

GOLD HILL
EST. — 1859
ELEV. — 8463
POP. — 118
TOTAL 10440

**Code
Generation
Super
Lectures**

Huge One-Slide Summary

- **Assembly language** is untyped, unstructured, low-level and imperative. In a **load-store** architecture, **instructions** operate on **registers** (which are like global variables). The **stack pointer** is a special-purpose register.
- We can **generate code** by targeting a **stack machine** and using assembly instructions to implement the stack. The stack holds intermediate values, temporaries, and function arguments. The **accumulator** register (conceptually, the top of the stack) holds the result of the last computation. As an **invariant**, the stack is unchanged by intermediate calculations.
- We will maintain a **stack discipline** (or **calling convention**). Each function call is represented on the stack by an **activation record** (or **stack frame**). The activation record contains the **frame pointer**, the **parameters**, the **self** object pointer, the **return address**, and space for **temporaries**. The code you generate for function calls and function bodies must consistently agree on the calling convention.
- Our **object layout** choice must support using a subtype whenever a supertype is expected. Objects are **contiguous** blocks of memory that hold bookkeeping information (e.g., type tags, method pointers) as well as space for **fields**. **Subobjects** will **extend** (be bigger than in memory) their superobjects and will **share a common prefix**.
- A **dispatch table** (or **virtual function** table or **vtable**) is an array of pointers to methods. Each object points to its vtable, and members of a class **share** one vtable. This allows us to implement **dynamic dispatch**: method invocation is resolved by looking up the method address in the object's vtable at **runtime**.

(Two Day) Lecture Outline

- Stack machines
 - e.g., Java Virtual Machine
- The COOL-ASM assembly language
 - It's MIPS/RISC + Java Bytecode
- A simple source language
- Stack-machine implementation of the simple language
- An optimization: stack-allocated variables
- Object Oriented Code Generation
 - Object Layout, Dynamic Dispatch

Stack Machines

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

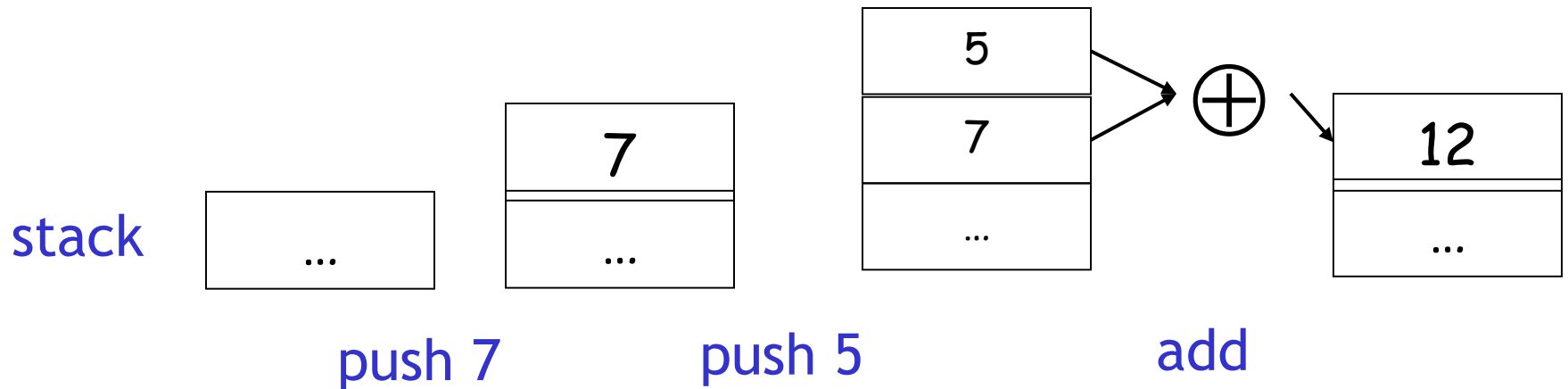


Example

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 the easiest way to do PA6
 - The reference compiler is more complicated

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 (= faster: why?)
- 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 the **accumulator**)
 - This should remind you of **Fold**
 - Register accesses are faster
- The “**add**” instruction is now
$$\text{acc} \leftarrow \text{acc} + \text{top_of_stack}$$
 - Only one memory operation!

Fear my course organization!

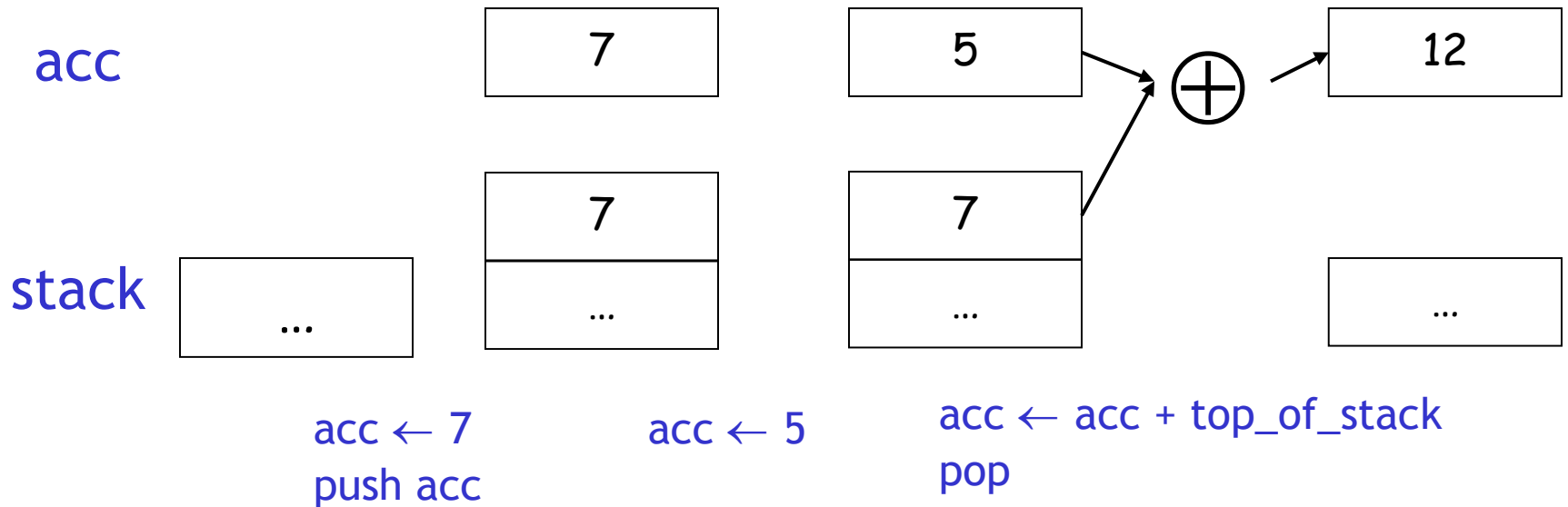
Accumulator Invariants

- 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}
 - e_n 's result is in the accumulator before **op**
 - After the operation **pop** $n-1$ values
- After computing an expression the stack is as before

Example on next slide!

Stack Machine with Accumulator: Example

- Compute $7 + 5$ using an accumulator

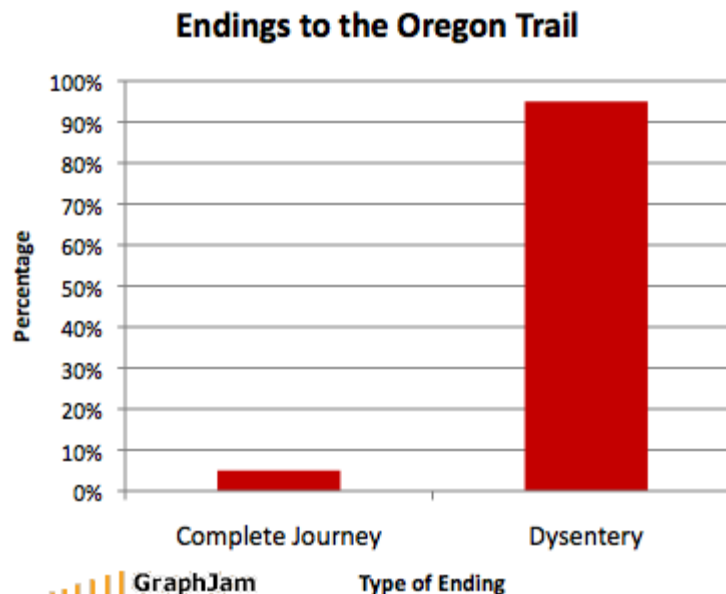


A Bigger Example: $3 + (7 + 5)$

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

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



From Stack Machines to RISC

- Our compiler will generate code for a stack machine with accumulator
- We want to run the resulting code on a processor
- We'll implement stack machine instructions using COOL-ASM instructions and registers
- Thus: Assembly Language



Risky Business

- COOL-ASM is a RISC-style **assembly language**
 - An untyped, unsafe, low-level, fast programming language with few-to-no primitives.
- A **register** is a fast-access untyped global variable shared by the entire assembly program.
 - COOL-ASM: 8 general registers and 3 special ones (stack pointer, frame pointer, return address)
- An **instruction** is a primitive statement in assembly language that operates on registers.
 - COOL-ASM: add, jmp, ld, push, ...
- A **load-store** architecture: bring values in to registers from memory to operate on them.

Drink Your Cool-Aid

- Sample COOL-ASM instructions:

- See the CRM for all of them ...

add r2 <- r5 r2 ; r2 = r5 + r2

li r5 <- 183 ; r5 = 183

ld r2 <- r1[5] ; r2 = *(r1+5)

st r1[6] <- r7 ; *(r1+6) = r7

my_label: -- dashdash also a comment

push r1 ; *sp = r1; sp --;

sub r1 <- r1 1 ; r1 -- ;

bnz r1 my_label ; if (r1 != 0) goto my_label



Simulating a Stack Machine...

- The **accumulator** is kept in register **r1**
 - This is just a convention. You could pick **r2**.
- The stack is kept in memory
- The stack **grows towards lower addresses**
 - Standard convention on the MIPS architecture
- The address of the next unused location on the stack is kept in register **sp**
 - The top of the stack is at address **sp + 1**
 - COOL-ASM “Word Size” = 1 = # of memory cells taken up by one integer/pointer/string

Cool Assembly Example

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

`acc <- 7`

`push acc`

`acc <- 5`

`acc <- acc + top_of_stack`

`pop`

`li r1 7`

`sw sp[0] <- r1`

`sub sp <- sp 1`

`li r1 5`

`lw r2 <- sp[1]`

`add r1 <- r1 r2`

`add sp <- sp 1`

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

Stack Instructions

- We have these COOL-ASM instructions:

push rX

```
st sp[0] <- rX
```

```
sub sp <- sp 1
```

pop rX

```
ld rX <- sp[1]
```

```
add sp <- sp 1
```

; Note:

rX <- top

```
ld rX <- sp[1]
```

A Small Language

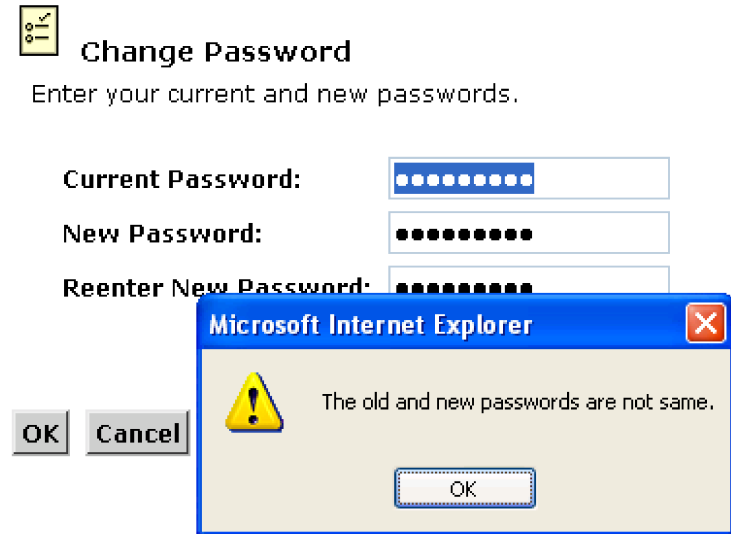
- A source language with integers and integer operations

$P \rightarrow D; P \mid D$

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

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

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



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:

```
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 COOL-ASM code that:
 - Computes the value of e in $r1$ (accumulator)
 - 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(123) = li r1 123

- Note that this also preserves the stack, as required



Code Generation: Add

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

$\text{cgen}(e_1)$

push r1

$\text{cgen}(e_2)$

;; e2 now in r1

pop t1

add r1 t1 r1

t1 is some
unused
“temporary”
register

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

Code Generation Mistake

- Unsafe Optimization: put the result of e_1 directly in $t1$?

```
cgen( $e_1 + e_2$ ) =  
  cgen( $e_1$ )  
  mov t1 <- r1  
  cgen( $e_2$ )  
  add r1 <- t1 r1
```

- 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 tree walk** of the AST
 - At least for expressions

Code Generation: Sub

- New instruction: `sub reg1 <- reg2 reg3`
 - Implements $reg_1 \leftarrow reg_2 - reg_3$

cgen(e₁ - e₂) =

`cgen(e1)`

`push r1`

`cgen(e2)`

`pop t1`

`sub r1 <- t1 r1`



Code Generation: If

- We need flow control instructions
- New instruction: **beq reg₁ reg₂ label**
 - **Conditional Branch** to label if $reg_1 = reg_2$
- New instruction: **jmp label**
 - **Unconditional Jump** to label

Code Generation for If (Cont.)

```
cgen(if  $e_1 = e_2$  then  $e_3$  else  $e_4$ ) =  
  cgen( $e_1$ )  
  push r1  
  cgen( $e_2$ )  
  pop t1  
  beq r1 t1 true_branch ;; else fall through  
  cgen( $e_4$ )  
  jmp end_if  
true_branch:  
  cgen( $e_3$ )  
end_if:
```

The Activation Record

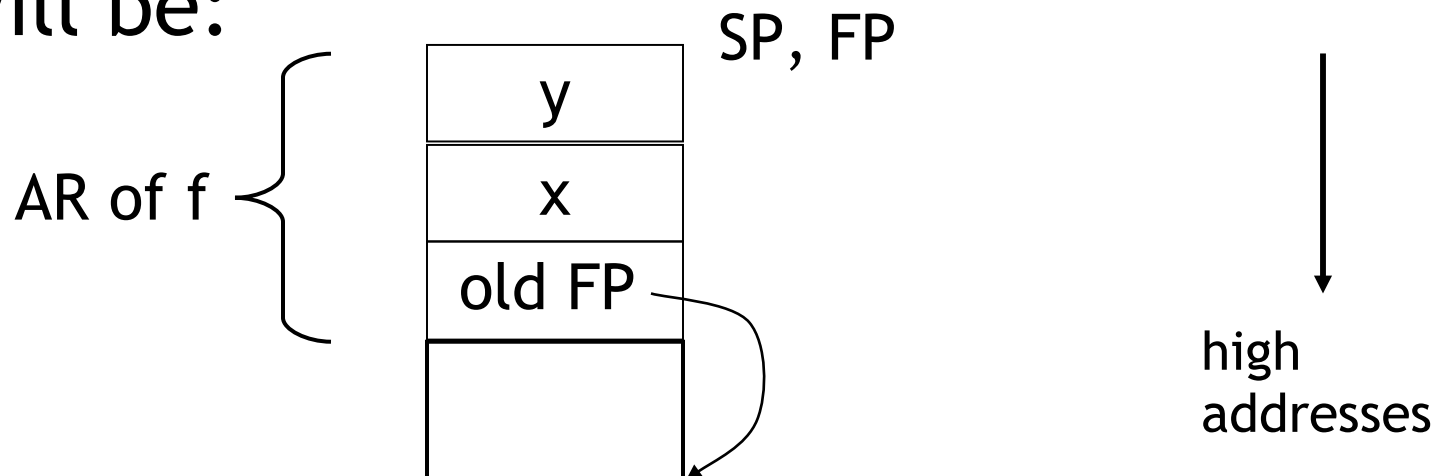
- An **activation record** (or **stack frame**) stores calling context information on the stack during a function call.
- Code for function calls/definitions depends on the layout of the activation record
- A very simple AR suffices for this language:
 - The result is always in the accumulator
 - No need to store the result in the AR
 - The activation record holds actual parameters
 - For $f(x_1, \dots, x_n)$ push x_1, \dots, x_n on the stack
 - These are the only variables in this language

Calling Convention

- This **calling convention** (or **stack discipline**) guarantees that on function exit **sp** is the same as it was on 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: Function Call

- The **calling sequence** is the instructions (of both caller and callee) to set up a function invocation
- New instruction: **call 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
 - (This is also called “branch and link”.)

Code Generation: Function Call

cgen(f(e₁,...,e_n)) =

push fp

cgen(e₁)

push r1

...

cgen(e_n)

push r1

call f_entry

pop fp

- The caller saves its value of the frame pointer
- Then it saves the actual arguments in order
- The caller saves the return address in register **ra**
- The AR so far is **n+1** bytes long
- Caller restores **fp**

Code Generation: Function Def

- New instruction: **return**
 - Jump to address in register **ra**

cgen(def f(x₁,...,x_n) = e) =

f_entry:

mov fp <- sp

push ra

cgen(e)

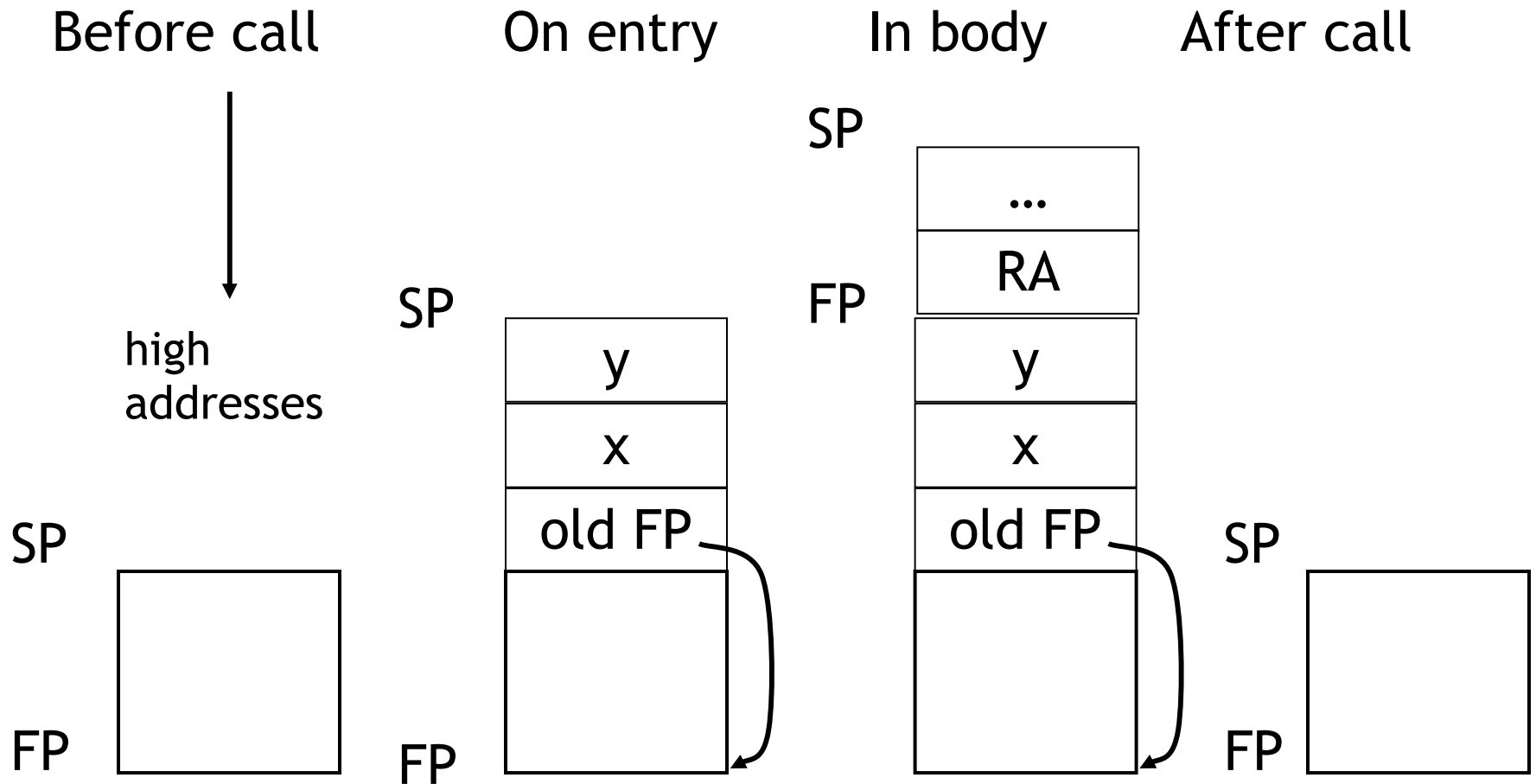
ra <- top

add sp <- sp z

return

- 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 = n + 2** (so far)

Calling Sequence: $f(x,y)$



Code Generation: Variables

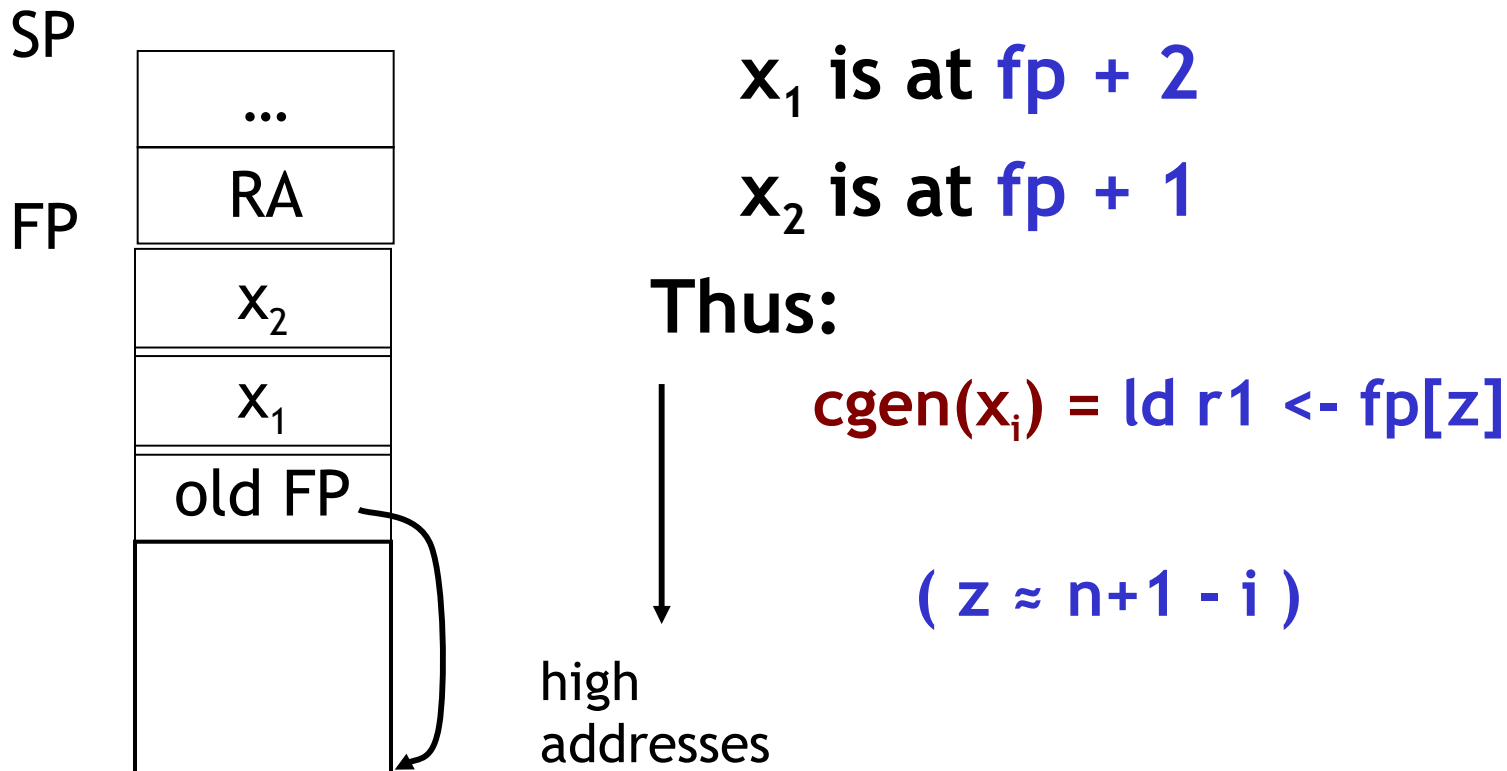
- Variable references are the last construct
- The “variables” of a function are just its parameters
 - They are all in the AR
 - Pushed by the caller
- Problem: Because the stack grows when intermediate results are saved, the variables are not at a fixed offset from `sp`
 - Impress me: what are they a fixed offset from?

Code Generation: Variables

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

Code Generation: Variables

- Example: For a function `def f(x1,x2) = e` the activation and frame pointer are set up as follows:



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)

More Information

- use cool --asm hello-worl.cl for examples
- 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

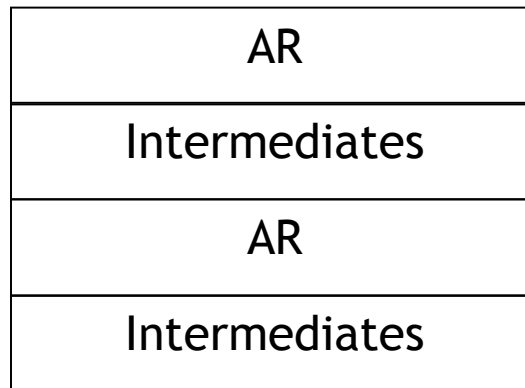


Optimization: Allocating Temporaries in the Activation Record



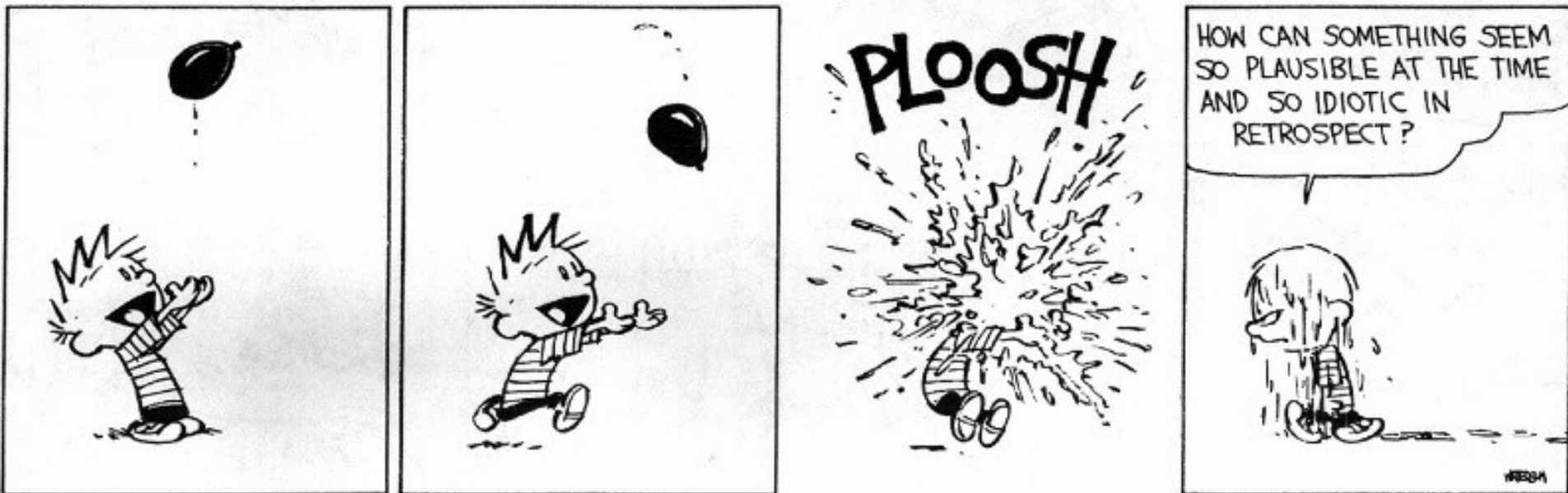
Review

- The stack machine code layout we've described so far has activation records and intermediate results interleaved on the stack



Stack Machine Implications

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



A Better Way

- Idea: Keep temporaries in the AR
- Work: The code generator must assign space in the AR for each temporary



Example

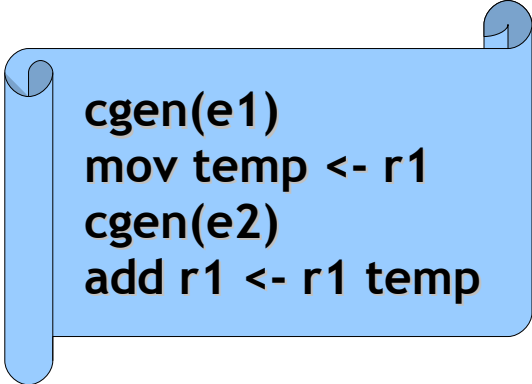
```
def fib(x) = if x = 1 then 0 else  
            if x = 2 then 1 else  
            fib(x - 1) + fib(x - 2)
```

- We must determine:
 - 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 eval e

- Example: $NT(e_1 + e_2)$



```
cgen(e1)
mov temp <- r1
cgen(e2)
add r1 <- r1 temp
```

- 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 NumTemps Equations

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

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

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

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

$$\text{NT}(\text{id}(e_1, \dots, e_n)) = \max(\text{NT}(e_1), \dots, \text{NT}(e_n))$$

$$\text{NT}(\text{int}) = 0$$

$$\text{NT}(\text{id}) = 0$$

Is this bottom-up or top-down? (you tell me)

What is $\text{NT}(\dots\text{code for fib}\dots)$?

The Revised AR

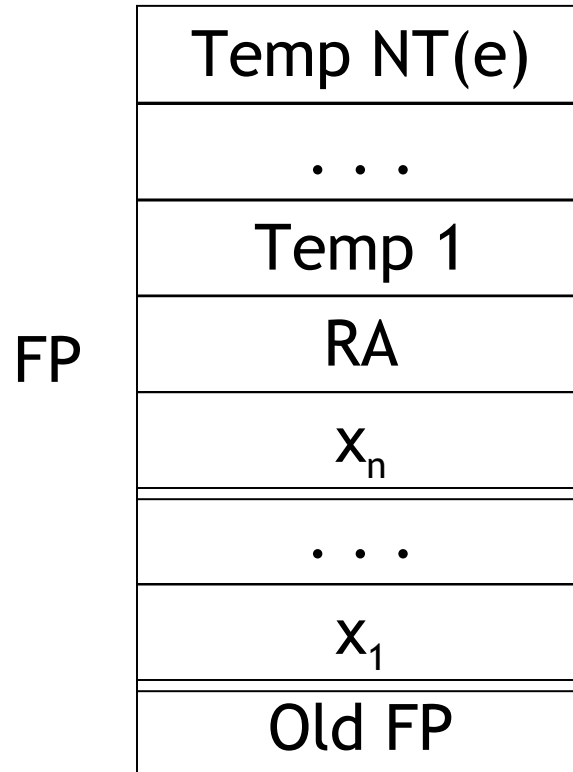
- For a function definition $f(x_1, \dots, x_n) = e$ the AR has $2 + n + NT(e)$ elements (so far)
 - Return address
 - Frame pointer
 - n arguments
 - $NT(e)$ locations for intermediate results



Stack Frame Picture

$$f(x_1, \dots, x_n) = e$$

SP



FP

high
addresses

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 +

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

$\text{cgen}(e_1)$

push r1

$\text{cgen}(e_2)$

pop temp

add r1 <- r1 temp

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

$\text{cgen}(e_1, nt)$

st fp[-nt] <- r1

$\text{cgen}(e_2, nt+1)$

ld temp <- fp[-nt]

add r1 <- r1 temp

Where are the savings?

Hint: “push” is more expensive than it looks.

Notes

- The temporary area is used like a small, fixed-size stack
- Exercise: Write out `cgen` for other constructs
- Hint: on function entry, you'll have to increment something by $NT(e)$
 - ... and on function exit, decrement it ...

Code Generation for Object-Oriented Languages



Object Layout

- OO implementation =
 - Stuff from before + More stuff
- **Liskov Substitution Principle**: 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 **must work unmodified** on 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 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 becomes `self` and the fields are the object's attributes

Cool Object Layout

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

	<i>Offset</i>
Class Type Tag	0
Object Size	1
Dispatch / Vtable Ptr	2
Attribute 1	3
Attribute 2	4
...	

(This is a convention that we made up, but it is similar to how Java and C++ lay things out. For example, you could swap #1 and #2 without loss.)

Cool Object Layout

- **Class tag** (or “**type tag**”) is a raw integer
 - Identifies class of the object (Int=1, Bool=2, ...)
- **Object size** is an integer
 - Size of the object in words
- **Dispatch pointer** (or “**vtable pointer**”) is a pointer to a table of methods
 - More later
- **Attributes** are laid out in subsequent slots
- The layout is contiguous

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 }; // Override
```

```
  g(): Int { a <- a - b };
```

```
};
```

```
Class C inherits A {
```

```
  c: Int <- 3;
```

```
  h(): Int { a <- a * c };
```

```
};
```

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

Subclass Layout

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**

(i.e., append new fields at bottom)

Leaves the layout of **A** unchanged

(**B** is an extension)

Object Layout Picture

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

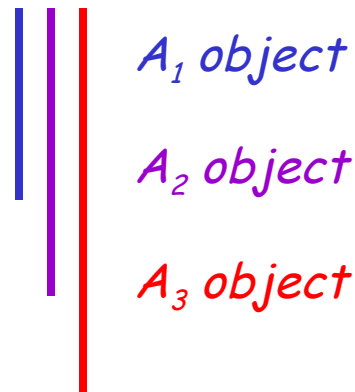
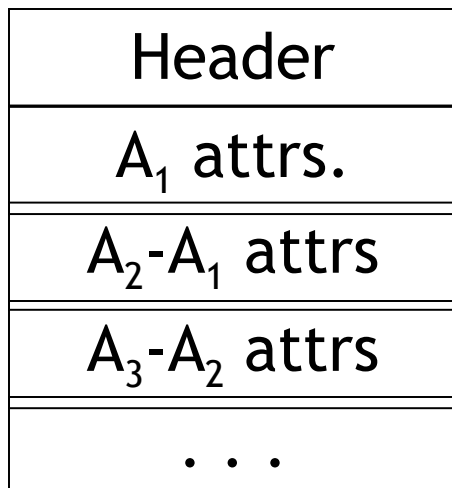
```
Class B inherits A {  
  b: Int <- 2;  
  f(): Int { a }; // Override  
  g(): Int { a <- a - b };  
};
```

Class	A	B	C
Offset			
0 (tag)	Atag	Btag	Ctag
1 (size)	5	6	6
2 (vtable)	*	*	*
3 (attr#1)	a	a	a
4 ...	d	d	d
5		b	c

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

Subclasses (Cont.)

- The **offset for an attribute** is the **same** in a class and all of its subclasses
 - This choice allows any method for an A_1 to be used on a subclass A_2
- Consider layout for $A_n \leq \dots \leq A_3 \leq A_2 \leq A_1$



*Extra Credit:
What about
multiple
inheritance?*

Dynamic Dispatch

- Consider **f** and **g**:

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

```
Class B inherits A {  
  b: Int <- 2;  
  f(): Int { a }; // Override  
  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** (or **virtual function table** or **vtable**) indexes these methods
 - A vtable is an array of method entry points
 - (Thus, a vtable is an array of function pointers.)
 - A method **f** lives at a **fixed offset** in the dispatch table for a class **and all of its subclasses**

Dispatch Table Example

Class	A	B	C
Offset			
0	f_A	f_B	f_A
1		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
 - (i.e., offset 0 here)

Using Dispatch Tables

- The dispatch pointer in an object of class X points to the dispatch table for class X
 - i.e., all objects of class X **share** one table
- Every method f of class X is assigned an offset O_f in the dispatch table at compile time
 - i.e., by you in PA6 when you're generating the assembly code

A Sense of Self

- Every method must know what object is “self”
 - Convention: **“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 $D[O_f](x)$
 - D is the dispatch table for x
 - In the call, **self** is bound to x

Dynamic Dispatch Hint

- To reiterate: objexp.mname(arg1)
 - push self
 - push fp
 - cgen(arg1)
 - push r1 ; push arg1
 - cgen(objexp)
 - bz r1 dispatch_on_void_error
 - push r1 ; will be “self” for callee
 - ld temp <- r1[2] ; temp <- vtable
 - ld temp <- temp[X] ; X is offset of mname in vtables
 - ; for objects of typeof(objexp)
 - call temp
 - pop fp
 - pop self

“Extra Credit”: Multiple Inheritance



Example

- Assume that we extend Cool with multiple inheritance
- Consider the following 3 classes:

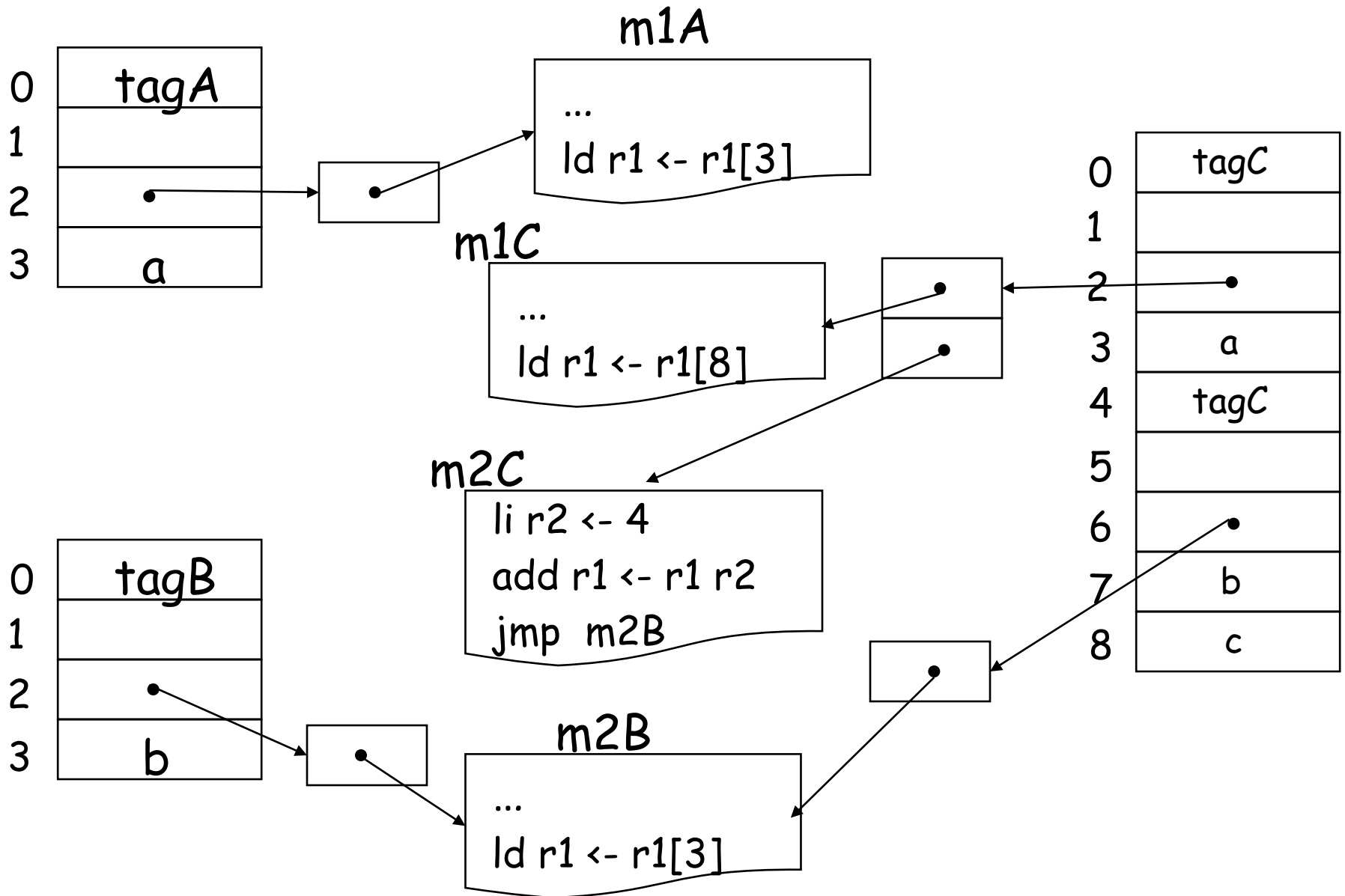
```
Class A { a : Int; m1() : Int { a }; }
```

```
Class B { b: Int; m2() : Int { b }; }
```

```
Class C inherit A, B { c : Int; m2() : Int { c }; }
```

- class C inherits attribute a and method m1 from A, attribute b from B and overrides m2

Multi-Inherit Object Layout



Homework

- PA3 (Parsing) Due
- WA3 Due
- Compilers: PA6c Due Next Week