COMP1521 23T3 — MIPS Data

https://www.cse.unsw.edu.au/~cs1521/23T3/

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

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] | mem[r_s+I+1] << 8	100001ssssstttttIIIIIIIIIIIIIIII
lw r_t, I(r_s)	r_t = mem[r_s+I] | mem[r_s+I+1] << 8 | mem[r_s+I+2] << 16 | mem[r_s+I+3] << 24	100011ssssstttttIIIIIIIIIIIIIIII
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 mem[r_s+I+1] = r_t >> 8 & 0xff	101001ssssstttttIIIIIIIIIIIIIIII
sw r_t, I(r_s)	mem[r_s+I] = r_t & 0xff 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	101011ssssstttttIIIIIIIIIIIIIIII

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

`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

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/Static Variables

Global and static variables need an 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
```

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

```
int val = 5;                  val: .word 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

```
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

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

source code for add_memory_array.s

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 (do
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

```
$ 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
```

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
```

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

```
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
```

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

C

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

source code for read10.c

MIPS

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

source code for read10.s

C

```c
i = 0;
while (i < 10) {
    printf("%d\n", numbers[i]);
    i++;
}
```

source code for read10.c

MIPS

```
    li   $t0, 0           # i = 0
loop1:
    bge  $t0, 10, end1    # while (i < 10) {
    mul  $t1, $t0, 4      #   calculate &number
    la   $t2, numbers     #
    add  $t3, $t1, $t2    #
    lw   $a0, ($t3)       #   load numbers[i] i
    li   $v0, 1           #   printf("%d", numb
    syscall
    li   $a0, '\n'        #   printf("%c", '\n'
    li   $v0, 11
    syscall
    addi $t0, $t0, 1      #   i++
    b    loop1            # }
end1:
```

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

```
$ 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:

```
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
```

```
        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:
```

```
# 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

```
    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

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

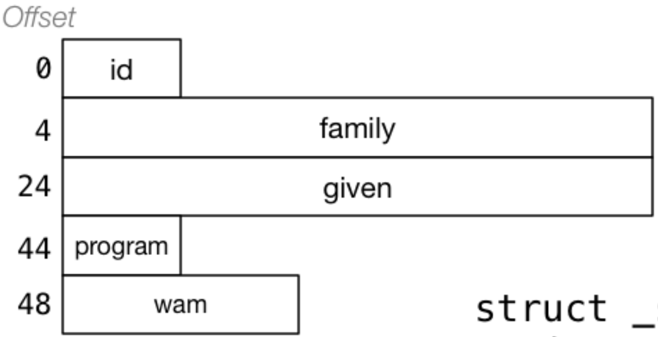
```
    .data
    # data will be aligned on a 4-byte boundary
    # most likely on at least a 128-byte boundary
    # but safer to just add a .align directive
    .align 2
    .space 1
v1: .space 1
v2: .space 4
v3: .space 2
v4: .space 4
    .space 1
    .align 2 # ensure e is on a 4 (2**2) byte boundary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




```
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:

```
                # 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;
```

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)

```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)

```
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, ','                          # 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

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:
```

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