Code Generation

TEACHING ASSISTANT: DAVID TRABISH

MIPS Architecture

- MIPS has 32 registers:
  - t0, …, t9
  - a0, a1, a2, a3
  - v0, v1
  - sp, fp
  - ra
  - …
- We will work with MIPS32
  - 32-bit registers

MIPS Architecture

- Arithmetic instructions operate on registers and constants:
  - add, sub, mul, div, and, or, xor, nor, …

```
li $t0, 3
li $t1, 4
add $t2, $t0, $t1
mul $t3, t1, 7
```

MIPS Architecture

- Read from memory:

```
lw $t0,4($t1)
lw $t0,label
lw $t0,label+4
lw $t0,label+8($t1)
```

MIPS Architecture

- Write to memory:

```
sw $t0,2($t1)
sw $t0,label
sw $t0,label+4
sw $t0,label+8($t1)
```

MIPS Architecture

- Branches and Jumps:

```
beq $t1, $t2, label
bne $t1, 7, label
j label
...
label:
```

MIPS Architecture

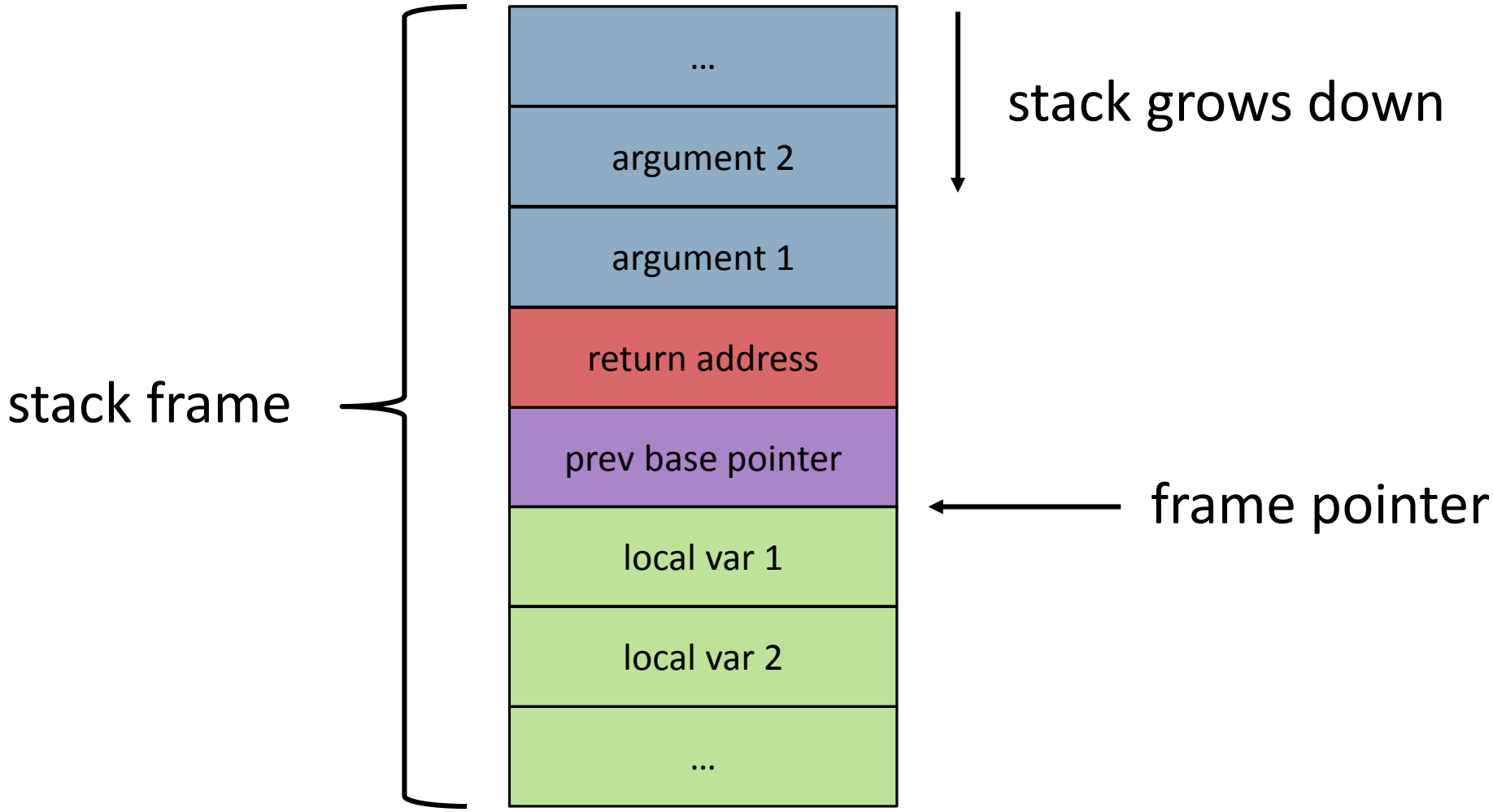
- System calls:
  - Syscall number passed via v0
  - Arguments are passed via a0, a1, a2, a3
- For example, calling PrintInt(17):

```
li $v0, 1
li $a0, 17
syscall
```

Stack Frames

- The stack consists of stack frame
- Each called function creates it’s stack frame

Stack


...
argument 2
argument 1
return address
prev base pointer
local var 1
local var 2
...
stack grows down
stack frame
frame pointer

Stack

```
int f(int x, int y){
   int z = x + y;
   return z;
}
int g() {
   int x = f(10, 20)
}
```

```
f:
subu $sp, $sp, 4
sw $ra, 0($sp)
subu $sp, $sp, 4
sw $fp, 0($sp)
move $fp, $sp
sub $sp, $sp, 16
lw $t0, 8($fp)
lw $t1, 12($fp)
add $t2, $t0, $t1
sw $t2, -4($fp)
lw $v0, -4($fp)
move $sp, $fp
lw $fp, 0($sp)
lw $ra, 4($sp)
addu $sp, $sp, 8
jr $ra
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g:
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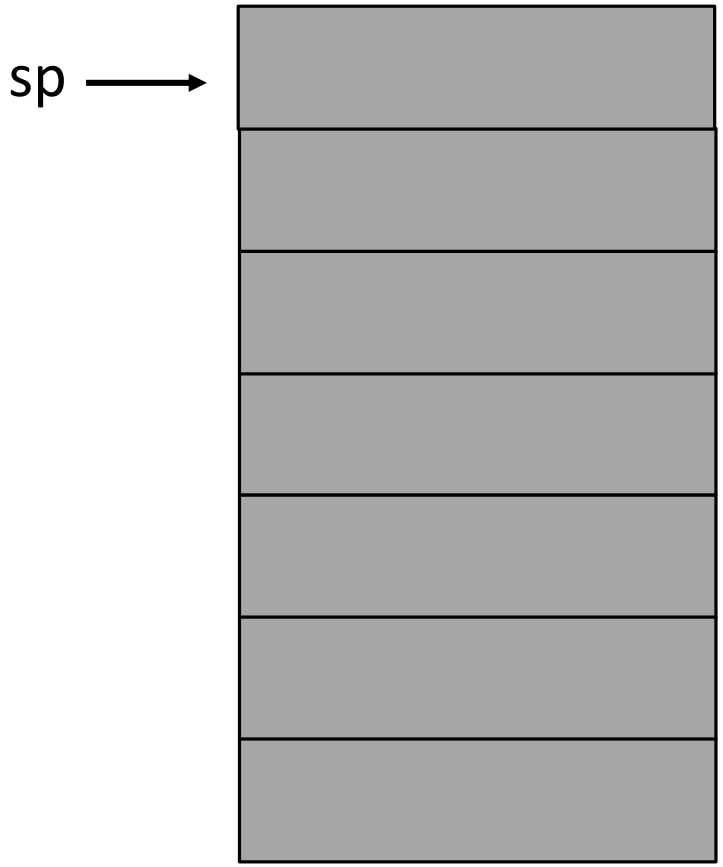


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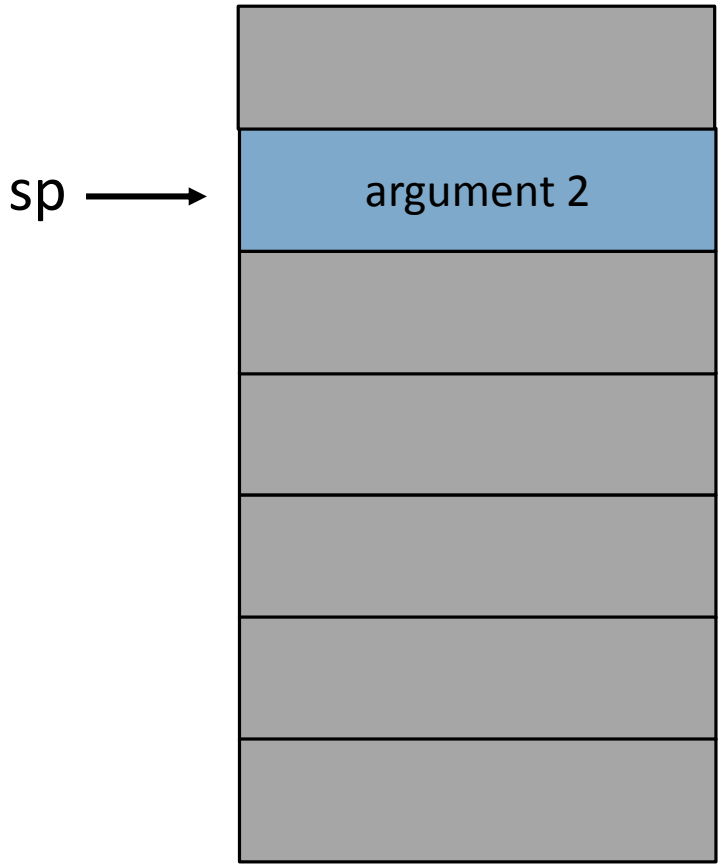


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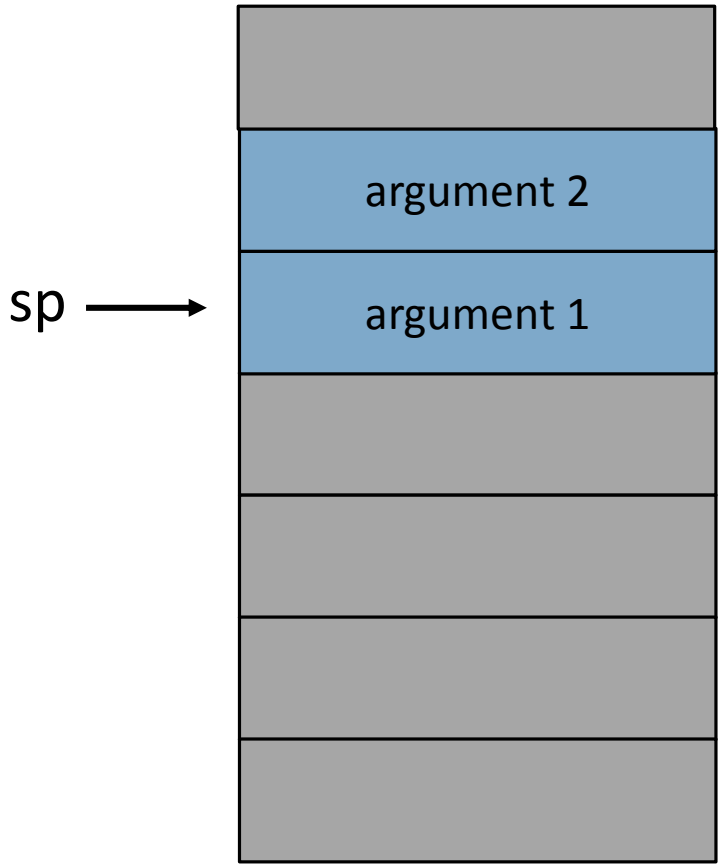


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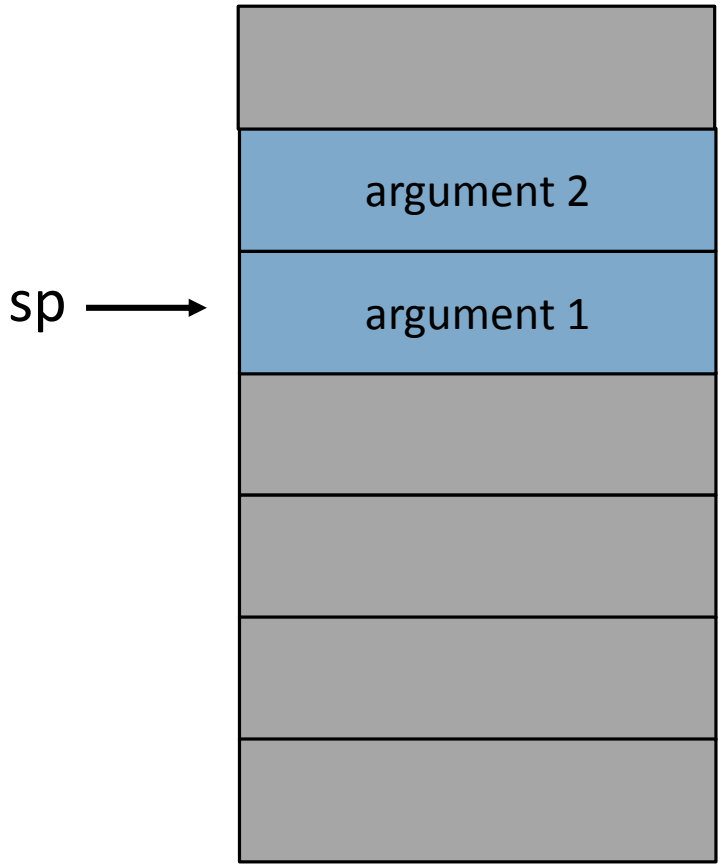


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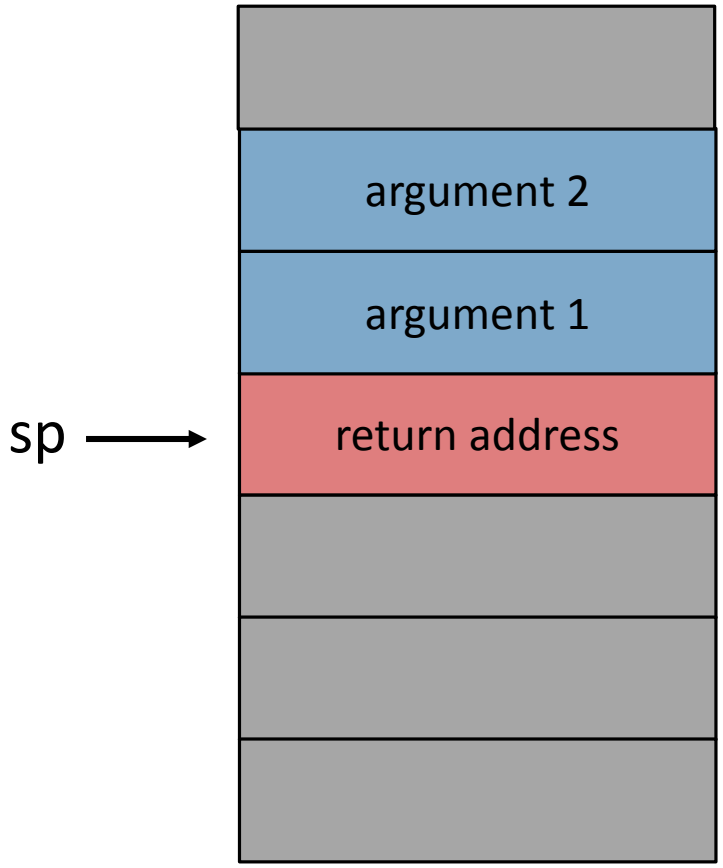


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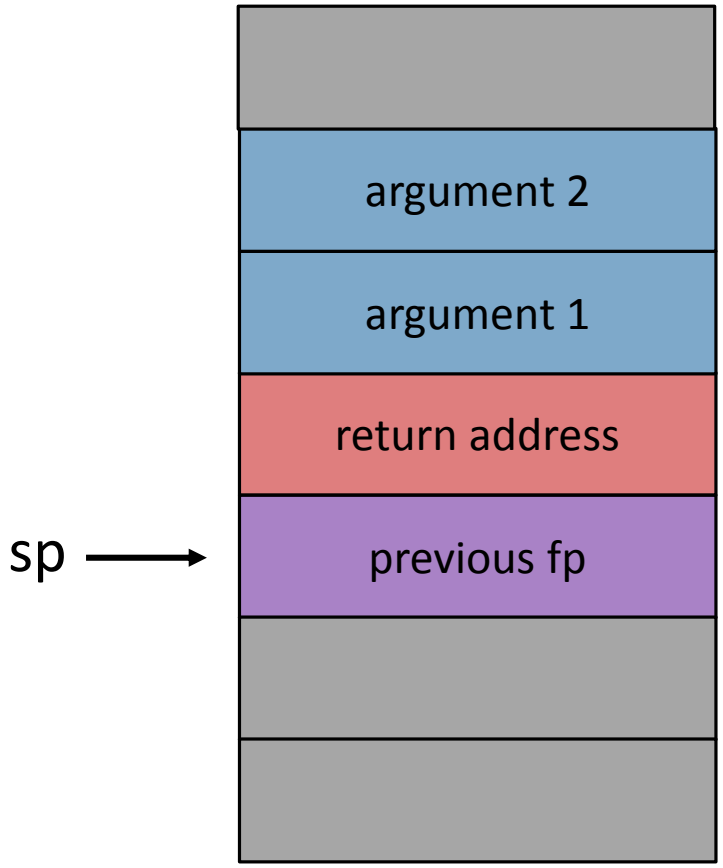


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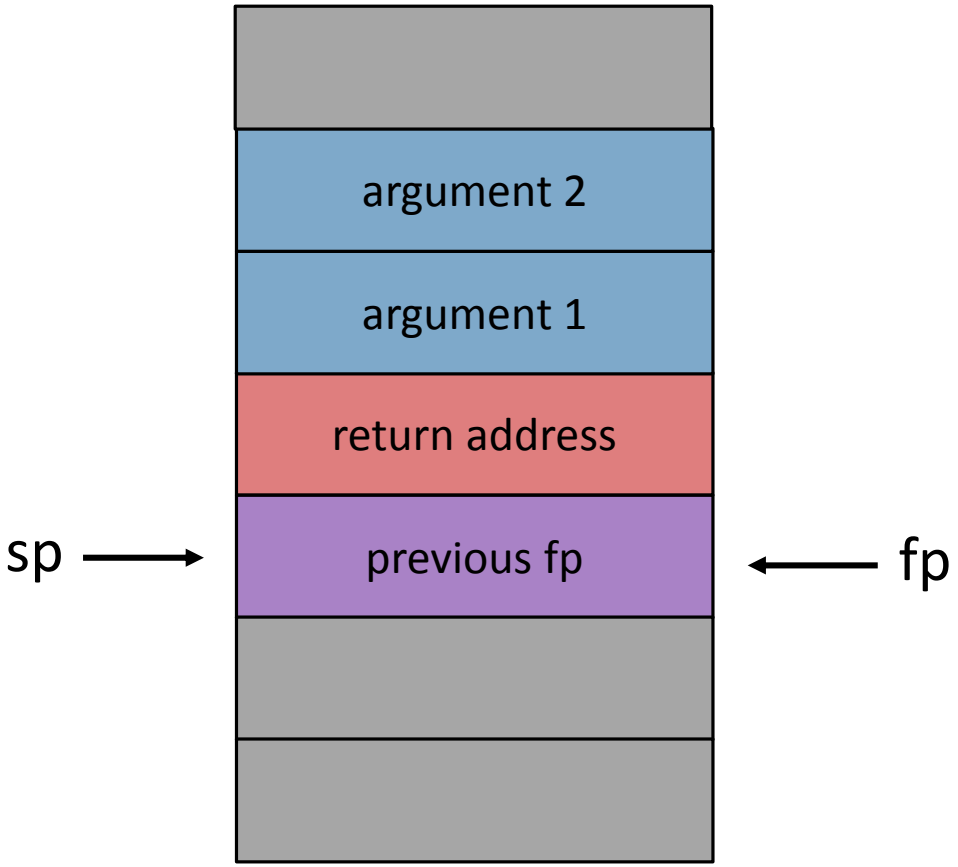


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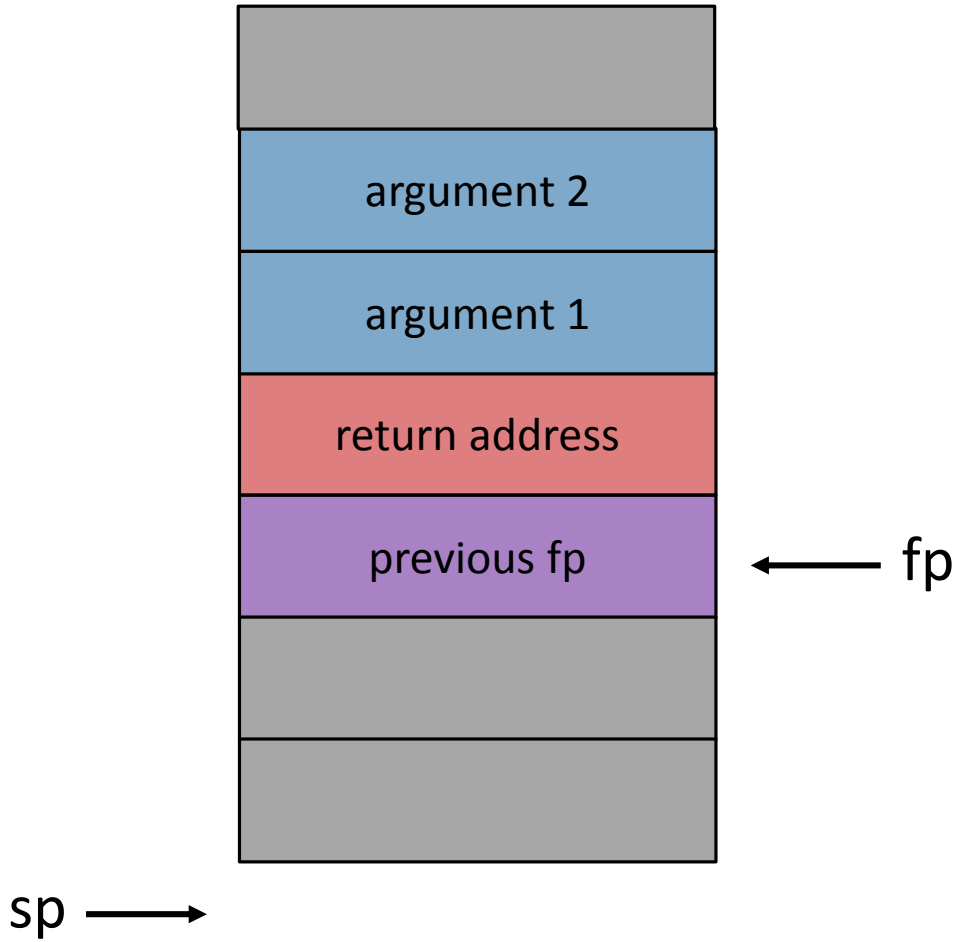


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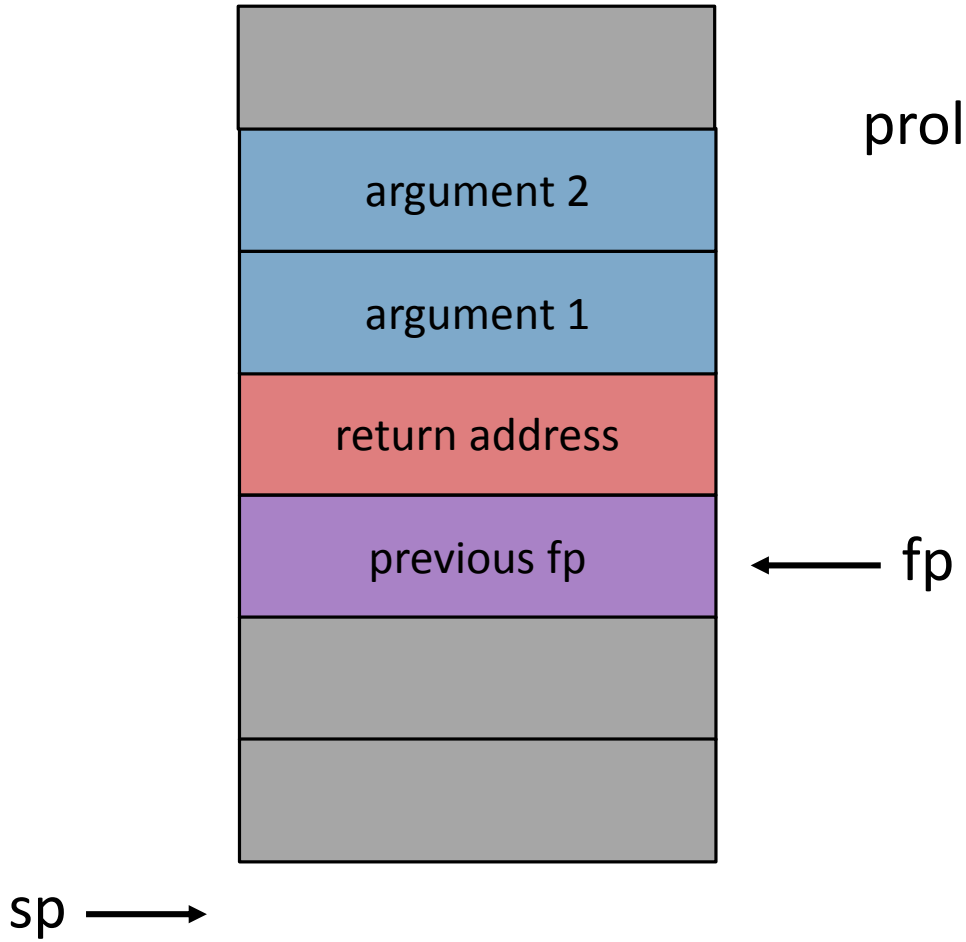

prologue

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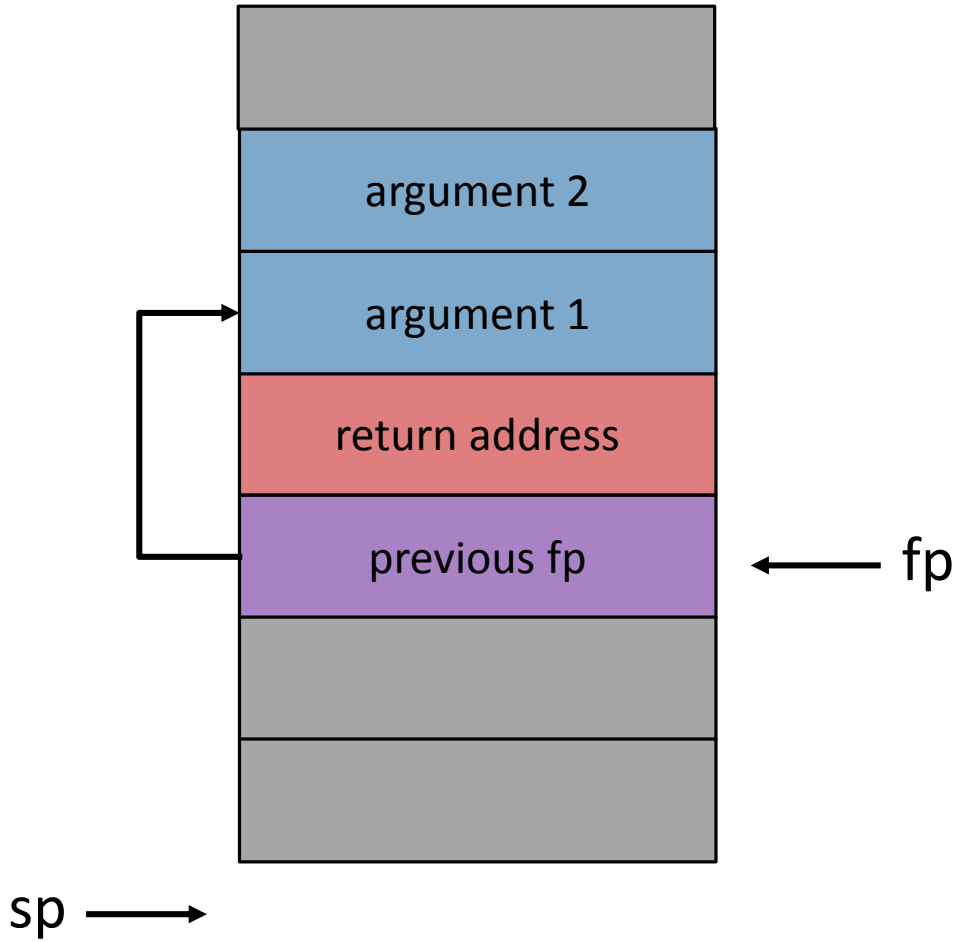
Stack

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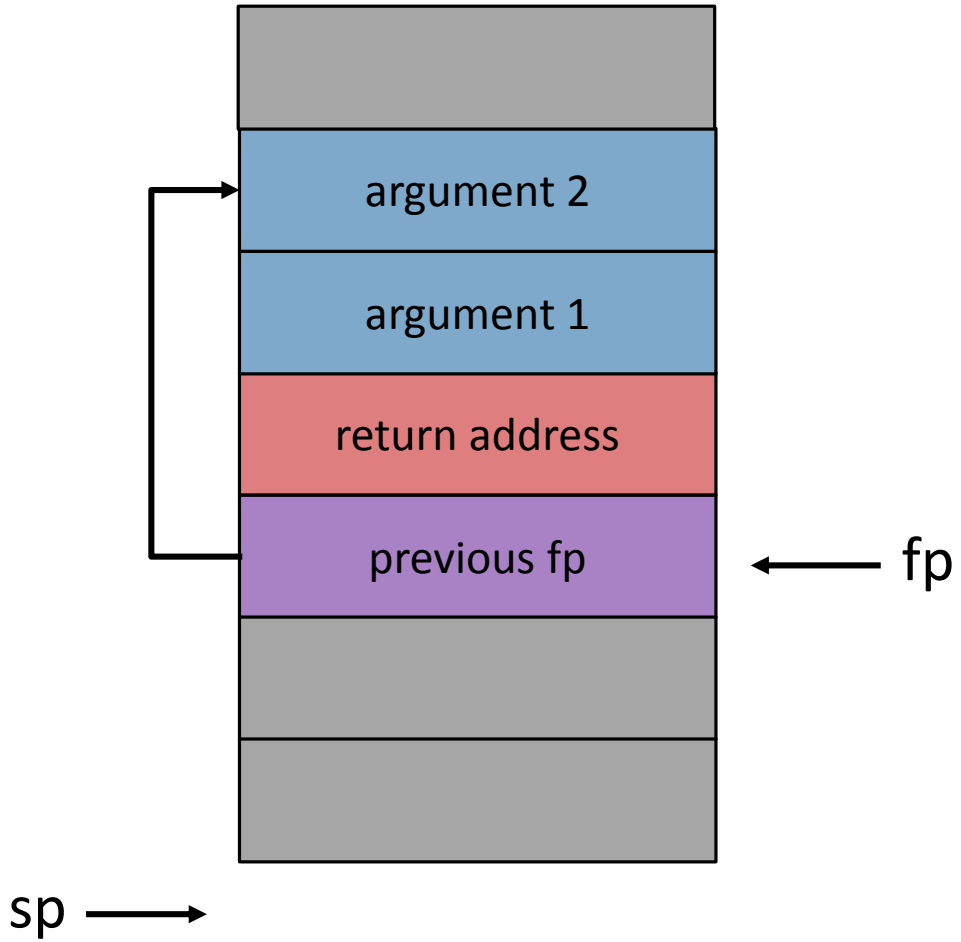


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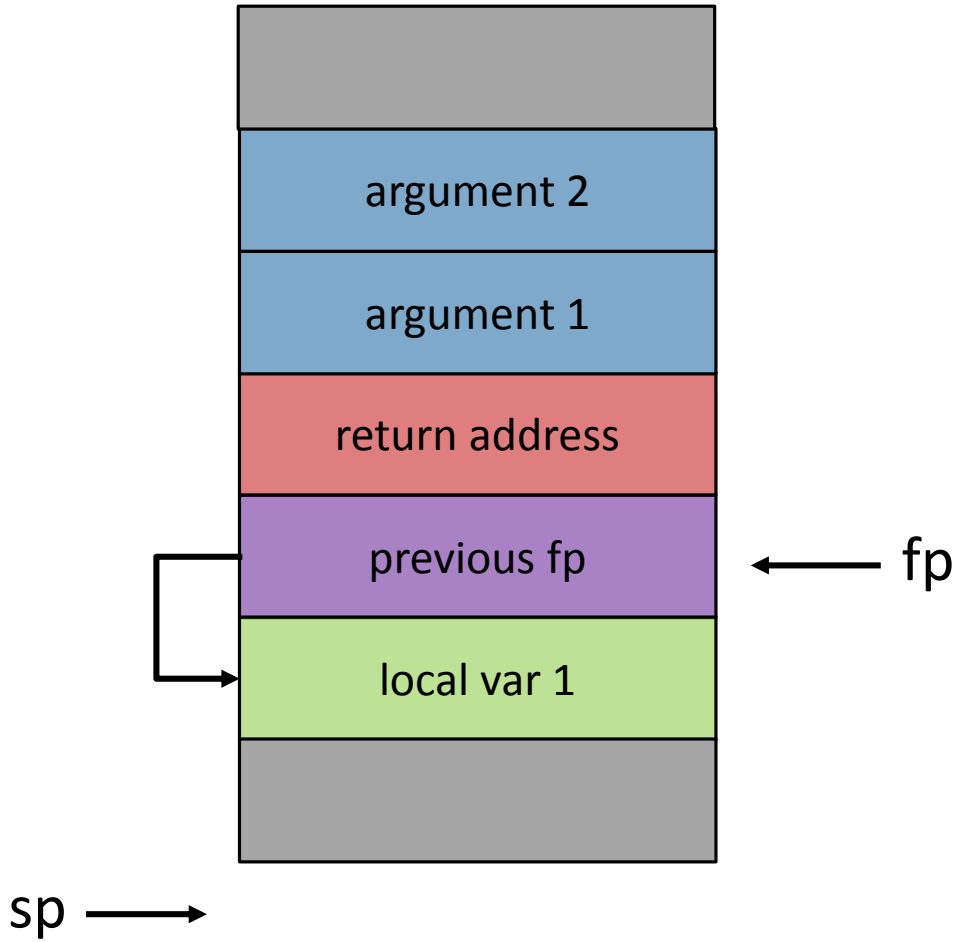


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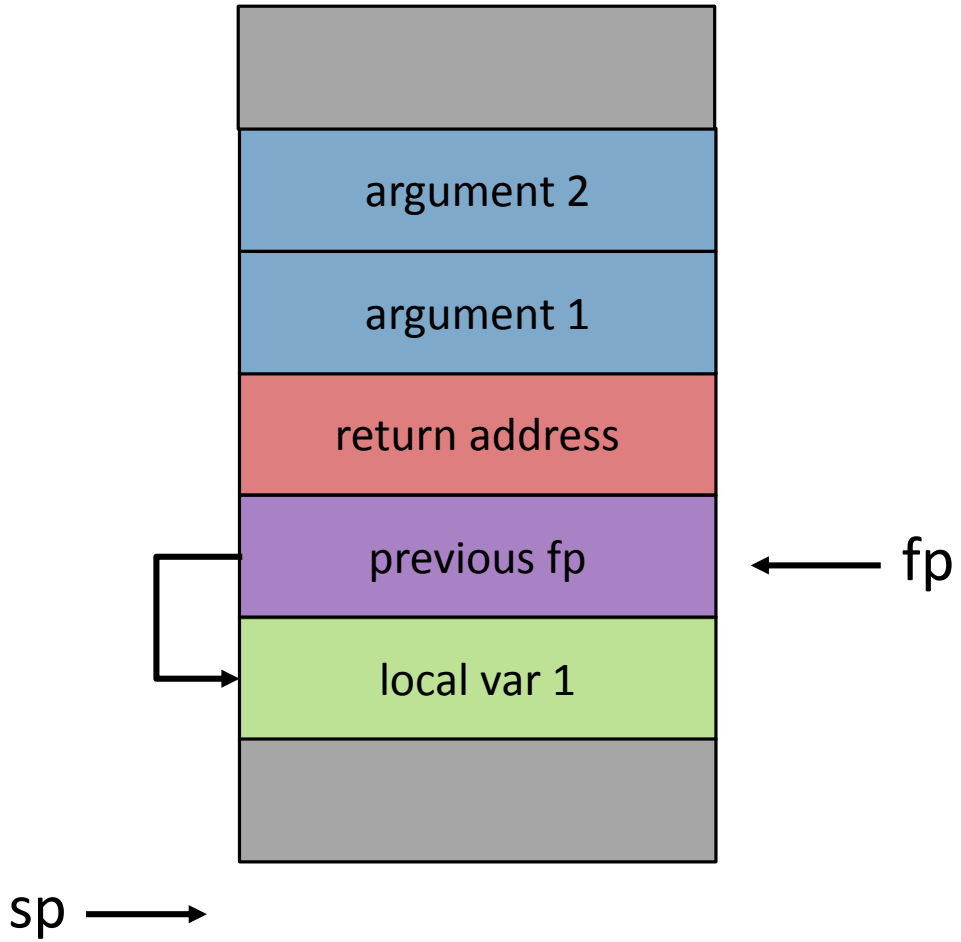


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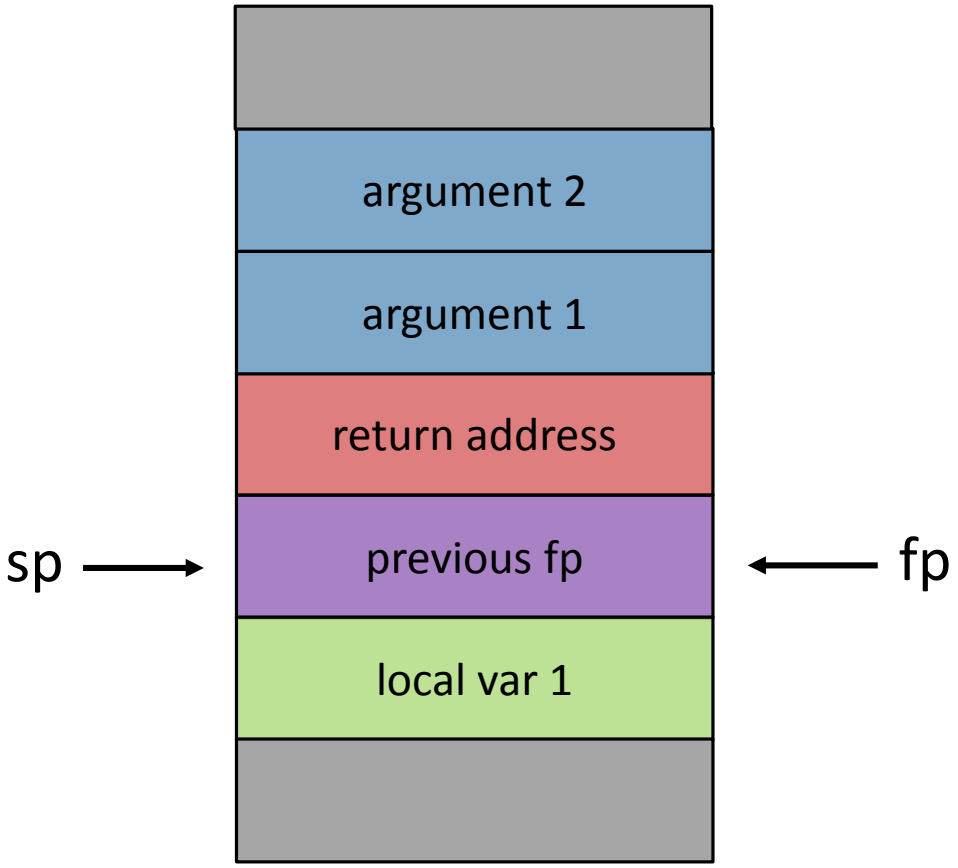


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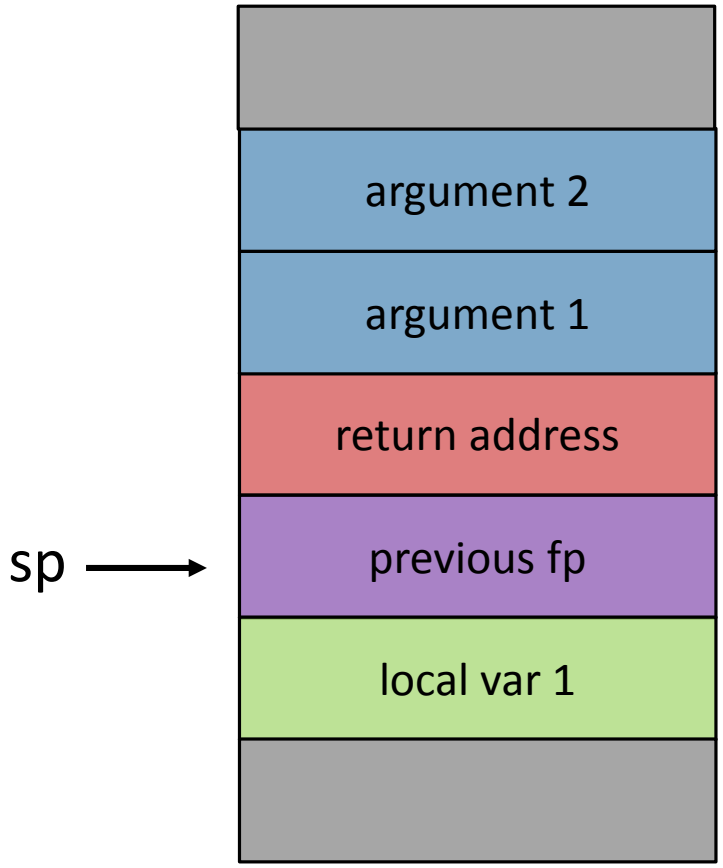


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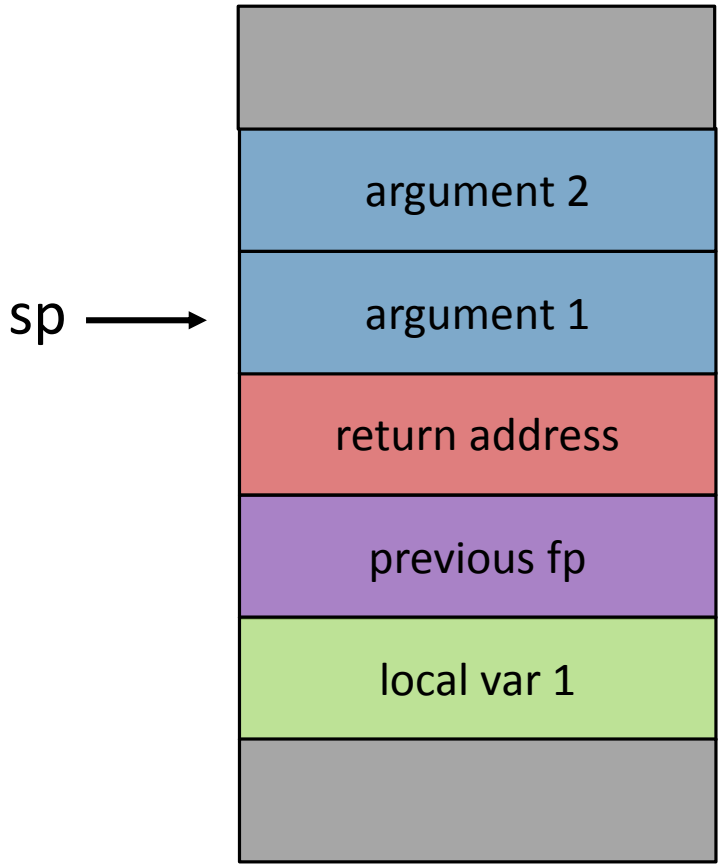


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```
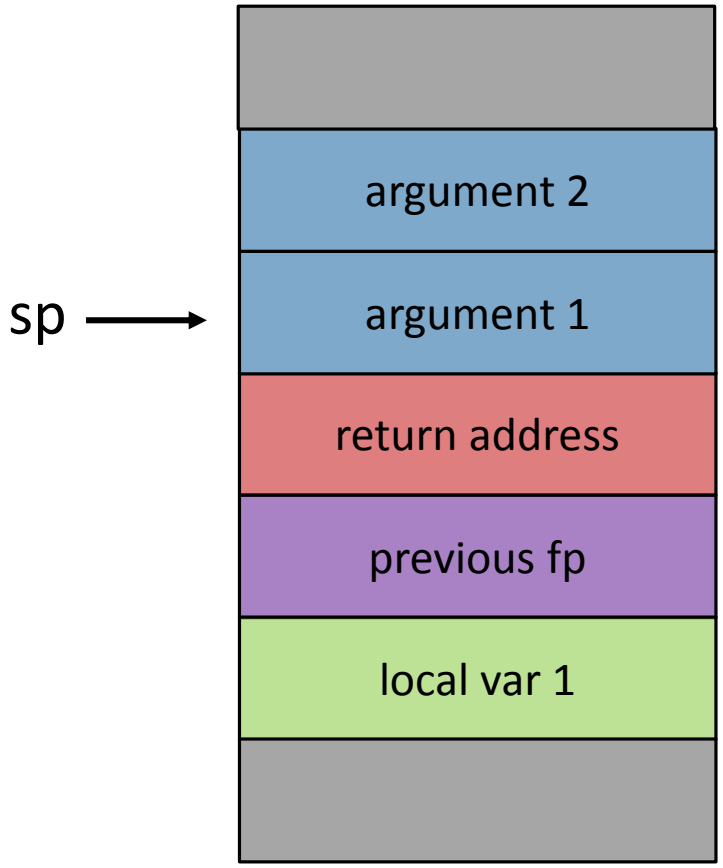
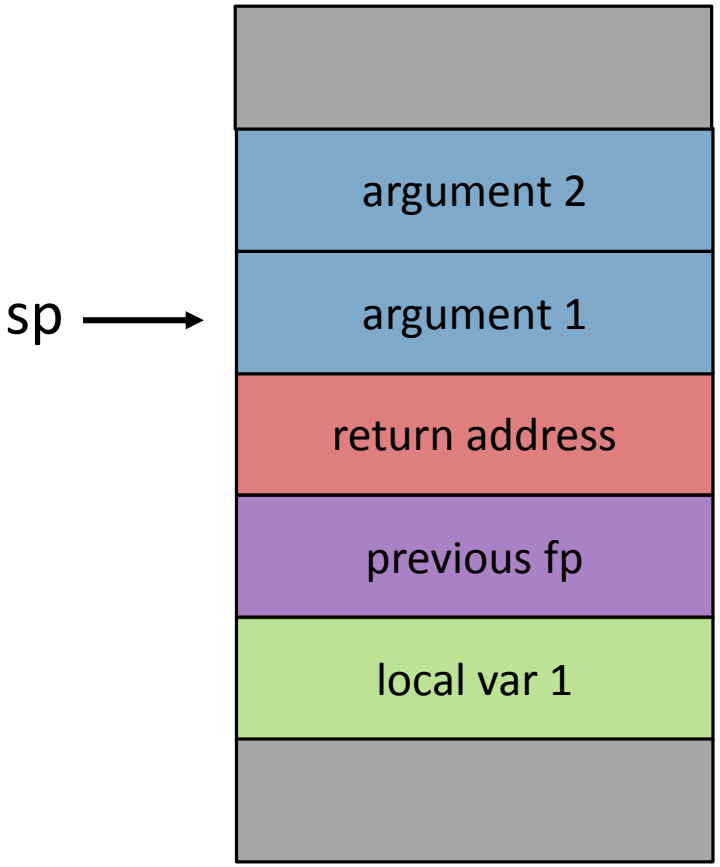

Stack




```
f:
subu $sp, $sp, 4
sw $ra, 0($sp)
subu $sp, $sp, 4
sw $fp, 0($sp)
move $fp, $sp
sub $sp, $sp, 16
lw $t0, 8($fp)
lw $t1, 12($fp)
add $t2, $t0, $t1
sw $t2, -4($fp)
lw $v0, -4($fp)
move $sp, $fp
lw $fp, 0($sp)
lw $ra, 4($sp)
addu $sp, $sp, 8
jr $ra
```

```
g:
...
li $t0, 20
subu $sp, $sp, 4
sw $t0, 0($sp)
li $t0, 10
subu $sp, $sp, 4
sw $t0, 0($sp)
jal f
addu $sp, $sp, 8
move $t0, $v0
...
```

Stack

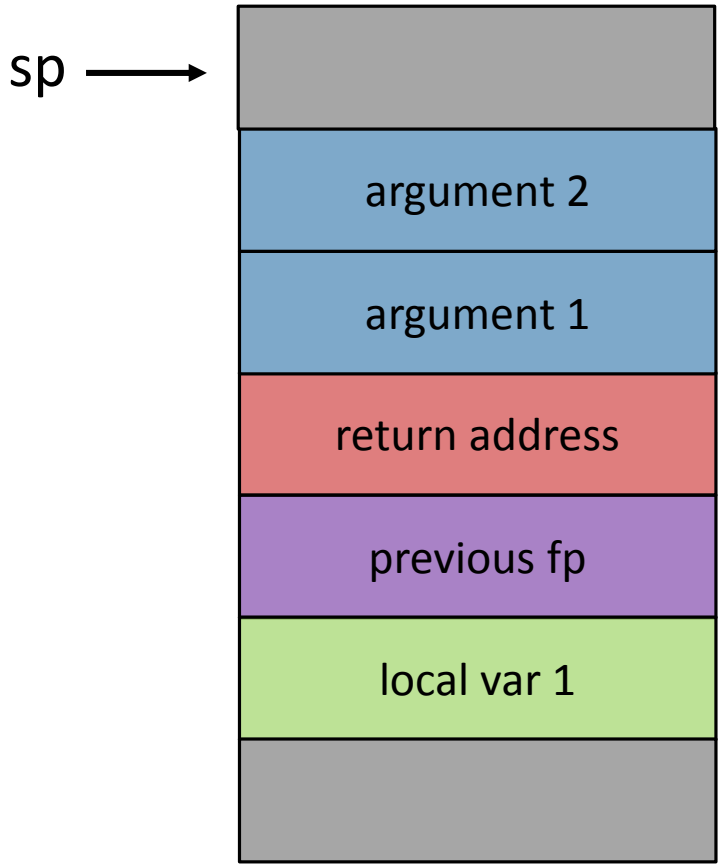



```
f:
subu $sp, $sp, 4
sw $ra, 0($sp)
subu $sp, $sp, 4
sw $fp, 0($sp)
move $fp, $sp
sub $sp, $sp, 16
lw $t0, 8($fp)
lw $t1, 12($fp)
add $t2, $t0, $t1
sw $t2, -4($fp)
lw $v0, -4($fp)
move $sp, $fp
lw $fp, 0($sp)
lw $ra, 4($sp)
addu $sp, $sp, 8
jr $ra
```

epilogue

```
g:
...
li $t0, 20
subu $sp, $sp, 4
sw $t0, 0($sp)
li $t0, 10
subu $sp, $sp, 4
sw $t0, 0($sp)
jal f
addu $sp, $sp, 8
move $t0, $v0
...
```

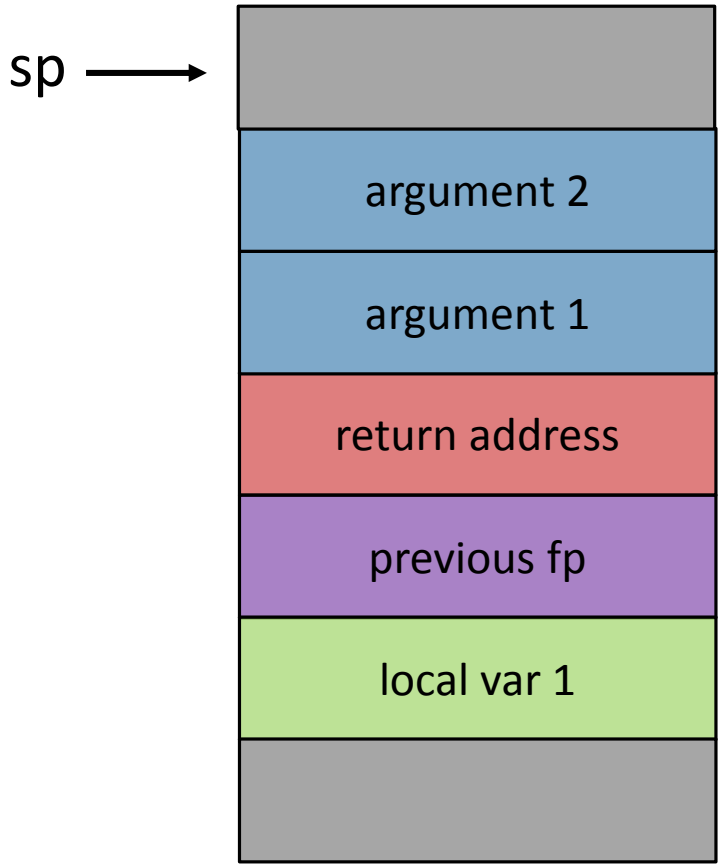
Stack




```
f:
subu $sp, $sp, 4
sw $ra, 0($sp)
subu $sp, $sp, 4
sw $fp, 0($sp)
move $fp, $sp
sub $sp, $sp, 16
lw $t0, 8($fp)
lw $t1, 12($fp)
add $t2, $t0, $t1
sw $t2, -4($fp)
lw $v0, -4($fp)
move $sp, $fp
lw $fp, 0($sp)
lw $ra, 4($sp)
addu $sp, $sp, 8
jr $ra
```

```
g:
...
li $t0, 20
subu $sp, $sp, 4
sw $t0, 0($sp)
li $t0, 10
subu $sp, $sp, 4
sw $t0, 0($sp)
jal f
addu $sp, $sp, 8
move $t0, $v0
...
```

Stack




```
f:
subu $sp, $sp, 4
sw $ra, 0($sp)
subu $sp, $sp, 4
sw $fp, 0($sp)
move $fp, $sp
sub $sp, $sp, 16
lw $t0, 8($fp)
lw $t1, 12($fp)
add $t2, $t0, $t1
sw $t2, -4($fp)
lw $v0, -4($fp)
move $sp, $fp
lw $fp, 0($sp)
lw $ra, 4($sp)
addu $sp, $sp, 8
jr $ra
```

```
g:
...
li $t0, 20
subu $sp, $sp, 4
sw $t0, 0($sp)
li $t0, 10
subu $sp, $sp, 4
sw $t0, 0($sp)
jal f
addu $sp, $sp, 8
move $t0, $v0
...
```

Translating IR

- Our IR is likely to use too many registers
- Assume for now, that the number of IR registers is reduced
  - Every **IR register** mapped to a **CPU register** (t0, … t7)
- We will see later how to compute this **register allocation**

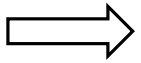
Translating IR

- Translate global variable initializations
- Translate the IR instructions for each function
  - Implement a translation function for each IR instruction
  - If the translation requires additional registers:
    - Use registers s0, s1, …

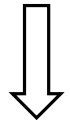
Translating IR

- Global initializations

```
int g_1 = 7;
string g_s = “1234”;
```



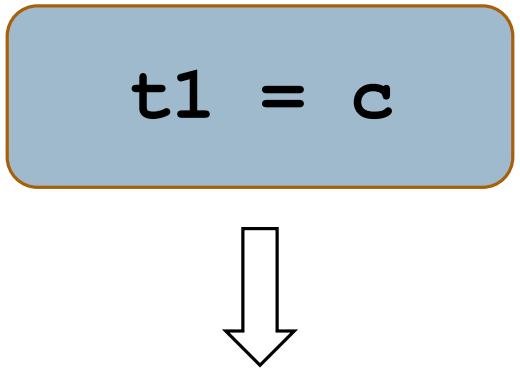
```
init g_1 = 7
init g_s = “1234”
```



```
.data:
g_1: .word 7
g_s: .asciiz “1234”
```

Translating IR

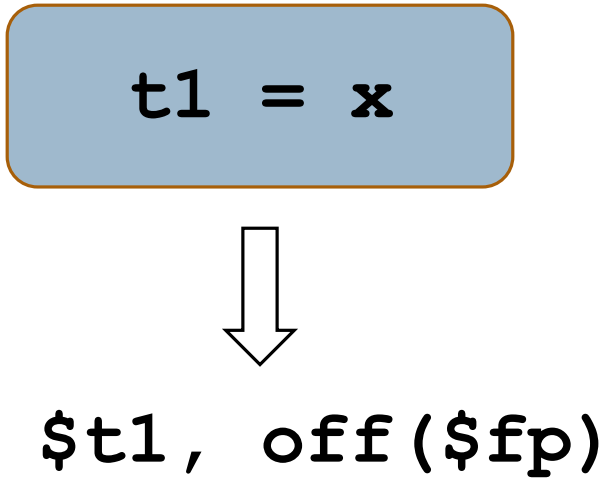
- Assignments (constant)




```
li $t1, c
```

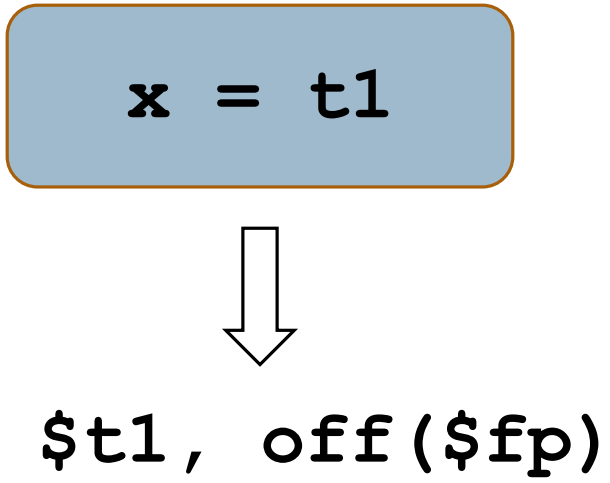
Translating IR

- Assignments (read from memory)
- For local variables and parameters:



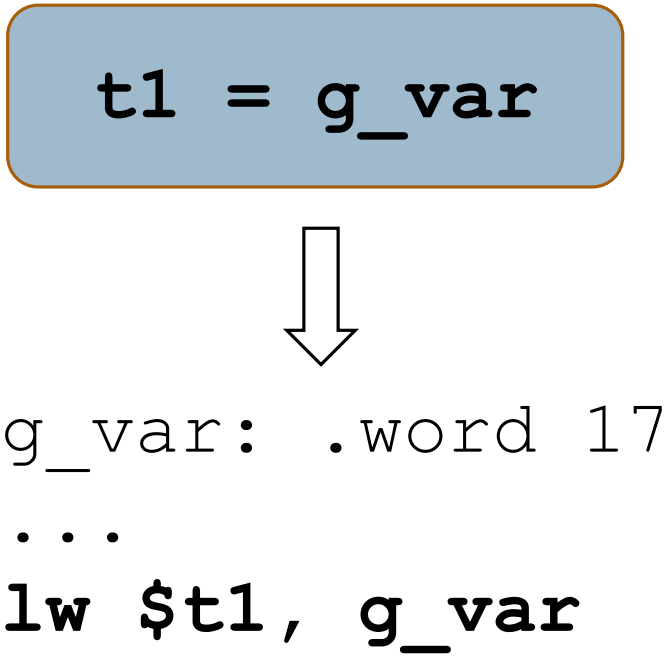
Translating IR

- Assignments (write to memory)
- For local variables and parameters:



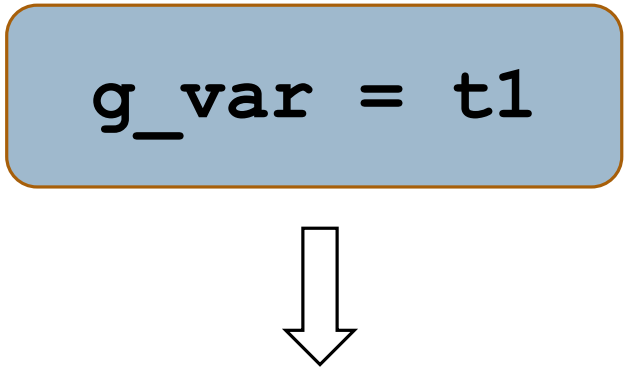
Translating IR

- Assignments (read from memory)
- For global variables:



Translating IR

- Assignments (write to memory)
- For global variables:

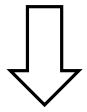



```
g_var: .word 17
...
sw $t1, g_var
```

Translating IR

- Arithmetic operation

```
t0 = add t1, t2
```

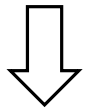


```
add $t0, $t1, $t2
```

Translating IR

- Arithmetic operation

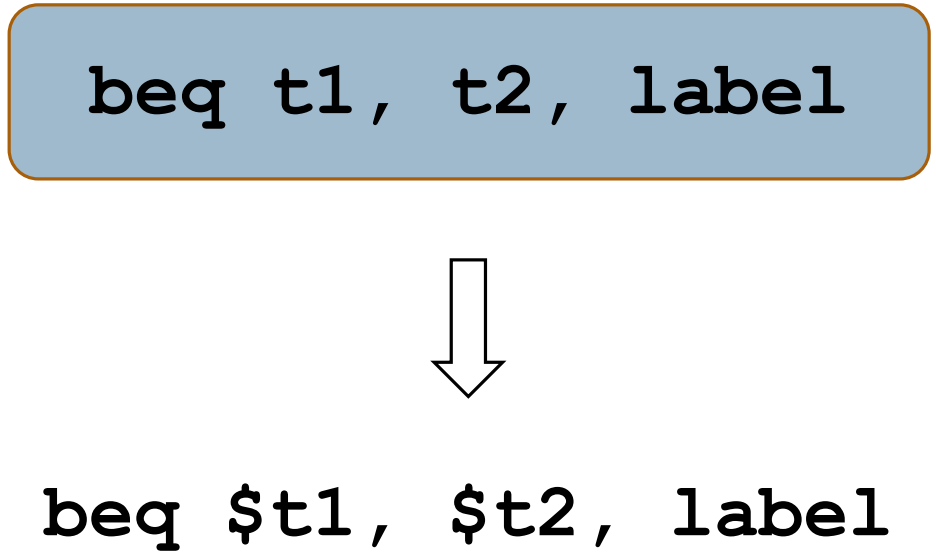
```
t0 = add t1, t2
```



```
add $t0, $t1, $t2
ble $t0, max, end
li $t0, max
end:
# more checks…
```

Translating IR

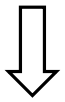
- Branch



Translating IR

- Function call

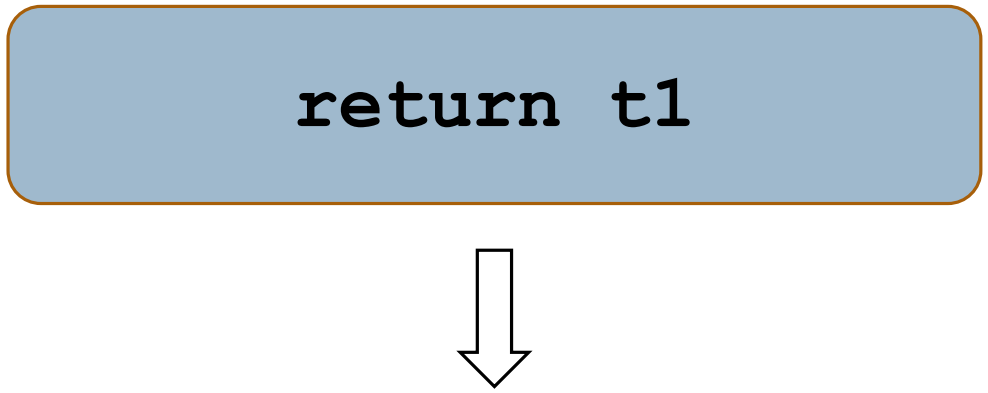
```
t0 = call f(t1, t2)
```



```
subu $sp, $sp, 4
sw $t2, 0($sp)
subu $sp, $sp, 4
sw $t1, 0($sp)
jal f
addu $sp, $sp, 8
move $t0, $v0
```

Translating IR

- Return (in a function f)
- Store result in **v0** and jump to f's **epilogue label** (f_epilogue)



Translating IR

- Another example

```
int g = 70;
int f(int x){
   int z = x;
   if (z) {
      z = g
   }
   return z;
}
```

```
t1 = x
z = t1
t1 = z
beq t1, 0, end
t1 = g
z = t1
end:
t1 = z
return t1
```

Translating IR

- Another example

```
int g = 70;
int f(int x){
   int z = x;
   if (z) {
      z = g
   }
   return z;
}
```

```
t1 = x
z = t1
t1 = z
beq t1, 0, end
t1 = g
z = t1
end:
t1 = z
return t1
```

```
.data
g: .word 70
```

Translating IR

- Another example

```
int g = 70;
int f(int x){
  int z = x;
  if (z) {
    z = g
  }
  return z;
}
```

```
t1 = x
z = t1
t1 = z
beq t1, 0, end
t1 = g
z = t1
end:
t1 = z
return t1
```

```
.data
g: .word 70
.text
f:
# prologue here
...
```

Translating IR

- Another example

```
int g = 70;
int f(int x){
  int z = x;
  if (z) {
    z = g
  }
  return z;
}
```

```
t1 = x
z = t1
t1 = z
beq t1, 0, end
t1 = g
z = t1
end:
t1 = z
return t1
```

```
.data
g: .word 70
.text
f:
# prologue here
...
lw $t1, 8($fp)
```

Translating IR

- Another example

```
int g = 70;
int f(int x){
  int z = x;
  if (z) {
    z = g
  }
  return z;
}
```

```
t1 = x
z = t1
t1 = z
beq t1, 0, end
t1 = g
z = t1
end:
t1 = z
return t1
```

```
.data
g: .word 70
.text
f:
# prologue here
...
lw $t1, 8($fp)
sw $t1, -4($fp)
```

Translating IR

- Another example

```
int g = 70;
int f(int x){
  int z = x;
  if (z) {
    z = g
  }
  return z;
}
```

```
t1 = x
z = t1
t1 = z
beq t1, 0, end
t1 = g
z = t1
end:
t1 = z
return t1
```

```
.data
g: .word 70
.text
f:
# prologue here
...
lw $t1, 8($fp)
sw $t1, -4($fp)
lw $t1, -4($fp)
```

Translating IR

- Another example

```
int g = 70;
int f(int x){
  int z = x;
  if (z) {
    z = g
  }
  return z;
}
```

```
t1 = x
z = t1
t1 = z
beq t1, 0, end
t1 = g
z = t1
end:
t1 = z
return t1
```

```
.data
g: .word 70
.text
f:
# prologue here
...
lw $t1, 8($fp)
sw $t1, -4($fp)
lw $t1, -4($fp)
beq $t1, 0, end
```

Translating IR

- Another example

```
int g = 70;
int f(int x){
  int z = x;
  if (z) {
    z = g
  }
  return z;
}
```

```
t1 = x
z = t1
t1 = z
beq t1, 0, end
t1 = g
z = t1
end:
t1 = z
return t1
```

```
.data
g: .word 70
.text
f:
# prologue here
...
lw $t1, 8($fp)
sw $t1, -4($fp)
lw $t1, -4($fp)
beq $t1, 0, end
lw $t1, g
```

Translating IR

- Another example

```
int g = 70;
int f(int x){
  int z = x;
  if (z) {
    z = g
  }
  return z;
}
```

```
t1 = x
z = t1
t1 = z
beq t1, 0, end
t1 = g
z = t1
end:
t1 = z
return t1
```

```
.data
g: .word 70
.text
f:
# prologue here
...
lw $t1, 8($fp)
sw $t1, -4($fp)
lw $t1, -4($fp)
beq $t1, 0, end
lw $t1, g
sw $t1, -4($fp)
```

Translating IR

- Another example

```
int g = 70;
int f(int x){
  int z = x;
  if (z) {
    z = g
  }
  return z;
}
```

```
t1 = x
z = t1
t1 = z
beq t1, 0, end
t1 = g
z = t1
end:
t1 = z
return t1
```

```
.data
g: .word 70
.text
f:
# prologue here
...
lw $t1, 8($fp)
sw $t1, -4($fp)
lw $t1, -4($fp)
beq $t1, 0, end
lw $t1, g
sw $t1, -4($fp)
end:
```

Translating IR

- Another example

```
int g = 70;
int f(int x){
  int z = x;
  if (z) {
    z = g
  }
  return z;
}
```

```
t1 = x
z = t1
t1 = z
beq t1, 0, end
t1 = g
z = t1
end:
t1 = z
return t1
```

```
.data
g: .word 70
.text
f:
# prologue here
...
lw $t1, 8($fp)
sw $t1, -4($fp)
lw $t1, -4($fp)
beq $t1, 0, end
lw $t1, g
sw $t1, -4($fp)
end:
lw $t1, -4($fp)
```

Translating IR

- Another example

```
int g = 70;
int f(int x){
  int z = x;
  if (z) {
    z = g
  }
  return z;
}
```

```
t1 = x
z = t1
t1 = z
beq t1, 0, end
t1 = g
z = t1
end:
t1 = z
return t1
```

```
.data
g: .word 70
.text
f:
# prologue here
...
lw $t1, 8($fp)
sw $t1, -4($fp)
lw $t1, -4($fp)
beq $t1, 0, end
lw $t1, g
sw $t1, -4($fp)
end:
lw $t1, -4($fp)
move $v0, $t1
j f_epilogue
```

Translating IR

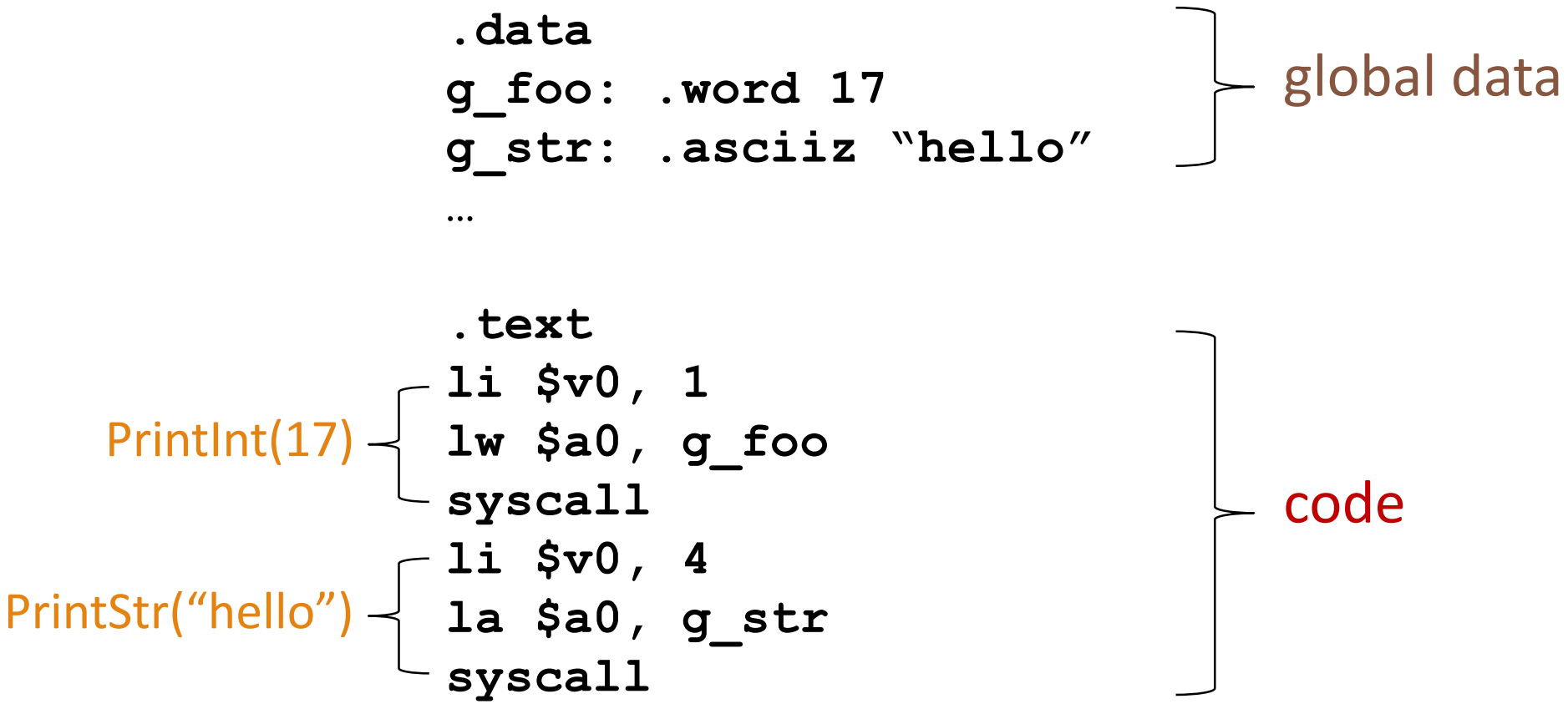
- Another example

```
int g = 70;
int f(int x){
  int z = x;
  if (z) {
    z = g
  }
  return z;
}
```

```
t1 = x
z = t1
t1 = z
beq t1, 0, end
t1 = g
z = t1
end:
t1 = z
return t1
```

```
.data
g: .word 70
.text
f:
# prologue here
...
lw $t1, 8($fp)
sw $t1, -4($fp)
lw $t1, -4($fp)
beq $t1, 0, end
lw $t1, g
sw $t1, -4($fp)
end:
lw $t1, -4($fp)
move $v0, $t1
j f_epilogue
f_epilogue:
# epilogue here…
```

SPIM


.data
g_foo: .word 17
g_str: .asciiz "hello"
…
.text
li $v0, 1
lw $a0, g_foo
syscall
li $v0, 4
la $a0, g_str
syscall
PrintInt(17)
PrintStr("hello")
global data
code

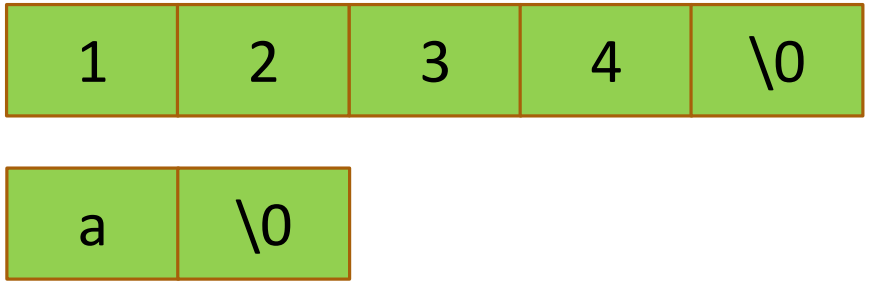
SPIM

- Runing SPIM:
  - spim –f *input_file*
- Interactive debugging:
  - xspim
- Tutorials:
  - https://courses.cs.washington.edu/courses/cse410/08sp/notes/spim/SpimTutorial.pdf
  - https://web.stanford.edu/class/cs143/materials/SPIM_Manual.pdf

Strings

- We use null terminated strings
- Every character is one byte

```
string s1 = "1234";
string s2 = "a";
...
...
```



Strings

- Assume that *s1* and *s2* are strings

```
if (s1 == s2) {

}
```

```
t1 = s1;
t2 = s2;
t3 = str_eq t1, t2
compare t3, 0
...
```

Strings

- Inline string comparison

```
t1 = s1;
t2 = s2;
t3 = str_eq t1, t2
compare t3, 0
...
```

```
li $t3, 1 // result
move $s0, $t1
move $s1, $t2
str_eq_loop:
lb $s2, 0($s0)
lb $s3, 0($s1)
bne $s2, $s3, neq_label
beq $s2, 0, str_eq_end
addu $s0, $s0, 1
addu $s1, $s1, 1
j str_eq_loop
neq_label:
li $t3, 0
str_eq_end:
```

Strings

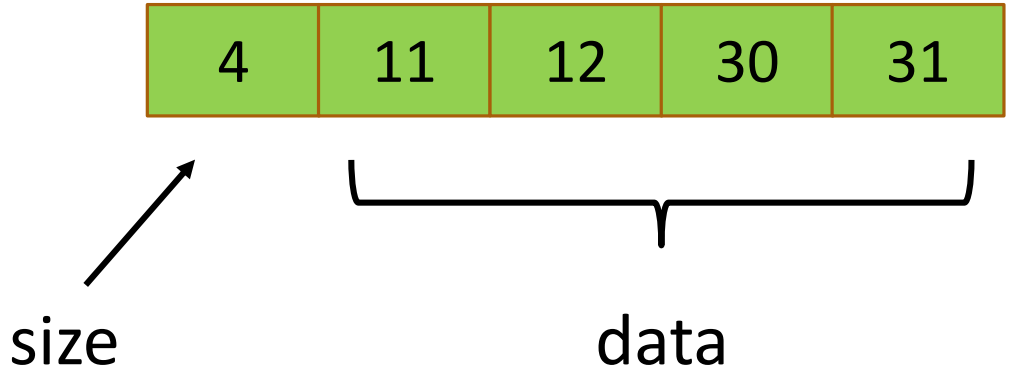
- Alternatively, create a function str_eq

```
t1 = s1;
t2 = s2;
t3 = str_eq t1, t2
compare t3, 0
...
```

```
subu $sp, $sp, 4
sw $t2, 0($sp)
subu $sp, $sp, 4
sw $t1, 0($sp)
jal str_eq
addu $sp, $sp, 8
move $t3, $v0
```

Arrays

- Each cell is 4 bytes (*int* or *pointer*)
- First cell is the **size** of the array
- The rest of the cells contain **data**



Arrays

- Creating arrays

```
t0 = new_array t1
```

```
li $v0, 9
move $a0, $t1
add $a0, $a0, 1
mul $a0, $a0, 4
syscall
move $t0, $v0
li $s0, size
sw $s0, 0($t0)
```

Arrays

- Array access

```
t0 = array_access t1, t2
```

```
move $s0, $t2
add $s0, $s0, 1
mult $s0, $s0, 4
addu $s0, $t1, $s0
lw $t0, 0($s0)
```

Runtime Errors

- Division by zero

```
t0 = div t1, t2
```

```
div $t0, $t1, $t2
```

Runtime Errors

- Division by zero

```
t0 = div t1, t2
```

```
beq $t2, 0, abort
div $t0, $t1, $t2
...
abort:
li $v0, 10
syscall
```

Runtime Errors

- Out of bounds array access

```
t0 = array_access t1, t2
```

```
move $s0, $t2
add $s0, $s0, 1
mult $s0, $s0, 4
addu $s0, $t1, $s0
lw $t0, 0($s0)
```

Runtime Errors

- Out of bounds array access

```
t0 = array_access t1, t2
```

```
bltz $t2, abort
lw $s0, 0($t1)
bge $t2, $s0, abort
move $s0, $t2
add $s0, $s0, 1
mult $s0, $s0, 4
addu $s0, $t1, $s0
lw $t0, 0($s0)
...
abort:
li $v0, 10
syscall
```

Runtime Errors

- Null pointer dereference
  - Arrays
  - Field access
  - Method calls

Runtime Errors

- Null pointer dereference
- For example, in arrays:

```
t0 = array_access t1, t2
```

```
beq $t1, 0, abort
move $s0, $t2
add $s0, $s0, 1
mult $s0, $s0, 4
addu $s0, $t1, $s0
lw $t0, 0($s0)
...
abort:
li $v0, 10
syscall
```

Runtime Errors

- Null pointer dereference
- For example, in field accesses:

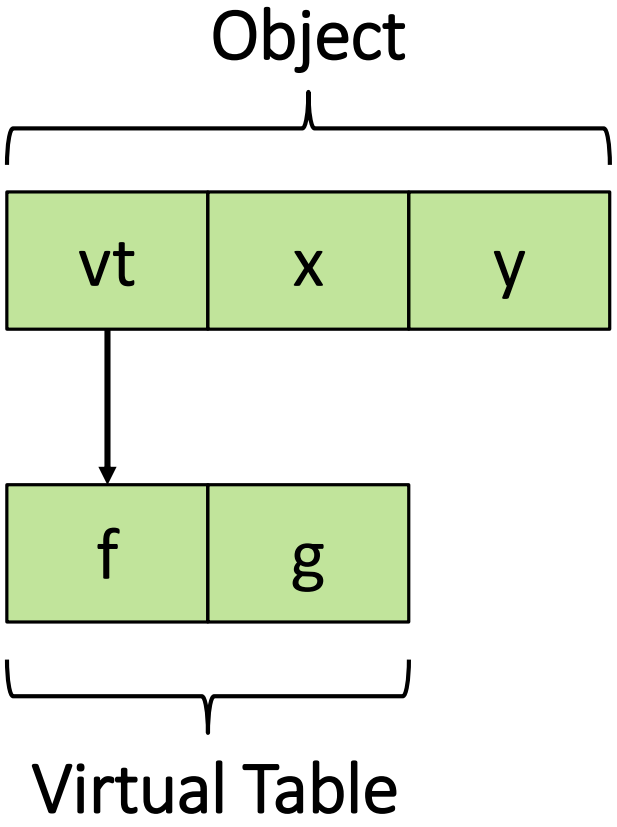
```
t0 = field_access t1, foo
```

```
beq $t1, 0, abort
lw $t0, off($t1)
...
abort:
li $v0, 10
syscall
```

Classes

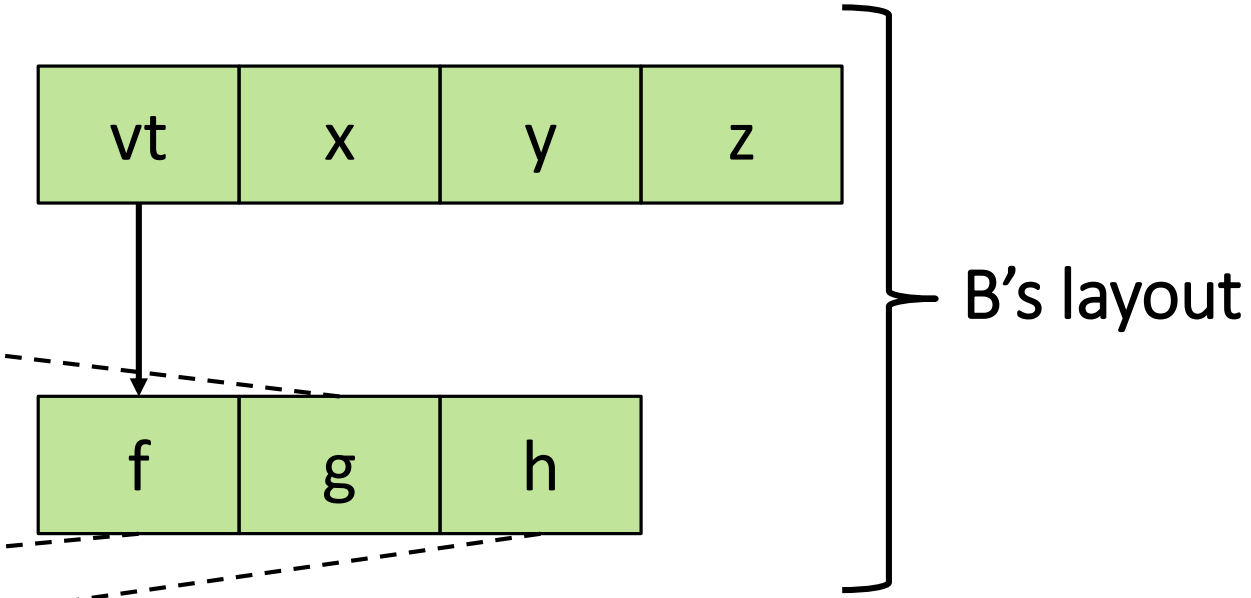
Class Layout

```
class A {
   int x;
   string y;
   int f() { …
   int g() { …
}
```



Class Layout

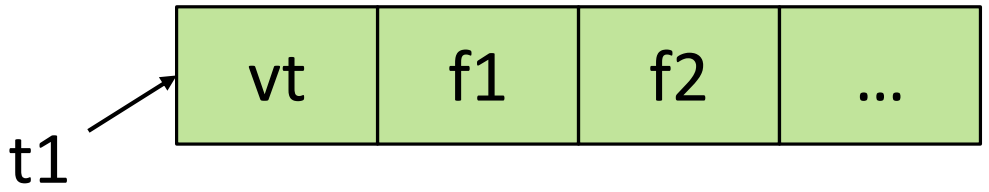
```
class A {
  int x;
  string y;
  int f() { …
  int g() { …
}
class B extends A {
  int z;
  int f() { …
  int h() { …
}
```



Field Access

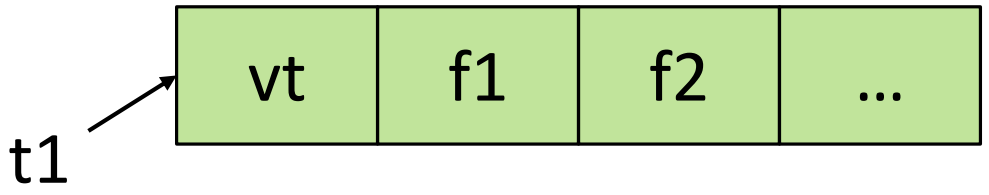
```
t0 = field_access t1, f2
```

```
lw $t0, 8($t1)
```



Field Access

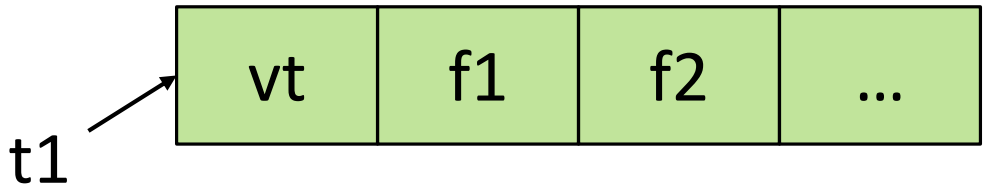
```
t0 = field_access t1, f2
```




```
beq $t1, 0, abort
lw $t0, 8($t1)
...
abort:
li $v0, 10
syscall
```

Field Access

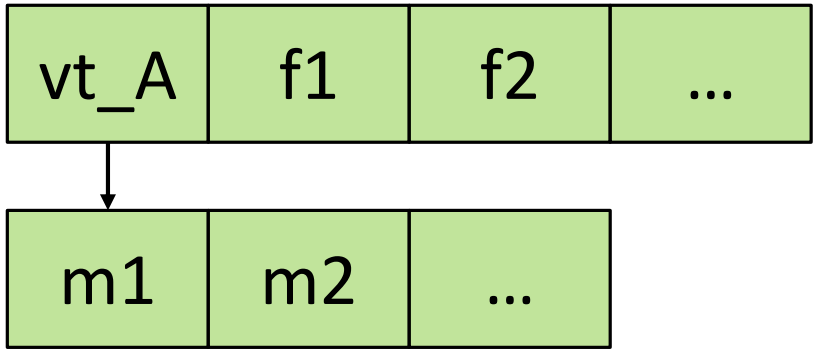
```
field_set t0, f2, t1
```




```
beq $t0, 0, abort
sw $t1, 8($t0)
...
abort:
li $v0, 10
syscall
```

Creating Objects

```
class A {
   int f1;
   …
   int m1() { …
   …
}

A a = new A;
```



Creating Objects

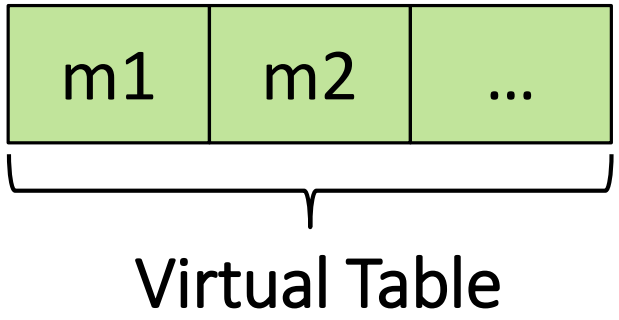
```
class A {
   int f1 = c;
   …
   int m1() { …
   …
}

A a = new A;
```

```
t0 = alloc (size)
set_vt t0, A
t1 = c
field_set t0, f1, t1
```

IR

Creating Objects

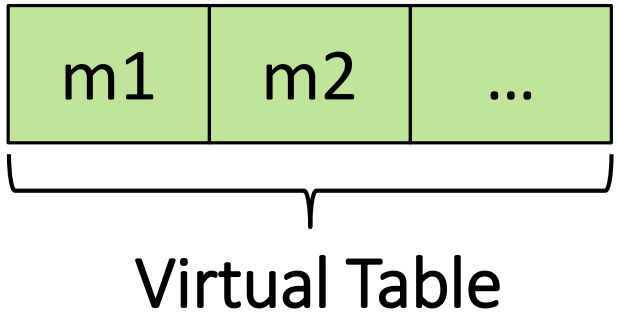
```
t0 = alloc (size)
set_vt t0, A
t1 = c
field_set t0, f1, t1
…
```




```
.data
vt_A:  .word m1, m2, …
```

Creating Objects

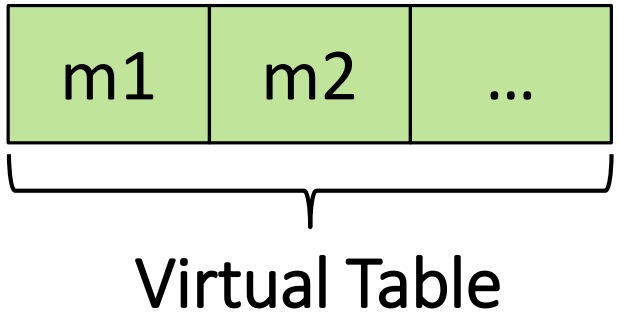
```
t0 = alloc (size)
set_vt t0, A
t1 = c
field_set t0, f1, t1
…
```




```
.data
vt_A:  .word m1, m2, …

.text
li $v0, 9
li $a0, size
syscall
move $t0, $v0
```

Creating Objects

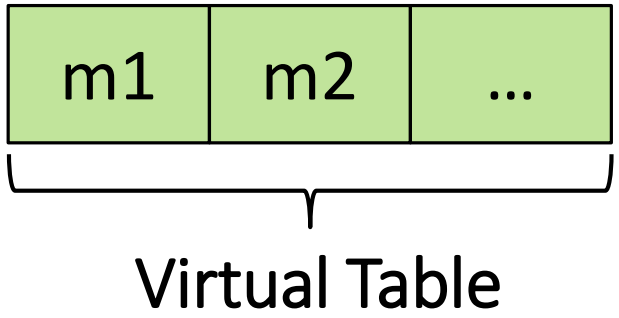
```
t0 = alloc (size)
set_vt t0, A
t1 = c
field_set t0, f1, t1
…
```




```
.data
vt_A: .word m1, m2, …

.text
li $v0, 9
li $a0, size
syscall
move $t0, $v0
la $s0, vt_A
sw $s0, 0($t0)
```

Creating Objects

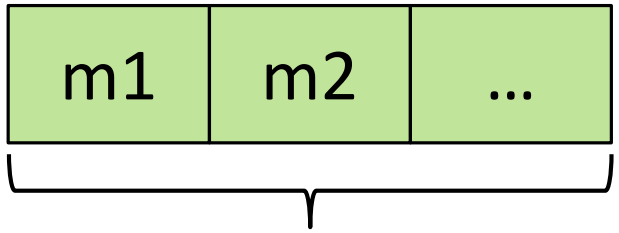
```
t0 = alloc (size)
set_vt t0, A
t1 = c
field_set t0, f1, t1
…
```




```
.data
vt_A: .word m1, m2, …

.text
li $v0, 9
li $a0, size
syscall
move $t0, $v0
la $s0, vt_A
sw $s0, 0($t0)
li $t1, c
```

Creating Objects

```
t0 = alloc (size)
set_vt t0, A
t1 = c
field_set t0, f1, t1
…
```




```
.data
vt_A: .word m1, m2, …

.text
li $v0, 9
li $a0, size
syscall
move $t0, $v0
la $s0, vt_A
sw $s0, 0($t0)
li $t1, c
sw $t1, 4($t0)
```

Method Calls

```
class A {
   int f1 = c;
   …
   int m1(int x) { …
   int m2(int x) { …
}

A a = new A;
z = a.m2(7)
```

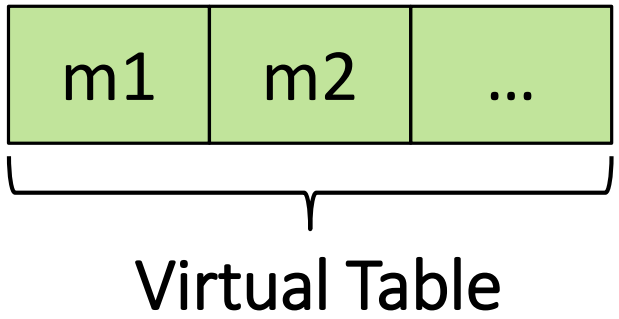
```
t0 = a
t1 = 7
t2 = virtual_call t0, m2, t1
z = t2
```

IR

Method Calls

```
t0 = a
t1 = 7
t2 = virtual_call t0, m2, t1
z = t2
```

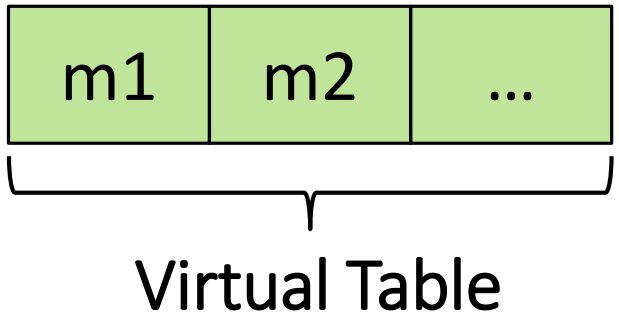
```
subu $sp, $sp, 4
sw $t1, 0($sp)
```



Method Calls

```
t0 = a
t1 = 7
t2 = virtual_call t0, m2, t1
z = t2
```

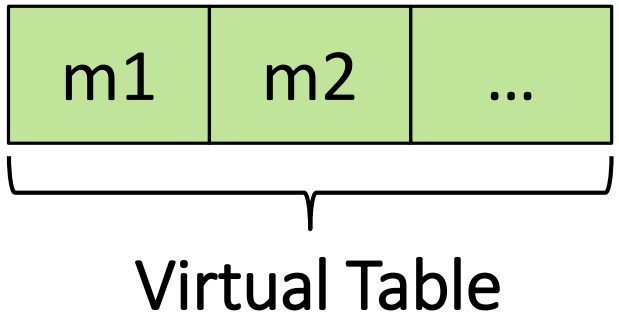
```
subu $sp, $sp, 4
sw $t1, 0($sp)
subu $sp, $sp, 4
sw $t0, 0($sp)
```



Method Calls

```
t0 = a
t1 = 7
t2 = virtual_call t0, m2, t1
z = t2
```

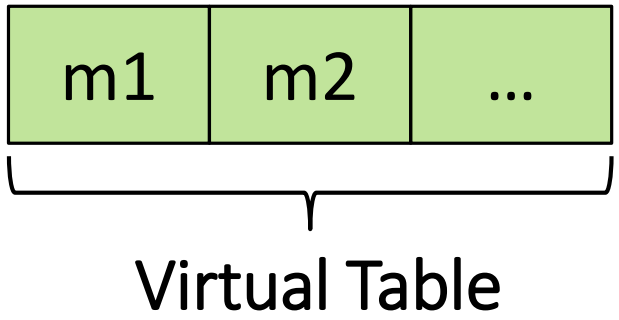
```
subu $sp, $sp, 4
sw $t1, 0($sp)
subu $sp, $sp, 4
sw $t0, 0($sp)
lw $s0, 0($t0)
```



Method Calls

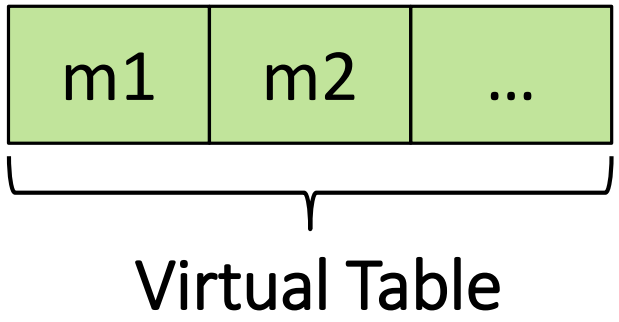
```
t0 = a
t1 = 7
t2 = virtual_call t0, m2, t1
z = t2
```

```
subu $sp, $sp, 4
sw $t1, 0($sp)
subu $sp, $sp, 4
sw $t0, 0($sp)
lw $s0, 0($t0)
lw $s1, 4($s0)
```



Method Calls

```
t0 = a
t1 = 7
t2 = virtual_call t0, m2, t1
z = t2
```




```
subu $sp, $sp, 4
sw $t1, 0($sp)
subu $sp, $sp, 4
sw $t0, 0($sp)
lw $s0, 0($t0)
lw $s1, 4($s0)
jalr $s1
addu $sp, $sp, 8
```