COMP1521 24T2 — MIPS Functions

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

Functions

Functions define named pieces of code

- to whom you can supply values (arguments/parameters)
- which do some computation on those values
- and which return a result

E.g.

```
int timesTwo(int x) {
    int two_x = x*2;
    return two_x;
}
```

Function Signatures

Each function has a signature

- defining the number and types of parameters
- defining the type of the return value

E.g.

```
// timesTwo takes an int parameter and returns an int result
int timesTwo(int);
```

A function call must supply an appropriate number of values, each with the correct type

Calling Functions

You invoke/call a function

- by giving its name
- by giving values for the parameters
- by using the result

E.g.

```
    int y;
    y = timesTwo(2);
```

In fact, C does not require you to use the result of a function

Calling a Function (in more detail)

Example function call

```
res = fun(expr1, expr2, ...)
```

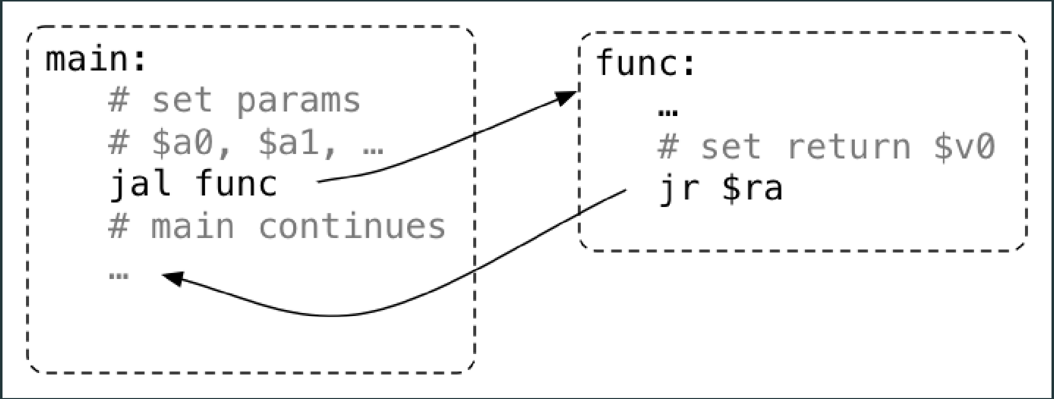
- each expression is evaluated and its value associated to a parameter
- control transfers to the body of the function
- function local variables are created
- the function code executes
- when the result is returned, control returns to the caller

Implementing Functions Calls in MIPS Assembler

When we call a function:

- in the caller code
  - the arguments are evaluated and set up for function (**`$a?`**)
  - control is transferred to the code for the function (**`jal fun`**)
- in code at the start of the function, called the ***prologue***
  - local variables are created (**`$t?`**)
  - registers to be preserved are saved (**`$s?`**)
- the code for the function body is then executed
- in code at the end of the function, called the ***epilogue***
  - the return value is set up (**`$v0`**)
  - control transfers back to where the function was called from (**`jr $ra`**)
  - the caller receives the return value

Simple view of implementing function calls in MIPS:



```
main:
    # set params
    # $a0, $a1, …
    jal func
    # main continues
    …
```

```
func:
    …
    # set return $v0
    jr $ra
```

Function with No Parameters or Return Value

- **jal hello** sets **$ra** to address of following instruction, and transfers execution to **hello**
- **jr $ra** transfers execution to the address in **$ra**

```c
int main(void) {
    hello();
    hello();
    hello();
    return 0;
}

void hello(void) {
    printf("hi\n");
}
```

```
main:
    ...
    jal   hello
    jal   hello
    jal   hello
    ...
hello:
    la $a0, string
    li $v0, 4
    syscall
    jr $ra
    .data
string:
    .asciiz "hi\n"
```

Function with a Return Value but No Parameters

By convention, function return value is passed back in **`$v0`**

```c
int main(void) {
    int a = answer();
    printf("%d\n", a);
    return 0;
}

int answer(void) {
    return 42;
}
```

```
main:
    ...
    jal  answer
    move $a0, $v0
    li   $v0, 1
    syscall
    ...
answer:
    li $v0, 42
    jr $ra
```

Function with a Return Value and Parameters

By convention, first 4 parameters are passed in **$a0**, **$a1**, **$a2**, **$a3**

If there are more parameters they are passed on the stack

Paremeters too big to fit in a register, such as structs, also passed on the stack.

```c
int main(void) {
    int a = product(6, 7);
    printf("%d\n", a);
    return 0;
}

int product(int x, int y) {
    return x * y;
}
```

```
main:
    ...
    li   $a0, 6
    li   $a1, 7
    jal  product
    move $a0, $v0
    li   $v0, 1
    syscall
    ...
product:
    mul  $v0, $a0, $a1
    jr   $ra
```

Function calling another function ... DO NOT DO THIS

Functions that do not call other functions - ***leaf functions*** - are easier to implement.

Function that call other function(s) are harder to implement, because they *must* save **`$ra`** in their prologue and restore it in their epilogue.

The **`jr $ra`** in **`main`** below **will fail**, because **`jal hello`** changed **`$ra`**

```c
int main(void) {
    hello();
    return 0;
}

void hello(void) {
    printf("hi\n");
}
```

```
main:
    jal  hello
    li $v0, 0
    jr $ra # THIS WILL FAIL
hello:
    la $a0, string
    li $v0, 4
    syscall
    jr $ra
    .data
string: .asciiz "hi\n"
```

Simple Function Call Example - C

```c
void f(void);
int main(void) {
    printf("calling function f\n");
    f();
    printf("back from function f\n");
    return 0;
}
void f(void) {
    printf("in function f\n");
}
```

source code for call_return.c

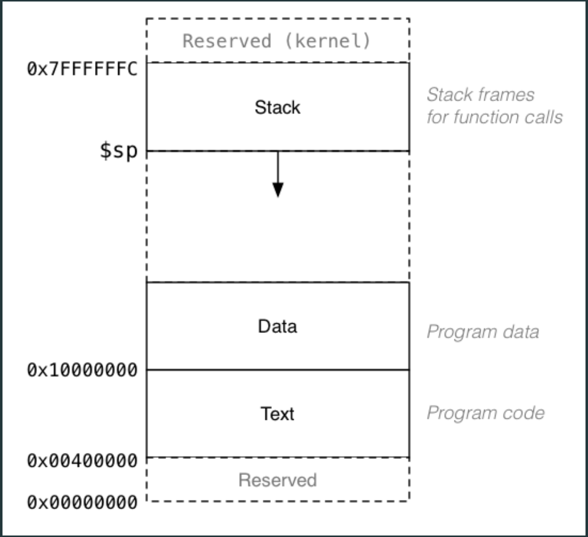
Simple Function Call Example - broken MIPS

```
    la   $a0, string0   # printf("calling function f\n");
    li   $v0, 4
    syscall
    jal  f              # set $ra to following address
    la   $a0, string1   # printf("back from function f\n");
    li   $v0, 4
    syscall
    li   $v0, 0         # fails because $ra changes since main called
    jr   $ra            # return from function main
f:
    la   $a0, string2   # printf("in function f\n");
    li   $v0, 4
    syscall
    jr   $ra            # return from function f
    .data
```

source code for call_return.broken.s

The Stack: Where it is in Memory

Data associated with a function call placed on the stack:



The Stack: Allocating Space

- **$sp** (stack pointer) initialized by operating system
- always 4-byte aligned (divisible by 4)
- points at currently used (4-byte) word
- grows downward (towards smaller addresses)
- a function can do this to allocate 40 bytes:

```
sub  $sp, $sp, 40     # move stack pointer down
```

- a function **must** leave $sp at original value
- so if you allocated 40 bytes, before return (**jr $ra**)

```
add  $sp, $sp, 40     # move stack pointer back
```

The Stack: Saving and Restoring Registers - the Hard Way

```
f:
    # function prologue code
    sub  $sp, $sp, 12   # allocate 12 bytes
    sw   $ra, 8($sp)    # save $ra on $stack
    sw   $s1, 4($sp)    # save $s1 on $stack
    sw   $s0, 0($sp)    # save $s0 on $stack

    ...                 # function body code

    # function epilogue code
    lw   $s0, 0($sp)    # restore $s0 from $stack
    lw   $s1, 4($sp)    # restore $s1 from $stack
    lw   $ra, 8($sp)    # restore $ra from $stack
    add  $sp, $sp, 12   # move stack pointer back
    jr   $ra            # return
```

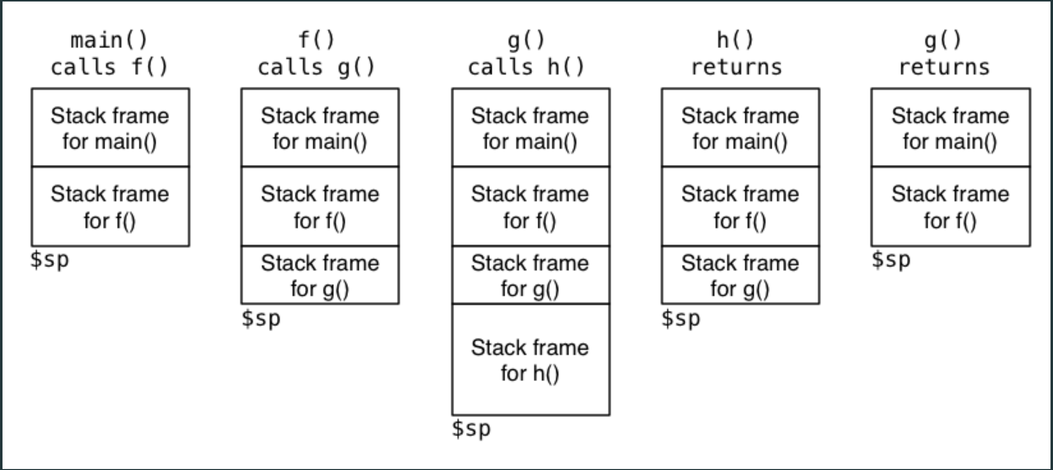
The Stack: Saving and Restoring Registers - the Easy way

```
f:
    # function prologue code
    push $ra                # save $ra on $stack
    push $s1                # save $s1 on $stack
    push $s0                # save $s0 on $stack

    ...                     # function body code

    # function epilogue code
    pop  $s0                # restore $s0 from $stack
    pop  $s1                # restore $s1 from $stack
    pop  $ra                # restore $ra from $stack
```

- note must **pop** everything **push**-ed, must be in reverse order
- **push** & **pop** are pseudo-instructions
    - **push** & **pop** available only on mipsy, not other MIPS emulators
    - but **push** & **pop** can be real instructions or pseudo-instructions on other architectures

The Stack: Growing & Shrinking

How stack changes as functions are called and return:



Function calling another function ... how to do it right

A function that calls another function must save **$ra**.

```
main:
    # prologue
    push   $ra           # save $ra on $stack

    jal  hello           # call hello

    # epilogue
    pop  $ra             # recover $ra from $stack
    li   $v0, 0          # return 0
    jr   $ra             #
```

Simple Function Call Example - correct hard way

```
    la   $a0, string0   # printf("calling function f\n");
    li   $v0, 4
    syscall
    jal  f              # set $ra to following address
    la   $a0, string1   # printf("back from function f\n");
    li   $v0, 4
    syscall
    lw   $ra, 0($sp)    # recover $ra from $stack
    addi $sp, $sp, 4    # move stack pointer back to what it was
    li   $v0, 0         # return 0 from function main
    jr   $ra            #
f:
    la   $a0, string2   # printf("in function f\n");
    li   $v0, 4
    syscall
    jr   $ra            # return from function f
```

source code for call_return_raw.s

Simple Function Call Example - correct easy way

```
    la   $a0, string0   # printf("calling function f\n");
    li   $v0, 4
    syscall
    jal  f              # set $ra to following address
    la   $a0, string1   # printf("back from function f\n");
    li   $v0, 4
    syscall
    pop $ra             # recover $ra from $stack
    li   $v0, 0         # return 0 from function main
    jr   $ra            #
# f is a leaf function so it doesn't need an epilogue or prologue
f:
    la   $a0, string2   # printf("in function f\n");
    li   $v0, 4
    syscall
    jr   $ra            # return from function f
```

source code for call_return.s

MIPS Calling conventions

- `$a0`..`$a3` contain first 4 arguments
- $v0 contains return value
- $ra contains return address
- if function changes `$sp`, `$fp`, `$s0`..`$s7` it restores their value
- callers assume `$sp`, `$fp`, `$s0`..`$s7` unchanged by call (`jal`)
- a function may destroy the value of other registers e.g. `$t0`..`$t9`
- callers must assume value in e.g. `$t0`..`$t9` changed by call (`jal`)

MIPS Register usage conventions (not covered in COMP1521)

- floating point registers used to pass/return float/doubles
- similar conventions for saving floating point registers
- stack used to pass arguments after first 4
- stack used to pass arguments which do not fit in register
- stack used to return values which do not fit in register
- for example a struct can be a C function argument or function return value but a struct can be any number of bytes

Example - Returning a Value - C

```c
int answer(void);
int main(void) {
    int a = answer();
    printf("%d\n", a);
    return 0;
}
int answer(void) {
    return 42;
}
```

source code for return_answer.c

Example - Returning a Value - MIPS

```
# code for function main
main:
    begin                   # move frame pointer
    push  $ra               # save $ra onto stack
    jal   answer            # call answer(), return value will be in $v0
    move  $a0, $v0          # printf("%d", a);
    li    $v0, 1            #
    syscall                 #
    li    $a0, '\n'         # printf("%c", '\n');
    li    $v0, 11           #
    syscall                 #
    pop   $ra               # recover $ra from stack
    end                     # move frame pointer back
    li    $v0, 0            # return
    jr    $ra               #
# code for function answer
answer:
```

Example - Argument & Return - C

```c
void two(int i);
int main(void) {
    two(1);
}
void two(int i) {
    if (i < 1000000) {
        two(2 * i);
    }
    printf("%d\n", i);
}
```

source code for two_powerful.c

Example - Argument & Return - MIPS (main)

```
main:
    begin               # move frame pointer
    push  $ra           # save $ra onto stack
    li    $a0, 1
    jal   two           # two(1);
    pop   $ra           # recover $ra from stack
    end                 # move frame pointer back
    li    $v0, 0        # return 0
    jr    $ra           #
```

source code for two_powerful.s

Example - Argument & Return - MIPS (two)

```
two:
    begin                   # move frame pointer
    push  $ra               # save $ra onto stack
    push  $s0               # save $s0 onto stack
    move  $s0, $a0
    bge   $a0, 1000000, two_end_if
    mul   $a0, $a0, 2
    jal   two
two_end_if:
    move  $a0, $s0
    li    $v0, 1            # printf("%d");
    syscall
    li    $a0, '\n'         # printf("%c", '\n');
    li    $v0, 11
    syscall
    pop   $s0               # recover $s0 from stack
    pop   $ra               # recover $ra from stack
    end                     # move frame pointer back
    jr    $ra               # return from two
```

source code for two_powerful.s

Example - More complex Calls - C

```c
int main(void) {
    int z = sum_product(10, 12);
    printf("%d\n", z);
    return 0;
}
int sum_product(int a, int b) {
    int p = product(6, 7);
    return p + a + b;
}
int product(int x, int y) {
    return x * y;
}
```

source code for more_calls.c

Example - more complex Calls - MIPS (main)

```
main:
    begin                   # move frame pointer
    push  $ra               # save $ra onto stack
    li    $a0, 10           # sum_product(10, 12);
    li    $a1, 12
    jal   sum_product
    move  $a0, $v0          # printf("%d", z);
    li    $v0, 1
    syscall
    li    $a0, '\n'         # printf("%c", '\n');
    li    $v0, 11
    syscall
    pop   $ra               # recover $ra from stack
    end                     # move frame pointer back
    li    $v0, 0            # return 0 from function main
    jr    $ra               # return from function main
```

source code for more_calls.s

Example - more complex Calls - MIPS (sum_product)

```
sum_product:
    begin                   # move frame pointer
    push   $ra              # save $ra onto stack
    push   $s0              # save $s0 onto stack
    push   $s1              # save $s1 onto stack
    move   $s0, $a0         # preserve $a0 for use after function call
    move   $s1, $a1         # preserve $a1 for use after function call
    li     $a0, 6           # product(6, 7);
    li     $a1, 7
    jal    product
    add    $v0, $v0, $s0    # add a and b to value returned in $v0
    add    $v0, $v0, $s1    # and put result in $v0 to be returned
    pop    $s1              # recover $s1 from stack
    pop    $s0              # recover $s0 from stack
    pop    $ra              # recover $ra from stack
    end                     # move frame pointer back
    jr     $ra              # return from sum_product
```

Example - more complex Calls - MIPS (product)

- a function which doesn't call other functions is called a ***leaf function***
- its code *can* be simpler...

```
int product(int x, int y) {
    return x * y;
}
```

source code for more_calls.c

```
product:                # product doesn't call other functions
                        # so it doesn't need to save any registers
    mul  $v0, $a0, $a1  # return argument * argument 2
    jr   $ra            #
```

source code for more_calls.s

Example - strlen using array - C

C

```
int main(void) {
    int i = my_strlen("Hello");
    printf("%d\n", i);
    return 0;
}
int my_strlen(char *s) {
    int length = 0;
    while (s[length] != 0) {
        length++;
    }
    return length;
}
```

source code for strlen_array.c

Simple C

```
int main(void) {
    int i = my_strlen("Hello");
    printf("%d\n", i);
    return 0;
}
int my_strlen(char *s) {
    int length = 0;
loop:;
    if (s[length] == 0) goto end;
       length++;
    goto loop;
end:;
    return length;
}
```

source code for strlen_array.simple.c

Example - strlen using array - MIPS (my_strlen)

```
my_strlen:                  # length in t0, s in $a0
    li   $t0, 0
loop:                       # while (s[length] != 0) {
    add  $t1, $a0, $t0      #   calculate &s[length]
    lb   $t2, ($t1)         #   load s[length] into $t2
    beq  $t2, 0, end        #
    addi $t0, $t0, 1        #   length++;
    b    loop               # }
end:
    move $v0, $t0           # return length
    jr   $ra                #
```

source code for strlen_array.s

Example - strlen using pointer - C

```c
int main(void) {
    int i = my_strlen("Hello Andrew");
    printf("%d\n", i);
    return 0;
}
int my_strlen(char *s) {
    int length = 0;
    while (*s != 0) {
        length++;
        s++;
    }
    return length;
}
```

source code for strlen_pointer.c

Example - strlen using pointer - MIPS (my_strlen)

```
my_strlen:                # length in t0, s in $a0
    li   $t0, 0
loop:                     #
    lb   $t1, ($a0)      # load *s into $t1
    beq  $t1, 0, end      #
    addi $t0, $t0, 1      # length++
    addi $a0, $a0, 1      # s++
    b    loop             #
end:
    move $v0, $t0         # return length
    jr   $ra              #
```

source code for strlen_pointer.s

Storing A Local Variables On the Stack

- some local (function) variables must be stored on stack
- e.g. variables such as arrays and structs

```
int main(void) {
    int squares[10];
    int i = 0;
    while (i < 10) {
        squares[i] = i * i;
        i++;
    }
```

source code for squares.c

```
main:
    sub  $sp, $sp, 40
    li   $t0, 0
loop0:
    mul  $t1, $t0, 4
    add  $t2, $t1, $sp
    mul  $t3, $t0, $t0
    sw   $t3, ($t2)
    add  $t0, $t0, 1
    b    loop0
end0:
```

source code for squares.s

What is a Frame Pointer

- frame pointer **`$fp`** is a second register pointing to stack
- by convention, set to point at start of stack frame
- provides a fixed point during function code execution
- useful for functions which grow stack (change **`$sp`**) during execution
- makes it easier for debuggers to forensically analyze stack
    - e.g if you want to print stack backtrace after error
- using a frame pointer is optional - both in COMP1521 and generally
- a frame pointer is often omitted when fast execution or small code a priority

Example of Growing Stack Breaking Function Return

```c
void f(int a) {
    int length;
    scanf("%d", &length);
    int array[length];
    // ... more code ...
    printf("%d\n", a);
}
```

source code for frame_pointer.c

```
f:
    # prologue
    sub  $sp, $sp, 4
    sw   $ra, 0($sp)
    li   $v0, 5
    syscall
    # allocate space for
    # array on stack
    mul  $t0, $v0, 4
    sub  $sp, $sp, $t0
    # ... more code ...
    # epilogue
    # breaks because $sp  has changed
    lw   $ra, 0($sp)
    add  $sp, $sp, 4
    jr   $ra
```

source code for frame_pointer.broken.s

Example of Frame Pointer Use - Hard Way

```c
void f(int a) {
    int length;
    scanf("%d", &length);
    int array[length];
    // ... more code ...
    printf("%d\n", a);
}
```

source code for frame_pointer.c

```
f:
    # prologue
    sub  $sp, $sp, 8
    sw   $fp, 4($sp)
    sw   $ra, 0($sp)
    add  $fp, $sp, 8

    li   $v0, 5
    syscall
    mul  $t0, $v0, 4
    sub  $sp, $sp, $t0
    # ... more code ...

    # epilogue
    lw   $ra, -4($fp)
    move $sp, $fp
    lw   $fp, 0($fp)
```

Example of Frame Pointer Use - Easy Way

```c
void f(int a) {
    int length;
    scanf("%d", &length);
    int array[length];
    // ... more code ...
    printf("%d\n", a);
}
```

source code for frame_pointer.c

```
f:
    # prologue
    begin
    push $ra

    li   $v0, 5
    syscall
    mul  $t0, $v0, 4
    sub  $sp, $sp, $t0
    # ... more code ...

    # epilogue
    pop $ra
    end
    jr   $ra
```

source code for frame_pointer.s

- **begin** & **end** are pseudo-instructions available only on mipsy