CODE GENERATION

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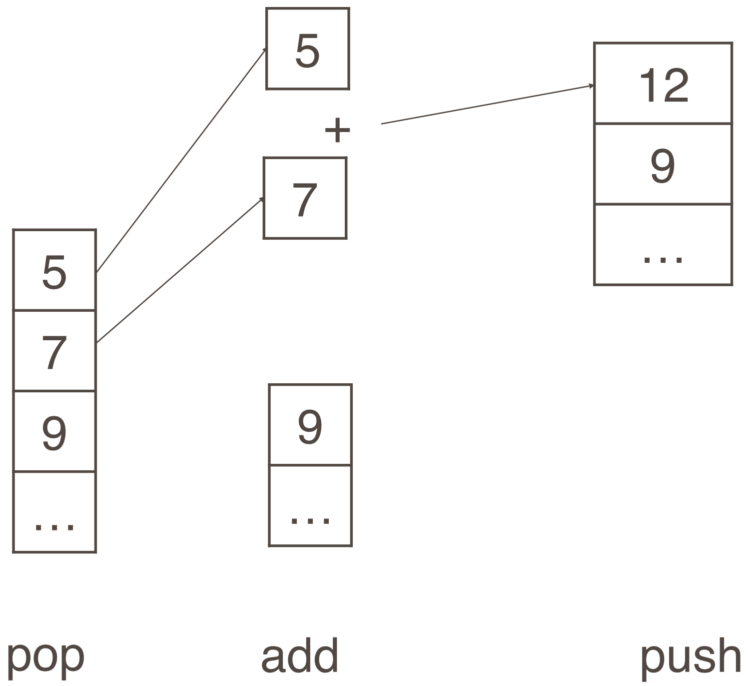
Stack Machine

- 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 on 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 two elements, add them and put the result back on 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 “add” as opposed to “add r1, r2”

  ⇒ Smaller encoding of instructions

  ⇒ More compact programs
- This is one reason why Java Bytecodes use 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 register (called accumulator)
  - Register accesses are faster
- The "add" instruction is now

  acc ← acc + top_of_stack

  - Only one memory operation!

Stack Machine with Accumulator

- Invariants
  - The result of an expression is in the accumulator
  - For op(e_1,…,e_n) push the accumulator on the stack after computing e_1,…,e_{n-1}
    - After the operation pops n-1 values
  - Expression evaluation preserves the stack

Stack Machine with Accumulator. Example

- Compute 7 + 5 using an accumulator

1. acc ← 7; push acc
2. acc ← 5
3. acc ← acc + top_of_stack
4. pop

A Bigger Example: 3 + (7 + 5)

Code	ACC	Stack
acc ← 3	3	<init>
push acc	3	3,<init>
acc ← 7	7	3,<init>
push	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>

It is very important evaluation of a subexpression preserves the stack

- Stack before the evaluation of 7 + 5 is 3
- Stack after the evaluation of 7 + 5 is 3
- The first operand is on top of the stack

From Stack Machines to MIPS

- The compiler generates code for a stack machine with accumulator
- Let's run the resulting code on a MIPS like processor.
  - Simulate stack machine instructions using MIPS instructions and registers
- The accumulator is kept in MIPS register $a0
- The stack is kept in memory
  - The stack grows towards lower addresses
- The address of the next location on the stack is kept in MIPS register $sp (stack pointer)
  - 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)

A Sample of MIPS Instructions

- lw reg1 offset(reg2)
  - Load 32-bit word from the value of reg2 (which is a memory address), add a fixed value offset into reg1
- add reg1 reg2 reg3
  - reg1 ← reg2 + reg3
- sw reg1 offset(reg2)
  - Store 32-bit word in reg1 at address reg2 + offset
- addiu reg1 reg2 imm
  - reg1 ← reg2 + imm
  - "u" means overflow is not checked
- li reg imm
  - reg ← imm

MIPS Assembly, Example

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

Steps	MIPS Instruction
`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`

- Let's generalize this to a simple language

A Small Language

- A language with integers and integer operations

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

- 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:

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

  cgen(i) = li $a0 i

- This preserves the stack, as required
- Color key:
  - RED: compile time
  - BLUE: 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
```

Code Generation for Sub and Constants

- New instruction: `sub reg1 reg2 reg3`

  Implements `reg1 ← reg2 - reg3`

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

Code Generation for Conditional

- We need flow control instructions
- New instruction: beq reg1 reg2 label
  - Branch to label if reg1 = reg2
- New instruction: b label
  - Unconditional jump to label

Code Generation for If (Cont.)

```
cgen(if e1 = e2 then e3 else e4) =
      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 on the layout of the AR

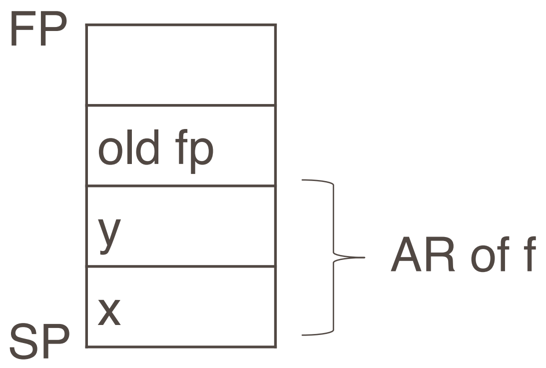
- A very simple AR suffices for this language:
  - The result is always in the accumulator
    - No need to store the result in the AR
  - The activation record holds actual parameters
    - For $f(x_1,\ldots,x_n)$ push $x_n,\ldots,x_1$ on the stack
    - These are the only variables in this language

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
- We need the return address
- A pointer to the current 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:



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 $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 Definition

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

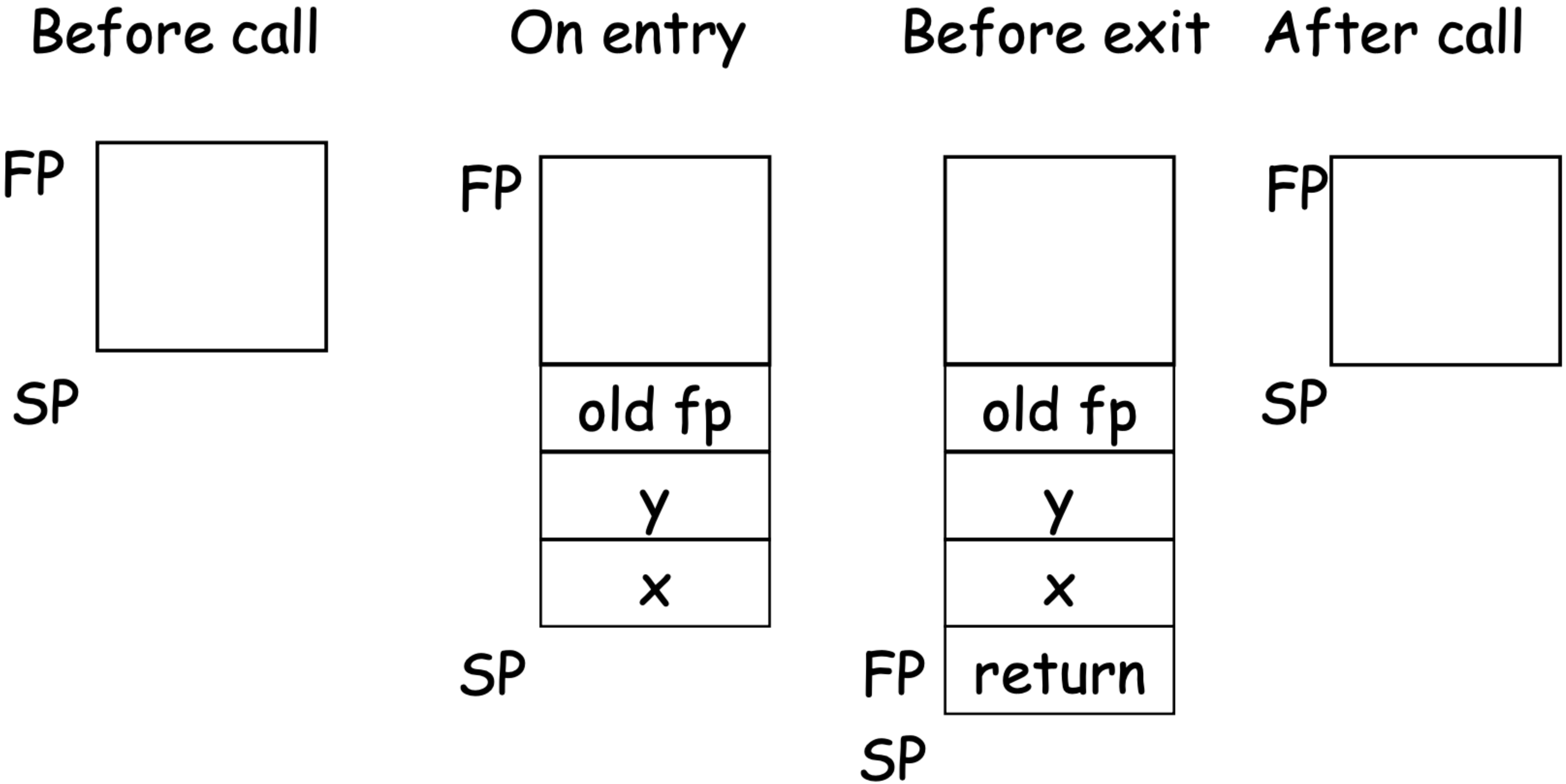
```
cgen(def f(x1,…,xn) = e) =
fEntry:
  move $fp $sp
  sw $ra 0($sp)
  addiu $sp $sp -4
  cgen(e)
  lw $ra 4($sp)
  addiu $sp $sp z
  lw $fp 0($sp)
  jr $ra
```

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

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

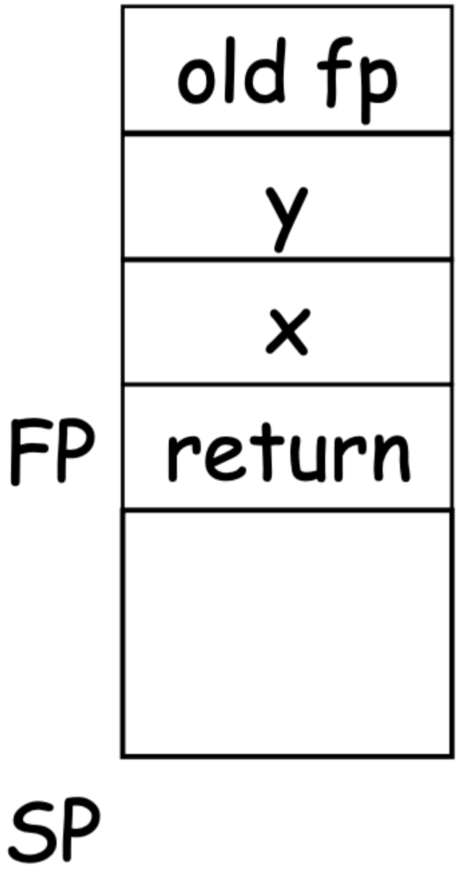
Code Generation for Variables (Cont.)

- 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

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

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.
- 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