Code Generation

Lecture 12

Lecture Outline

- Topic 1: Basic Code Generation
  - The MIPS assembly language
  - A simple source language
  - Stack-machine implementation of the simple language

- Topic 2: Code Generation for Objects

From Stack Machines to MIPS

- The compiler generates code for a stack machine with accumulator
  - Simplest code generation strategy, though it doesn't yield extremely efficient code
  - It's not totally unrealistic, and is sufficiently complex for our purposes
- We want to run the resulting code on a real machine: the MIPS processor
  - Of course, we'll run it on a simulator

From Stack Machines to MIPS

- We simulate stack machine instructions using MIPS instructions and registers
- Much of what is described here regarding MIPS will be review for you
  - Though some of it will be new, and part of it will be a different way of thinking about what you did in CS 301

Simulating a Stack Machine…

- The accumulator is kept in MIPS register $a0
  - Could have used any register
- The stack is kept in memory
  - The stack grows towards lower addresses
  - Standard convention on the MIPS architecture
  - Nominally, $a0 is top of stack, but we won't say that
    - So consider it distinct from the stack
- The address of the next location on the stack (the unallocated memory where the next push goes) is kept in MIPS register $sp
  - The top of the stack is at address $sp + 4

MIPS Assembly

MIPS architecture

- Prototypical Reduced Instruction Set Computer (RISC) architecture
- Arithmetic operations use registers for operands and results
- Must use load and store instructions to use operands and results in memory
- 32 general purpose registers (32 bits each)
  - We will use $sp, $a0 and $t1 (a temporary register)

- Read the SPIM documentation for details
  - Or just review your notes from CS 301

A Sample of MIPS Instructions

- lw reg_1 offset(reg_2)
  - Load 32-bit word from address reg_2 + offset into reg_1
- add reg_1 reg_2 reg_3
  - $reg_1 \leftarrow reg_2 + reg_3$
- sw reg_1 offset(reg_2)
  - Store 32-bit word in reg_1 at address reg_2 + offset
- addiu reg_1 reg_2 imm
  - $reg_1 \leftarrow reg_2 + imm$
  - "u" means unsigned: overflow is not checked
- li reg imm
  - $reg \leftarrow imm$

MIPS Assembly. Example.

- The stack-machine code for 7 + 5 in MIPS:

acc ← 7	li $a0 7
push acc	sw $a0 0($sp)
	addiu $sp $sp -4
acc ← 5	li $a0 5
acc ← acc + top_of_stack	lw $t1 4($sp)
	add $a0 $a0 $t1
pop	addiu $sp $sp 4

- We now generalize this to a simple language…

A Small Language

- A language with integers and integer operations (with the following grammar)

$$
\begin{aligned}
P &\rightarrow D; P \mid D \\
D &\rightarrow \text{def id(ARGS)} = E; \\
ARGS &\rightarrow \text{id, } ARGS \mid \text{id} \\
E &\rightarrow \text{int} \mid \text{id} \mid \text{if } E_1 = E_2 \text{ then } E_3 \text{ else } E_4 \\
&\quad \mid E_1 + E_2 \mid E_1 - E_2 \mid \text{id}(E_1, \ldots, E_n)
\end{aligned}
$$

A Small Language (Cont.)

- The first function definition f is the "main" routine (the entry point of the program)
- Running the program on input i means computing f(i)
- Program for computing the Fibonacci numbers:

```
def fib(x) = if x = 1 then 0 else
             if x = 2 then 1 else
               fib(x - 1) + fib(x – 2)
```

Code Generation Strategy

- For each expression e we generate MIPS code that:
  - Computes the value of e and places it in $a0
  - Preserves $sp and the contents of the stack
    - So whatever stack looked like before executing code for e, stack should look exactly like that after code is executed

- We define a code generation function cgen(e) whose result is the code generated for e
  - Note cgen() produces code (that accomplishes the above requirements)

- As usual, we will work by cases (show how to do this for various language constructs)
- So we focus on expressions, and we show how our cgen() code will work for each kind of expression in the language

Code Generation for Constants

- The code to evaluate a constant simply copies it into the accumulator:

  cgen(i) = li $a0 i

- This preserves the stack, as required
  - No modification to stack pointer, or push or pop of data
- Convention: Color key:
  - RED: compile time
  - BLUE: run time

Code Generation for Constants

- The code to evaluate a constant simply copies it into the accumulator:

  cgen(i) = li $a0 i

- Convention: Color key:
  - RED: compile time
    - So at compile time, we run cgen(i), which produces the code in blue, that will run at run time
  - BLUE: run time
- Purpose here is to help you separate mentally that we have things that happen at compile time and thing deferred to run time

Code Generation for Add

```
cgen(e1 + e2) =
        cgen(e1)
        sw $a0 0($sp)
        addiu $sp $sp -4
        cgen(e2)
        lw $t1 4($sp)
        add $a0 $t1 $a0
        addiu $sp $sp 4
```

```
cgen(e1 + e2) =
    cgen(e1)
    print "sw $a0 0($sp)"
    print "addiu $sp $sp -4"
    cgen(e2)
    print "lw $t1 4($sp)"
    print "add $a0 $t1 $a0"
    print "addiu $sp $sp 4"
```

Code Generation for Add

- Possible Optimization: Put the result of e_1 directly in $t1?

  cgen(e_1 + e_2) =

  cgen(e_1)

  move $t1 $a0

  cgen(e_2)

  add $a0 $t1 $a0

- Try to generate code for : 3 + (7 + 5)

Code Generation for Add. Wrong!

- Possible Optimization: Put the result of e_1 directly in \$t1?

cgen(e_1 + e_2) =
    cgen(e_1)
    move \$t1 \$a0
    cgen(e_2)
    add \$a0 \$t1 \$a0

1 + (2 + 3)

```
li $a0 1
move $t1 $a0
li $a0 2
move $t1 $a0        (2 + 3)
li $a0 3
add $a0 $t1 $a0     (get 5)
add $a0 $t1 $a0     (get 7)
```

- Try to generate code for : 1 + (2 + 3)

Code Generation for Add. Wrong!

- Possible Optimization: Put the result of e_1 directly in \$t1?

cgen(e_1 + e_2) =

```
cgen(e1)
move $t1 $a0
cgen(e2)
add $a0 $t1 $a0
```

1 + (2 + 3)

```
li $a0 1
move $t1 $a0
li $a0 2
move $t1 $a0      (2 + 3)
li $a0 3
add $a0 $t1 $a0  (get 5)
add $a0 $t1 $a0  (get 7)
```

- Try to generate code for : 1 + (2 + 3)

So the problem is that nested expressions will step on \$t1.
Need a stack to store intermediate values

Code Generation Points to Emphasize

- The code for + is a template with "holes" for code for evaluating e_1 and e_2

- Stack machine code generation is recursive
  - Code for $e_1 + e_2$ is code for e_1 and e_2 glued together

- Code generation can be written as a recursive-descent of the AST
  - At least for expressions

Code Generation for Sub and Constants

- New instruction: sub reg_1 reg_2 reg_3
  - Implements $reg_1 \leftarrow reg_2 - reg_3$

```
cgen(e1 - e2) =
        cgen(e1)
        sw $a0 0($sp)
        addiu $sp $sp -4
        cgen(e2)
        lw $t1 4($sp)
        sub $a0 $t1 $a0   (only difference from add)
        addiu $sp $sp 4
```

Code Generation for Conditional

- We need flow control instructions

- New instruction: beq reg_1 reg_2 label
  - Branch to label if $reg_1 = reg_2$

- New instruction: b label
  - Unconditional jump to label

Code Generation for If (Cont.)

cgen(if e_1 = e_2 then e_3 else e_4) =

```
  cgen(e1)
  sw $a0 0($sp)
  addiu $sp $sp -4
  cgen(e2)
  lw $t1 4($sp)
  addiu $sp $sp 4
  beq $a0 $t1 true_branch
```

```
false_branch:
  cgen(e4)
  b end_if
true_branch:
  cgen(e3)
end_if:
```

The Activation Record

- Code for function calls and function definitions depends intimately on the layout of the AR

- A very simple AR suffices for our current language:
  - The result is always in the accumulator
    - No need to store the result in the AR
  - The activation record holds actual parameters
    - For $f(x_1,\ldots,x_n)$ push $x_n,\ldots,x_1$ on the stack
    - These are the only variables in this language – no local or global vars other than arguments to function calls

The Activation Record (Cont.)

- The stack discipline guarantees that on function exit $sp is the same as it was on function entry
  - No need for a control link – purpose is to help us find previous AR, but preservation of $sp means we already have this
  - Also, never need to look for another AR during function call, since no non-local vars

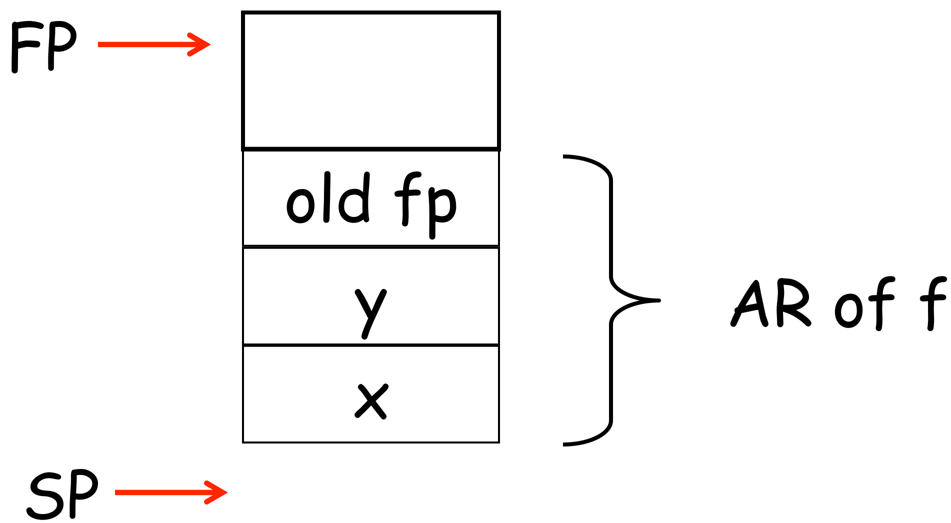
The Activation Record (Cont.)

- We need the return address

- A pointer to the current (not previous) activation is useful
  - This pointer lives in register $fp (frame pointer)
  - Reason for frame pointer will be clear shortly

The Activation Record

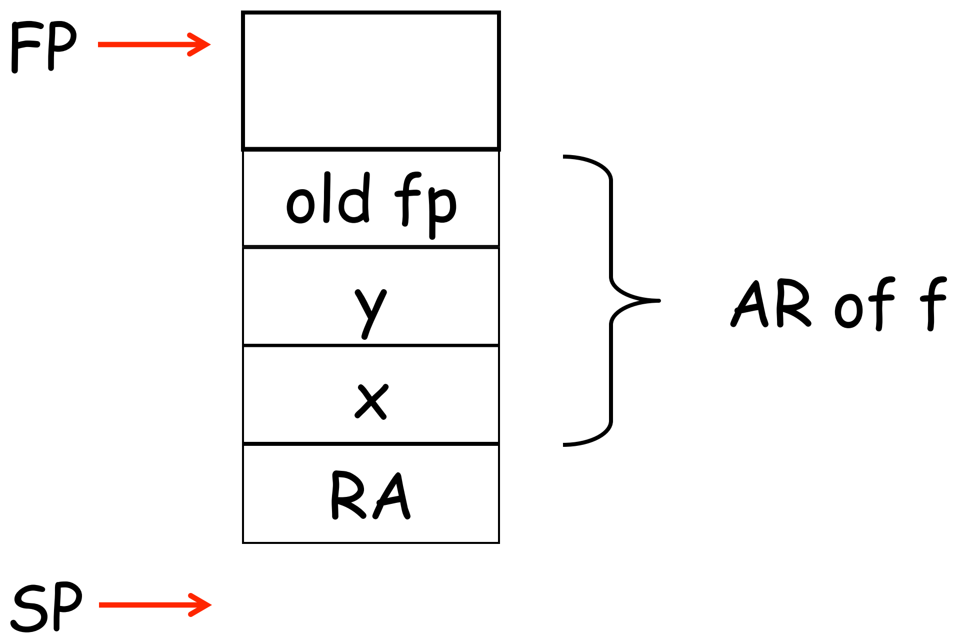
- Summary: For this language, an AR with the caller's frame pointer, the actual parameters, and the return address suffices
- Picture: Consider a call to f(x,y), the AR is:



Note: caller's fp needs to be saved, because pointer to current frame is in $fp

The Activation Record

- Summary: For this language, an AR with the caller's frame pointer, the actual parameters, and the return address suffices
- Picture: Consider a call to f(x,y), the AR is:



Note: last argument (y) pushed on first – this makes finding the arguments a little easier

Code Generation for Function Call

- The *calling sequence* is the instructions (of both caller and callee) to set up a function invocation

- New instruction (jump and link): jal label
  - Jump to label, save address of next instruction (instruction following jal) in $ra
  - On other architectures the return address is stored on the stack by the "call" instruction

Code Generation for Function Call (Cont.)

```
cgen(f(e1,…,en)) =
    sw $fp 0($sp)
    addiu $sp $sp -4
    cgen(en)
    sw $a0 0($sp)
    addiu $sp $sp -4
    …
    cgen(e1)
    sw $a0 0($sp)
    addiu $sp $sp -4
    jal f_entry
```

- The caller saves its value of the frame pointer
- Then it saves the actual parameters in reverse order
- The caller saves the return address in register $ra
- The AR so far is 4*n+4 bytes long

Code Generation for Function Call (Cont.)

caller side

```
cgen(f(e1,…,en)) =
    sw $fp 0($sp)
    addiu $sp $sp -4
    cgen(en)
    sw $a0 0($sp)
    addiu $sp $sp -4
    …
    cgen(e1)
    sw $a0 0($sp)
    addiu $sp $sp -4
    jal f_entry
```

- The caller saves its value of the frame pointer
- Then it saves the actual parameters in reverse order
- The caller saves the return address in register $ra
- The AR so far is 4*n+4 bytes long

Code Generation for Function Definition

- New instruction: jr reg
  - Jump to address in register reg

cgen(def f(x_1,…,x_n) = e) =

```
f_entry: move $fp $sp
         sw $ra 0($sp)
         addiu $sp $sp -4
         cgen(e)
         lw $ra 4($sp)
         addiu $sp $sp z
         lw $fp 0($sp)
         jr $ra
```

- Note: The frame pointer points to the top, not bottom of the frame
- The callee pops the return address, the actual arguments and the saved value of the frame pointer
- z = 4*n + 8

Code Generation for Function Definition

- New instruction: jr reg
  - Jump to address in register reg

c a l l e e s i d e

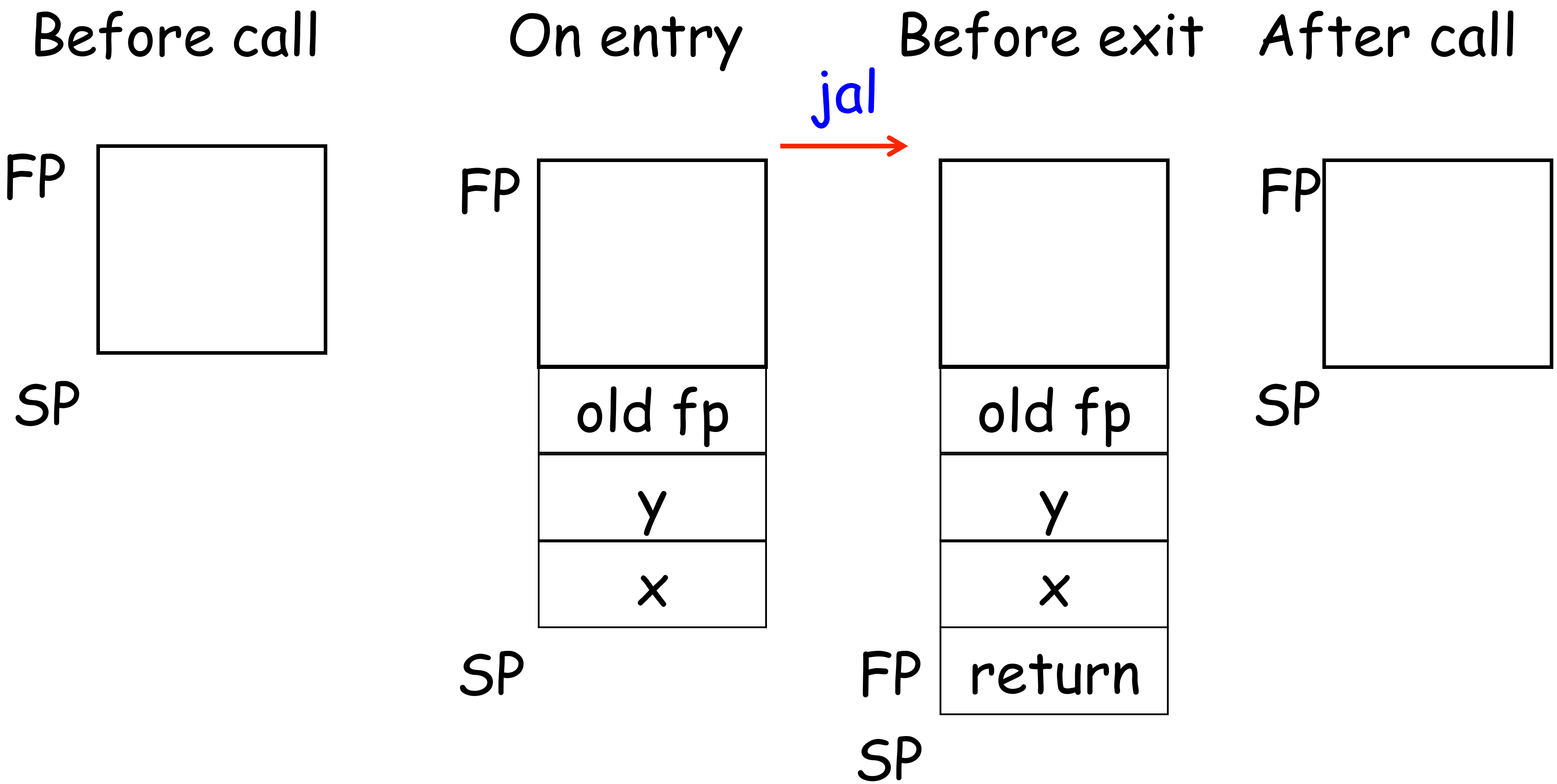
cgen(def f(x_1,…,x_n) = e) =

```
f_entry: move $fp $sp
         sw $ra 0($sp)
         addiu $sp $sp -4
         cgen(e)
         lw $ra 4($sp)
         addiu $sp $sp z
         lw $fp 0($sp)
         jr $ra
```

- Note: The frame pointer points to the top, not bottom of the frame
- The callee pops the return address, the actual arguments and the saved value of the frame pointer
- z = 4*n + 8

Note: callee must push $ra on stack since not known by caller until jal instruction

Calling Sequence: Example for f(x,y)



Code Generation for Variables

- Variable references are the last construct

- The "variables" of a function are just its parameters
  - They are all in the AR
  - Pushed by the caller

- Problem: Because the stack grows when intermediate results are saved, the variables are not at a fixed offset from $sp

Code Generation for Variables (Cont.)

- Solution: use a frame pointer
  - Always points to the return address on the stack
  - Since it does not move it can be used to find the variables
- Let x_i be the i^{th} ($i = 1,\ldots,n$) formal parameter of the function for which code is being generated

$$cgen(x_i) = \text{lw } \$a0 \; z(\$fp) \qquad (z = 4*i)$$

(note: this index calculation is why we push arguments onto stack in reverse order)

Code Generation for Variables (Cont.)

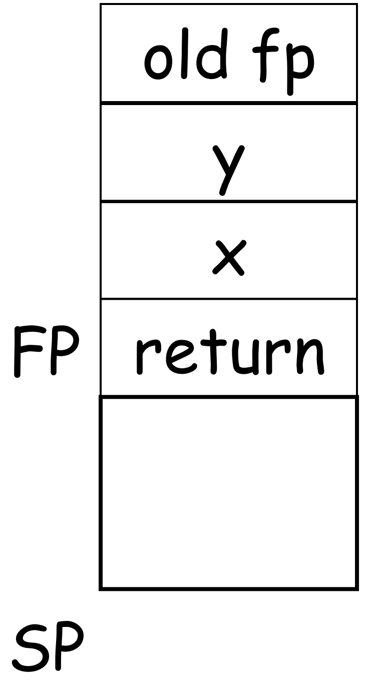
- Solution: use a frame pointer
  - Always points to the return address on the stack
  - Since it does not move it can be used to find the variables
- Let x_i be the i^{th} ($i = 1,\ldots,n$) formal parameter of the function for which code is being generated

$$cgen(x_i) = \text{lw } \$a0 \; z(\$fp) \qquad (z = 4*i)$$

(Also: value of z computed at compile time, not run time)

Code Generation for Variables (Cont.)

- Example: For a function def f(x,y) = e the activation and frame pointer are set up as follows:



- X is at fp + 4
- Y is at fp + 8

Summary

- The activation record must be designed together with the code generator

- Code generation can be done by recursive traversal of the AST

- We recommend you use a stack machine for your Cool compiler (it's simple)

Summary

- Production compilers do different things
  - Emphasis is on keeping values (esp. current stack frame) in registers
  - Intermediate results are laid out in the AR, not pushed and popped from the stack

Example

- In the next few slides, we'll generate code for a small sample program

```
def sumto(x) = if x = 0 then 0 else x + sumto(x-1)
```

- What does this do?
  - Not super interesting, but does illustrate all of the issues we've been discussing in the previous few slides

def sumto(x) = if x = 0 then 0 else x + sumto(x-1)

```
sumto_entry: move $fp $sp
             sw $ra 0($sp)
             addiu $sp $sp -4
             lw $a0  4($fp)
             sw $a0 0($sp)
             addiu $sp $sp -4
             li $a0 0
             lw $t1 4($sp)
             addiu $sp $sp 4
             beq $a0 $t1 true1
false1:      lw $a0 4($fp)
             sw $a0 0($sp)
             addiu $sp $sp -4
             sw $fp 0($sp)
             addiu $sp $sp -4
             lw $a0  4($fp)
             sw $a0 0($sp)
             addiu $sp $sp -4
             li $a0 1
             lw $t1 4($sp)
             sub $a0 $t1 $a0
             addiu $sp $sp 4
             sw $a0 0($sp)
             addiu $sp $sp -4
             jal sumto_entry
             lw $t1 4($sp)
             add $a0 $t1 $a0
             addiu $sp $sp 4
             b endif1
true1:       li $a0 0
endif1:      lw $ra 4($sp)
             addiu $sp $sp 12
             lw $fp 0($sp)
             jr $ra
```

def sumto(x) = if x = 0 then 0 else x + sumto(x-1)

```
sumto_entry: move $fp $sp
             sw $ra 0($sp)
             addiu $sp $sp -4
             lw $a0  4($fp)
             sw $a0 0($sp)
             addiu $sp $sp -4
             li $a0 0
             lw $t1 4($sp)
             addiu $sp $sp 4
             beq $a0 $t1 true1
false1:      lw $a0 4($fp)
             sw $a0 0($sp)
             addiu $sp $sp -4
             sw $fp 0($sp)
             addiu $sp $sp -4
             lw $a0  4($fp)
             sw $a0 0($sp)
             addiu $sp $sp -4
             li $a0 1
             lw $t1 4($sp)
             sub $a0 $t1 $a0
             addiu $sp $sp 4
             sw $a0 0($sp)
             addiu $sp $sp -4
             jal sumto_entry
             lw $t1 4($sp)
             add $a0 $t1 $a0
             addiu $sp $sp 4
             b endif1
true1:       li $a0 0
endif1:      lw $ra 4($sp)
             addiu $sp $sp 12
             lw $fp 0($sp)
             jr $ra
```

Notes

- Code is constructed as a bunch of templates pasted together
  - But you do wind up with one linear sequence of code
- If you're confused, review the templates and see how they fit into the example
- Note also that this is extremely inefficient code
  - How many times do we load x, then immediately store it on the stack, then reload it, etc.
  - This is result of our simple code generation strategy
  - Code does not have to be this inefficient
    - We'll see improved cgen techniques in subsequent lectures

Real Compilers…

- Do a better job of keeping values in registers
- Do a better job managing temporaries that have to be stored in the AR
- Let's discuss these improvements
  - Starting with the second issue

An Improvement

- Idea: Keep temporaries in the AR
  - Not as efficient as keeping temporaries in registers (which we'll discuss at a future date)
  - Right now: let's discuss improving management of temporaries that, for whatever reason, happen to be in the AR
- The code generator must assign a fixed location in the AR for each temporary
  - So code generator pre-allocates memory for each temporary, allowing access without stack manipulation

Example

```
def fib(x) = if x = 1 then 0 else
        if x = 2 then 1 else
            fib(x - 1) + fib(x - 2)
```

- What intermediate values are placed on the stack?

- How many slots are needed in the AR to hold these values?

Example

```
def fib(x) = if x = 1 then 0 else
      if x = 2 then 1 else
      fib(x - 1) + fib(x - 2)
```

- How many temporaries do we need?
  - We need 5 total
  - BUT, we don't need them all at the same time
    - After check involving 1, don't need that temporary anymore. So can reclaim that memory before getting to 2
    - Same with check involving 2 (cleared before getting to 3) and 3 (cleared before getting to 4)
    - But can't clear 4 before getting to 5 (need both at same time)
  - Bottom line: Can do this with only 2 temporaries)

Example

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def fib(x) = if x = 1 then 0 else
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    - But can't clear 4 before getting to 5 (need both at same time)
  - Bottom line: Can do this with only 2 temporaries)

How Many Temporaries?

- Let $NT(e)$ = # of temps needed in current AR in order to evaluate e

- $NT(e_1 + e_2) = max(NT(e_1), NT(e_2) + 1)$
  - Needs at least as many temporaries as $NT(e_1)$
  - Needs at least as many temporaries as $NT(e_2) + 1$
    - The $+1$ needed since need to hold onto the value of e_1 while evaluating e_2
  - max, not sum, since once e_1 evaluated, don't need any of space for those temporaries
- Space used for temporaries in e_1 can be reused for temporaries in e_2

The Equations

$$NT(e_1 + e_2) = max(NT(e_1), 1 + NT(e_2))$$
$$NT(e_1 - e_2) = max(NT(e_1), 1 + NT(e_2))$$
$$NT(if\ e_1 = e_2\ then\ e_3\ else\ e_4) = max(NT(e_1), 1 + NT(e_2), NT(e_3), NT(e_4))$$
$$NT(id(e_1,\ldots,e_n) = max(NT(e_1),\ldots,NT(e_n))$$
$$NT(int) = 0$$
$$NT(id) = 0$$

Is this bottom-up or top-down?

What is NT(…code for fib…)?

The Equations

$$NT(e_1 + e_2) = \max(NT(e_1), 1 + NT(e_2))$$
$$NT(e_1 - e_2) = \max(NT(e_1), 1 + NT(e_2))$$
$$NT(\text{if } e_1 = e_2 \text{ then } e_3 \text{ else } e_4) = \max(NT(e_1), 1 + NT(e_2), NT(e_3), NT(e_4))$$
$$NT(id(e_1,\ldots,e_n) = \max(NT(e_1),\ldots,NT(e_n))$$
$$NT(int) = 0$$
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What is NT(...code for fib...)?

Why don't we need space to store all the e_i?

The Equations

$$NT(e_1 + e_2) = \max(NT(e_1), 1 + NT(e_2))$$
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$$NT(int) = 0$$
$$NT(id) = 0$$

Is this bottom-up or top-down?

What is NT(...code for fib...)?

Why don't we need space to store all the e_i? Because these are stored not in the current AR, but in the new AR we are building for the function call.

Use the Equations on Our Example

```
def fib(x) = if x = 1 then 0 else
             if x = 2 then 1 else
                fix(x-1) + fib(x-2)
```

Use the Equations on Our Example

```
                 0    1        0
def fib(x) = if  x =  1 then   0 else

             0    1        0
          if x =  2 then   1 else     2
                                 ___________
                        1             1
                 _______________    _______
                        0   1       0  1
                 fix(x-1) + fib(x-2)
```

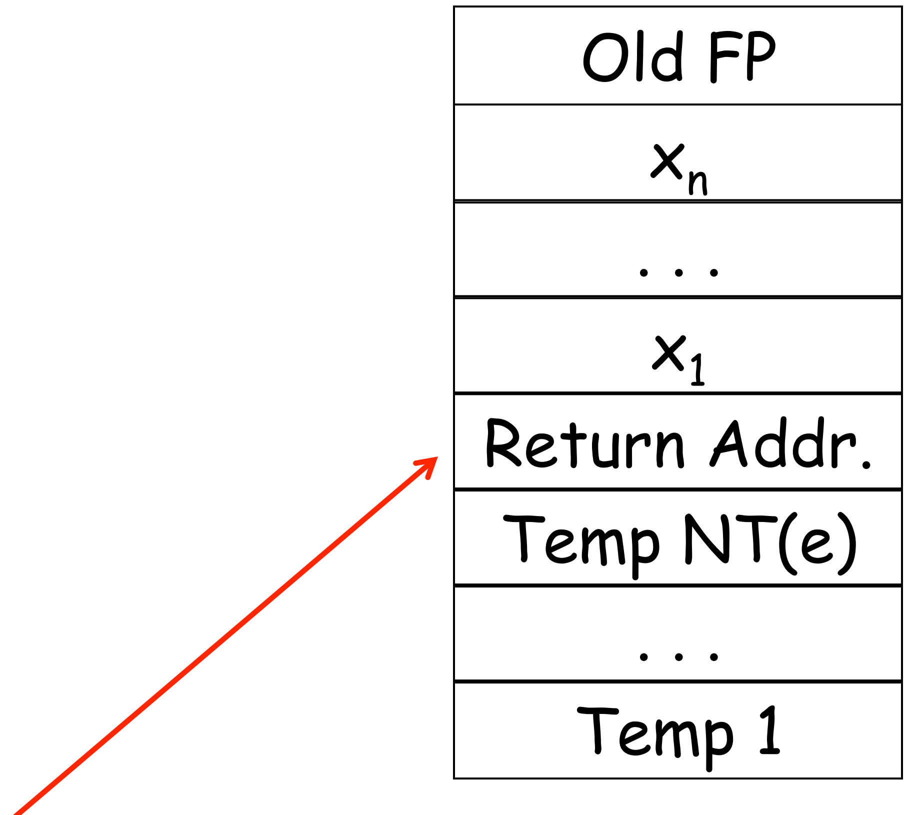
Use the Equations on Our Example

```
                0    1         0
def fib(x) = if x = 1 then 0 else

             0    1         0
             if x = 2 then 1 else    2
                                 ┌─────────┐
                        1              1
                  ┌──────────┐       ┌────┐
                         0  1         0  1
                  fix(x-1) + fib(x-2)
```

The Revised AR

- For a function definition $f(x_1,\ldots,x_n) = e$ the AR has $2 + n + NT(e)$ elements
  - Return address
  - Frame pointer
  - n arguments
  - $NT(e)$ locations for intermediate results

Picture



Recall that the current frame pointer points to the memory location where the RA is stored

Revised Code Generation

- Code generation must know how many temporaries are in use at each point

- Add a new argument to code generation: the position of the next available temporary

Code Generation for + (original)

$\text{cgen}(e_1 + e_2) =$

```
cgen(e1)
sw $a0 0($sp)
addiu $sp $sp -4
cgen(e2)
lw $t1 4($sp)
add $a0 $t1 $a0
addiu $sp $sp 4
```

Code Generation for + (revised)

$cgen(e_1 + e_2, nt) =$

```
cgen(e1, nt)
sw $a0 nt($fp)
cgen(e2, nt + 4)
lw $t1 nt($fp)
add $a0 $t1 $a0
```

Notes

- The temporary area is used like a small, fixed-size stack

- Exercise: Write out cgen for other constructs

Code Generation for OO Languages

Topic II

Object Layout

- OO implementation = Stuff from last part + more stuff
- OO Slogan: If B is a subclass of A, than an object of class B can be used wherever an object of class A is expected
  - Substitutability property…
- This means that code in class A works unmodified for an object of class B
  - Note with regards to code generation strategy, that our generated code for A must work even on subclasses not even yet written when we compile A!

Only Two Questions We Need to Answer Here

- How are objects represented in memory?
  - I.e., layout and representation for objects

- How is dynamic dispatch implemented?
  - This is the characteristic feature of using objects, so we better have a handle on this

Object Layout Example

```
Class A {
    a: Int <- 0;
    d: Int <- 1;
    f(): Int { a <- a + d };
};

Class B inherits A {
    b: Int <- 2;
    f(): Int { a };
    g(): Int { a <- a - b };
};

Class C inherits A {
    c: Int <- 3;
    h(): Int { a <- a * c };
};
```

Object Layout Example (cont.)

```
Class A {
    a: Int <- 0;
    d: Int <- 1;
    f(): Int { a <- a + d };
};

Class B inherits A {
    b: Int <- 2;
    f(): Int { a };
    g(): Int { a <- a - b };
};

Class C inherits A {
    c: Int <- 3;
    h(): Int { a <- a * c };
};
```

Attributes a and d are inherited by classes B and C

Object Layout Example (cont.)

```
Class A {
    a: Int <- 0;
    d: Int <- 1;
    f(): Int { a <- a + d };
};

Class B inherits A {
    b: Int <- 2;
    f(): Int { a };
    g(): Int { a <- a - b };
};
```

```
Class  C inherits A {
    c: Int <- 3;
    h(): Int { a <- a * c };
};
```

All methods in all classes (in this example) refer to a

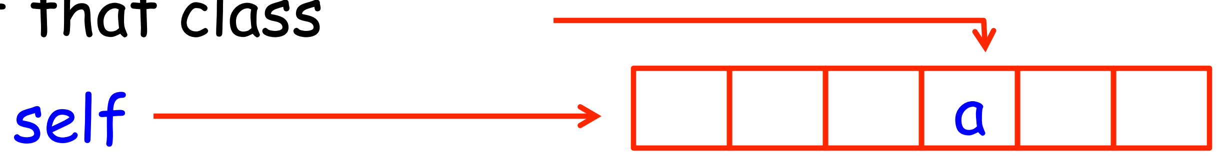
Object Layout Example (cont.)

```
Class A {
    a: Int <- 0;
    d: Int <- 1;
    f(): Int { a <- a + d };
};

Class  B inherits A {
    b: Int <- 2;
    f(): Int { a };
    g(): Int { a <- a - b };
};

Class  C inherits A {
    c: Int <- 3;
    h(): Int { a <- a * c };
};
```

So, for all of these methods to work correctly in A, B, and C, attribute a must be in the same "place" in each object. Consider, e.g., the method f

How Do We Accomplish This?

- Objects are laid out in contiguous memory
- Each attribute stored at a fixed offset in the object
  - The attribute is in the same place in every object of that class



- When a method is invoked, the object itself is the self parameter and the fields are the object's attributes

Object Layout (Cont.)

An object is like a struct in C. The reference

foo.field

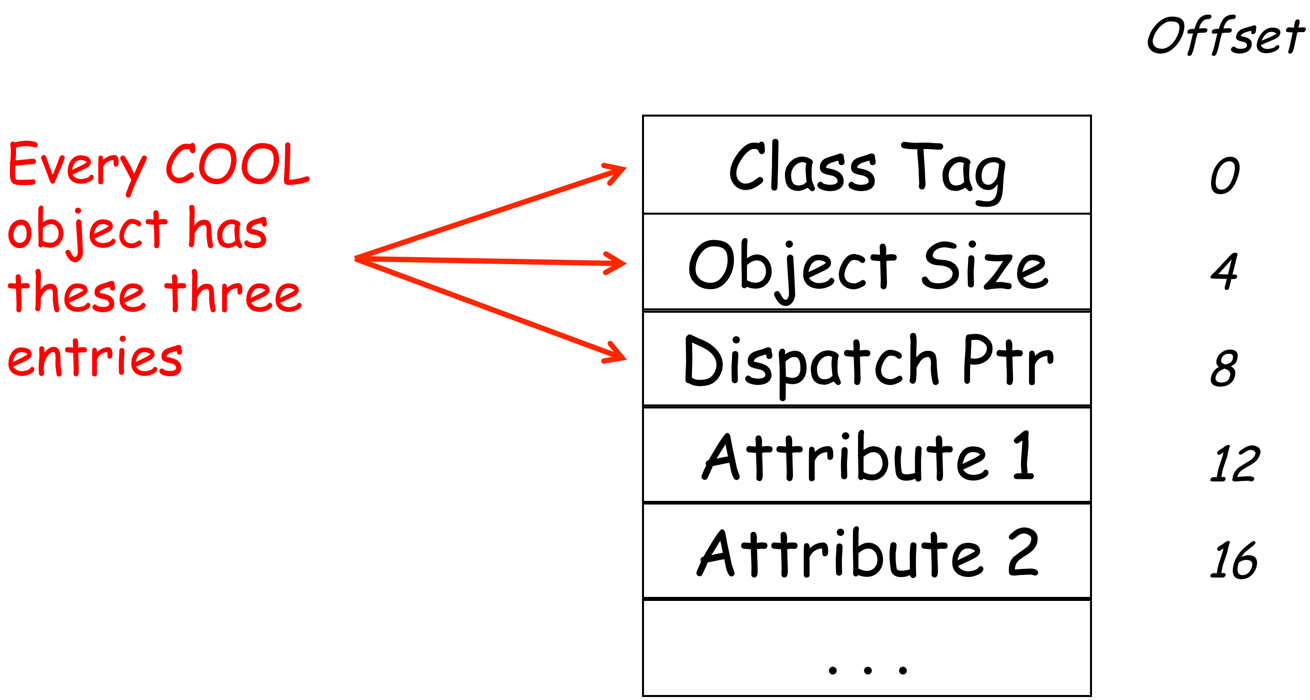
is an index into a foo struct at an offset corresponding to field

Objects in Cool are implemented similarly

- Objects are laid out in contiguous memory
- Each attribute stored at a fixed offset in object
- When a method is invoked, the object is self and the fields are the object's attributes

Cool Object Layout

- The first 3 words of Cool objects contain header information:



Cool Object Layout (Cont.)

- Class tag is an integer
  - Identifies class of the object
  - Compiler numbers all of the classes
  - Each class has its own unique identifier

- Object size is an integer
  - Size of the object in words

Cool Object Layout (Cont.)

- Dispatch ptr is a pointer to a table of methods
  - More later
- Attributes in subsequent slots
  - In some order determined by the compiler
  - All objects of that class will have the attributes of that class laid out in the same order

- And again: All of this laid out in contiguous chunk of memory

Subclasses

Observation: Given a layout for class A, a layout for subclass B can be defined by extending the layout of A with additional slots for the additional attributes of B

Leaves the layout of A unchanged
(B is an extension)

Layout Picture

Offset Class	0	4	8	12	16	20
A	Atag	5	*	a	d	
B	Btag	6	*	a	d	b
C	Ctag	6	*	a	d	c

After A's field come all of B's fields laid out, in order, as they appear textually in the code

Layout Picture

Offset Class	0	4	8	12	16	20
A	Atag	5	*	a	d	
B	Btag	6	*	a	d	b
C	Ctag	6	*	a	d	c

Note: can't call a method of class B on an object of class C, because different attributes in third position, and that's OK since B, C unrelated

Subclasses (Cont.)

- The offset for an attribute is the same in a class and all of its subclasses
  - Any method for an A_1 can be used on a subclass A_2
- Consider layout for $A_n < \ldots < A_3 < A_2 < A_1$

What about chain of inheritance?

Dynamic Dispatch

- Consider the following dispatches (using the same example)

Object Layout Example (Repeat)

```
Class A {
    a: Int <- 0;
    d: Int <- 1;
    f(): Int { a <- a + d };
};

Class B inherits A {
    b: Int <- 2;
    f(): Int { a };
    g(): Int { a <- a - b };
};

Class C inherits A {
    c: Int <- 3;
    h(): Int { a <- a * c };
};
```

Dynamic Dispatch Example

- e.g()
  - g refers to method in B if e is a B
- e.f()
  - f refers to method in A if f is an A or C (inherited in the case of C)
  - f refers to method in B for a B object

- The implementation of methods and dynamic dispatch strongly resembles the implementation of attributes

Dispatch Tables

- Every class has a fixed set of methods (including inherited methods)
- A *dispatch table* indexes these methods
  - An array of method entry points
  - A method f lives at a fixed offset in the dispatch table for a class and all of its subclasses

Dispatch Table Example

Offset Class	0	4
A	fA	
B	fB	g
C	fA	h

- The dispatch table for class A has only 1 method
- The tables for B and C extend the table for A to the right
- Because methods can be overridden, the method for f is not the same in every class, but is always at the same offset

Using Dispatch Tables

- The dispatch pointer in an object of class X points to the dispatch table for class X

- Every method f of class X is assigned an offset O_f in the dispatch table at compile time

Using Dispatch Tables (Cont.)

- To implement a dynamic dispatch e.f() we
  - Evaluate e, giving an object x
  - Call $D[O_f]$
    - D is the dispatch table for x
    - In the call, self is bound to x