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 anyt 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 betwen processes.

Address Size

- 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

Accessing Memory on the MIPS

- 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
`lb` r_t, I(r_s)	r_t = mem[r_s+I]	100000ssssstttttIIIIIIIIIIIIIIII
`lh` r_t, I(r_s)	r_t = mem[r_s+I] |	100001ssssstttttIIIIIIIIIIIIIIII
	mem[r_s+I+1] << 8	
`lw` r_t, I(r_s)	r_t = mem[r_s+I] |	100011ssssstttttIIIIIIIIIIIIIIII
	mem[r_s+I+1] << 8 |	
	mem[r_s+I+2] << 16 |	
	mem[r_s+I+3] << 24	
`sb` r_t, I(r_s)	mem[r_s+I] = r_t & 0xff	101000ssssstttttIIIIIIIIIIIIIIII
`sh` r_t, I(r_s)	mem[r_s+I] = r_t & 0xff	101001ssssstttttIIIIIIIIIIIIIIII
	mem[r_s+I+1] = r_t >> 8 & 0xff	
`sw` r_t, I(r_s)	mem[r_s+I] = r_t & 0xff	101011ssssstttttIIIIIIIIIIIIIIII
	mem[r_s+I+1] = r_t >> 8 & 0xff	
	mem[r_s+I+2] = r_t >> 16 & 0xff	
	mem[r_s+I+3] = r_t >> 24 & 0xff	

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 nows 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_label.s

Assembler Directives

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 nows 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 nows 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
```

source code for load_store.s

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

MIPSY Memory Layout

Region	Address	Notes
`.text`	`0x00400000`..	instructions only; read-only; cannot expand
`.data`	`0x10000000`..	data objects; read/write; can be expanded
`.stack`	..`0x7fffffef`	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

Data Structures and MIPS

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

```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;
```

source code for global_increment.s

add: local variables in registers

C

```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

```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

```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

```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

```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

```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

```c
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 (dc
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

```
$ dcc 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

```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

```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;
}
```

source code for print5.c

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;
}
```

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
```


Printing Array: MIPS (continued)

```
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

```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

```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

```c
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

```
$ dcc 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:

```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

```
    .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

```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

```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
```

source code for print2d.s

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
```

source code for print2d.s

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 flag.s

Alignment

- 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

```c
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
```

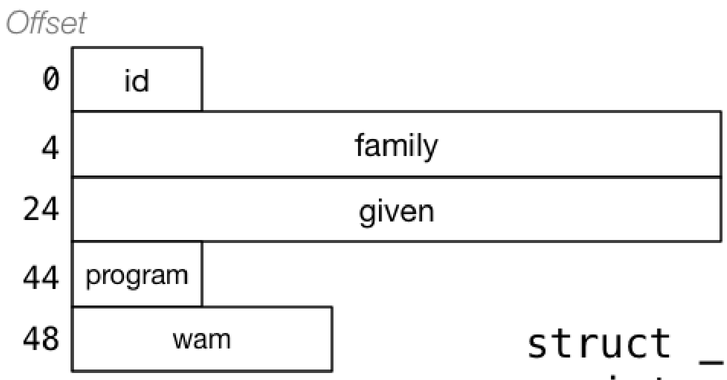
source code for unalign.s

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 succeeed because v2 is 2-byte aligned
sw   $t0, v2  # will fail because v2 is not 4-byte aligned
sh   $t0, v3  # will succeeed because v3 is 2-byte aligned
sw   $t0, v3  # will fail because v3 is not 4-byte aligned
sh   $t0, v4  # will succeeed because v4 is 2-byte aligned
sw   $t0, v4  # will succeeed because v4 is 4-byte aligned
sw   $t0, v5  # will succeeed because v5 is 4-byte aligned
sw   $t0, v6  # will succeeed because v6 is 4-byte aligned
li   $v0, 0
jr   $ra    # return
```

source code for unalign.s

Structs in MIPS




```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:

```
                 # sizeof(Student) == 56
stu1:            # student_t stu1;
     .space 56
stu2:            # student_t stu2;
     .space 56
stu:
     .space 4    # student_t *stu;
```


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

```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"
#                         //  Becase 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
main:
```

source code for student.s

Student Details: MIPS

```
### 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 student.s

More complex student info: C

```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

```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 struct.s

Array of Structs: C

```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

```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_array.s

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, ','                          # putchar(',');
    li   $v0, 11
    syscall
    lw   $a0, OFFSET_POINT_Y($t1)          # printf("%d", last->y);
    li   $v0, 1
    syscall
    li   $a0, '\n'                         # putchar('\n');
    li   $v0, 11
    syscall
    jr   $ra
```

source code for struct_array.s

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_array.s

Implementing Pointers in MIPS

C

```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)

```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

Example - Accessing Struct within Array within Struct (main)

```c
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)

```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

```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, ','                          # putchar(',');
    li   $v0, 11
    syscall
    lw   $a0, OFFSET_POINT_Y($t1)          # printf("%d", last->y);
    li   $v0, 1
    syscall
    li   $a0, '\n'                         # putchar('\n');
    li   $v0, 11
    syscall
    jr   $ra
```

source code for struct_array.s

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;
}
```

source code for pointer5.c

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", '\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:
```

source code for pointer5.s

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