Code Generation

Lecture 12-14

Lecture Outline

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

Stack Machines

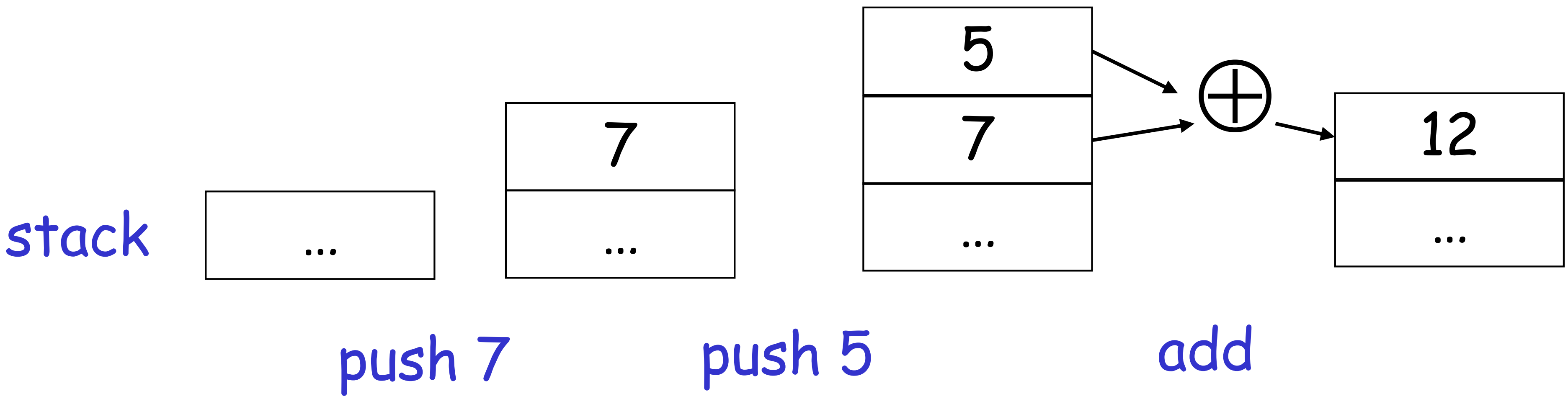
- A simple evaluation model
- No variables or registers
- A stack of values for intermediate results

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
```

Stack Machine. Example



- 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 ?

- 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
  - This is what you have to do for PA3

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 r_1, r_2"
  - ⇒ 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!

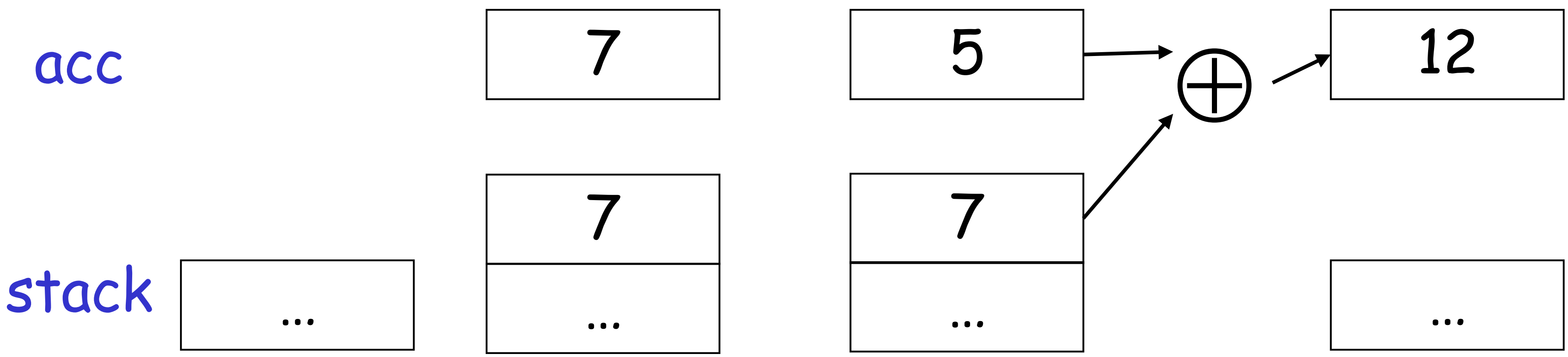
Stack Machine with Accumulator

Invariants

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

- Compute $7 + 5$ using an accumulator



$acc \leftarrow 7$
push acc

$acc \leftarrow 5$

$acc \leftarrow acc + top\_of\_stack$
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 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 Assembly

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

Simulating a Stack Machine…

- The accumulator is kept in the register a0
- The stack is kept in memory
- The stack grows towards lower addresses
  - Standard convention on the RISC-V architecture
- The address of the next location on the stack is kept in RISC-V register sp
  - The top of the stack is at address sp + 4

RISC-V Assembly

RISC-V 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
- general purpose registers
  - We will use sp, a0, and t1 (a temporary register)

A Sample of RISC-V 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
- addi reg_1, reg_2, imm
  - $reg_1 \leftarrow reg_2 + imm$
- li reg, imm
  - $reg \leftarrow imm$

RISC-V Assembly. Example.

- The stack-machine code for 7 + 5 in RISC-V:

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

- We now generalize this to a simple language…

Some Useful Macros

- We define the following abbreviations
- push t   sw t, 0(sp)
  addi sp, sp, -4
- pop   addi sp, sp, 4
- $t \leftarrow$ top   lw t, 4(sp)

A Small Language

- A language with integers and integer operations

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

A Small Language (Cont.)

- The first function definition f is the "main" routine
- 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 RISC-V 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

- 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

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

```
cgen(e1)
push a0
cgen(e2)
t1 ← top
add a0, t1, a0
pop
```

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

Code Generation for Add. Wrong!

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

```
cgen(e1 + e2) =
        cgen(e1)
        mv t1, a0
        cgen(e2)
        add a0, t1, a0
```

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

Code Generation Notes

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

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: j label
  - Unconditional jump to label

Code Generation for If (Cont.)

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

```
  cgen(e1)
  push a0
  cgen(e2)
  t1 ← top
  pop
  beq a0, t1, true_branch
false_branch:
  cgen(e4)
  j end_if
true_branch:
  cgen(e3)
end_if:
```

The Activation Record

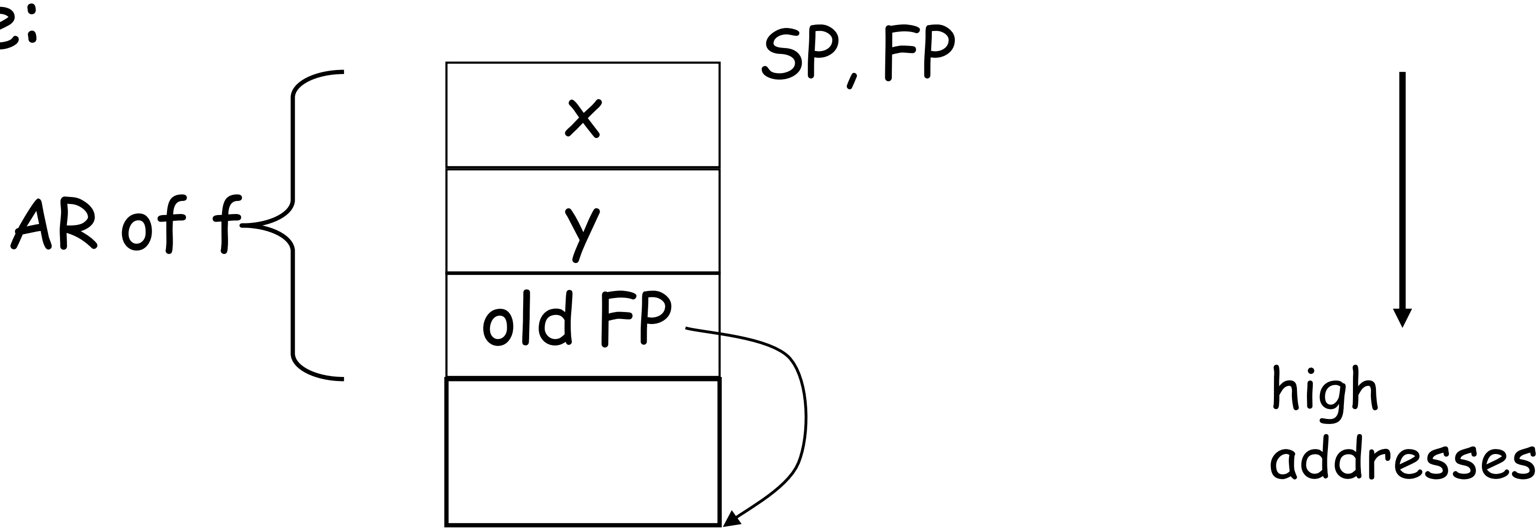
- Code for function calls and function definitions depends on the layout of the activation record
- A very simple AR suffices for this language:
  - The result is always in the accumulator
    - No need to store the result in the AR
  - The activation record holds actual parameters
    - For $f(x_1,\dots,x_n)$ push $x_n,\dots,x_1$ 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 to save sp
- We need the return address
- It's handy to have a pointer to start of the current activation
  - 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 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 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)) =
    push fp
    cgen(en)
    push a0
    …
    cgen(e1)
    push a0
    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

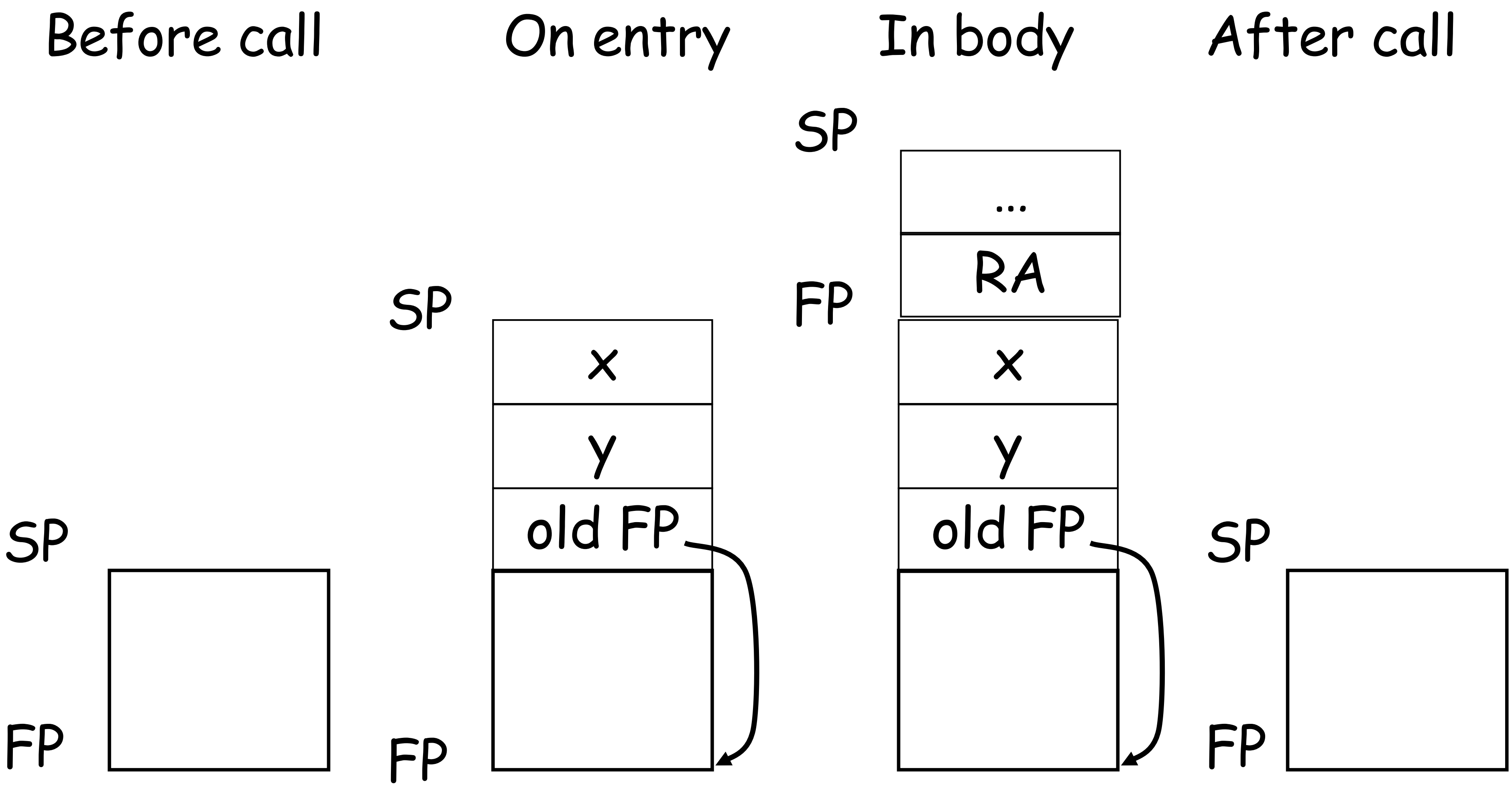
Code Generation for Function Definition

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

```
cgen(def f(x1,…,xn) = e) =
f_entry:
  mv fp, sp
  push ra
  cgen(e)
  ra ← top
  addi 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

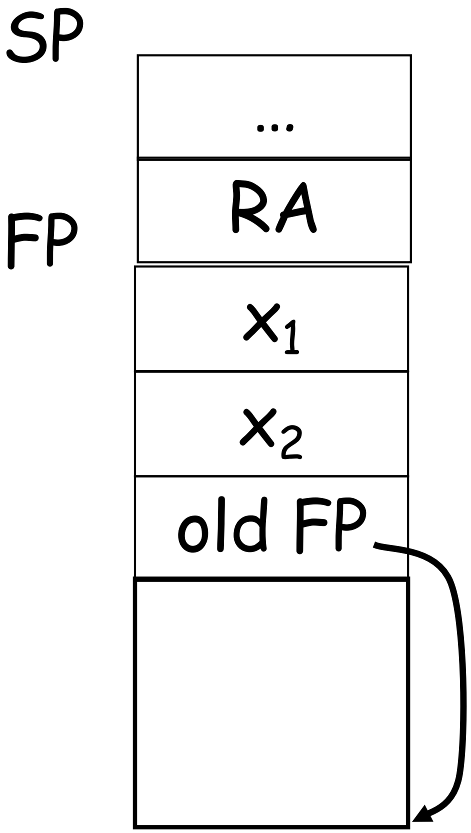
- Problem: Because the stack grows when intermediate results are saved, the variables are not at a fixed offset from sp

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} ($i = 1,\dots,n$) formal parameter of the function for which code is being generated

Code Generation for Variables (Cont.)

- Example: For a function def $f(x_1,x_2) = e$ the activation and frame pointer are set up as follows:



x_1 is at fp + 4

x_2 is at fp + 8

- Thus:

cgen(x_i) = lw a0, z(fp)

(z = 4*i)

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 ChocoPy compiler (it's simple)

Summary

- Reference implementation of ChocoPy for PA3 will contain a large code generation example

- 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

Allocating Temporaries in the AR

Review

- The stack machine has activation records and intermediate results interleaved on the stack

AR
Intermediates
AR
Intermediates

Review (Cont.)

- Advantage: Very simple code generation

- Disadvantage: Very slow code
  - Storing/loading temporaries requires a store/load and sp adjustment

A Better Way

- Idea: Keep temporaries in the AR

- The code generator must assign a location in the AR for each temporary

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?

How Many Temporaries?

- Let $NT(e)$ = # of temps needed to evaluate e

$NT(e_1 + e_2)$

  - Needs at least as many temporaries as $NT(e_1)$
  - Needs at least as many temporaries as $NT(e_2) + 1$

- Space used for temporaries in e_1 can be reused for temporaries in e_2

The Equations

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

$$NT(e_1 - e_2) = \max(NT(e_1), 1 + NT(e_2))$$

$$NT(\text{if } e_1 = e_2 \text{ then } e_3 \text{ else } e_4) = \max(NT(e_1), 1 + NT(e_2), NT(e_3), NT(e_4))$$

$$NT(id(e_1,\dots,e_n)) = \max(NT(e_1)+n-1,\dots,NT(e_n))$$

$$NT(int) = 0$$

$$NT(id) = 0$$

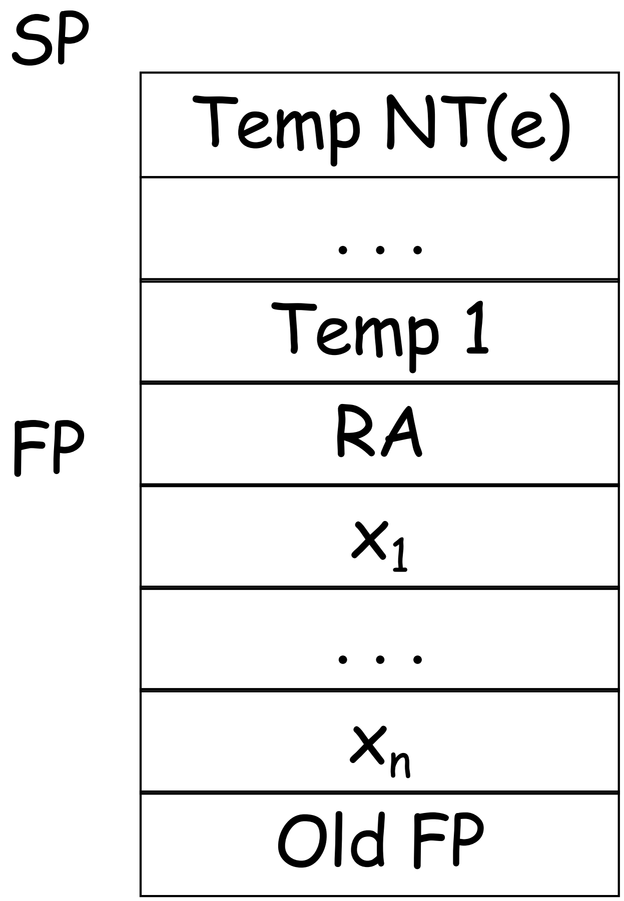
Is this bottom-up or top-down?

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

The Revised AR

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

Picture



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

cgen(e, n) : generate code for e and use temporaries whose address is (fp - n) or lower

Code Generation for + (original)

$cgen(e_1 + e_2)$ =

```
cgen(e1)
sw a0, 0(sp)
addi sp, sp, -4
cgen(e2)
lw t1, 4(sp)
add a0, t1, a0
addi 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 Object-Oriented Languages

Object Layout

- OO implementation = Stuff from codegen lecture + More stuff

- OO Slogan: If B is a subclass of A, then an object of class B can be used wherever an object of class A is expected

- This means that code in class A works unmodified for an object of class B

Two Issues

- How are objects represented in memory?

- How is dynamic dispatch implemented?

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 ChocoPy 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

ChocoPy Object Layout

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

	Offset
Class Tag	*0*
Object Size	*4*
Dispatch Ptr	*8*
Attribute 1	*12*
Attribute 2	*16*
. . .	

ChocoPy Object Layout (Cont.)

- Class tag is an integer
  - Identifies class of the object
- Object size is an integer
  - Size of the object in words
- Dispatch ptr is a pointer to a table of methods
  - More later
- Attributes in subsequent slots

- Lay out in contiguous memory

Object Layout Example

```
class A(object):
    a: int = 0
    d: int = 1
    def f(self:A) -> int:
        a = a + d
        return a

class B(A):
    b: int = 2
    def f(self:B) -> int:
        return a // Override
    def g(self: B) -> int:
        a = a – b
        return a

class C(A):
    c: int = 3
    def h(self: C) -> int:
        a = a * c
        return a
```

Object Layout (Cont.)

- Attributes a and d are inherited by classes B and C

- All methods in all classes refer to a

- For A methods to work correctly in A, B, and C objects, attribute a must be in the same "place" in each object

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

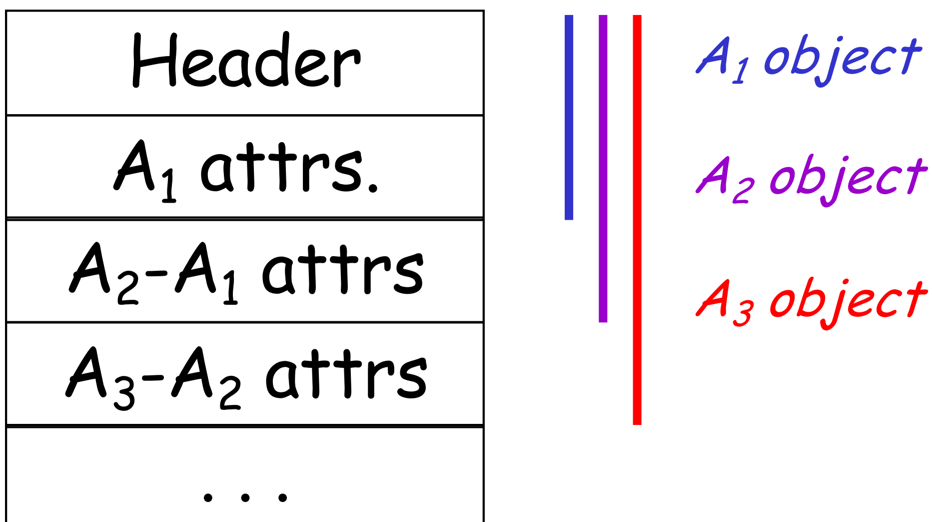
Leaves the layout of A unchanged
(B is an extension)

Layout Picture

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

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 $A_n \leq \ldots \leq A_3 \leq A_2 \leq A_1$



Dynamic Dispatch: the example again

```
class A(object):
    a: int = 0
    d: int = 1
    def f(self:A) -> int:
        a = a + d
        return a

class  B(A):
    b: int = 2
    def f(self:B) -> int:
        return a // Override
    def g(self: B) -> int:
        a = a – b
        return a
```

```
class  C(A):
    c: int = 3
    def h(self: C) -> int:
        a = a * c
        return a
```

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 e 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

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

- The dispatch table for class A has only 1 method
- The tables for B and C extend the table for A with more methods
- 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.)

- Every method must know what object is "self"
  - "self" is passed as the first argument to all methods
- To implement a dynamic dispatch e.f() we
  - Evaluate e, obtaining an object x
  - Find D by reading the dispatch-table field of x
  - Call $D[Offset_f](x)$
    - D is the dispatch table for x
    - In the call, self is bound to x