

# Code Generation

## Lecture 30 (based on slides by R. Bodik)

# Lecture Outline

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- Stack machines
- The MIPS assembly language
- The x86 assembly language
- A simple source language
- Stack-machine implementation of the simple language

# Stack Machines

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- A simple evaluation model
- No variables or registers
- A stack of values for intermediate results

# Example of a Stack Machine Program

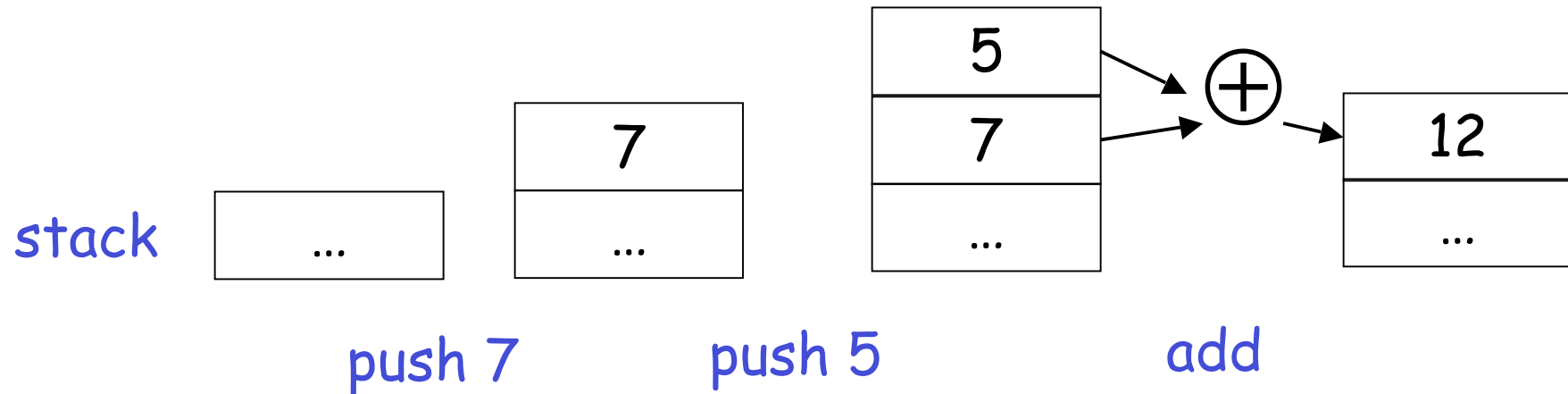
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- Consider two instructions
  - `push i` - place the integer `i` on top of the stack
  - `add` - pop two elements, add them and put the result back on the stack
- A program to compute  $7 + 5$ :

```
push 7  
push 5  
add
```

# Stack Machine. Example

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- 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

# Why Use a Stack Machine ?

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- 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 ?

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- 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 r<sub>1</sub>, r<sub>2</sub>"
  - ⇒ Smaller encoding of instructions
  - ⇒ More compact programs
- This is one reason why Java Bytecodes use a stack evaluation model

# Optimizing the Stack Machine

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- 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
$$\text{acc} \leftarrow \text{acc} + \text{top\_of\_stack}$$
  - Only one memory operation!



# Stack Machine with Accumulator

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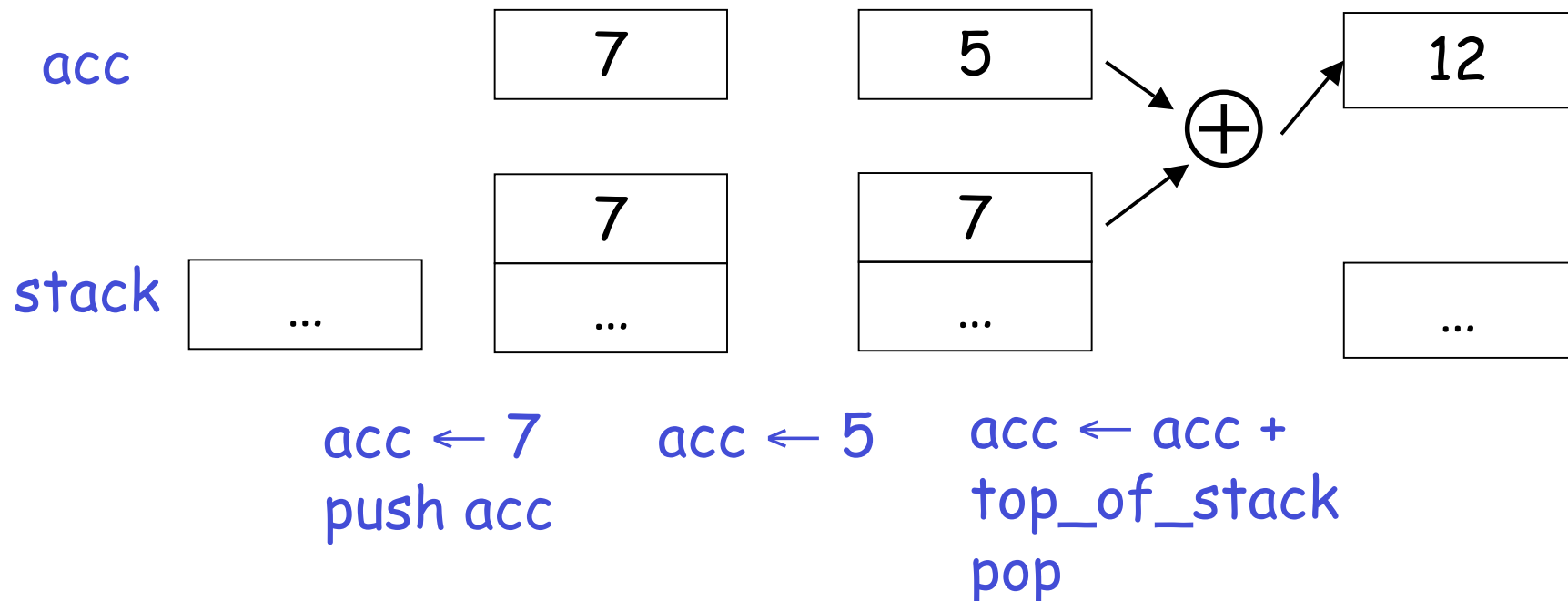
## Invariants

- The result of computing an expression is always in the accumulator
- For an operation  $op(e_1, \dots, e_n)$  push the accumulator on the stack after computing each of  $e_1, \dots, e_{n-1}$ 
  - The result of  $e_n$  is in the accumulator before  $op$
  - After the operation pop  $n-1$  values
- After computing an expression the stack is as before

# Stack Machine with Accumulator. Example

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- Compute  $7 + 5$  using an accumulator



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

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

# Notes

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- It is **very important** that the stack is preserved across the evaluation of a subexpression
  - Stack before the evaluation of  $7 + 5$  is  $3, \langle \text{init} \rangle$
  - Stack after the evaluation of  $7 + 5$  is  $3, \langle \text{init} \rangle$
  - The first operand is on top of the stack

# From Stack Machines to MIPS

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- The compiler generates code for a stack machine with accumulator
- We want to run the resulting code on an x86 or MIPS processor (or simulator)
- We implement stack machine instructions using MIPS instructions and registers

# MIPS assembly vs. x86 assembly

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- In Project 4, you will generate x86 code
  - because we have no MIPS machines around
  - and using a MIPS simulator is less exciting
- In this lecture, we will use MIPS assembly
  - it's somewhat more readable than x86 assembly
  - e.g. in x86, both store and load are called movl
- translation from MIPS to x86 trivial
  - see the translation table in a few slides

# Simulating a Stack Machine...

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- The accumulator is kept in MIPS register  $\$a0$ 
  - in x86, it's in  $\%eax$
- The stack is kept in memory
- The stack grows towards lower addresses
  - standard convention on both MIPS and x86
- The address of the next location on the stack is kept in MIPS register  $\$sp$ 
  - The top of the stack is at address  $\$sp + 4$
  - in x86, it's  $\%esp$

# MIPS Assembly

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## 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

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

# x86 Assembly

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## x86 architecture

- Complex Instruction Set Computer (CISC) architecture
- Arithmetic operations can use both registers and memory for operands and results
- So, you don't have to use separate load and store instructions to operate on values in memory
- CISC gives us more freedom in selecting instructions (hence, more powerful optimizations)
- but we'll use a simple RISC subset of x86
  - so translation from MIPS to x86 will be easy

# x86 assembly

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- x86 has two-operand instructions:
  - ex.: `ADD dest, src`                      `dest := dest + src`
  - in MIPS: `dest := src1 + src2`
- An annoying fact to remember ☹
  - different x86 assembly versions exists
  - one important difference: order of operands
  - the manuals assume
    - `ADD dest, src`
  - the gcc assembler we'll use uses opposite order
    - `ADD src, dest`

## Sample x86 instructions (gcc order of operands)

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- `movl offset(reg2), reg1`
  - Load 32-bit word from address `reg2 + offset` into `reg1`
- `add reg2, reg1`
  - $reg_1 \leftarrow reg_1 + reg_2$
- `movl reg1 offset(reg2)`
  - Store 32-bit word in `reg1` at address `reg2 + offset`
- `add imm, reg1`
  - $reg_1 \leftarrow reg_1 + imm$
  - use this for MIPS' `addiu`
- `movl imm, reg`
  - $reg \leftarrow imm$

# MIPS to x86 translation

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MIPS	x86
<code>lw reg<sub>1</sub>, offset(reg<sub>2</sub>)</code>	<code>movl offset(reg<sub>2</sub>), reg<sub>1</sub></code>
<code>add reg<sub>1</sub>, reg<sub>1</sub>, reg<sub>2</sub></code>	<code>add reg<sub>2</sub>, reg<sub>1</sub></code>
<code>sw reg<sub>1</sub>, offset(reg<sub>2</sub>)</code>	<code>movl reg<sub>1</sub>, offset(reg<sub>2</sub>)</code>
<code>addiu reg<sub>1</sub>, reg<sub>1</sub>, imm</code>	<code>add imm, reg<sub>1</sub></code>
<code>li reg, imm</code>	<code>movl imm, reg</code>

# x86 vs. MIPS registers

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MIPS	x86
\$a0	%eax
\$sp	%esp
\$fp	%ebp
\$t	%ebx

# MIPS Assembly. Example.

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

$acc \leftarrow 7$

push acc

$acc \leftarrow 5$

$acc \leftarrow acc + \text{top\_of\_stack}$

pop

li \$a0, 7

sw \$a0, 0(\$sp)

addiu \$sp, \$sp, -4

li \$a0, 5

lw \$t1, 4(\$sp)

add \$a0, \$a0, \$t1

addiu \$sp, \$sp, 4

- We now generalize this to a simple language...

## Some Useful Macros

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- We define the following abbreviation
- push \$t `sw $t, 0($sp)`  
`addiu $sp, $sp, -4`
- pop `addiu $sp, $sp, 4`
- $\$t \leftarrow \text{top}$  `lw $t, 4($sp)`





# A Small Language

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- A language with integers and integer operations

$P \rightarrow D; P \mid D$

$D \rightarrow \text{def id}(\text{ARGS}) = E;$

$\text{ARGS} \rightarrow \text{id}, \text{ARGS} \mid \text{id}$

$E \rightarrow \text{int} \mid \text{id} \mid \text{if } E_1 = E_2 \text{ then } E_3 \text{ else } E_4$   
 $\mid E_1 + E_2 \mid E_1 - E_2 \mid \text{id}(E_1, \dots, E_n)$

## A Small Language (Cont.)

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- 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

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- 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  $e$

# Code Generation for Constants

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

`cgen(i) = li $a0, i`

- Note that this also preserves the stack, as required

# Code Generation for Add

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```
cgen( $e_1 + e_2$ ) =  
    cgen( $e_1$ )  
    push $a0  
    cgen( $e_2$ )  
    $t1 ← top  
    add $a0, $t1, $a0  
    pop
```

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

# Code Generation for Add. Wrong!

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- 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 Notes

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- 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  $e_1 + e_2$  consists of code for  $e_1$  and  $e_2$  glued together
- Code generation can be written as a (modified) post-order traversal of the AST
  - At least for expressions



# Code Generation for Sub and Constants

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- New instruction: `sub reg1 reg2 reg3`

- Implements  $reg_1 \leftarrow reg_2 - reg_3$

```
cgen(e1 - e2) =  
    cgen(e1)  
    push $a0  
    cgen(e2)  
    $t1 ← top  
    sub $a0, $t1, $a0  
    pop
```

# Code Generation for Conditional

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- We need flow control instructions
- New instruction: `beq reg1, reg2, label`
  - Branch to label if `reg1 = reg2`
  - x86: `cmpl reg1, reg2`  
`je label`
- New instruction: `b label`
  - Unconditional jump to label
  - x86: `jmp label`

## Code Generation for If (Cont.)

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```
cgen(if  $e_1 = e_2$  then  $e_3$  else  $e_4$ ) =  
  false_branch = new_label ()  
  true_branch = new_label ()  
  end_if = new_label ()  
  cgen( $e_1$ )  
  push $a0  
  cgen( $e_2$ )  
  $t1  $\leftarrow$  top  
  pop  
  beq $a0, $t1, true_branch
```

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