

# COMP1521 24T2 — MIPS Data

---

<https://www.cse.unsw.edu.au/~cs1521/24T2/>

# The Memory Subsystem

- memory subsystem typically provides capability to load or store **bytes** (not bits)
  - 1 byte == 8 bits (on general purpose modern machines)
- each byte has unique **address**, think of:
  - memory as implementing a gigantic array of bytes
  - and the address is the array index
- typically, a small (1,2,4,8,...) group of bytes can be loaded/stored in a single operation
- general purpose computers typically have complex *cache systems* to improve memory performance
  - if we have time we'll look at cache systems a little, late in this course

## Virtual Memory - Quick Summary

- we'll come back to **virtual memory** if any time left in week 10
- operating systems on general purpose computers typically provide **virtual memory**
- **virtual memory** make it look to every running program that it has entire address space
  - hugely convenient for multi-process systems
- disconnects addresses running programs (processes) use from actual RAM address.
- operating system translates (virtual) address a process uses to an physical (actual) RAM address.
- translation needs to be really fast - needs to be largely implemented in hardware (silicon)
- **virtual memory** can be several times larger than actual RAM size
- multiple processes can be in RAM, allowing fast switching
- part of processes can be load into RAM on demand.
- provides a mechanism to share memory between processes.

- most modern general purpose computers use 64-bit addresses
  - CSE servers use 64-bit addresses
- some (older) general purpose computers use 32-bit addresses
- many special purpose (embedded) CPUs use 32-bit addresses
  - but some use 64-bit addresses
  - some use 16-bit addresses
- on the MIPS32 machine implemented by `mipsy`, all addresses are 32-bit so in COMP1521 assembler we'll be using 32-bit addresses
- there are 64-bit MIPS CPUs

- addresses are 32 bits
- 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
- signed and unsigned integer representations covered later in course

# MIPS Load/Store Instructions

assembly	meaning	bit pattern
<b>lb</b> $r_t, I(r_s)$	$r_t = \text{mem}[r_s + I]$	100000ssssssttttIIIIIIIIIIIIIIIIII
<b>lh</b> $r_t, I(r_s)$	$r_t = \text{mem}[r_s + I] \mid$ $\text{mem}[r_s + I + 1] \ll 8$	100001ssssssttttIIIIIIIIIIIIIIIIII
<b>lw</b> $r_t, I(r_s)$	$r_t = \text{mem}[r_s + I] \mid$ $\text{mem}[r_s + I + 1] \ll 8 \mid$ $\text{mem}[r_s + I + 2] \ll 16 \mid$ $\text{mem}[r_s + I + 3] \ll 24$	100011ssssssttttIIIIIIIIIIIIIIIIII
<b>sb</b> $r_t, I(r_s)$	$\text{mem}[r_s + I] = r_t \& 0\text{xff}$	101000ssssssttttIIIIIIIIIIIIIIIIII
<b>sh</b> $r_t, I(r_s)$	$\text{mem}[r_s + I] = r_t \& 0\text{xff}$ $\text{mem}[r_s + I + 1] = r_t \gg 8 \& 0\text{xff}$	101001ssssssttttIIIIIIIIIIIIIIIIII
<b>sw</b> $r_t, I(r_s)$	$\text{mem}[r_s + I] = r_t \& 0\text{xff}$ $\text{mem}[r_s + I + 1] = r_t \gg 8 \& 0\text{xff}$ $\text{mem}[r_s + I + 2] = r_t \gg 16 \& 0\text{xff}$ $\text{mem}[r_s + I + 3] = r_t \gg 24 \& 0\text{xff}$	101011ssssssttttIIIIIIIIIIIIIIIIII

## Code example: storing and loading a value (no labels)

```
# simple example of load & storing a byte
# we normally use directives and labels
# lb & sb require address in a register, but mipsy will do this for us
main:
    li    $t0, 42
    sb    $t0, 0x10000000    # store 42 in byte at address 0x10000000
    lb    $a0, 0x10000000    # load $a0 from same address
    li    $v0, 1             # print $a0 which will now contain 42
    syscall
    li    $a0, '\n'          # print '\n'
    li    $v0, 11
    syscall
    li    $v0, 0             # return 0
    jr    $ra
```

source code for load\_store\_no\_labels

mipsy has directives to initialise memory, and to associate labels with addresses.

```
.text          # following instructions placed in text segment

.data          # following objects placed in data segment

a: .space 18    # int8_t a[18];
   .align 2     # align next object on 4-byte addr
i: .word 42     # int32_t i = 42;
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 t[3] {'a','b','c'};
```



## Code example: storing and loading a value with a label

```
# simple example of load & storing a byte
# we normally use directives and labels
# lb & sb require address in a register, but mipsy will do this for us
main:
    li    $t0, 42
    sb    $t0, answer      # store 42 in byte at address labelled answer
    lb    $a0, answer      # load $a0 from same address
    li    $v0, 1           # print $a0 which will now contain 42
    syscall
    li    $a0, '\n'        # print '\n'
    li    $v0, 11
    syscall
    li    $v0, 0           # return 0
    jr    $ra

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

## Code example: storing and loading a value with address in register

```
# simple example of storing & loading a byte
```

```
main:
```

```
    li    $t0, 42
    la    $t1, answer
    sb    $t0, 0($t1)    # store 42 in byte at address labelled answer
    lb    $a0, 0($t1)    # load $a0 from same address
    li    $v0, 1         # print $a0 which will now contain 42
    syscall
    li    $a0, '\n'      # print '\n'
    li    $v0, 11
    syscall
    li    $v0, 0         # return 0
    jr    $ra
```

```
.data
```

```
answer:
```

```
    .space 1             # set aside 1 byte and associate label answer with its address
```

## Setting A Register to An Address

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

```
la $t8, start
```

- mipsy converts labels to addresses (numbers) before a program is run,
  - no real difference between **la** and **li** instructions
- 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 mipsy short-cuts

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

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

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

```
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

Region	Address	Notes
.text	0x00400000..	instructions only; read-only; cannot expand
.data	0x10000000..	data objects; read/write; can be expanded
.stack	..0x7ffffffef	this address and below; read/write
.ktext	0x80000000..	kernel code; read-only; only accessible in kernel mode
.kdata	0x90000000..	kernel data; only accessible in kernel mode

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

# Global Variables

Labels and *directives* used to allocate space for global variables in the `.data` segment.

```
.data
a:
.word    16          # int a = 16;
b:
.space   4           # int b;
c:
.space   4           # char c[4];
d:
.byte    1, 2, 3, 4   # char d[4] = {1, 2, 3, 4};
e:
.byte    0:4         # char e[4] = {0, 0, 0, 0};
f:
.asciiz  "hello"      # char *f = "hello";
.align   2
g:
.space   4           # int g;
```

source code for `sample_data.s`

## Incrementing a Global Variable: C

```
#include <stdio.h>

int global_counter = 0;

int main(void) {
    // Increment the global counter.
    // The following is the same as global_counter = global_counter + 1 (generally)
    global_counter++;
    printf("%d", global_counter);
    putchar('\n');
}
```

source code for global\_increment.c



## Incrementing a Global Variable: MIPS

```
lw  $t1, global_counter
addi $t1, $t1, 1
sw  $t1, global_counter # global_counter = global_counter + 1;
# Method 2: Explicitly load the address of
# global_counter into a register.
li  $v0, 1              # syscall 1: print_int
la  $t0, global_counter #
lw  $a0, ($t0)
syscall                  # printf("%d", global_counter);
li  $v0, 11             # syscall 11: print_char
li  $a0, '\n'
syscall                  # putchar('\n');
li  $v0, 0
jr  $ra                 # return 0;
.data
global_counter:
.word 0                  # int global_counter = 0;
```

## add: local variables in registers

C

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

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

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

MIPS (.data)

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

MIPS (.text)

```
main:
    li $t0, 17
    la $t1, x
    sw $t0, ($t1) # x = 17;
    li $t0, 25
    la $t1, y
    sw $t0, ($t1) # y = 25;
    la $t0, x
    lw $t1, ($t0)
    la $t0, y
    lw $t2, ($t0)
    add $t3, $t1, $t2
    la $t0, z
    sw $t3, 0($t0) # z = x + y;
    li $v0, 1      # syscall 1: print_int
```

source code for add\_memory.s

## add variables in memory (initialized)

C

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

MIPS .data

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

MIPS

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

source code for add\_memory\_initialized.s

## add variables in memory (uninitialized)

C

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

MIPS (.data)

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

MIPS (.text)

```
main:
    li  $t0, 17
    la  $t1, x
    sw  $t0, ($t1)  # x = 17;
    li  $t0, 25
    la  $t1, y
    sw  $t0, ($t1)  # y = 25;
    la  $t0, x
    lw  $t1, ($t0)
    la  $t0, y
    lw  $t2, ($t0)
    add $t3, $t1, $t2
    la  $t0, z
    sw  $t3, 0($t0) # z = x + y;
    li  $v0, 1      # syscall 1: print_int
```

source code for add\_memory.s

## add variables in memory (initialized)

C

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

MIPS .data

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

MIPS

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

source code for add\_memory\_initialized.s

## add variables in memory (array)

C

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

MIPS .text

```
main:  
    la  $t0, x  
    lw  $t1, 0($t0)  
    lw  $t2, 4($t0)  
    add $t3, $t1, $t2    # x[2] = x[0] + x[1];  
    sw  $t3, 8($t0)  
    li  $v0, 1          # syscall 1: print_int  
    lw  $a0, 8($t0) #  
    syscall             # printf("%d", x[2]);  
    li  $v0, 11         # syscall 11: print_char  
    li  $a0, '\n'      #  
    syscall             # putchar('\n');  
    li  $v0, 0  
    jr  $ra            # return 0;  
    .data  
x:    .word 17, 25, 0    # int x[] = {17, 25, 0}
```

## Address of C 1-d Array Elements - Code

```
double array[10];
for (int i = 0; i < 10; i++) {
    printf("&array[%d]=%p\n", i, &array[i]);
}

printf("\nExample computation for address of array element\n");
uintptr_t a = (uintptr_t)&array[0];
printf("&array[0] + 7 * sizeof (double) = 0x%lx\n",      a + 7 * sizeof (double));
printf("&array[0] + 7 * %lx                = 0x%lx\n", sizeof (double), a + 7 * sizeof (double));
printf("0x%lx + 7 * %lx                    = 0x%lx\n", a, sizeof (double), a + 7 * sizeof (double));
printf("&array[7]                          = %p\n", &array[7]);
```

source code for array\_element\_address.c

- this code uses types covered later in the course



## Address of C 1-d Array Elements - Output

```
$ gcc array_element_address.c -o array_element_address
$ ./array_element_address
&array[0]=0x7fffdd841d00
&array[1]=0x7fffdd841d08
&array[2]=0x7fffdd841d10
&array[3]=0x7fffdd841d18
&array[4]=0x7fffdd841d20
&array[5]=0x7fffdd841d28
&array[6]=0x7fffdd841d30
&array[7]=0x7fffdd841d38
&array[8]=0x7fffdd841d40
&array[9]=0x7fffdd841d48
```

Example computation for address of array element

```
&array[0] + 7 * sizeof (double) = 0x7fffdd841d38
&array[0] + 7 * 8                = 0x7fffdd841d38
0x7fffdd841d00 + 7 * 8            = 0x7fffdd841d38
&array[7]                        = 0x7fffdd841d38
```

## store value in array element — example 1

C

```
int x[10];

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

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

```
#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

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

source code for print5.c

## Simplified 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;  
}
```

source code for print5.simple.c

## Printing Array: 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
```

source code for print5.s

## Changing an Array: C

```
int i;  
i = 0;  
while (i < 5) {  
    numbers[i] *= 42;  
    i++;  
}
```

source code for change\_array.c

## Changing an Array MIPS

```
# i in register $t0
# registers $t1..$t3 used to hold calculations
main:
    li    $t0, 0           # i = 0

loop1:
    bge   $t0, 5, end1     # while (i < 5) {
    mul   $t1, $t0, 4       #
    la    $t2, numbers     # calculate &numbers[i]
    add   $t1, $t1, $t2     #
    lw    $t3, ($t1)        # load numbers[i] into $t3
    mul   $t3, $t3, 42      # numbers[i] *= 42;
    sw    $t3, ($t1)        # store scaled number in array
    addi  $t0, $t0, 1       # i++;
    b     loop1

end1:
```

source code for change\_array.s



## Reading into an Array: C

```
int i = 0;
while (i < 10) {
    printf("Enter a number: ");
    scanf("%d", &numbers[i]);
    i++;
}
```

source code for read10.c

## Reading into an Array: MIPS

```
    li    $t0, 0           # i = 0
loop0:
    bge   $t0, 10, end0    # while (i < 10) {
    la    $a0, string0     #   printf("Enter a number: ");
    li    $v0, 4
    syscall
    li    $v0, 5           #   scanf("%d", &numbers[i]);
    syscall                #
    mul   $t1, $t0, 4      #   calculate &numbers[i]
    la    $t2, numbers     #
    add   $t3, $t1, $t2    #
    sw    $v0, ($t3)       #   store entered number in array
    addi  $t0, $t0, 1      #   i++;
    b     loop0            # }
end0:
```

source code for read10.s

## Printing in reverse order: C

```
printf("Reverse order:\n");  
count = 9;  
while (count >= 0) {  
    printf("%d\n", numbers[count]);  
    count--;  
}
```

source code for reverse10.c

## Printing in reverse order: C

```
la    $a0, string1      # printf("Reverse order:\n");
li    $v0, 4
syscall

li    $t0, 9             # count = 9;

next:
    blt    $t0, 0, end1    # while (count >= 0) {
    mul    $t1, $t0, 4      #   printf("%d", numbers[count])
    la     $t2, numbers     #   calculate &numbers[count]
    add    $t1, $t1, $t2    #
    lw     $a0, ($t1)       #   load numbers[count] into $a0
    li     $v0, 1
    syscall
    li     $a0, '\n'        #   printf("%c", '\n');
    li     $v0, 11
    syscall
    addi   $t0, $t0, -1     #   count--;
    b      next             # }

end1:
```

source code for reverse10.s

## Address of C 2-d Array Elements - Code

```
int array[X][Y];
printf("sizeof array[2][3] = %lu\n", sizeof array[2][3]);
printf("sizeof array[1] = %lu\n", sizeof array[1]);
printf("sizeof array = %lu\n", sizeof array);
printf("&array=%p\n", &array);
for (int x = 0; x < X; x++) {
    printf("&array[%d]=%p\n", x, &array[x]);
    for (int y = 0; y < Y; y++) {
        printf("&array[%d][%d]=%p\n", x, y, &array[x][y]);
    }
}
```

source code for 2d\_array\_element\_address.c

- this code uses types covered later in the course

## Address of 2-d C Array Elements - Output

```
$ gcc 2d_array_element_address.c -o 2d_array_element_address
$ ./2d_array_element_address
sizeof array[2][3] = 4
sizeof array[1] = 16
sizeof array = 48
&array=0x7ffd93bb16c0
&array[0]=0x7ffd93bb16c0
&array[0][0]=0x7ffd93bb16c0
&array[0][1]=0x7ffd93bb16c4
&array[0][2]=0x7ffd93bb16c8
&array[0][3]=0x7ffd93bb16cc
&array[1]=0x7ffd93bb16d0
&array[1][0]=0x7ffd93bb16d0
&array[1][1]=0x7ffd93bb16d4
&array[1][2]=0x7ffd93bb16d8
&array[1][3]=0x7ffd93bb16dc
&array[2]=0x7ffd93bb16e0
&array[2][0]=0x7ffd93bb16e0
&array[2][1]=0x7ffd93bb16e4
&array[2][2]=0x7ffd93bb16e8
&array[2][3]=0x7ffd93bb16ec
```

## Computing sum of 2-d Array : C

Assume we have a 2d-array:

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

We can sum its value like this in 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

```
.data
matrix: .space 120 # 6 * 5 == 30 array elements each 4 bytes
```

## Computing sum of 2-d Array : MIPS

```
        li    $t0, 0           # sum = 0
        li    $t1, 0           # row = 0
loop1:  bge    $t1, 6, end1      # if (row >= 6) break
        li    $t2, 0           # col = 0
loop2:  bge    $t2, 5, end2      # if (col >= 5) break
        la    $t3, matrix
        mul   $t4, $t1, 20      # t1 = row*rowsize
        mul   $t5, $t2, 4       # t2 = col*intsize
        add   $t6, $t3, $t4     # offset = t0+t1
        add   $t7, $t6, $t5     # offset = t0+t1
        lw    $t5, 0($t7)       # t0 = *(matrix+offset)
        add   $t0, $t0, $t5     # sum += t0
        addi  $t2, $t2, 1       # col++
        j     loop2
end2:   addi  $t1, $t1, 1       # row++
        j     loop1
end1:
```



## Printing 2-d Array: C to simplified C

C

```
int main(void) {
    int i = 0;
    while (i < 3) {
        int j = 0;
        while (j < 5) {
            printf("%d", numbers[i][j]);
            printf("%c", ' ');
            j++;
        }
        printf("%c", '\n');
        i++;
    }
    return 0;
}
```

source code for print2d.c

Simplified C

```
int main(void) {
    int i = 0;
loop1:
    if (i >= 3) goto end1;
    int j = 0;
loop2:
    if (j >= 5) goto end2;
    printf("%d", numbers[i][j]);
    printf("%c", ' ');
    j++;
    goto loop2;
end2:
    printf("%c", '\n');
    i++;
    goto loop1;
end1:
```

## Printing 2-d Array: MIPS

```
# print a 2d array
# i in $t0
# j in $t1
# $t2..$t6 used for calculations
main:
    li    $t0, 0          # int i = 0;
loop1:
    bge   $t0, 3, end1    # if (i >= 3) goto end1;
    li    $t1, 0          # int j = 0;
loop2:
    bge   $t1, 5, end2    # if (j >= 5) goto end2;
    la    $t2, numbers    # printf("%d", numbers[i][j]);
    mul   $t3, $t0, 20
    add   $t4, $t3, $t2
    mul   $t5, $t1, 4
    add   $t6, $t5, $t4
    lw    $a0, 0($t6)
    li    $v0, 1
    syscall
```

## Printing 2-d Array: MIPS (continued)

```
li    $a0, ' '      #    printf("%c", ' ');
li    $v0, 11
syscall
addi  $t1, $t1, 1    #    j++;
b     loop2          #    goto loop2;
end2:
li    $a0, '\n'      #    printf("%c", '\n');
li    $v0, 11
syscall
addi  $t0, $t0, 1    #    i++
b     loop1          #    goto loop1
end1:
li    $v0, 0          #    return 0
jr    $ra

.data
# int numbers[3][5] = {{3,9,27,81,243},{4,16,64,256,1024},{5,25,125,625,3125}};
numbers:
    .word  3, 9, 27, 81, 243, 4, 16, 64, 256, 1024, 5, 25, 125, 625, 3125
```

## Printing a Flag: C

```
// Print a 2D array of characters.
#include <stdio.h>
#define N_ROWS 6
#define N_COLS 12
char flag[N_ROWS][N_COLS] = {
    {'#', '#', '#', '#', '#', '.', '.', '#', '#', '#', '#', '#'},
    {'#', '#', '#', '#', '#', '.', '.', '#', '#', '#', '#', '#'},
    {'.', '.', '.', '.', '.', '.', '.', '.', '.', '.', '.', '.'},
    {'.', '.', '.', '.', '.', '.', '.', '.', '.', '.', '.', '.'},
    {'#', '#', '#', '#', '#', '.', '.', '#', '#', '#', '#', '#'},
    {'#', '#', '#', '#', '#', '.', '.', '#', '#', '#', '#', '#'}
};

int main(void) {
    for (int row = 0; row < N_ROWS; row++) {
        for (int col = 0; col < N_COLS; col++) {
            printf("%c", flag[row][col]);
        }
    }
}
```

## Printing a Flag: simplified C

```
row_loop__init:
    int row = 0;
row_loop__cond:
    if (row >= N_ROWS) goto row_loop__end;
row_loop__body:
col_loop__init:
    int col = 0;
col_loop__cond:
    if (col >= N_COLS) goto col_loop__end;
col_loop__body:
    printf("%c", flag[row][col]);    // &flag[row][col] = flag + offset * sizeof(element)
                                    //                               = flag + (row * N_COLS + col) * sizeof(element)
col_loop__step:
    col++;
    goto col_loop__cond;
col_loop__end:
    printf("\n");
row_loop__step:
    row++;
    goto row_loop__cond;
row_loop__end:
```

source code for flag.simple.c

## Printing a Flag: MIPS

```
N_ROWS = 6
N_COLS = 12
main:
    # Locals:
    #   - $t0: int row
    #   - $t1: int col
    #   - $t2: temporary result

main__row_loop_init:
    li $t0, 0                # int row = 0;

main__row_loop_cond:
    bge $t0, N_ROWS, main__row_loop_end    # if (row >= N_ROWS) goto main__row_loop_end;

main__row_loop_body:
main__col_loop_init:
    li $t1, 0                # int col = 0;

main__col_loop_cond:
    bge $t1, N_COLS, main__col_loop_end    # if (col >= N_COLS) goto main__col_loop_end;

main__col_loop_body:
    li $v0, 11                # syscall 11: print_char
```

source code for flag.s

# Printing a Flag: MIPS

```
mul $t2, $t0, N_COLS           # (row * N_COLS
add $t2, $t2, $t1              # + col)
lb  $a0, flag($t2)             #
syscall                        # printf("%c", flag[row][col]);

main__col_loop_step:
addi $t1, $t1, 1              # col++;
j    main__col_loop_cond

main__col_loop_end:
li   $v0, 11                  # syscall 11: print_char
li   $a0, '\n'                #
syscall                          # putchar('\n');

main__row_loop_step:
addi $t0, $t0, 1              # i++;
j    main__row_loop_cond

main__row_loop_end:
li   $v0, 0
jr   $ra                      # return 0;

.data

flag:

.byte '#', '#', '#', '#', '#', '.', '.', '#', '#', '#', '#', '#',
.byte '#', '#', '#', '#', '#', '.', '.', '#', '#', '#', '#', '#',
.byte '.', '.', '.', '.', '.', '.', '.', '.', '.', '.', '.',
.byte '.', '.', '.', '.', '.', '.', '.', '.', '.', '.', '.',
.byte '#', '#', '#', '#', '#', '.', '.', '#', '#', '#', '#', '#',
.byte '#', '#', '#', '#', '#', '.', '.', '#', '#', '#', '#', '#'
```

source code for flags

- C standard requires simple types of size N bytes to be stored only at addresses which are divisible by N
  - if `int` is 4 bytes, must be stored at address divisible by 4
  - if `double` is 8 bytes, must be stored at address divisible by 8
- compound types (arrays, structs) must be aligned so their components are aligned
- MIPS requires this alignment
- on other architectures aligned access faster



## Example C with unaligned accesses

```
char bytes[32];  
int *i = (int *)&bytes[1];  
// illegal store - not aligned on a 4-byte boundary  
*i = 42;  
printf("%d\n", *i);
```

source code for unalign.c

## Example MIPS with unaligned accesses

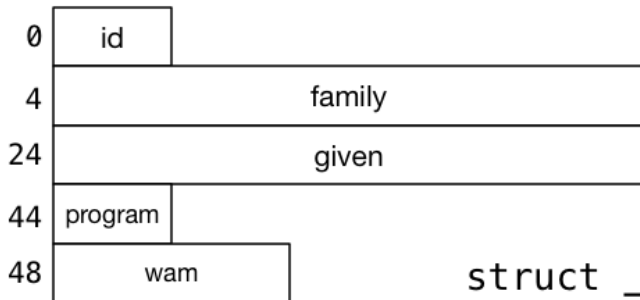
```
.data
# data will be aligned on a 4-byte boundary
# most likely on at least a 128-byte boundary
# but safer to just add a .align directive
.align 2
.space 1
v1: .space 1
v2: .space 4
v3: .space 2
v4: .space 4
    .space 1
    .align 2 # ensure e is on a 4 (2**2) byte boundary
v5: .space 4
    .space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

source code for unalign.s

## Example MIPS with unaligned accesses

```
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

*Offset*

```
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.

```
// 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:

```
                # 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 $t2, stu2        # stu = &stu2;
li $t0, 3707
sw $t0, 44($t2)     # stu->program = 3707;
li $t0, 5034567
sw $t0, 0($t2)      # stu->id = 5034567;
```

## Student Details: C

```
struct details {
    uint16_t  postcode;
    uint8_t   wam;
    uint32_t  zid;
};

struct details student;

int main(void) {
    student.postcode = 2052;
    student.wam = 95;
    student.zid = 5123456;
    printf("%d", student.zid);
    putchar(' ');
    printf("%d", student.wam);
    putchar(' ');
    printf("%d", student.postcode);
    putchar('\n');
    return 0;
}
```

source code for student.c

## Student Details: MIPS

```
# access fields of a simple struct
# struct details {
#     uint16_t  postcode; // Size = 2 bytes, Offset = 0 bytes
#     uint8_t   wam;      // Size = 1 byte , Offset = 2 bytes
#                               // Hidden 1 byte of "padding"
#                               // Because the Offset of each field must be a multiple of the S
#     uint32_t  zid;      // Size = 4 bytes, Offset = 4 bytes
# }; // Total Size = 8
# // The Total Size must be a multiple of the Size of the largest field in the struct
# // More padding will be added to the end of the struct to make this true
# // (not needed in this example)
# offset in bytes of fields of struct details
OFFSET_POSTCODE    = 0
OFFSET_WAM         = 2
OFFSET_ZID         = 4 # unused padding byte before zid field to ensure it is on a 4-byte l
main:
```



```
### Save values into struct ###  
la    $t0, student          # student.postcode = 2052;  
addi  $t1, $t0, OFFSET_POSTCODE  
li    $t2, 2052  
sh    $t2, ($t1)  
la    $t0, student          # student.wam = 95;  
addi  $t1, $t0, OFFSET_WAM  
li    $t2, 95  
sb    $t2, ($t1)  
la    $t0, student          # student.zid = 5123456  
addi  $t1, $t0, OFFSET_ZID  
li    $t2, 5123456  
sw    $t2, ($t1)
```

source code for student.s

# Student Details: MIPS

```
### Load values from struct ###
la  $t0, student      # printf("%d", student.zid);
addi $t1, $t0, OFFSET_ZID
lw   $a0, ($t1)
li   $v0, 1
syscall
li   $a0, ' '          # putchar(' ');
li   $v0, 11
syscall
la  $t0, student      # printf("%d", student.wam);
addi $t1, $t0, OFFSET_WAM
lbu  $a0, ($t1)
li   $v0, 1
syscall
li   $a0, ' '          # putchar(' ');
li   $v0, 11
syscall
la  $t0, student      # printf("%d", student.postcode);
addi $t1, $t0, OFFSET_POSTCODE
lhu  $a0, ($t1)
li   $v0, 1
syscall
li   $a0, '\n'         # putchar('\n');
li   $v0, 11
syscall
li   $v0, 0            # return 0
jr   $ra

.data
student:      # struct details student;
.space 8      # 1 unused padding byte included to ensure zid field alligned on 4-byte boundary
```

source code for students

## More complex student info: C

```
// An example program making use of structs.
#include <stdio.h>
struct student {
    int zid;
    char first[20];
    char last[20];
    int program;
    char alias[10];
};
struct student abiram = {
    .zid = 5308310,
    .first = "Abiram",
    .last = "Nadarajah",
    .program = 3778,
    .alias = "abiramn"
};
struct student xavier = {
    .zid = 5417087,
    .first = "Xavier",
    .last = "Cooney",
    .program = 3778,
    .alias = "xavc"
};
```

source code for struct.c

## More complex student info: C

```
int main(void) {
    struct student *selection = &abiram;
    printf("zID: z%d\n", selection->zid);
    printf("First name: %s\n", selection->first);
    printf("Last name: %s\n", selection->last);
    printf("Program: %d\n", selection->program);
    printf("Alias: %s\n", selection->alias);
    // What's the size of each field of this struct,
    // as well as the overall struct?
    printf("sizeof(zid) = %zu\n", sizeof(selection->zid));
    printf("sizeof(first) = %zu\n", sizeof(selection->first));
    printf("sizeof(last) = %zu\n", sizeof(selection->last));
    printf("sizeof(program) = %zu\n", sizeof(selection->program));
    printf("sizeof(alias) = %zu\n", sizeof(selection->alias));
    // What's the size of the overall struct?
    printf("sizeof(struct student) = %zu\n", sizeof(struct student));
    // We can see that two extra padding bytes were added to the end
    // of the struct, to ensure that the next struct in memory is aligned
    // to a word boundary.
    return 0;
}
```

source code for struct.c

## More complex student info: MIPS

```
# A demo of accessing fields of structs in MIPS.
# Offsets for fields in `struct student`
STUDENT_OFFSET_ZID = 0
STUDENT_OFFSET_FIRST = 4
STUDENT_OFFSET_LAST = 20 + STUDENT_OFFSET_FIRST
STUDENT_OFFSET_PROGRAM = 20 + STUDENT_OFFSET_LAST
STUDENT_OFFSET_ALIAS = 4 + STUDENT_OFFSET_PROGRAM
# sizeof the struct - note that there are 2 padding
# bytes at the end of the struct.
SIZEOF_STRUCT_STUDENT = 10 + STUDENT_OFFSET_ALIAS + 2

.text
main:
```

source code for struct.s

# More complex student info: MIPS

```
# Locals:
# - $t0: struct student *selection
la $t0, xavier
li $v0, 4          # syscall 4: print_string
la $a0, zid_msg    #
syscall           # printf("zID: z");
li $v0, 1          # syscall 1: print_int
lw $a0, STUDENT_OFFSET_ZID($t0) #
syscall           # printf("%d", selection->zid);
li $v0, 11         # syscall 11: print_char
li $a0, '\n'       #
syscall           # putchar('\n');
li $v0, 4          # syscall 4: print_string
la $a0, first_name_msg #
syscall           # printf("First name: ");
li $v0, 4          # syscall 4: print_string
la $a0, STUDENT_OFFSET_FIRST($t0) #
syscall           # printf("%s", selection->first);
li $v0, 11         # syscall 11: print_char
li $a0, '\n'       #
syscall           # putchar('\n');
li $v0, 4          # syscall 4: print_string
la $a0, last_name_msg #
syscall           # printf("Last name: ");
li $v0, 4          # syscall 4: print_string
la $a0, STUDENT_OFFSET_LAST($t0) #
syscall           # printf("%s", selection->last);
li $v0, 11         # syscall 11: print_char
li $a0, '\n'       #
syscall           # putchar('\n');
li $v0, 4          # syscall 4: print_string
la $a0, program_msg #
syscall           # printf("Program: ");
li $v0, 1          # syscall 1: print_int
lw $a0, STUDENT_OFFSET_PROGRAM($t0) #
syscall           # printf("%d", selection->program);
li $v0, 11         # syscall 11: print_char
li $a0, '\n'       #
syscall           # putchar('\n');
li $v0, 4          # syscall 4: print_string
la $a0, alias_msg  #
syscall           # printf("Alias: ");
li $v0, 4          # syscall 4: print_string
la $a0, STUDENT_OFFSET_ALIAS($t0) #
syscall           # printf("%s", selection->alias);
li $v0, 11         # syscall 11: print_char
li $a0, '\n'       #
syscall           # putchar('\n');
li $v0, 0          #
jr $ra            # return 0;
```

source code for slides

## Array of Structs: C

```
// simple example of accessing struct within array within struct
#include <stdio.h>
#define MAX_POLYGON 6
struct point {
    int x;
    int y;
};
struct polygon {
    int          degree;
    struct point  vertices[MAX_POLYGON]; // C also allows variable size array here
};
void print_last_vertex(struct polygon *p);
struct polygon triangle = {3, {{0,0}, {3,0}, {0,4}}};
```

source code for struct\_array.c

## Array of Structs: C

```
int main(void) {  
    print_last_vertex(&triangle); // prints 0,4  
    return 0;  
}
```

source code for struct\_array.c



## Array of Structs: MIPS

```
# simple example of accessing struct within array within struct
# struct point {
#   int x;
#   int y;
# };
#
# struct polygon {
#   int          degree;
#   struct point vertices[6];
# };
OFFSET_POINT_X      = 0
OFFSET_POINT_Y      = 4
SIZEOF_POINT        = 8
OFFSET_POLYGON_DEGREE = 0
OFFSET_POLYGON_VERTICES = 4
SIZEOF_POLYGON      = 52
main:
```

source code for struct\_arrays

# Array of Structs: MIPS

```
push    $ra
la      $a0, triangle
jal     print_last_vertex      # print_last_vertex(&triangle);
li      $v0, 0
pop     $ra
jr      $ra

print_last_vertex:
# $a0: p
# $t0: n
# $t1: last
# $t2..$t5: temporaries
lw      $t2, OFFSET_POLYGON_DEGREE($a0) # int n = p->degree - 1;
addi    $t0, $t2, -1
addi    $t3, $a0, OFFSET_POLYGON_VERTICES # calculate &(p->vertices[n])
mul     $t4, $t0, sizeof_POINT
add     $t1, $t3, $t4
lw      $a0, OFFSET_POINT_X($t1)      # printf("%d", last->x);
li      $v0, 1
syscall

li      $a0, ','
li      $v0, 11
syscall

lw      $a0, OFFSET_POINT_Y($t1)      # printf("%d", last->y);
li      $v0, 1
syscall

li      $a0, '\n'
li      $v0, 11
syscall

jr      $ra
```

source code for struct\_arrays

## Array of Structs: MIPS

```
.data
# struct polygon triangle = {3, {{0,0}, {3,0}, {0,4}}};
triangle:
    .word 3
    .word 0,0, 3,0, 0,4, 0,0, 0,0, 0,0
```

source code for struct\_arrays

# Implementing Pointers in MIPS

C

```
int i;  
int *p;  
p = &answer;  
i = *p;  
// prints 42  
printf("%d\n", i);  
*p = 27;  
// prints 27  
printf("%d\n", answer);
```

source code for pointer.c

MIPS

```
la    $t0, answer # p = &answer;  
lw    $t1, ($t0)  # i = *p;  
move  $a0, $t1    # printf("%d\n", i);  
li    $v0, 1  
syscall  
li    $a0, '\n'    # printf("%c", '\n');  
li    $v0, 11  
syscall  
li    $t2, 27      # *p = 27;  
sw    $t2, ($t0)  #  
lw    $a0, answer # printf("%d\n", answer);  
li    $v0, 1  
syscall  
li    $a0, '\n'    # printf("%c", '\n');  
li    $v0, 11  
syscall
```

## Example - Accessing Struct within Array within Struct (main)

```
// simple example of accessing struct within array within struct
#include <stdio.h>
#define MAX_POLYGON 6
struct point {
    int x;
    int y;
};
struct polygon {
    int          degree;
    struct point vertices[MAX_POLYGON]; // C also allows variable size array here
};
void print_last_vertex(struct polygon *p);
struct polygon triangle = {3, {{0,0}, {3,0}, {0,4}}};
```

source code for struct\_array.c

## Example - Accessing Struct within Array within Struct (main)

```
int main(void) {  
    print_last_vertex(&triangle); // prints 0,4  
    return 0;  
}
```

source code for struct\_array.c

```
main:  
    push    $ra  
    la     $a0, triangle  
    jal    print_last_vertex          # print_last_vertex(&triangle);  
    li     $v0, 0  
    pop    $ra  
    jr     $ra
```

source code for struct\_array.s

## Example - Accessing Struct within Array within Struct (C)

```
void print_last_vertex(struct polygon *p) {  
    printf("%d", p->vertices[p->degree - 1].x);  
    putchar(',');  
    printf("%d", p->vertices[p->degree - 1].y);  
    putchar('\n');  
}
```

source code for struct\_array.c

```
void print_last_vertex(struct polygon *p) {  
    int n = p->degree - 1;  
    struct point *last = &(p->vertices[n]);  
    printf("%d", last->x);  
    putchar(',');  
    printf("%d", last->y);  
    putchar('\n');  
}
```

source code for struct\_array.simple.c

## Example - Accessing Struct within Array within Struct (MIPS)

```
print_last_vertex:
    # $a0: p
    # $t0: n
    # $t1: last
    # $t2..$t5: temporaries
    lw    $t2, OFFSET_POLYGON_DEGREE($a0)    # int n = p->degree - 1;
    addi  $t0, $t2, -1
    addi  $t3, $a0, OFFSET_POLYGON_VERTICES # calculate &(p->vertices[n])
    mul   $t4, $t0, SIZEOF_POINT
    add   $t1, $t3, $t4
    lw    $a0, OFFSET_POINT_X($t1)           # printf("%d", last->x);
    li    $v0, 1
    syscall
    li    $a0, ','
    li    $v0, 11
    syscall
    lw    $a0, OFFSET_POINT_Y($t1)           # printf("%d", last->y);
    li    $v0, 1
    syscall
    li    $a0, '\n'
    li    $v0, 11
    syscall
    jr    $ra
```

source code for struct\_arrays



# Printing Array with Pointers: C to simplified C

C

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

source code for pointer5.c

Simplified 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", '\n');  
    p++;  
    goto loop;  
end:  
    return 0;  
}
```

source code for pointer5.simple.c

## Printing Array with Pointers: 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, '\n'        # printf("%c", '\n');
    li    $v0, 11
    syscall
    addi  $t0, $t0, 4      # p++
    b     loop             # goto loop
end:
```

## Printing Array with Pointers: MIPS - faster

```
# this is closer to the code a compiler might produce
# p in $t0
# q in $t1
main:
    la    $t0, numbers    # int *p = &numbers[0];
    addi  $t1, $t0, 16     # int *q = &numbers[4];
loop:
    lw    $a0, ($t0)       # printf("%d", *p);
    li    $v0, 1
    syscall
    li    $a0, '\n'        # printf("%c", '\n');
    li    $v0, 11
    syscall
    addi  $t0, $t0, 4      # p++
    ble   $t0, $t1, loop  # if (p <= q) goto loop;
```

source code for pointer5.faster.s