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
- addresses are 32 bit on the MIPS CPU we are using
- most general purpose computers now use 64-bit addresses (and there are 64-bit MIPS)
- typically small group of (1,2,4,8,...) bytes can be loaded/stored in single operations
- general purpose computers typically have complex caching 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 \textit{lb}/\textit{sb}
- 2 bytes (16-bit) called a \textbf{half-word}, loaded/stored with \textit{lh}/\textit{sh}
- 4 bytes (32-bits) called a \textbf{word}, loaded/stored with \textit{lw}/\textit{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 \textit{sb} & \textit{sh} operations low (least significant) bits of source register are used.
- \textit{lb}/\textit{lh} assume byte/halfword contains a 8-bit/16-bit \textbf{signed} integer
  - high 24/16-bits of destination register set to 1 if 8-bit/16-bit integer negative
- unsigned equivalents \textit{lbu} & \textit{lhu} assume integer is \textbf{unsigned}
  - high 24/16-bits of destination register always set to 0
<table>
<thead>
<tr>
<th>assembly</th>
<th>meaning</th>
<th>bit pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>lb r_t, I(r_s)</code></td>
<td>( r_t = \text{mem}[r_s + I] )</td>
<td>100000ssssstttttIIIIIIIIIIIIIIII</td>
</tr>
<tr>
<td><code>lh r_t, I(r_s)</code></td>
<td>( r_t = \text{mem}[r_s + I] )</td>
<td>100001ssssstttttIIIIIIIIIIIIIIII</td>
</tr>
<tr>
<td></td>
<td>( \text{mem}[r_s + I + 1] \ll 8 )</td>
<td></td>
</tr>
<tr>
<td><code>lw r_t, I(r_s)</code></td>
<td>( r_t = \text{mem}[r_s + I] )</td>
<td>100011ssssstttttIIIIIIIIIIIIIIII</td>
</tr>
<tr>
<td></td>
<td>( \text{mem}[r_s + I + 1] \ll 8 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \text{mem}[r_s + I + 2] \ll 16 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \text{mem}[r_s + I + 3] \ll 24 )</td>
<td></td>
</tr>
<tr>
<td><code>sb r_t, I(r_s)</code></td>
<td>( \text{mem}[r_s + I] = r_t &amp; 0xff )</td>
<td>101000ssssstttttIIIIIIIIIIIIIIII</td>
</tr>
<tr>
<td><code>sh r_t, I(r_s)</code></td>
<td>( \text{mem}[r_s + I] = r_t &amp; 0xff )</td>
<td>101001ssssstttttIIIIIIIIIIIIIIII</td>
</tr>
<tr>
<td></td>
<td>( \text{mem}[r_s + I + 1] = r_t \gg 8 &amp; 0xff )</td>
<td></td>
</tr>
<tr>
<td><code>sw r_t, I(r_s)</code></td>
<td>( \text{mem}[r_s + I] = r_t &amp; 0xff )</td>
<td>101011ssssstttttIIIIIIIIIIIIIIII</td>
</tr>
<tr>
<td></td>
<td>( \text{mem}[r_s + I + 1] = r_t \gg 8 &amp; 0xff )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \text{mem}[r_s + I + 2] = r_t \gg 16 &amp; 0xff )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \text{mem}[r_s + I + 3] = r_t \gg 24 &amp; 0xff )</td>
<td></td>
</tr>
</tbody>
</table>
# Simple example of load & storing a byte
# We normally use directives and labels

```assembly
main:
    li  $t0, 42
    li  $t1, 0x10000000
    sb  $t0, 0($t1)  # Store 42 in byte at address 0x10000000
    lb  $a0, 0($t1)  # Load $a0 from same address
    li  $v0, 1      # Print $a0
    syscall
    li  $a0, '\n'   # Print '\n'
    li  $v0, 11     # Print '
'
    syscall
    li  $v0, 0      # Return 0
    jr   $ra
```

Source code for load_store_no_label.s
SPIM has directive to initialize memory and associate labels with addresses.

```asm
.text # following instructions placed in text
.data  # following objects placed in data
.globl # make symbol available globally

a: .space 18  # int8_t a[18];
.align 2  # align next object on 4-byte addr
i: .word 2   # int32_t i = 2;
v: .word 1,3,5 # int32_t v[3] = {1,3,5};
h: .half 2,4,6 # int16_t h[3] = {2,4,6};
b: .byte 7:5  # int8_t b[5] = {7,7,7,7,7};
f: .float 3.14 # float f = 3.14;
s: .asciiz "abc" # char s[4] { 'a','b','c','\0' };
t: .ascii "abc"  # char s[3] { 'a','b','c' };
```
Code example: storing and loading a value

# simple example of load & storing a byte

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

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

source code for load_store.s
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);
```

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\n", b);
syscall
li $a0, \n'
# printf("%c\n", b);
li $v0, 11
syscall
li $v0, 0 # return 0
jr $ra
```

.source code for endian.c

.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.

```assembly
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:

```assembly
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 the `lw` instruction.
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.

\[
\text{sb } \$t0, \ 0(\$t1) \ # \text{ store } \$t0 \text{ in byte at address in } \$t1 \\
\text{sb } \$t0, \ (\$t1) \quad \# \text{ same}
\]

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

\[
\text{sb } \$t0, \ x \quad \# \text{ store } \$t0 \text{ in byte at address labelled } x \\
\text{sb } \$t1, \ x+15 \quad \# \text{ store } \$t1 \ 15 \text{ bytes past address labelled } x \\
\text{sb } \$t2, \ x(\$t3) \quad \# \text{ store } \$t2 \ $t3 \text{ bytes past address labelled } x
\]

- 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>0x7ffeefef</td>
<td>grows down from that address; read/write</td>
</tr>
<tr>
<td>k_text</td>
<td>0x80000000</td>
<td>kernel code; read-only</td>
</tr>
<tr>
<td></td>
<td></td>
<td>only accessible in kernel mode</td>
</tr>
<tr>
<td>k_data</td>
<td>0x90000000</td>
<td>kernel data’</td>
</tr>
<tr>
<td></td>
<td></td>
<td>only accessible in kernel mode</td>
</tr>
</tbody>
</table>
Global/Static Variables

- global/static variables need appropriate number of bytes allocated in data segment using `.space`:

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

initialized to 0 by default, other directives allow initialization to other values:

  ```
  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
    sw $t0, 0($t1)
    li $t0, 25    # y = 25;
    la $t1, y
    sw $t0, 0($t1)
    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)
```

source code for add_memory.s
C
int x=17, y=25, z;
int main(void) {
    z = x + y;
}

MIPS .data
.data
x: .word 17
y: .word 25
z: .space 4

MIPS .text
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 (array)

C

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

MIPS .text

```mips
main:
    la $t0, x
    lw $t1, 0($t0)
    lw $t2, 4($t0)
    add $t3, $t1, $t2  # z = x + y
    sw $t3, 8($t0)
```

MIPS .data

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

int16_t x[30];

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

```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
```
Printing Array: C to simplified C

C

```c
int main(void) {
    int i = 0;
    while (i < 5) {
        printf("%d\n", 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", '\n');
        i++;
        goto loop;

    end:
        return 0;
}
```
# 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++
    j loop
    # goto loop

end:
Printing Array: MIPS (continued)

```assembly
end:
    li $v0, 0         # return 0
    jr $ra
.data
numbers:            # int numbers[10] = { 3, 9, 27, 81, 243};
    .word 3, 9, 27, 81, 243
```

Source code for `print5.s`
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("\n");
        p++;
        goto loop;
    end:
        return 0;
}
```

source code for pointer5.c

source code for pointer5.simple.c
# 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, '\n'  # printf("%c", '\n');
    li $v0, 11
    syscall
    addi $t0, $t0, 4  # p++
    j loop  # goto loop

derived from source code for pointer5.s
C

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

- i in $s0
```

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

.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
jr $ra     # return
```

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 $f$? 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
C

```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++;
}
// ....
```

- `p` in `$s0$
- `end` in `$s1$

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
.text
```

Computing sum of 2-d Array : MIPS
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:
```
struct _student {
    int id;
    char family[20];
    char given[20];
    int program;
    double wam;
};
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
#define sizeof(Student) == 56
stu1:      # student_t stu1;
    .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;
```