigned char)0,        (unsigned


(short)SHRT_MIN,         (short)SHRT_MAX);
(unsigned short)0,       (unsigned

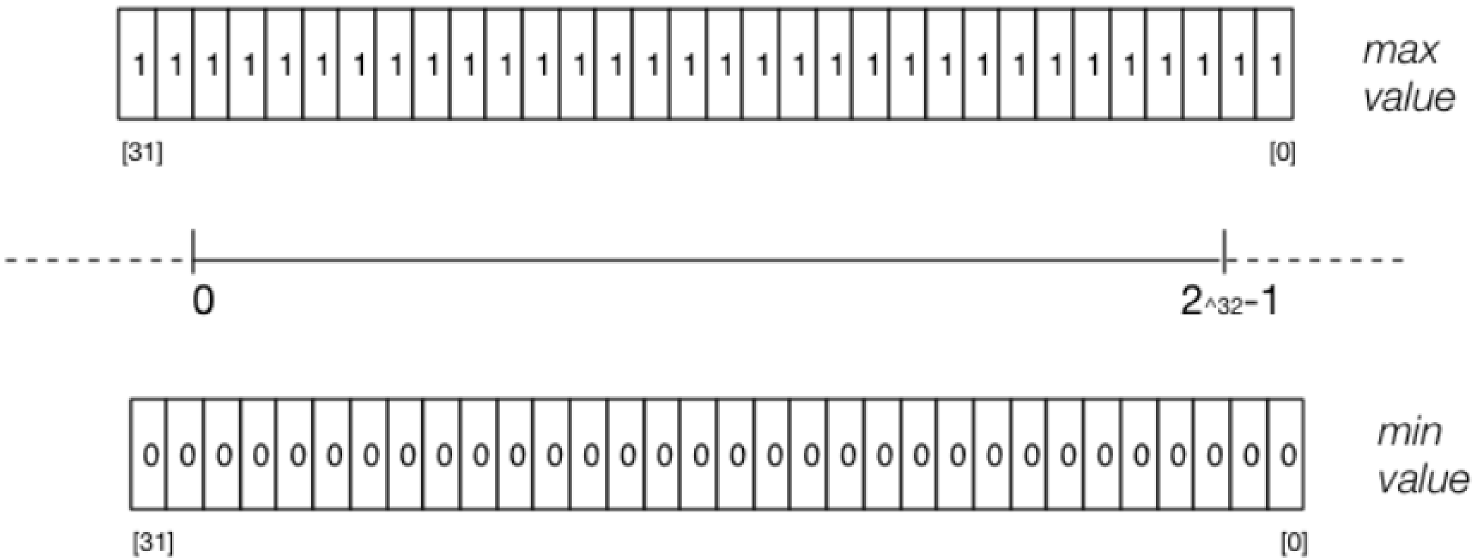

INT_MIN,                 INT_MAX);
(unsigned int)0,         UINT_MAX);

LONG_MIN,                LONG_MAX);
(unsigned long)0,        ULONG_MAX);

LLONG_MIN,               LLONG_MAX);
, (unsigned long long)0, ULLONG_MAX);
```

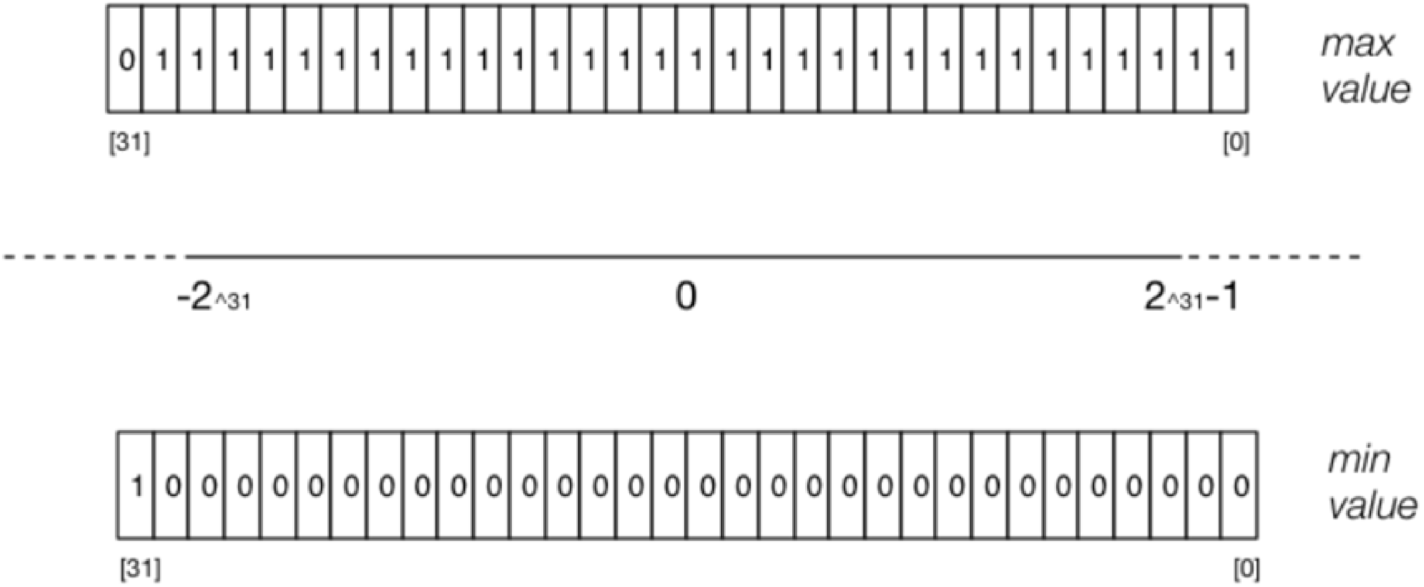
Unsigned integers

- 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



Signed integers

- In C the `int` data type is 4 bytes on our system
  - we can store values from the range $-2^{31} .. 2^{31}-1$



Bitwise Operators

Why Learn Bitwise Operators

Used extensively in this course and also:

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

Why Learn Bitwise Operators

MIPS-161 supervisor registers (not examinable)

<table>
<tr><th>31</th><th>30</th><th>29</th><th>28</th><th>27</th><th>26</th><th>25</th><th>24</th><th>23</th><th>22</th><th>21</th><th>20</th><th>19</th><th>18</th><th>17</th><th>16</th><th>15</th><th>14</th><th>13</th><th>12</th><th>11</th><th>10</th><th>9</th><th>8</th><th>7</th><th>6</th><th>5</th><th>4</th><th>3</th><th>2</th><th>1</th><th>0</th><th>Bits</th></tr>
<tr><td>P</td><td colspan="17">0</td><td colspan="6">SLOT</td><td colspan="8">0</td><td>INDEX</td></tr>
<tr><td colspan="18">0</td><td colspan="6">SLOT</td><td colspan="8">0</td><td>RANDOM</td></tr>
<tr><td colspan="20">PPAGE</td><td>N</td><td>D</td><td>V</td><td>G</td><td colspan="8">0</td><td>TLBLO</td></tr>
<tr><td colspan="11">PTBASE</td><td colspan="19">VSHIFT</td><td colspan="2">0</td><td>CONTEXT</td></tr>
<tr><td colspan="32">BADVADDR</td><td>BADVADDR</td></tr>
<tr><td colspan="20">VPAGE</td><td colspan="6">ASID</td><td colspan="6">0</td><td>TLBHI</td></tr>
<tr><td>d</td><td>c</td><td>b</td><td>a</td><td colspan="5">0</td><td>B</td><td>T</td><td>E</td><td>M</td><td>Z</td><td>S</td><td>I</td><td>H</td><td>H</td><td>H</td><td>H</td><td>H</td><td>H</td><td>F</td><td>F</td><td colspan="2">0</td><td>KUo</td><td>IEo</td><td>KUp</td><td>IEp</td><td>KUc</td><td>IEc</td><td>STATUS</td></tr>
<tr><td>BD</td><td>0</td><td colspan="2">CE</td><td colspan="12">0</td><td>H</td><td>H</td><td>H</td><td>H</td><td>H</td><td>H</td><td>F</td><td>F</td><td colspan="2">0</td><td colspan="4">EXC</td><td colspan="2">0</td><td>CAUSE</td></tr>
<tr><td colspan="32">EPC</td><td>EPC</td></tr>
<tr><td colspan="16">0</td><td colspan="16">PRID</td><td>PRID</td></tr>
</table>

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 particular bits are set (that is, set to 1) or unsetting bits (that is, setting them to 0)

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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For example:

```
int8_t x = 0x13;               //00010011
int8_t mask = 0x7;             //00000111  &
int8_t result = x & mask;      //00000011
```

Checking if a number is odd

The obvious way to check if a number is odd in 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	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?

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

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

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

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

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

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

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:

```
int8_t x = 0x13;                          //00010011
int8_t mask = 0x7;                        //00000111
int8_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 use a mask to both set and unset bits

- Example:
  - Mask 0x7 with | to set the least significant 3 bits
  - ~ that mask and use it with & to unset the least significant 3 bits

Bit Masks with ~

We can use a mask to both set and unset bits

- Example:
  - Mask 0x7 with | to set the least significant 3 bits
  - ~ that mask and use it with & to unset the least significant 3 bits

For example:

```
int8_t x = 0x13;              //00010011
int8_t mask = ~0x7;           //11111000
int8_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 e.g. 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

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:

```
int8_t x = 0x13;               //00010011
int8_t mask = 0x7;             //00000111
int8_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:

```
int8_t x = 0x13;              //00010011
int8_t mask = 0x7;            //00000111
int8_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?

Bitwise Operations

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

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]

<< Exercise <<

- Can you program x * 6 without multiplication?

<< Exercise <<

- Can you program x * 6 without multiplication?

$$x * 6 = x * 4 + x * 2$$

$$= (x \ll 2) + (x \ll 1)$$

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

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

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

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

Code Demos

- get_nth_bit.c
- xor.c
- pokemon.c
- set_low_bits.c

Demo: pokemon.c

```
#define FIRE_TYPE       0x0001
#define FIGHTING_TYPE   0x0002
#define WATER_TYPE      0x0004
#define FLYING_TYPE     0x0008
#define POISON_TYPE     0x0010
#define ELECTRIC_TYPE   0x0020
#define GROUND_TYPE     0x0040
#define PSYCHIC_TYPE    0x0080
#define ROCK_TYPE       0x0100
#define ICE_TYPE        0x0200
#define BUG_TYPE        0x0400
#define DRAGON_TYPE     0x0800
#define GHOST_TYPE      0x1000
#define DARK_TYPE       0x2000
#define STEEL_TYPE      0x4000
#define FAIRY_TYPE      0x8000
```

Exercise 2

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;
```

MIPS - Bit manipulation instructions

assembly	meaning	bit pattern
and r_d, r_s, r_t	$r_d = r_s \,\&\, r_t$	`000000ssssstttttddddd00000100100`
or r_d, r_s, r_t	$r_d = r_s \mid r_t$	`000000ssssstttttddddd00000100101`
xor r_d, r_s, r_t	$r_d = r_s \,\char`^\, r_t$	`000000ssssstttttddddd00000100110`
nor r_d, r_s, r_t	$r_d = \sim(r_s \mid r_t)$	`000000ssssstttttddddd00000100111`
andi r_t, r_s, I	$r_t = r_s \,\&\,$ I	`001100ssssstttttIIIIIIIIIIIIIIII`
ori r_t, r_s, I	$r_t = r_s \mid$ I	`001101ssssstttttIIIIIIIIIIIIIIII`
xori r_t, r_s, I	$r_t = r_s$ ^ 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	$r_d = r_t \ll$ I	00000000000tttttdddddIIIII000000
srl r_d, r_t, I	$r_d = r_t \gg$ I	00000000000tttttdddddIIIII000010
sra r_d, r_t, I	$r_d = r_t \gg$ 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

What did we learn today?

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

Reach Out

Content Related Questions:
[Forum]

Admin related Questions
email:
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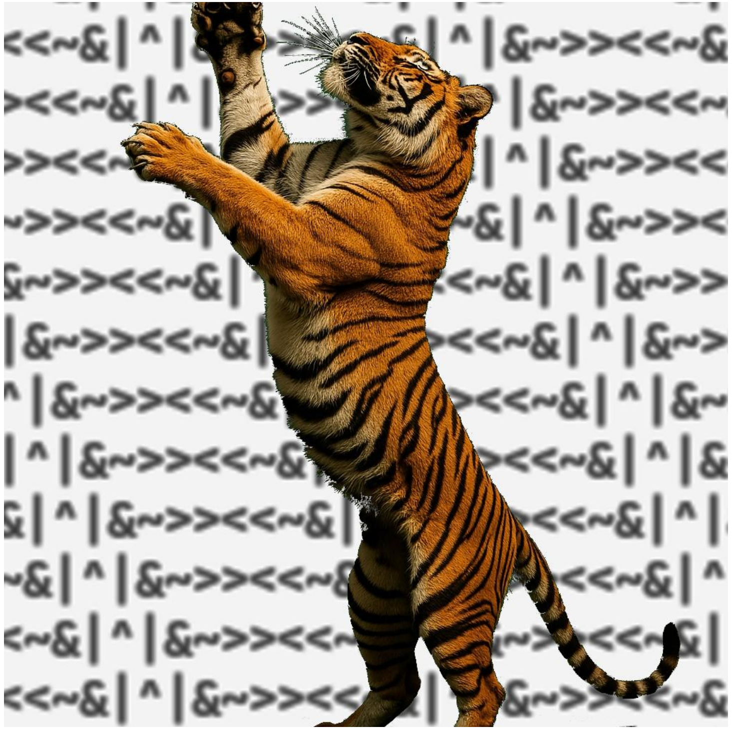

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My Feelings and Mental Health Managing Low Mood, Unusual Feelings & Depression	**Mental Health Connect**	student.unsw.edu.au/**counselling** Telehealth	**In Australia Call Afterhours UNSW Mental Health Support Line** — 1300 787 026 5pm-9am
	Mind HUB	student.unsw.edu.au/**mind-hub** Online Self-Help Resources	**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**	