MIPS Programming

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In This Lecture

- Small review from last week
- Programming (continued)
- Addressing Modes
- Lights, Camera, Action: Compiling, Assembling, and Loading
- Odds and Ends

Assembly Language

- **To command a computer, you must understand its language**
  - ***Instructions:*** words in a computer's language
  - ***Instruction set:*** the vocabulary of a computer's language
- **Instructions indicate the operation to perform and the operands to use**
  - ***Assembly language:*** human-readable format of instructions
  - ***Machine language:*** computer-readable format (1's and 0's)
- **MIPS architecture:**
  - Developed by John Hennessy and colleagues at Stanford in the 1980's
  - Used in many commercial systems (Silicon Graphics, Nintendo, Cisco)
- **Once you've learned one architecture, it's easy to learn others**

Operands: Registers

- **Main Memory is slow**

- **Most architectures have a small set of (fast) registers**
  - MIPS has thirty-two 32-bit registers

- **MIPS is called a 32-bit architecture because it operates on 32-bit data**
  - A 64-bit version of MIPS also exists, but we will consider only the 32-bit version

The MIPS Register Set

Name	Register Number	Usage
`$0`	0	the constant value 0
`$at`	1	assembler temporary
`$v0-$v1`	2-3	procedure return values
`$a0-$a3`	4-7	procedure arguments
`$t0-$t7`	8-15	temporaries
`$s0-$s7`	16-23	saved variables
`$t8-$t9`	24-25	more temporaries
`$k0-$k1`	26-27	OS temporaries
`$gp`	28	global pointer
`$sp`	29	stack pointer
`$fp`	30	frame pointer
`$ra`	31	procedure return address

Operands: Memory

- **Too much data to fit in only 32 registers**
- **Store more data in memory**
  - Memory is large, so it can hold a lot of data
  - But it's also slow
- **Commonly used variables kept in registers**
- **Using a combination of registers and memory, a program can access a large amount of data fairly quickly**

Machine Language

- **Computers only understand 1's and 0's**
- **Machine language: binary representation of instructions**
- **32-bit instructions**
  - Again, simplicity favors regularity: 32-bit data, 32-bit instructions, and possibly also 32-bit addresses
- **Three instruction formats:**
  - **R-Type**: register operands
  - **I-Type**: immediate operand
  - **J-Type**: for jumping (we'll discuss later)

R-Type

R-Type

op	rs	rt	rd	shamt	funct
6 bits	5 bits	5 bits	5 bits	5 bits	6 bits

- **Register-type, 3 register operands:**
  - **rs**, **rt**: source registers
  - **rd**: destination register
- **Other fields:**
  - **op**: the operation code or opcode (0 for R-type instructions)
  - **funct**: the function together, the opcode and function tell the computer what operation to perform
  - **shamt**: the shift amount for shift instructions, otherwise it's 0

R-Type Examples

Assembly Code

```
add $s0, $s1, $s2

sub $t0, $t3, $t5
```

Field Values

op	rs	rt	rd	shamt	funct
0	17	18	16	0	32
0	11	13	8	0	34
6 bits	5 bits	5 bits	5 bits	5 bits	6 bits

Machine Code

op	rs	rt	rd	shamt	funct	
000000	10001	10010	10000	00000	100000	(0x02328020)
000000	01011	01101	01000	00000	100010	(0x016D4022)
6 bits	5 bits	5 bits	5 bits	5 bits	6 bits	

Note the order of registers in the assembly code:

```
add rd, rs, rt
```

Review: Instruction Formats

R-Type

op	rs	rt	rd	shamt	funct
6 bits	5 bits	5 bits	5 bits	5 bits	6 bits

I-Type

op	rs	rt	imm
6 bits	5 bits	5 bits	16 bits

J-Type

op	addr
6 bits	26 bits

The Power of the Stored Program

- **32-bit instructions and data stored in memory**
- **Sequence of instructions: only difference between two applications (for example, a text editor and a video game)**
- **To run a new program:**
  - No rewiring required
  - Simply store new program in memory
- **The processor hardware executes the program:**
  - fetches (reads) the instructions from memory in sequence
  - performs the specified operation

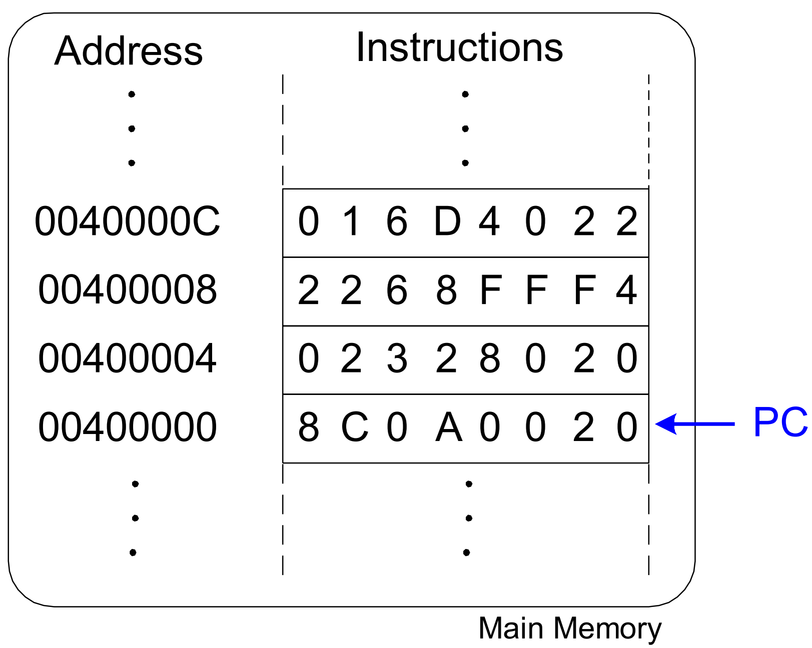
Program counter

- **The processor hardware executes the program:**
  - fetches (reads) the instructions from memory in sequence
  - performs the specified operation
  - continues with the next instruction
- **The program counter (PC) keeps track of the current instruction**
  - In MIPS, programs typically start at memory address `0x00400000`

Review: The Stored Program

Assembly Code	Machine Code
`lw   $t2, 32($0)`	`0x8C0A0020`
`add  $s0, $s1, $s2`	`0x02328020`
`addi $t0, $s3, -12`	`0x2268FFF4`
`sub  $t0, $t3, $t5`	`0x016D4022`

Stored Program



Interpreting Machine Language Code

Machine Code

	op	rs	rt	imm
(0x2237FFF1)	001000	10001	10111	1111 1111 1111 0001
	2 2		3 7	F F F 1

	op	rs	rt	rd	shamt	funct
(0x02F34022)	000000	10111	10011	01000	00000	100010
	0 2		F 3	4 0		2 2

Field Values

op	rs	rt	imm
8	17	23	-15

op	rs	rt	rd	shamt	funct
0	23	19	8	0	34

Assembly Code

```
addi $s7, $s1, -15
sub $t0, $s7, $s3
```

- **Start with opcode**
  - Opcode tells how to parse the remaining bits
- **If opcode is all 0’s**
  - R-type instruction
  - Function bits tell what instruction it is
- **Otherwise**
  - opcode tells what instruction it is

Branching

- **Allows a program to execute instructions out of sequence**

- ***Conditional branches***
  - branch if equal: **beq** (I-type)
  - branch if not equal: **bne** (I-type)

- ***Unconditional branches***
  - jump: **`j`** (J-type)
  - jump register: **`jr`** (R-type)
  - jump and link: **`jal`** (J-type)

these are the only two J-type instructions

Conditional Branching (beq)

```
# MIPS assembly
 addi $s0, $0, 4
 addi $s1, $0, 1
 sll  $s1, $s1, 2
 beq  $s0, $s1, target
 addi $s1, $s1, 1
 sub  $s1, $s1, $s0

target:
 add  $s1, $s1, $s0
```

Blackboard

Labels indicate instruction locations in a program. They cannot use reserved words and must be followed by a colon (:).

Conditional Branching (beq)

```
# MIPS assembly
 addi $s0, $0, 4          # $s0 = 0 + 4 = 4
 addi $s1, $0, 1          # $s1 = 0 + 1 = 1
 sll  $s1, $s1, 2         # $s1 = 1 << 2 = 4
 beq  $s0, $s1, target    # branch is taken
 addi $s1, $s1, 1         # not executed
 sub  $s1, $s1, $s0       # not executed

target:                   # label
 add  $s1, $s1, $s0       # $s1 = 4 + 4 = 8
```

Labels indicate instruction locations in a program. They cannot use reserved words and must be followed by a colon (:).

The Branch Not Taken (bne)

```
# MIPS assembly
  addi   $s0, $0, 4           # $s0 = 0 + 4 = 4
  addi   $s1, $0, 1           # $s1 = 0 + 1 = 1
  sll    $s1, $s1, 2          # $s1 = 1 << 2 = 4
  bne    $s0, $s1, target     # branch not taken
  addi   $s1, $s1, 1          # $s1 = 4 + 1 = 5
  sub    $s1, $s1, $s0        # $s1 = 5 – 4 = 1

target:
  add    $s1, $s1, $s0        # $s1 = 1 + 4 = 5
```

Unconditional Branching / Jumping (j)

```
# MIPS assembly
      addi   $s0, $0, 4       # $s0 = 4
      addi   $s1, $0, 1       # $s1 = 1
      j      target           # jump to target
      sra    $s1, $s1, 2      # not executed
      addi   $s1, $s1, 1      # not executed
      sub    $s1, $s1, $s0    # not executed

  target:
      add    $s1, $s1, $s0    # $s1 = 1 + 4 = 5
```

Unconditional Branching (jr)

```
# MIPS assembly
0x00002000  addi $s0, $0, 0x2010   # load 0x2010 to $s0
0x00002004  jr   $s0               # jump to $s0
0x00002008  addi $s1, $0, 1        # not executed
0x0000200C  sra  $s1, $s1, 2       # not executed
0x00002010  lw   $s3, 44($s1)      # program continues
```

High-Level Code Constructs

- `if` statements
- `if/else` statements
- `while` loops
- `for` loops

If Statement

High-level code

```
if (i == j)
  f = g + h;

f = f - i;
```

MIPS assembly code

```
# $s0 = f, $s1 = g, $s2 = h
# $s3 = i, $s4 = j
```

If Statement

High-level code

```
if (i == j)
  f = g + h;

f = f - i;
```

MIPS assembly code

```
# $s0 = f, $s1 = g, $s2 = h
# $s3 = i, $s4 = j
    bne $s3, $s4, L1
    add $s0, $s1, $s2

L1: sub $s0, $s0, $s3
```

- **Notice that the assembly tests for the opposite case (i != j) than the test in the high-level code (i == j)**

If / Else Statement

High-level code

```
if (i == j)
  f = g + h;
else
  f = f - i;
```

MIPS assembly code

```
# $s0 = f, $s1 = g, $s2 = h
# $s3 = i, $s4 = j
```

If / Else Statement

High-level code

```
if (i == j)
  f = g + h;
else
  f = f - i;
```

MIPS assembly code

```
# $s0 = f, $s1 = g, $s2 = h
# $s3 = i, $s4 = j
      bne $s3, $s4, L1
      add $s0, $s1, $s2
      j   done
L1:   sub $s0, $s0, $s3
done:
```

While Loops

High-level code

```
// determines the power
// of x such that 2x = 128
int pow = 1;
int x   = 0;

while (pow != 128) {
  pow = pow * 2;
  x = x + 1;
}
```

MIPS assembly code

```
# $s0 = pow, $s1 = x
```

While Loops

High-level code

```
// determines the power
// of x such that 2x = 128
int pow = 1;
int x   = 0;

while (pow != 128) {
  pow = pow * 2;
  x = x + 1;
}
```

MIPS assembly code

```
# $s0 = pow, $s1 = x

       addi $s0, $0, 1
       add  $s1, $0, $0
       addi $t0, $0, 128
while: beq  $s0, $t0, done
       sll  $s0, $s0, 1
       addi $s1, $s1, 1
       j    while
done:
```

- **Notice that the assembly tests for the opposite case (pow == 128) than the test in the high-level code (pow != 128)**

For Loops

The general form of a for loop is:

```
for (initialization; condition; loop operation)
  loop body
```

- `initialization`: **executes before the loop begins**
- `condition:` **is tested at the beginning of each iteration**
- `loop operation:` **executes at the end of each iteration**
- `loop body:` **executes each time the condition is met**

For Loops

High-level code

```
// add the numbers from 0 to 9
int sum = 0;
int i;

for (i = 0; i != 10; i = i+1) {
  sum = sum + i;
}
```

MIPS assembly code

```
# $s0 = i, $s1 = sum
```

For Loops

High-level code

```
// add the numbers from 0 to 9
int sum = 0;
int i;

for (i = 0; i != 10; i = i+1) {
  sum = sum + i;
}
```

MIPS assembly code

```
# $s0 = i, $s1 = sum
       addi $s1, $0, 0
       add  $s0, $0, $0
       addi $t0, $0, 10
for:   beq  $s0, $t0, done
       add  $s1, $s1, $s0
       addi $s0, $s0, 1
       j    for
done:
```

- **Notice that the assembly tests for the opposite case (i == 10) than the test in the high-level code (i != 10)**

Less Than Comparisons

High-level code

```
// add the powers of 2 from 1
// to 100
int sum = 0;
int i;

for (i = 1; i < 101; i = i*2) {
  sum = sum + i;
}
```

MIPS assembly code

```
# $s0 = i, $s1 = sum
```

Less Than Comparisons

High-level code

```
// add the powers of 2 from 1
// to 100
int sum = 0;
int i;

for (i = 1; i < 101; i = i*2) {
  sum = sum + i;
}
```

MIPS assembly code

```
# $s0 = i, $s1 = sum
       addi $s1, $0, 0
       addi $s0, $0, 1
       addi $t0, $0, 101
loop:  slt  $t1, $s0, $t0
       beq  $t1, $0, done
       add  $s1, $s1, $s0
       sll  $s0, $s0, 1
       j    loop
done:
```

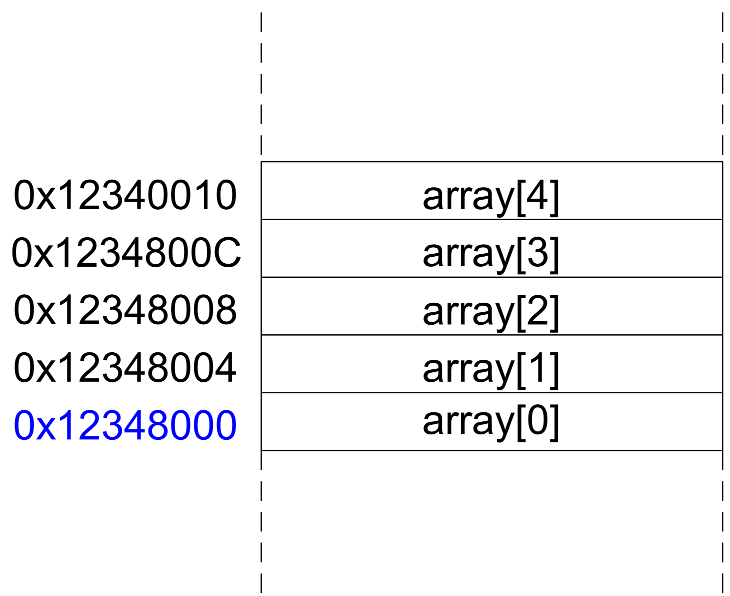
- **\$t1 = 1 if i < 101**

Arrays

- Useful for accessing large amounts of similar data
- Array element: accessed by index
- Array size: number of elements in the array

Arrays

- **5-element array**
- **Base address = `0x12348000`**
  (address of the first array element, array[0])
- **First step in accessing an array:**
  - Load base address into a register



Arrays

High-level code

```
// high-level code
  int array[5];
  array[0] = array[0] * 2;
  array[1] = array[1] * 2;
```

MIPS Assembly code

```
# MIPS assembly code
# array base address = $s0

# Initialize $s0 to 0x12348000
```

How to get a 32-bit address into register $s0?

Arrays

High-level code

```
// high-level code
  int array[5];
  array[0] = array[0] * 2;
  array[1] = array[1] * 2;
```

MIPS Assembly code

```
# MIPS assembly code
# array base address = $s0

# Initialize $s0 to 0x12348000
lui  $s0, 0x1234      # upper $s0
ori  $s0, $s0, 0x8000 # lower $s0
```

How to load a[0] and a[1] into a register?

Arrays

High-level code

```
// high-level code
  int array[5];
  array[0] = array[0] * 2;
  array[1] = array[1] * 2;
```

MIPS Assembly code

```
# MIPS assembly code
# array base address = $s0

# Initialize $s0 to 0x12348000
lui  $s0, 0x1234       # upper $s0
ori  $s0, $s0, 0x8000 # lower $s0

lw   $t1, 0($s0)    # $t1=array[0]
sll  $t1, $t1, 1    # $t1=$t1*2
sw   $t1, 0($s0)    # array[0]=$t1

lw   $t1, 4($s0)    # $t1=array[1]
sll  $t1, $t1, 1    # $t1=$t1*2
sw   $t1, 4($s0)    # array[1]=$t1
```

Arrays Using For Loops

High-level code

```
// high-level code
int arr[1000];
int i;

for (i = 0; i < 1000; i = i + 1)
    arr[i] = arr[i] * 8;
```

MIPS Assembly code

```
# $s0 = array base, $s1 = i
lui  $s0, 0x23B8       # upper $s0
ori  $s0, $s0, 0xF000 # lower $s0
```

Arrays Using For Loops

High-level code

```
// high-level code
int arr[1000];
int i;

for (i = 0; i < 1000; i = i + 1)
    arr[i] = arr[i] * 8;
```

MIPS Assembly code

```
# $s0 = array base, $s1 = i
lui  $s0, 0x23B8      # upper $s0
ori  $s0, $s0, 0xF000 # lower $s0

addi $s1, $0, 0    # i = 0
addi $t2, $0, 1000 # $t2 = 1000

loop:
slt  $t0, $s1, $t2 # i < 1000?
beq  $t0, $0, done # if not done
sll  $t0, $s1, 2   # $t0=i * 4
add  $t0, $t0, $s0 # addr of arr[i]
lw   $t1, 0($t0)   # $t1=arr[i]
sll  $t1, $t1, 3   # $t1=arr[i]*8
sw   $t1, 0($t0)   # arr[i] = $t1
addi $s1, $s1, 1   # i = i + 1
j    loop          # repeat
done:
```

Procedures

- **Definitions**
  - ***Caller:*** calling procedure (in this case, main)
  - ***Callee:*** called procedure (in this case, sum)

```
// High level code
void main()
{
  int y;
  y = sum(42, 7);
  ...
}

int sum(int a, int b)
{
  return (a + b);
}
```

Procedure Calling Conventions

- **Caller:**
  - passes arguments to callee
  - jumps to the callee

- **Callee:**
  - performs the procedure
  - returns the result to caller
  - returns to the point of call
  - must not overwrite registers or memory needed by the caller

MIPS Procedure Calling Conventions

- **Call procedure:**
  - jump and link (`jal`)
- **Return from procedure:**
  - jump register (`jr`)
- **Argument values:**
  - `$a0 - $a3`
- **Return value:**
  - `$v0`

Procedure Calls

High-level code

```
int main() {
  simple();
  a = b + c;
}

void simple() {
  return;
}
```

MIPS Assembly code

```
0x00400200 main: jal simple
0x00400204       add $s0,$s1,$s2


...
0x00401020 simple: jr $ra
```

- *void* **means that simple doesn't return a value**

Procedure Calls

High-level code

```
int main() {
  simple();
  a = b + c;
}

void simple() {
  return;
}
```

MIPS Assembly code

```
0x00400200 main:  jal simple
0x00400204        add $s0,$s1,$s2



...
0x00401020 simple: jr $ra
```

- **`jal`: jumps to `simple` and saves PC+4 in the return address register (`$ra`)**
  - In this case, `$ra` = `0x00400204` after `jal` executes
- **`jr $ra`: jumps to address in `$ra`**
  - in this case jump to address `0x00400204`

Input Arguments and Return Values

- **MIPS conventions:**
  - Argument values: `$a0 - $a3`
  - Return value: `$v0`

Input Arguments and Return Values

```c
// High-level code
int main()
{
  int y;
  ...
  // 4 arguments
  y = diffofsums(2, 3, 4, 5);
  ...
}

int diffofsums(int f, int g,
  int h, int i)
{
  int result;
  result = (f + g) - (h + i);
  return result; // return value
}
```

```
# MIPS assembly code
# $s0 = y

main:
  ...
  addi $a0, $0, 2     # argument 0 = 2
  addi $a1, $0, 3     # argument 1 = 3
  addi $a2, $0, 4     # argument 2 = 4
  addi $a3, $0, 5     # argument 3 = 5
  jal  diffofsums     # call procedure
  add  $s0, $v0, $0   # y = returned value
  ...

# $s0 = result
diffofsums:
  add $t0, $a0, $a1   # $t0 = f + g
  add $t1, $a2, $a3   # $t1 = h + i
  sub $s0, $t0, $t1   # result = (f + g) - (h + i)
  add $v0, $s0, $0    # put return value in $v0
  jr  $ra             # return to caller
```

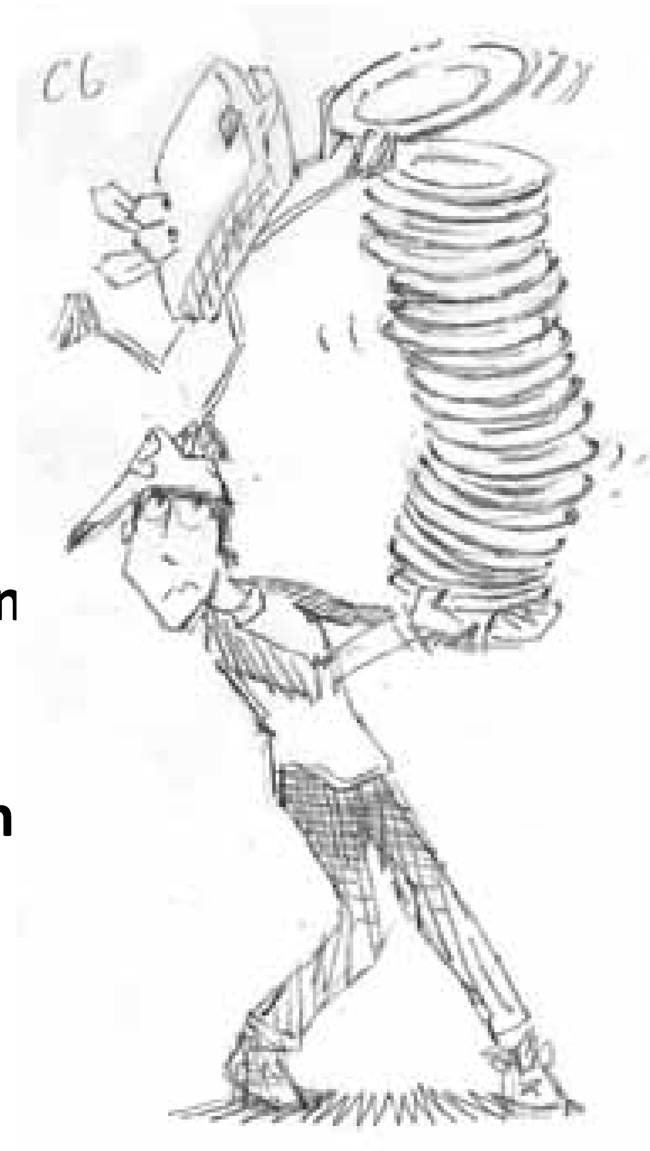
Input Arguments and Return Values

```
# $s0 = result
diffofsums:
  add $t0, $a0, $a1  # $t0 = f + g
  add $t1, $a2, $a3  # $t1 = h + i
  sub $s0, $t0, $t1  # result = (f + g) - (h + i)
  add $v0, $s0, $0   # put return value in $v0
  jr  $ra            # return to caller
```

- `diffofsums` **overwrote 3 registers: `$t0`, `$t1`, and `$s0`**
- `diffofsums` **can use the *stack* to temporarily store registers (comes next)**

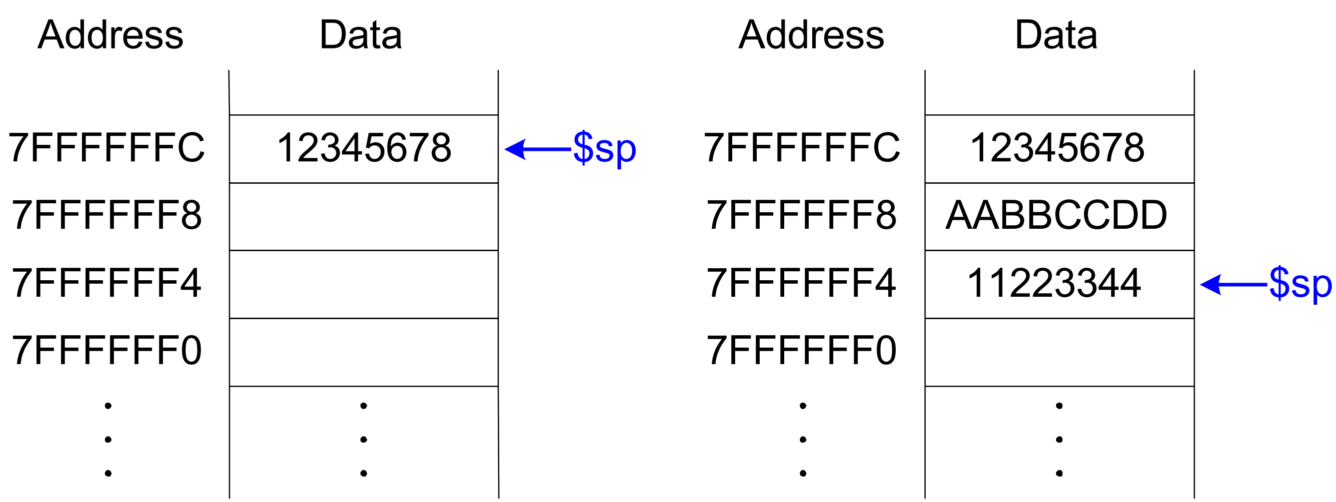
The Stack

- **Memory used to temporarily save variables**
- **Like a stack of dishes, last-in-first-out (LIFO) queue**
- ***Expands:* uses more memory when more space is needed**
- ***Contracts:* uses less memory when the space is no longer needed**



The Stack

- **Grows down (from higher to lower memory addresses)**
- **Stack pointer: $sp, points to top of the stack**



How Procedures use the Stack

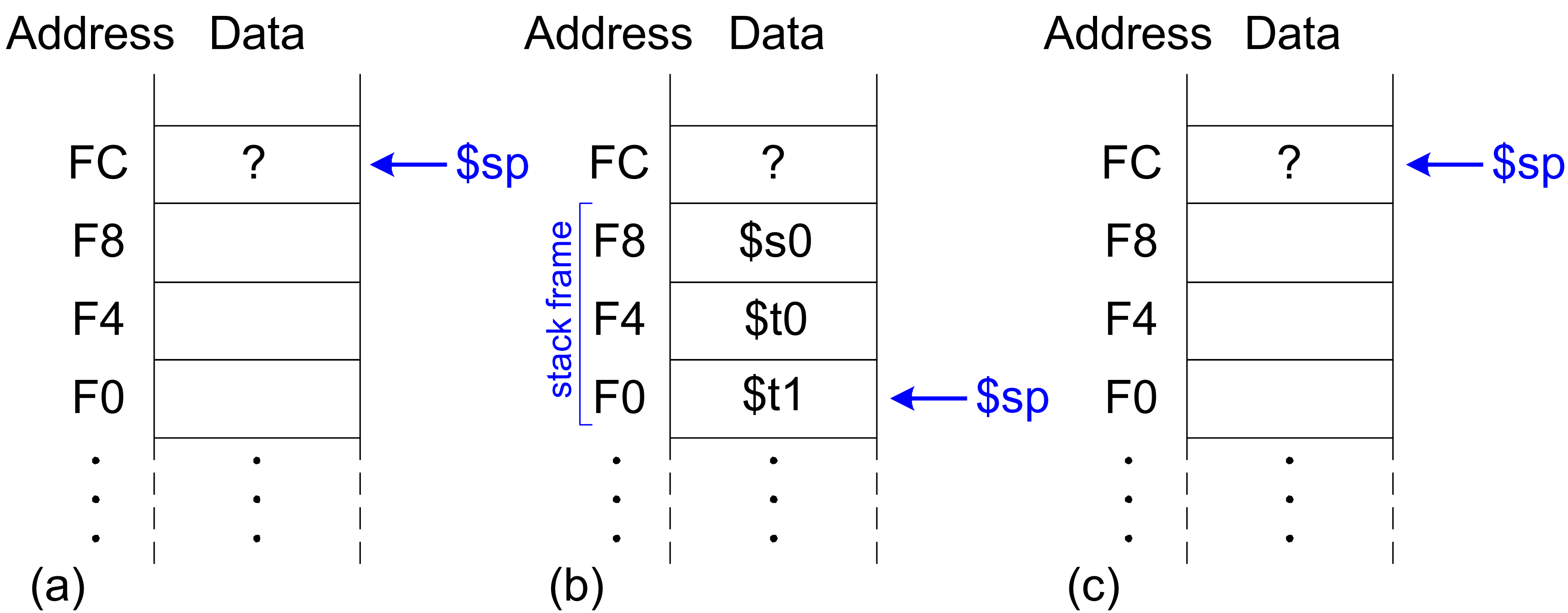
- **Called procedures must have no other unintended side effects**
- **But `diffofsums` overwrites 3 registers: `$t0`, `$t1`, `$s0`**

```
# MIPS assembly
# $s0 = result
diffofsums:
  add $t0, $a0, $a1  # $t0 = f + g
  add $t1, $a2, $a3  # $t1 = h + i
  sub $s0, $t0, $t1  # result = (f + g) - (h + i)
  add $v0, $s0, $0   # put return value in $v0
  jr  $ra            # return to caller
```

Storing Register Values on the Stack

```
# $s0 = result
diffofsums:
  addi $sp, $sp, -12  # make space on stack
                      # to store 3 registers
  sw   $s0, 8($sp)    # save $s0 on stack
  sw   $t0, 4($sp)    # save $t0 on stack
  sw   $t1, 0($sp)    # save $t1 on stack
  add  $t0, $a0, $a1  # $t0 = f + g
  add  $t1, $a2, $a3  # $t1 = h + i
  sub  $s0, $t0, $t1  # result = (f + g) - (h + i)
  add  $v0, $s0, $0   # put return value in $v0
  lw   $t1, 0($sp)    # restore $t1 from stack
  lw   $t0, 4($sp)    # restore $t0 from stack
  lw   $s0, 8($sp)    # restore $s0 from stack
  addi $sp, $sp, 12   # deallocate stack space
  jr   $ra            # return to caller
```

The Stack during `diffofsums` Call



Registers

Preserved **Callee-saved** **= Callee must preserve**	**Nonpreserved** **Caller-saved** **= Callee can overwrite**
$s0 - $s7	$t0 - $t9
$ra	$a0 - $a3
$sp	$v0 - $v1
stack above $sp	stack below $sp

Storing Saved Registers on the Stack

```
# $s0 = result
diffofsums:




  add $t0, $a0, $a1  # $t0 = f + g
  add $t1, $a2, $a3  # $t1 = h + i
  sub $s0, $t0, $t1  # result = (f + g) - (h + i)
  add $v0, $s0, $0   # put return value in $v0


  jr  $ra            # return to caller
```

which of these registers may not be overwritten by `diffofsums`?

Storing Saved Registers on the Stack

```
# $s0 = result
diffofsums:
  addi $sp, $sp, -4  # make space on stack to
                     # store one register
  sw  $s0, 0($sp)    # save $s0 on stack
                     # no need to save $t0 or $t1
  add $t0, $a0, $a1  # $t0 = f + g
  add $t1, $a2, $a3  # $t1 = h + i
  sub $s0, $t0, $t1  # result = (f + g) - (h + i)
  add $v0, $s0, $0   # put return value in $v0
  lw  $s0, 0($sp)    # restore $s0 from stack
  addi $sp, $sp, 4   # deallocate stack space
  jr  $ra            # return to caller
```

which of these registers may not be overwritten by diffofsums?

`$s0` – hence it has to be stored on the stack and restored

Multiple Procedure Calls

```
proc1:
  addi $sp, $sp, -4   # make space on stack
  sw   $ra, 0($sp)    # save $ra on stack
  jal  proc2
  ...
  lw   $ra, 0($sp)    # restore $s0 from stack
  addi $sp, $sp, 4    # deallocate stack space
  jr  $ra             # return to caller
```

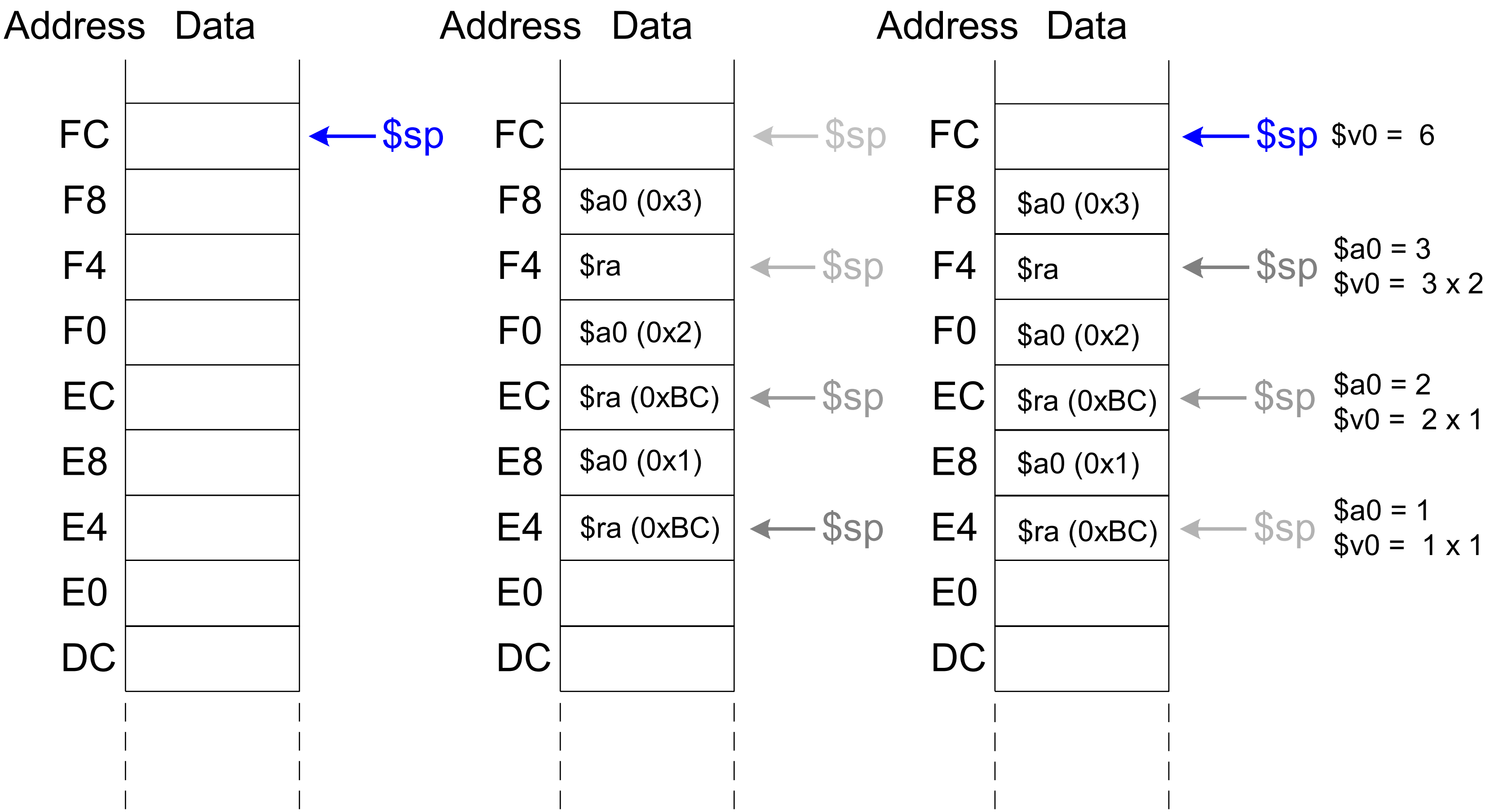
Recursive Procedure Call

```
// High-level code

int factorial(int n) {
  if (n <= 1)
    return 1;
  else
    return (n * factorial(n-1));
}
```

Recursive Procedure Call

```
# MIPS assembly code

0x90 factorial: addi $sp, $sp, -8  # make room
0x94            sw   $a0, 4($sp)   # store $a0
0x98            sw   $ra, 0($sp)   # store $ra
0x9C            addi $t0, $0, 2
0xA0            slt  $t0, $a0, $t0 # a <= 1 ?
0xA4            beq  $t0, $0, else # no: go to else
0xA8            addi $v0, $0, 1    # yes: return 1
0xAC            addi $sp, $sp, 8   # restore $sp
0xB0            jr   $ra           # return
0xB4      else: addi $a0, $a0, -1  # n = n - 1
0xB8            jal  factorial     # recursive call
0xBC            lw   $ra, 0($sp)   # restore $ra
0xC0            lw   $a0, 4($sp)   # restore $a0
0xC4            addi $sp, $sp, 8   # restore $sp
0xC8            mul  $v0, $a0, $v0 # n * factorial(n-1)
0xCC            jr   $ra           # return
```

Stack during Recursive Call



Procedure Call Summary

- **Caller**
  - Put arguments in `$a0-$a3`
  - Save any registers that are needed (`$ra`, maybe `$t0-t9`)
  - `jal callee`
  - Restore registers
  - Look for result in `$v0`

- **Callee**
  - Save registers that might be disturbed (`$s0-$s7`)
  - Perform procedure
  - Put result in `$v0`
  - Restore registers
  - `jr $ra`

Addressing Modes

- **How do we address the operands?**
  - Register Only
  - Immediate
  - Base Addressing
  - PC-Relative
  - Pseudo Direct

Register Only Addressing

- **Operands found in registers**
  - *Example:*
    `add $s0, $t2, $t3`
  - *Example:*
    `sub $t8, $s1, $0`

Immediate Addressing

- **16-bit immediate used as an operand**
  - *Example:*
    ```
    addi $s4, $t5, -73
    ```
  - *Example:*
    ```
    ori  $t3, $t7, 0xFF
    ```

Base Addressing

- **Address of operand is:**

  `base address + sign-extended immediate`

  - *Example:*
    `lw  $s4, 72($0)`   Address = `$0 + 72`
  - *Example:*
    `sw  $t2, -24($t1)`   Address = `$t1 - 24`

PC-Relative Addressing

```
0x10          beq    $t0, $0, else
0x14          addi   $v0, $0, 1
0x18          addi   $sp, $sp, i
0x1C          jr     $ra
0x20   else:  addi   $a0, $a0, -1
0x24          jal    factorial
```

Assembly Code

```
beq $t0, $0, else
(beq $t0, $0, 3)
```

Field Values

op	rs	rt	imm
4	8	0	3

6 bits   5 bits   5 bits   5 bits   5 bits   6 bits

Pseudo-direct Addressing

```
0x0040005C        jal    sum
...
0x004000A0  sum:  add    $v0, $a0, $a1
```

JTA 0000 0000 0100 0000 0000 0000 1010 0000 (0x004000A0)

26-bit addr 0000 0000 0100 0000 0000 0000 1010 0000 (0x0100028)

0 1 0 0 0 2 8

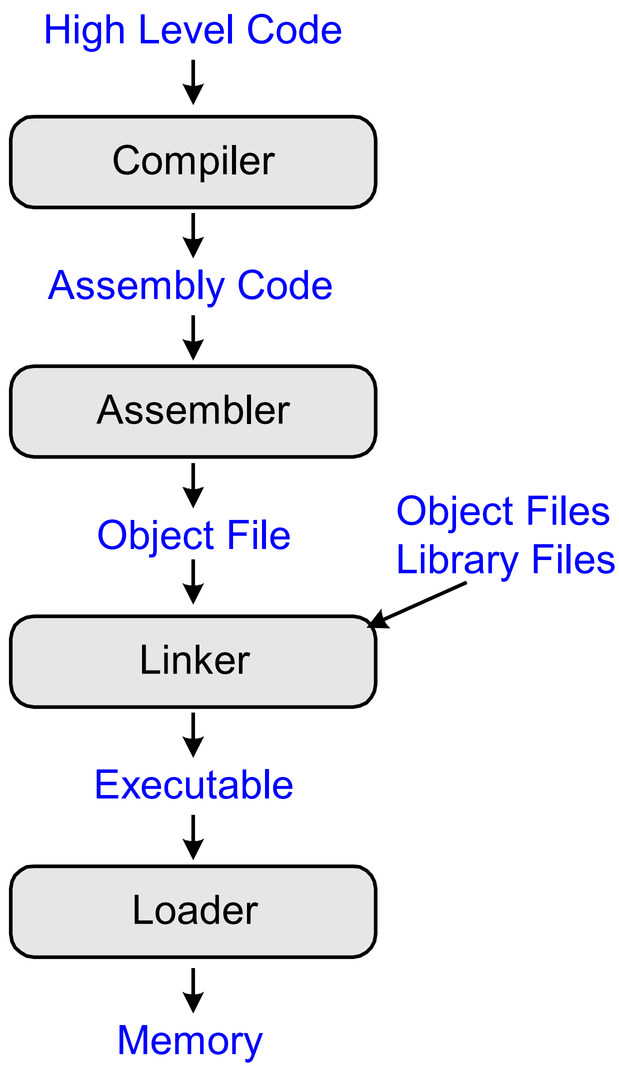
Field Values

op	imm
3	0x0100028
6 bits	26 bits

Machine Code

op	addr	
000011	00 0001 0000 0000 0000 0010 1000	(0x0C100028)
6 bits	26 bits	

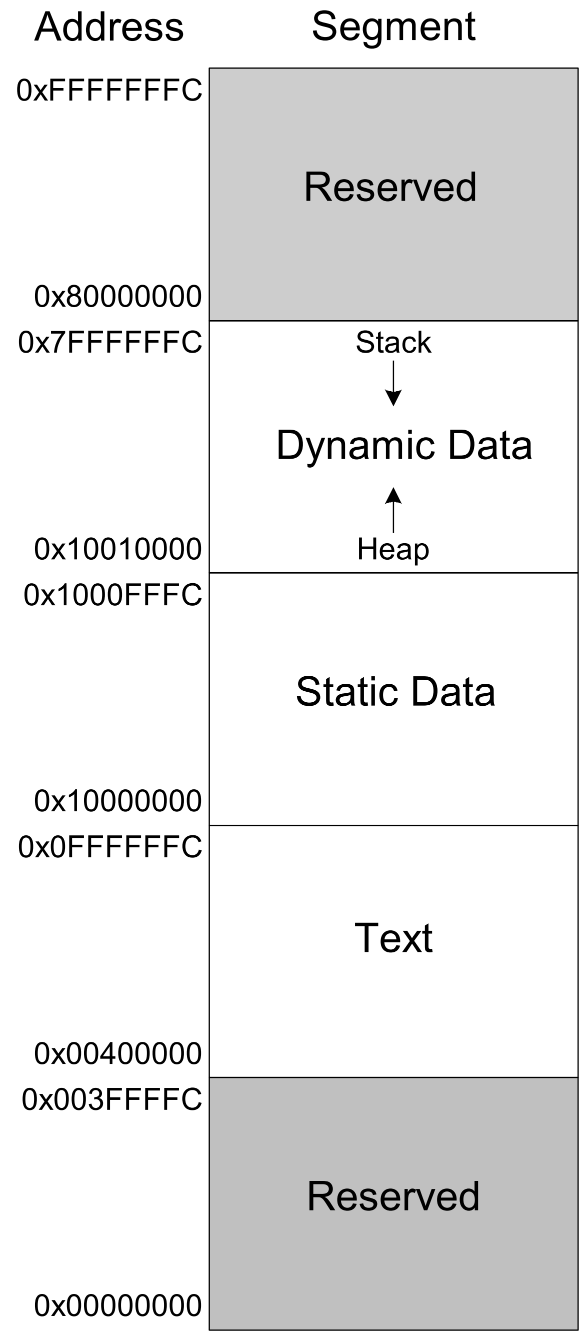
How Do We Compile & Run an Application?



What needs to be stored in memory?

- **Instructions (also called text)**
- **Data**
  - Global/static: allocated before program begins
  - Dynamic: allocated within program
- **How big is memory?**
  - At most 2^{32} = 4 gigabytes (4 GB)
  - From address `0x00000000` to `0xFFFFFFFF`

The MIPS Memory Map



Example Program: C Code

```
int f, g, y;  // global variables

int main(void)
{
  f = 2;
  g = 3;
  y = sum(f, g);

  return y;
}

int sum(int a, int b) {
  return (a + b);
}
```

Example Program: Assembly Code

```c
int f, g, y;  // global




int main(void)
{


  f = 2;

  g = 3;

  y = sum(f, g);
  return y;
}


int sum(int a, int b) {
  return (a + b);
}
```

```
.data
f:
g:
y:
.text
main: addi $sp, $sp, -4 # stack
      sw   $ra, 0($sp)  # store $ra
      addi $a0, $0, 2   # $a0 = 2
      sw   $a0, f       # f = 2
      addi $a1, $0, 3   # $a1 = 3
      sw   $a1, g       # g = 3
      jal  sum          # call sum
      sw   $v0, y       # y = sum()
      lw   $ra, 0($sp)  # rest. $ra
      addi $sp, $sp, 4  # rest. $sp
      jr   $ra          # return
sum:  add  $v0, $a0, $a1 # $v0= a+b
      jr   $ra          # return
```

Example Program: Symbol Table

Symbol	Address
f	`0x10000000`
g	`0x10000004`
y	`0x10000008`
main	`0x00400000`
sum	`0x0040002C`

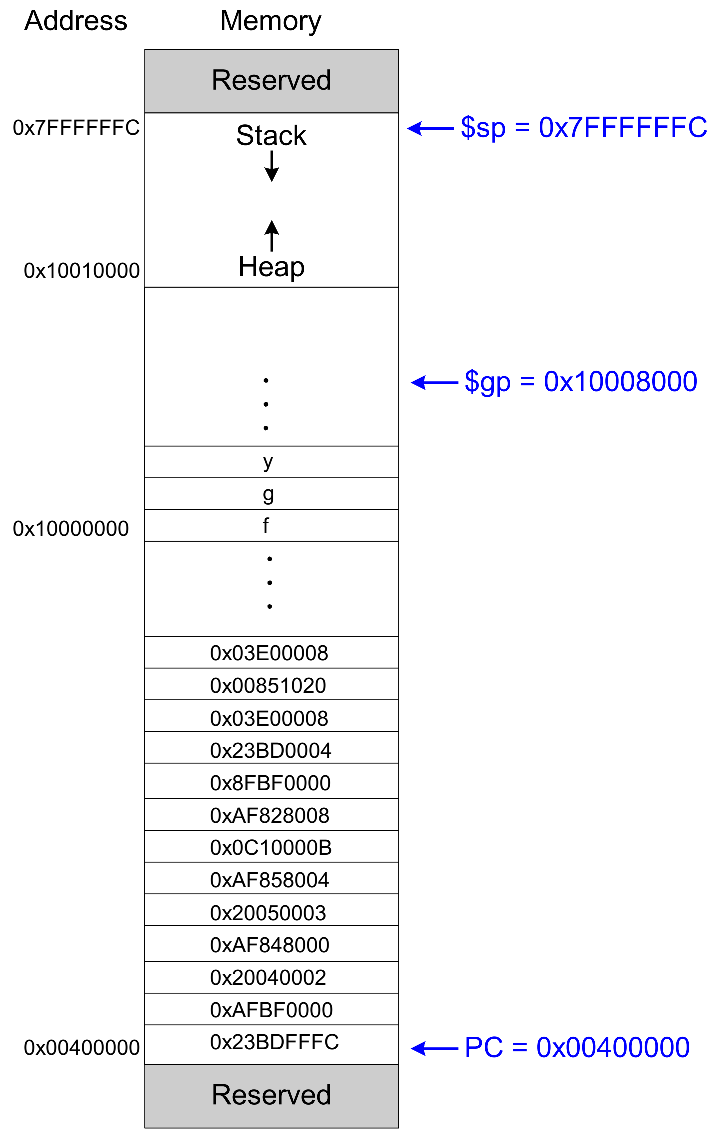
Example Program: Executable

Executable file header	Text Size	Data Size
	0x34 (52 bytes)	0xC (12 bytes)

Text segment	Address	Instruction	
	0x00400000	0x23BDFFFC	addi $sp, $sp, -4
	0x00400004	0xAFBF0000	sw $ra, 0 ($sp)
	0x00400008	0x20040002	addi $a0, $0, 2
	0x0040000C	0xAF848000	sw $a0, 0x8000 ($gp)
	0x00400010	0x20050003	addi $a1, $0, 3
	0x00400014	0xAF858004	sw $a1, 0x8004 ($gp)
	0x00400018	0x0C10000B	jal 0x0040002C
	0x0040001C	0xAF828008	sw $v0, 0x8008 ($gp)
	0x00400020	0x8FBF0000	lw $ra, 0 ($sp)
	0x00400024	0x23BD0004	addi $sp, $sp, +4
	0x00400028	0x03E00008	jr $ra
	0x0040002C	0x00851020	add $v0, $a0, $a1
	0x00400030	0x03E0008	jr $ra

Data segment	Address	Data
	0x10000000	f
	0x10000004	g
	0x10000008	y

Example Program: In Memory



Odds and Ends

- Pseudoinstructions
- Exceptions
- Signed and unsigned instructions
- Floating-point instructions

Pseudoinstruction Examples

Pseudoinstruction	MIPS Instructions
`li    $s0, 0x1234AA77`	`lui   $s0, 0x1234` `ori   $s0, 0xAA77`
`mul   $s0, $s1, $s2`	`mult  $s1, $s2` `mflo  $s0`
`clear $t0`	`add   $t0, $0, $0`
`move  $s1, $s2`	`add   $s2, $s1, $0`
`nop`	`sll   $0, $0, 0`

Exceptions

- **Unscheduled procedure call to the exception handler**
- **Caused by:**
  - Hardware, also called an interrupt, e.g. keyboard
  - Software, also called traps, e.g. undefined instruction
- **When exception occurs, the processor:**
  - Records the cause of the exception
  - Jumps to the exception handler at instruction address 0x80000180
  - Returns to program

Exception Registers

- **Not part of the register file.**
  - Cause
    - Records the cause of the exception
  - EPC (Exception PC)
    - Records the PC where the exception occurred
- **EPC and Cause: part of Coprocessor 0**
- **Move from Coprocessor 0**
  - mfc0 $t0, EPC
  - Moves the contents of EPC into $t0

Exception Causes

Exception	Cause
Hardware Interrupt	0x00000000
System Call	0x00000020
Breakpoint / Divide by 0	0x00000024
Undefined Instruction	0x00000028
Arithmetic Overflow	0x00000030

Exceptions

- **Processor saves cause and exception PC in Cause and EPC**
- **Processor jumps to exception handler (0x80000180)**
- **Exception handler:**
  - Saves registers on stack
  - Reads the Cause register
    - `mfc0 $t0, Cause`
  - Handles the exception
  - Restores registers
  - Returns to program
    - `mfc0 $k0, EPC`
    - `jr   $k0`

What Did We Learn?

- **How to translate common programming constructs**
  - Conditons
  - Loops
  - Procedure calls
- **Stack**
- **The compiled program**
- **Odds and Ends**
  - Floating point (F-type) instructions
- **What Next?**
  - Actually building the MIPS Microprocessor!!