# Code Generation

## The Main Idea of Today's Lecture

We can emit stack-machine-style code for expressions via recursion

(We will use MIPS assembly as our target language)



## Lecture Outline

- What are stack-machines?
- The MIPS assembly language
- A simple source language (**"Mini Bar"**)
- A stack-machine implementation of the simple language

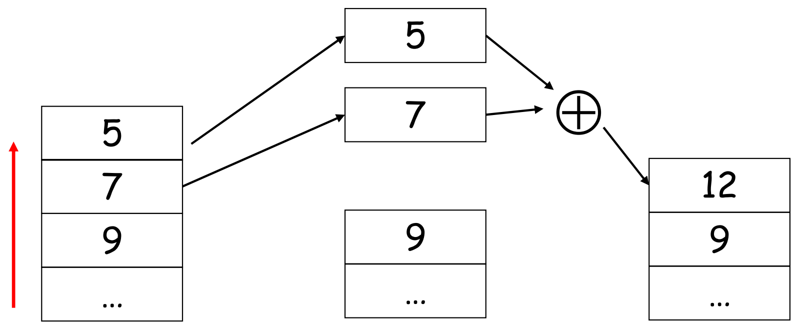


## Stack Machines

- A simple evaluation model
- No variables or registers
- A stack of values for intermediate results
- Each instruction:
  - Takes its operands from the top of the stack
  - Removes those operands from the stack
  - Computes the required operation on them
  - Pushes the result onto the stack

## Example of Stack Machine Operation

The addition operation on a stack machine






## Example of a Stack Machine Program

- Consider two instructions
  - push i - place the integer i on top of the stack
  - add - pop topmost two elements, add them and put the result back onto the stack
- A program to compute 7 + 5:

  push 7
  push 5
  add



## Why Use a Stack Machine?

- Each operation takes operands from the same place and puts results in the same place
- This means a uniform compilation scheme
- And therefore a simpler compiler



## Why Use a Stack Machine?

- Location of the operands is implicit
  - Always on the top of the stack
- No need to specify operands explicitly
- No need to specify the location of the result
- Instruction is “add” as opposed to “add $r_1$, $r_2$”
  - ⇒ Smaller encoding of instructions
  - ⇒ More compact programs
- This is one of the reasons why Java Bytecode uses a stack evaluation model

## Optimizing the Stack Machine

- The add instruction does 3 memory operations
  - Two reads and one write to the stack
  - The top of the stack is frequently accessed
- Idea: keep the top of the stack in a dedicated register (called the "accumulator")
  - Register accesses are faster (why?)
- The "add" instruction is now

  acc ← acc + top_of_stack
  - Only one memory operation!



## Stack Machine with Accumulator

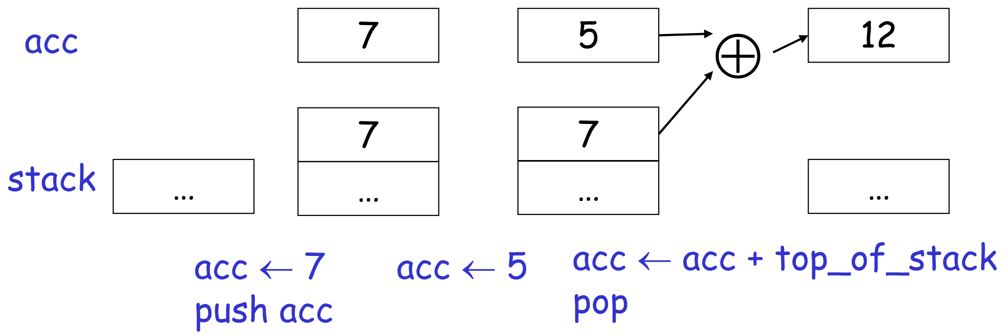
**Invariants**

- The result of computing an expression is always placed in the accumulator
- For an operation $op(e_1,\ldots,e_n)$ compute each $e_i$ and then push the accumulator (= the result of evaluating $e_i$) onto the stack
- After the operation pop n-1 values
- After computing an expression the stack is as before



## Stack Machine with Accumulator: Example

Compute 7 + 5 using an accumulator






## A Bigger Example: 3 + (7 + 5)

| Code | Acc | Stack |
|---|---|---|
| acc ← 3 | 3 | <init> |
| push acc | 3 | 3, <init> |
| acc ← 7 | 7 | 3, <init> |
| push acc | 7 | 7, 3, <init> |
| acc ← 5 | 5 | 7, 3, <init> |
| acc ← acc + top_of_stack | 12 | 7, 3, <init> |
| pop | 12 | 3, <init> |
| acc ← acc + top_of_stack | 15 | 3, <init> |
| pop | 15 | <init> |

## Notes

- It is very important that the stack is preserved across the evaluation of a subexpression
  - Stack before the evaluation of 7 + 5 is 3, <init>
  - Stack after the evaluation of 7 + 5 is 3, <init>
  - The first operand is on top of the stack



## From Stack Machines to MIPS

- The compiler generates code for a stack machine with accumulator
- We want to run the resulting code on the MIPS processor (or simulator)
- We simulate the stack machine instructions using MIPS instructions and registers



## Simulating a Stack Machine on the MIPS…

- The accumulator is kept in MIPS register $a0
- The stack is kept in memory
- The stack grows towards lower addresses
  - Standard convention on the MIPS architecture
- The address of the next location on the stack is kept in MIPS register $sp
  - Guess: what does "sp" stand for?
  - 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 store 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 more details

## A Sample of MIPS Instructions

- lw $reg_1$ offset($reg_2$) "load word"
  - 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 word"
  - Store 32-bit word in $reg_1$ at address $reg_2$ + offset
- addiu $reg_1$ $reg_2$ imm "add immediate"
  - $reg_1 \leftarrow reg_2 + imm$
  - "u" means overflow is not checked
- li reg imm "load immediate"
  - reg ← 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 only integers and integer operations ("**Mini Bar**")

$$P \rightarrow F\ P \mid F$$
$$F \rightarrow id(ARGS)\ begin\ E\ end$$
$$ARGS \rightarrow id,\ ARGS \mid id$$
$$E \rightarrow int \mid id \mid if\ E_1 = E_2\ then\ E_3\ else\ E_4$$
$$\mid E_1 + E_2 \mid E_1 - E_2 \mid id(E_1,\ldots,E_n)$$



## A Small Language (Cont.)

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

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

## Code Generation Strategy

- For each expression e we generate MIPS code that:
  - Computes the value of e in $a0
  - Preserves $sp and the contents of the stack
- We define a code generation function cgen(e) whose result is the code generated for e
  - cgen(e) will be recursive



## Code Generation for Constants

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

cgen(int) = li $a0 int

- Note that this also preserves the stack, as required



## Code Generation for Add

```
cgen(e1 + e2) =
      cgen(e1)              ; $a0 ← value of e1
      sw $a0 0($sp)         ; push that value
      addiu $sp $sp -4      ; onto the stack
      cgen(e2)              ; $a0 ← value of e2
      lw $t1 4($sp)         ; grab value of e1
      add $a0 $t1 $a0       ; do the addition
      addiu $sp $sp 4       ; pop the stack
```

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



## Code Generation for Add: Wrong Attempt!

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

```
cgen(e1 + e2) =
      cgen(e1)              ; $a0 ← value of e1
      move $t1 $a0          ; save that value in $t1
      cgen(e2)              ; $a0 ← value of e2
                            ; may clobber $t1
      add $a0 $t1 $a0       ; perform the addition
```

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

## Code Generation Notes

- The code for $e_1 + e_2$ is a template with "holes" for code for evaluating $e_1$ and $e_2$
- Stack machine code generation is recursive
- Code for $e_1 + e_2$ consists of code for $e_1$ and $e_2$ glued together
- Code generation can be written as a recursive-descent of the AST
  - At least for (arithmetic) 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($e_1$ - $e_2$) =

| | |
|---|---|
| cgen($e_1$) | ; \$a0 ← value of $e_1$ |
| sw \$a0 0(\$sp) | ; push that value |
| addiu \$sp \$sp -4 | ; onto the stack |
| cgen($e_2$) | ; \$a0 ← value of $e_2$ |
| lw \$t1 4(\$sp) | ; grab value of $e_1$ |
| sub \$a0 \$t1 \$a0 | ; do the subtraction |
| addiu \$sp \$sp 4 | ; pop the stack |



## Code Generation for Conditional

- We need flow control instructions
- New MIPS instruction: beq $reg_1$ $reg_2$ label
  - Branch to label if $reg_1 = reg_2$
- New MIPS 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($e_1$)
sw \$a0 0(\$sp)
addiu \$sp \$sp -4
cgen($e_2$)
lw \$t1 4(\$sp)
addiu \$sp \$sp 4
beq \$a0 \$t1 true_branch

false_branch:
cgen($e_4$)
b end_if
true_branch:
cgen($e_3$)
end_if:

## Meet The Activation Record

- Code for function calls and function definitions depends on the layout of the activation record (or "AR")
- A very simple AR suffices for this 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 the arguments $x_n,\ldots,x_1$ onto the stack
    - These are the only variables in this language



## Meet The Activation Record (Cont.)

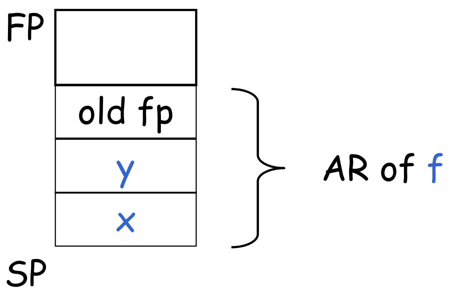
- The stack discipline guarantees that on function exit, $sp is the same as it was before the args got pushed (i.e., before function call)
- We need the return address
- It's also handy to have a pointer to the current activation
  - This pointer lives in register $fp (frame pointer)
  - Reason for frame pointer will be clear shortly (at least I hope!)



## Layout of 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 will be:






## Code Generation for Function Call

- The calling sequence is the instructions (of both *caller* and *callee*) to set up a function invocation
- New instruction: jal label
  - Jump to label, save address of next instruction in special register $ra
  - On other architectures the return address is stored on the stack by the "call" instruction

## Code Generation for Function Call (Cont.)

cgen(f($e_1$,…,$e_n$)) =
  sw \$fp 0(\$sp)
  addiu \$sp \$sp -4
  cgen($e_n$)
  sw \$a0 0(\$sp)
  addiu \$sp \$sp -4
  …
  cgen($e_1$)
  sw \$a0 0(\$sp)
  addiu \$sp \$sp -4
  jal f_entry

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



## Code Generation for Function Definition

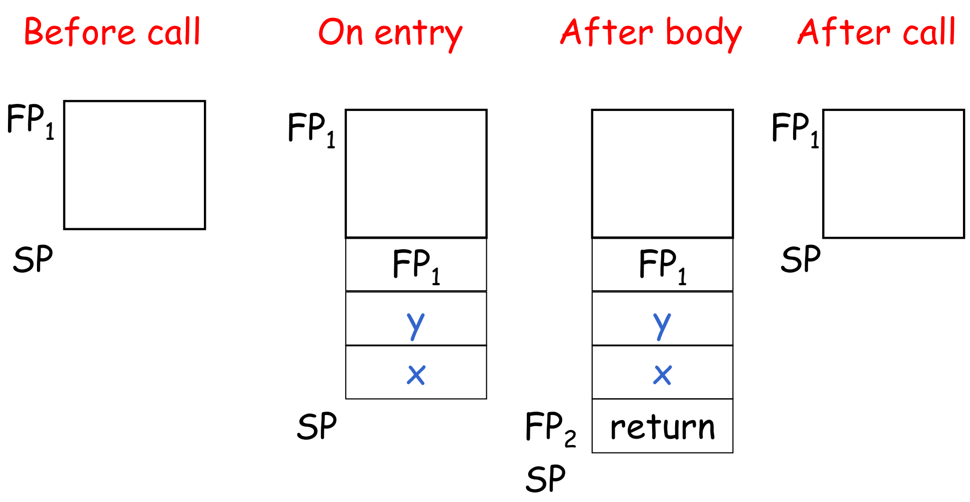
- New MIPS instruction: jr reg
  - Jump to address in register reg

cgen(f($x_1$,…,$x_n$) begin e end) =
f_entry: move \$fp \$sp
  sw \$ra 0(\$sp)
  addiu \$sp \$sp -4
  cgen(e)
  lw \$ra 4(\$sp)
  addiu \$sp \$sp frame_size
  lw \$fp 0(\$sp)
  jr \$ra

- Note: The frame pointer points to the top, not bottom of the frame
- Callee saves old return addr, evaluates its body, pops the return addr, pops the args, and then restores \$fp
- frame_size = 4*n + 8



## Calling Sequence: Example for f(x,y)






## Code Generation for Variables/Parameters

- 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/Parameters

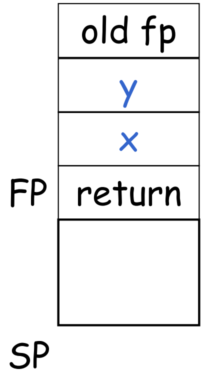
- Solution: use the frame pointer
  - Always points to the return address on the stack
  - Since it does not move, it can be used to find the variables
- Let $x_i$ be the $i^{th}$ ($i = 1,\ldots,n$) formal parameter of the function for which code is being generated

cgen($x_i$) = lw $a0 offset($fp)  ( offset = 4*i )



## Code Generation for Variables/Parameters

- Example: For a function f(x,y) begin e end the activation and frame pointer are set up as follows (when evaluating e):




- x is at fp + 4
- y is at fp + 8



## Activation Record & Code Generation Summary

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

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



## Discussion

- 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
  - As a result, code generation is often performed in synergy with register allocation

- Next time: code generation for temporaries and a deeper look into parameter passing mechanisms