The Memory Subsystem

- memory subsystem typically provides capability to load or store bytes
- each byte has unique address, think of:
  - memory as implementing a gigantic array of bytes
  - and the address is the array index
- on the MIPS32 machine, all addresses are 32-bit
- most general purpose computers now use 64-bit addresses (and there are 64-bit MIPS)
- typically, a small (1, 2, 4, 8, ...) group of bytes can be loaded/stored in single operations
- general purpose computers typically have complex cache systems to improve memory performance (not covered in this course)
- operating systems on general purpose computers typically provide virtual memory (covered later in this course)

Accessing Memory on the MIPS

- addresses are 32 bit (but there are 64-bit MIPS CPUs)
- only load/store instructions access memory on the MIPS
- 1 byte (8-bit) loaded/stored with `lb`/`sb`
- 2 bytes (16-bit) called a half-word, loaded/stored with `lh`/`sh`
- 4 bytes (32-bits) called a word, loaded/stored with `lw`/`sw`
- memory address used for load/store instructions is sum of a specified register and a 16-bit constant (often 0) which is part of the instruction
- for `sb` & `sh` operations low (least significant) bits of source register are used.
- `lb`/`lh` assume byte/halfword contains a 8-bit/16-bit signed integer
  - high 24/16-bits of destination register set to 1 if 8-bit/16-bit integer negative
  - unsigned equivalents `lbu` & `lhu` assume integer is unsigned
  - high 24/16-bits of destination register always set to 0
### MIPS Load/Store Instructions

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Meaning</th>
<th>Bit Pattern</th>
</tr>
</thead>
</table>
| **lb** \( r_t, I(r_s) \) | \( r_t = \text{mem}[r_s + I] \) | 100000ssssstttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttttt
# simple example of storing & loading a byte

main:
li $t0, 42
la $t1, x
sb $t0, 0($t1)  # store $a0 in byte at address labelled x
lb $a0, 0($t1)  # load $a0 from same address
li $v0, 1      # print $a0
syscall
li $a0, \n'       # print \n'
li $v0, 11
syscall
li $v0, 0      # return 0
jr $ra

.data
x: .space 1  # set aside 1 byte and associate label x with its address

source code for load_store.s

https://www.cse.unsw.edu.au/~cs1521/21T3/ COMP1521 21T3 — MIPS Data

Testing Endian-ness

C

```c
uint8_t b;
uint32_t u;
u = 0x03040506;
// load first byte of u
b = *(uint8_t *)&u;
// prints 6 if little-endian
// and 3 if big-endian
printf("%d\n", b);
```

source code for endian.c

MIPS

```mips
li $t0, 0x03040506
la $t1, u
sw $t0, 0($t1)  # u = 0x03040506;
lb $a0, 0($t1)  # b = *(uint8_t *)&u;
li $v0, 1      # printf("%d", a0);
syscall
li $a0, \n'       # printf("%c", \n');
li $v0, 11
syscall
li $v0, 0      # return 0
jr $ra
.data
u: .space 4
```

source code for endian.s

Setting A Register to An Address

- Note the `la` (load address) instruction is used to set a register to a labelled memory address.

```
la $t8, start
```

- The memory address will be fixed before the program is run, so this differs only syntactically from the `li` instruction.

- For example, if `vec` is the label for memory address `0x10000100` then these two instructions are equivalent:

```
la $t7, vec
li $t7, 0x10000100
```

- In both cases the constant is encoded as part of the instruction(s).

- Neither `la` or `li` access memory!
  They are very different to `lw` etc
Specifying Addresses: Some SPIM short-cuts

- SPIM allows the constant which is part of load & store instructions can be omitted in the common case it is 0.

```plaintext
sb $t0, 0($t1)  # store $t0 in byte at address in $t1
sb $t0, ($t1)   # same
```

- For convenience, SPIM allows addresses to be specified in a few other ways and will generate appropriate real MIPS instructions.

```plaintext
sb $t0, x       # store $t0 in byte at address labelled x
sb $t1, x+15   # store $t1 15 bytes past address labelled x
sb $t2, x($t3) # store $t2 $t3 bytes past address labelled x
```

- These are effectively pseudo-instructions.
- You can use these short cuts but won't help you much.
- Most assemblers have similar short cuts for convenience.

---

SPIM Memory Layout

<table>
<thead>
<tr>
<th>Region</th>
<th>Address</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>.text</td>
<td>0x00400000</td>
<td>instructions only; read-only; cannot expand</td>
</tr>
<tr>
<td>.data</td>
<td>0x10000000</td>
<td>data objects; read/write; can be expanded</td>
</tr>
<tr>
<td>.stack</td>
<td>.0x7fffffff</td>
<td>this address and below; read/write</td>
</tr>
<tr>
<td>.ktext</td>
<td>0x80000000</td>
<td>kernel code; read-only; only accessible in kernel mode</td>
</tr>
<tr>
<td>.kdata</td>
<td>0x90000000</td>
<td>kernel data; only accessible in kernel mode</td>
</tr>
</tbody>
</table>

---

Global/Static Variables

Global and static variables need an appropriate number of bytes allocated in .data segment, using .space:

```plaintext
double  val;  val: .space 8
char    str[20]; str: .space 20
int     vec[20]; vec: .space 80
```

Initialised to 0 by default ... other directives allow initialisation to other values:

```plaintext
int val = 5;       val: ..double 5
int arr[4] = {9,8,7,6}; arr: .word 9, 8, 7, 6
char msg[7] = "Hello\n"; msg: .asciiz "Hello\n"
```
add: local variables in registers

C

```c
int main(void) {
    int x, y, z;
    x = 17;
    y = 25;
    z = x + y;
}
```

MIPS

```mips
main:
    # x in $t0
    # y in $t1
    # z in $t2
    li $t0, 17
    li $t1, 25
    add $t2, $t1, $t0
    // ...
```

add variables in memory (uninitialized)

C

```c
int x, y, z;
int main(void) {
    x = 17;
    y = 25;
    z = x + y;
}
```

MIPS (.data)

```mips
.data
    x: .space 4
    y: .space 4
    z: .space 4
```

MIPS (.text)

```mips
main:
    li $t0, 17 # x = 17;
    la $t1, x
    lw $t1, 0($t0)
    li $t0, 25 # y = 25;
    la $t0, y
    lw $t0, 0($t0)
    la $t0, x
    lw $t0, 0($t0)
    add $t3, $t1, $t2 # z = x + y
    la $t0, z
    sw $t3, 0($t0)
```

source code for add_memory.s

add variables in memory (initialized)

C

```c
int x=17, y=25, z;
int main(void) {
    z = x + y;
}
```

MIPS .data

```mips
.data
    x: .word 17
    y: .word 25
    z: .space 4
```

MIPS .text

```mips
main:
    la $t0, x
    lw $t1, 0($t0)
    la $t0, y
    lw $t2, 0($t0)
    add $t3, $t1, $t2 # z = x + y
    la $t0, z
    sw $t3, 0($t0)
    la $t0, z
```

source code for add_memory_initialized.s

add variables in memory (initialized)
add variables in memory (array)

C

```c
int x[] = {17,25,0};
int main(void) {
    x[2] = x[0] + x[1];
}
```

MIPS .data

```mips
.data
# int x[] = {17,25,0}
x: .word 17, 25, 0
```

store value in array element — example 1

C

```c
int x[10];

int main(void) {
    // sizeof x[0] == 4
    x[3] = 17;
}
```

MIPS

```mips
main:
    li $t0, 3
    # each array element is 4 bytes
    mul $t0, $t0, 4
    la $t1, x
    add $t2, $t1, $t0
    li $t3, 17
    sw $t3, 0($t2)
    .data
    x: .space 40
```

store value in array element - example 2

C

```c
#include <stdint.h>

int16_t x[30];

int main(void) {
    // sizeof x[0] == 2
    x[13] = 23;
}
```

MIPS

```mips
main:
    li $t0, 13
    # each array element is 2 bytes
    mul $t0, $t0, 2
    la $t1, x
    add $t2, $t1, $t0
    li $t3, 23
    sh $t3, 0($t2)
    .data
    x: .space 60
```
C

```c
int main(void) {
    int i = 0;
    while (i < 5) {
        printf("%d
", numbers[i]);
        i++;
    }
    return 0;
}
```

Simplified C

```c
int main(void) {
    int i = 0;
    loop:
        if (i >= 5) goto end;
        printf("%d", numbers[i]);
        printf("%c", 
        i++;
        goto loop;
    end:
        return 0;
}
```

Printing Array: MIPS

```mips
# print array of ints
# i in $t0
main:
    li $t0, 0  # int i = 0;
loop:
    bge $t0, 5, end  # if (i >= 5) goto end;
    la $t1, numbers  # int j = numbers[i];
    mul $t2, $t0, 4
    add $t3, $t2, $t1
    lw $a0, 0($t3)  # printf("%d", j);
    li $v0, 1
    syscall
    li $a0, \n  # printf("%c", \n;
    li $v0, 11
    syscall
    addi $t0, $t0, 1  # i++
    b loop  # goto loop
end:
    li $v0, 0  # return 0
    jr $ra
.data
numbers:  # int numbers[10] = { 3, 9, 27, 81, 243};
    .word 3, 9, 27, 81, 243
```

Printing Array: MIPS (continued)
Printing Array with Pointers: C to simplified C

C

```c
int main(void) {
    int *p = &numbers[0];
    int *q = &numbers[4];
    while (p <= q) {
        printf("%d\n", *p);
        p++;
    }
    return 0;
}
```

Simplified C

```c
int main(void) {
    int *p = &numbers[0];
    int *q = &numbers[4];
    loop:
        if (p > q) goto end;
        int j = *p;
        printf("%d", j);
        printf("%c", \
        p++;
        goto loop;
    end:
        return 0;
}
```

Printing Array with Pointers: MIPS

```mips
# p in $t0, q in $t1
main:
    la $t0, numbers # int *p = &numbers[0];
    la $t0, numbers # int *q = &numbers[4];
    addi $t1, $t0, 16 #

loop:
    bgt $t0, $t1, end # if (p > q) goto end;
    lw $a0, 0($t0) # int j = *p;
    li $v0, 1
    syscall
    li $a0, \
    li $v0, 11
    syscall
    addi $t0, $t0, 4 # p++
    b loop # goto loop
end:
```

Printing 1-d Arrays in MIPS - v1

C

```c
int vec[5]={0,1,2,3,4};
int i = 0
while (i < 5) {
    printf("%d", vec[i]);
    i++;
}
```

MIPS

```mips
# ...
    li $s0, 0

loop:
    bge $s0, 5, end
    la $t0, vec
    mul $t1, $s0, 4
    add $t2, $t1, $t0
    lw $a0, ($t2)
    li $v0, 1
    syscall
    addi $s0, $s0, 1
    b loop
end:
```

.data

```mips
vec: .word 0, 1, 2, 3, 4
```

https://www.cse.unsw.edu.au/~cs1521/21T3/ COMP1521 21T3 — MIPS Data 22 / 34

https://www.cse.unsw.edu.au/~cs1521/21T3/ COMP1521 21T3 — MIPS Data 23 / 34

https://www.cse.unsw.edu.au/~cs1521/21T3/ COMP1521 21T3 — MIPS Data 24 / 34
Example C with unaligned accesses

```c
uint8_t bytes[32];
uint32_t *i = (int *)&bytes[1];
// illegal store - not aligned on a 4-byte boundary
*i = 0x03040506;
printf("%d\n", bytes[1]);
```

source code for unalign.c

Example MIPS with unaligned accesses

```mips
.data
# data will be aligned on a 4-byte boundary
# most likely on at least a 128-byte boundary
# but safer to just add a .align directive
.align 2
.space 1
v1: .space 1
v2: .space 4
v3: .space 2
v4: .space 4
.space 1
.align 2 # ensure e is on a 4 (2**2) byte boundary
v5: .space 4
.space 1
v6: .word 0 # word directive aligns on 4 byte boundary
```

source code for unalign.s

Example MIPS with unaligned accesses

```mips
li $t0, 1
sb $t0, v1 # will succeed because no alignment needed
sh $t0, v1 # will fail because v1 is not 2-byte aligned
sw $t0, v1 # will fail because v1 is not 4-byte aligned
sh $t0, v2 # will succeed because v2 is 2-byte aligned
sw $t0, v2 # will fail because v2 is not 4-byte aligned
sh $t0, v3 # will succeed because v3 is 2-byte aligned
sw $t0, v3 # will fail because v3 is not 4-byte aligned
sh $t0, v4 # will succeed because v4 is 2-byte aligned
sw $t0, v4 # will succeed because v4 is 4-byte aligned
sw $t0, v5 # will succeed because v5 is 4-byte aligned
sw $t0, v6 # will succeed because v6 is 4-byte aligned
li $v0, 0 # return
jr $ra
```

source code for unalign.s
C data structures and their MIPS representations:

- **char** as byte in memory, or register
- **int** as 4 bytes in memory, or register
- **double** as 8 bytes in memory, or register
- **arrays** sequence of bytes in memory, elements accessed by index (calculated on MIPS)
- ** structs** sequence of bytes in memory, accessed by fields (constant offsets on MIPS)

A char, int or double

- can be stored in register if local variable and no pointer to it
- otherwise stored on stack if local variable
- stored in data segment if global variable

### Printing 1-d Array in MIPS - v2

```c
int vec[5]={0,1,2,3,4};
// ...
int *p = &vec[0];
int *end = &vec[4];
while (p <= end) {
    int y = *p;
    printf("%d", y);
    p++;
}
// ....
```

```mips
li $s0, vec
la $t0, vec
add $s1, $t0, 16
loop:
    bgt $s0, $s1, end
    lw $a0, 0($s0)
    li $v0, 1
    syscall
    addi $s0, $s0, 4
    b loop
end:
.data
vec: .word 0, 1, 2, 3, 4
```

### Computing sum of 2-d Array : C

Assume we have a 2d-array:

```c
int32_t matrix[6][5];
```

We can sum its value like this in C

```c
int row, col, sum = 0;
// row-by-row
for (row = 0; row < 6; row++) {
    // col-by-col within row
    for (col = 0; col < 5; row++) {
        sum += matrix[row][col];
    }
}
```

MIPS directives for an equivalent 2d-array

```mips
.data
matrix: .space 120 # 6 * 5 == 30 array elements each 4 bytes
```
Computing sum of 2-d Array: MIPS

li $s0, 0  # sum = 0
li $s2, 0  # row = 0
loop1: bge $s2, 6, end1  # if (row >= 6) break
li $s4, 0  # col = 0
loop2: bge $s4, 5, end2  # if (col >= 5) break
la $t0, matrix
mul $t1, $s2, 20  # t1 = row*rowsize
mul $t2, $s4, 4  # t2 = col*intsize
add $t3, $t0, $t1  # offset = t0+t1
add $t4, $t3, $t2  # offset = t0+t1
lw $t5, 0($t4)  # t0 = *(matrix+offset)
add $s0, $s0, $t5  # sum += t0
addi $s4, $s4, 1  # col++
j loop2
end2: addi $s2, $s2, 1  # row++
j loop1
end1:

Structs in MIPS

Offset

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>id</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>family</td>
</tr>
<tr>
<td>24</td>
<td></td>
<td>given</td>
</tr>
<tr>
<td>44</td>
<td>program</td>
<td></td>
</tr>
<tr>
<td>48</td>
<td></td>
<td>wam</td>
</tr>
</tbody>
</table>

```c
struct _student {
    int id;
    char family[20];
    char given[20];
    int program;
    double wam;
};
```

Implementing Structs in MIPS

C `struct` definitions effectively define a new type.

```c
// new type called "struct student"
struct student {...};

// new type called student_t
typedef struct student student_t;
```

Instances of structures can be created by allocating space:

```c
stu1: # sizeof(Student) == 56
    .space 56

stu2:  # student_t stu2;
    .space 56

stu:   # student_t *stu;
    .space 4
```
Implementing Structs in MIPS

Accessing structure components is by offset, not name

```
li $t0, 5012345
la $t1, stu1
sw $t0, 0($t1) # stu1.id = 5012345;
li $t0, 3778
sw $t0, 44($t1) # stu1.program = 3778;

la $s1, stu2 # stu = &stu2;
li $t0, 3707
sw $t0, 44($s1) # stu->program = 3707;
li $t0, 5034567
sw $t0, 0($s1) # stu->id = 5034567;
```