# Code Generation II

FEBRUARY 6, 2014

# 3-Address Code

Abstraction of assembly code.

Similar enough to allow certain optimizations.

- E.g. `push r0; pop r0` can be dropped

Abstract enough to target different hardware.

- E.g. gcc uses the same front-end for all target platforms

# 3-Address Code

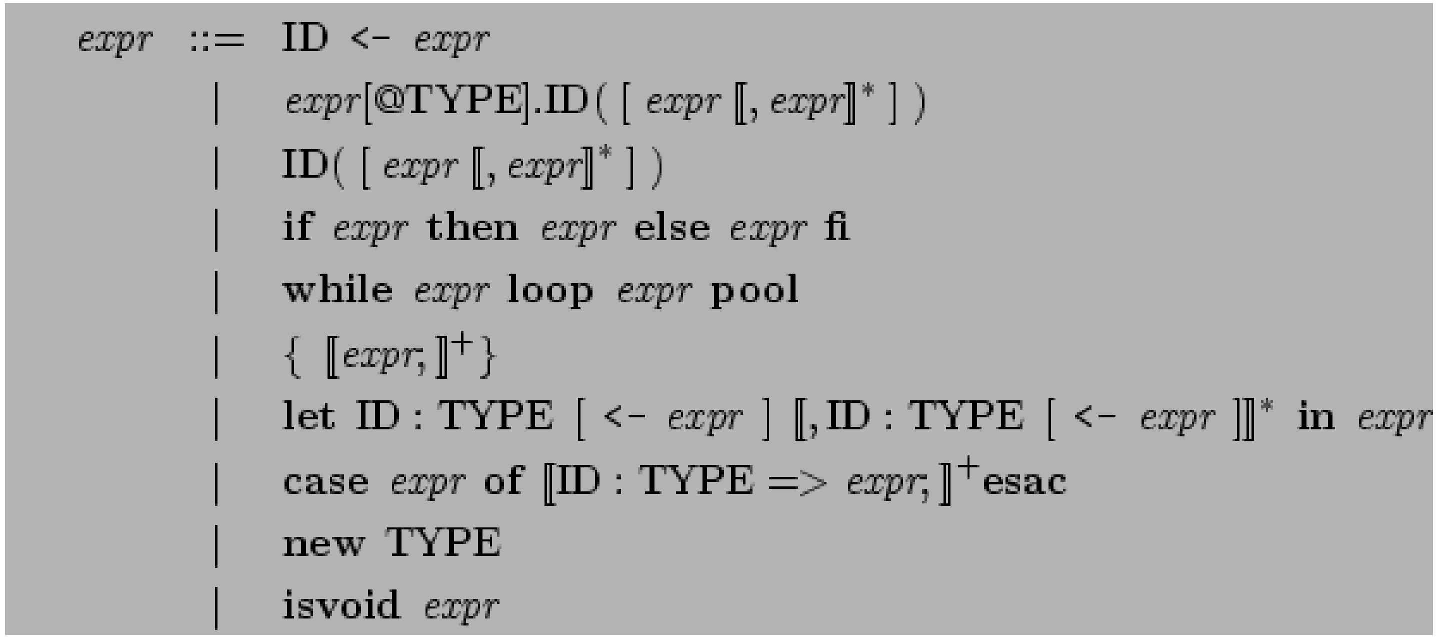
```
x := y ⊙ z
x := ⊙ y
x := y
x[i] := y
x := y[i]
if x ⊙ y goto z
goto x
```

Up to ***three addresses*** per statement.

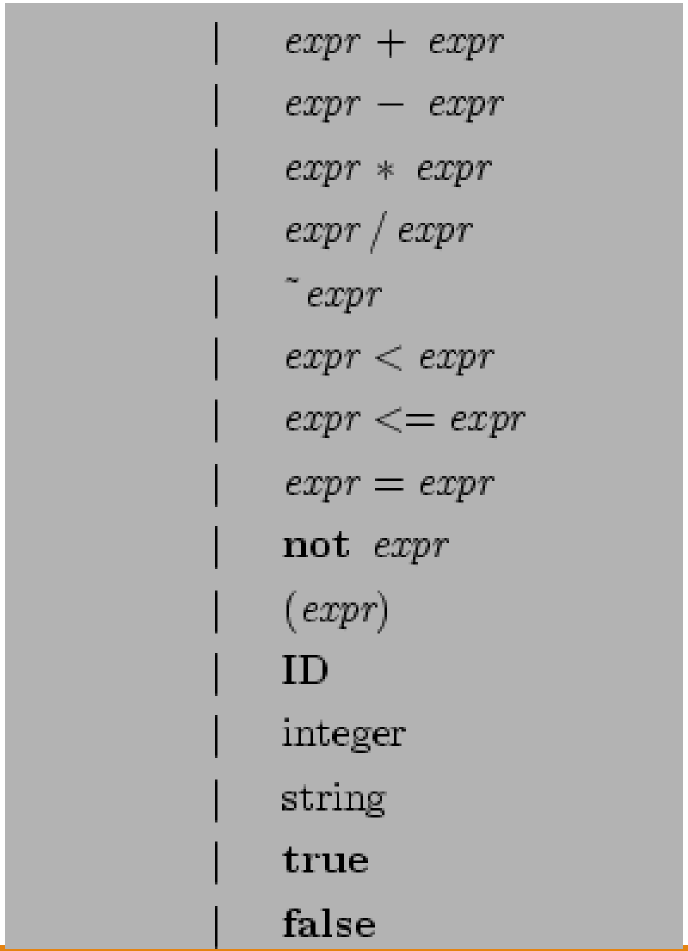
Addresses may store ***operands*** or ***results***.

“Addresses” may be ***constants***, ***registers***, ***symbol names***, or ***labels***.

# Code Generation for Expressions

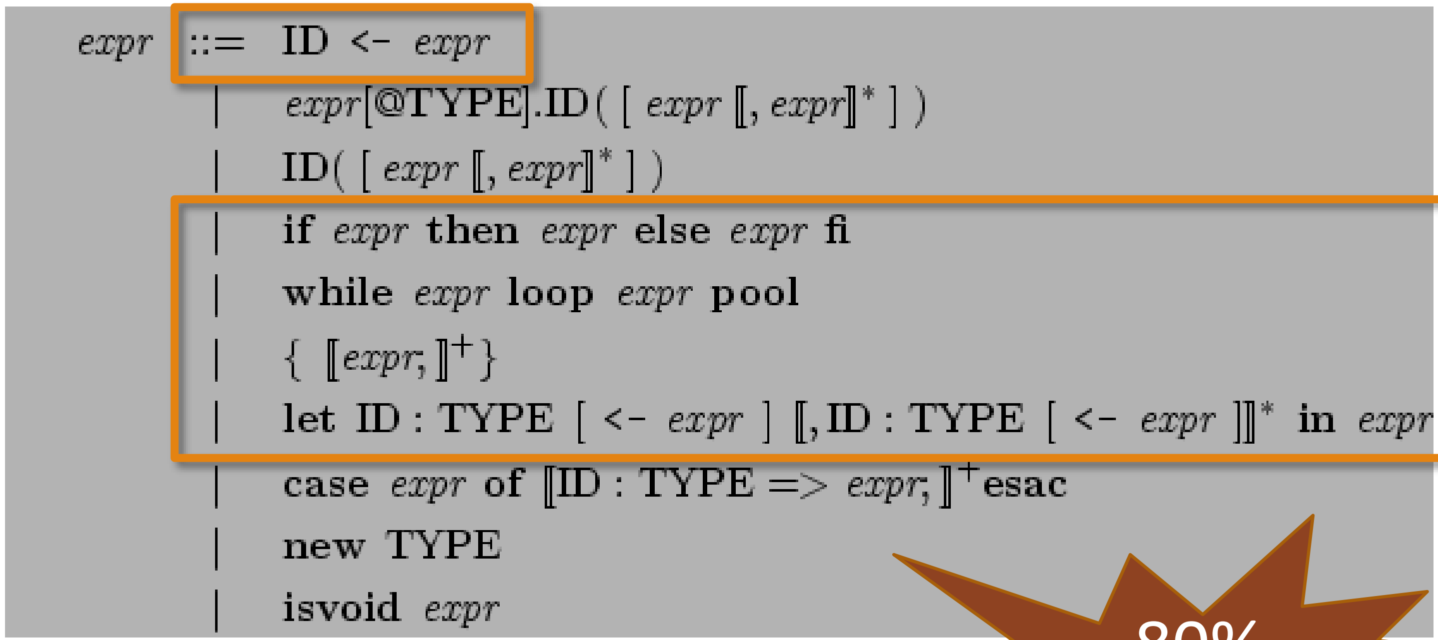


```
expr ::= ID <- expr
       | expr[@TYPE].ID( [ expr ⟦, expr⟧* ] )
       | ID( [ expr ⟦, expr⟧* ] )
       | if expr then expr else expr fi
       | while expr loop expr pool
       | { ⟦expr; ⟧+}
       | let ID : TYPE [ <- expr ] ⟦,ID : TYPE [ <- expr ]⟧* in expr
       | case expr of ⟦ID : TYPE => expr; ⟧+esac
       | new TYPE
       | isvoid expr
```

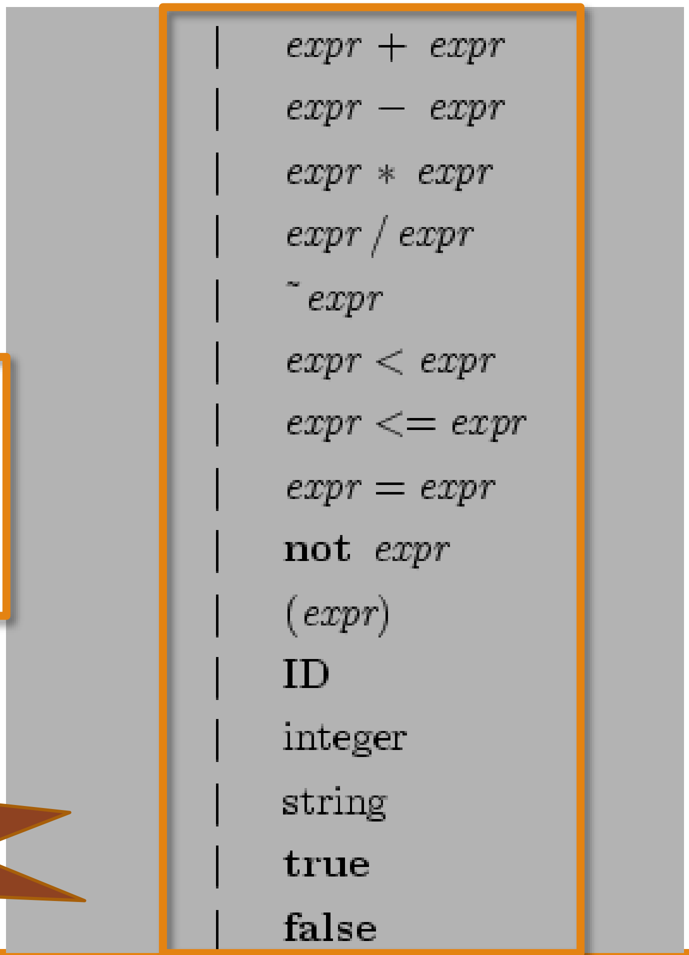


```
       | expr + expr
       | expr − expr
       | expr ∗ expr
       | expr / expr
       | ~expr
       | expr < expr
       | expr <= expr
       | expr = expr
       | not expr
       | (expr)
       | ID
       | integer
       | string
       | true
       | false
```

# Code Generation For Expressions



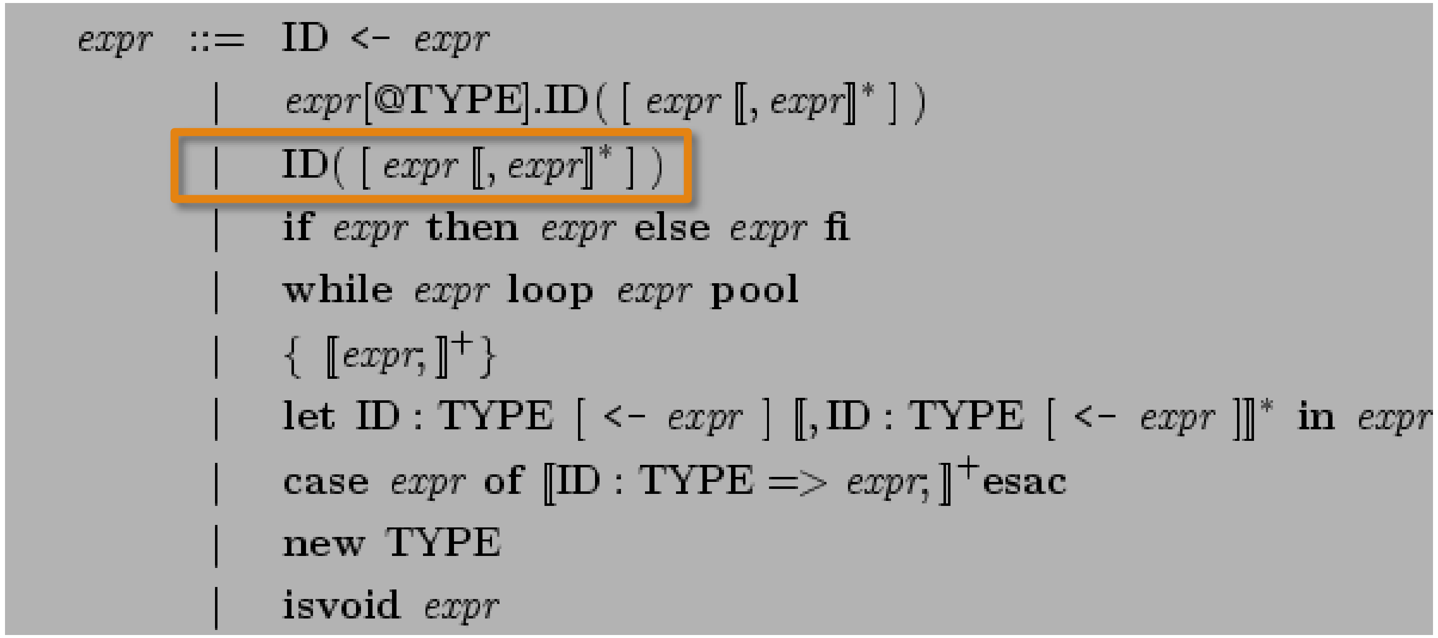
```
expr ::= ID <- expr
       | expr[@TYPE].ID( [ expr [[, expr]]* ] )
       | ID( [ expr [[, expr]]* ] )
       | if expr then expr else expr fi
       | while expr loop expr pool
       | { [[expr; ]]+ }
       | let ID : TYPE [ <- expr ] [[,ID : TYPE [ <- expr ]]]* in expr
       | case expr of [[ID : TYPE => expr; ]]+ esac
       | new TYPE
       | isvoid expr
```



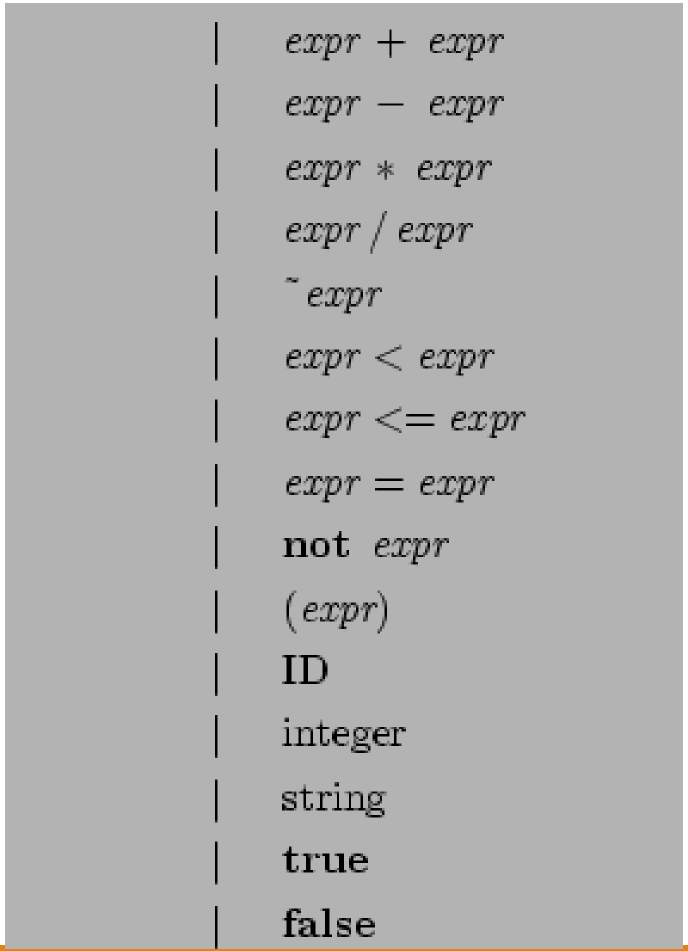
```
       | expr + expr
       | expr − expr
       | expr ∗ expr
       | expr / expr
       | ˜expr
       | expr < expr
       | expr <= expr
       | expr = expr
       | not expr
       | (expr)
       | ID
       | integer
       | string
       | true
       | false
```

80% Complete!

# Function Calls



```
expr ::= ID <- expr
       | expr[@TYPE].ID( [ expr ⟦, expr⟧* ] )
       | ID( [ expr ⟦, expr⟧* ] )
       | if expr then expr else expr fi
       | while expr loop expr pool
       | { ⟦expr; ⟧+}
       | let ID : TYPE [ <- expr ] ⟦,ID : TYPE [ <- expr ]⟧* in expr
       | case expr of ⟦ID : TYPE => expr; ⟧+esac
       | new TYPE
       | isvoid expr
```

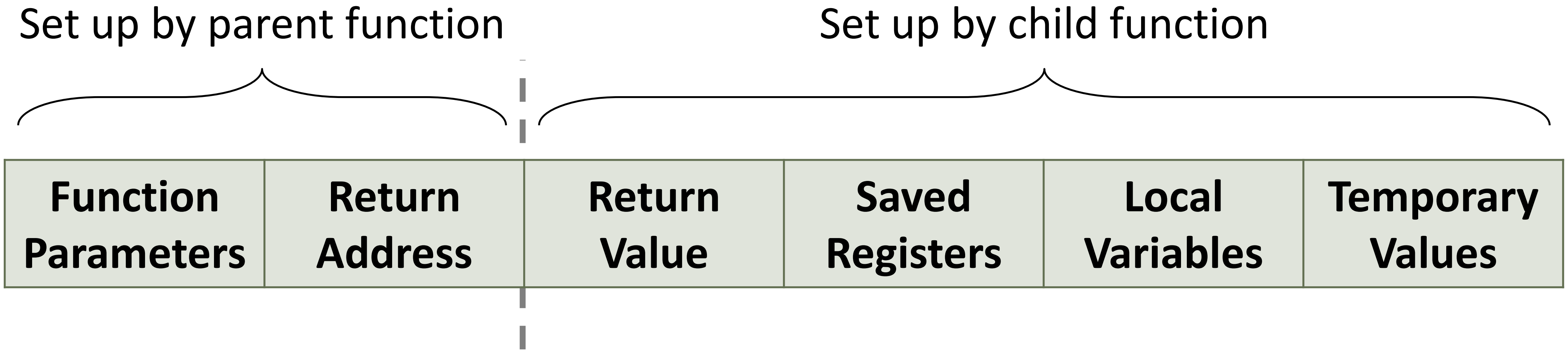


```
       | expr + expr
       | expr − expr
       | expr ∗ expr
       | expr / expr
       | ~expr
       | expr < expr
       | expr <= expr
       | expr = expr
       | not expr
       | (expr)
       | ID
       | integer
       | string
       | true
       | false
```

# Activation Records

Memory allocation for a single function call.

Also known as ***call frames*** or ***stack frames***.



| Set up by parent function | | Set up by child function | | | |
|---|---|---|---|---|---|
| **Function Parameters** | **Return Address** | **Return Value** | **Saved Registers** | **Local Variables** | **Temporary Values** |

# Activation Records

| **Function Parameters** | **Return Address** | **Return Value** | **Saved Registers** | **Local Variables** | **Temporary Values** |
|---|---|---|---|---|---|

The ***frame pointer*** identifies the start of the record.

- Typically set by callee based on stack pointer.

Some fields may be kept in registers.

- Cool: `ra` register for return addresses.
- x86_64 keeps (some) parameters and return value in registers.

# Calling Conventions

***Pre-*** and ***post-conditions*** for function calls.

- Specify how arguments are passed.
- Specify how to return the result.
- Specify which registers are unaffected by call.

# Which Calling Conventions to Use?

## COOL COMPILERS

- Cool's `call` instruction sets `ra`.
- Otherwise, it's entirely up to you.

## X86_64 COMPILERS

- x86_64's `call` instruction stores address on stack.
- Must be consistent to call external functions (e.g. `puts`).
- Refer to [x86_64 Machine Level Programming]().

# Function Call Example

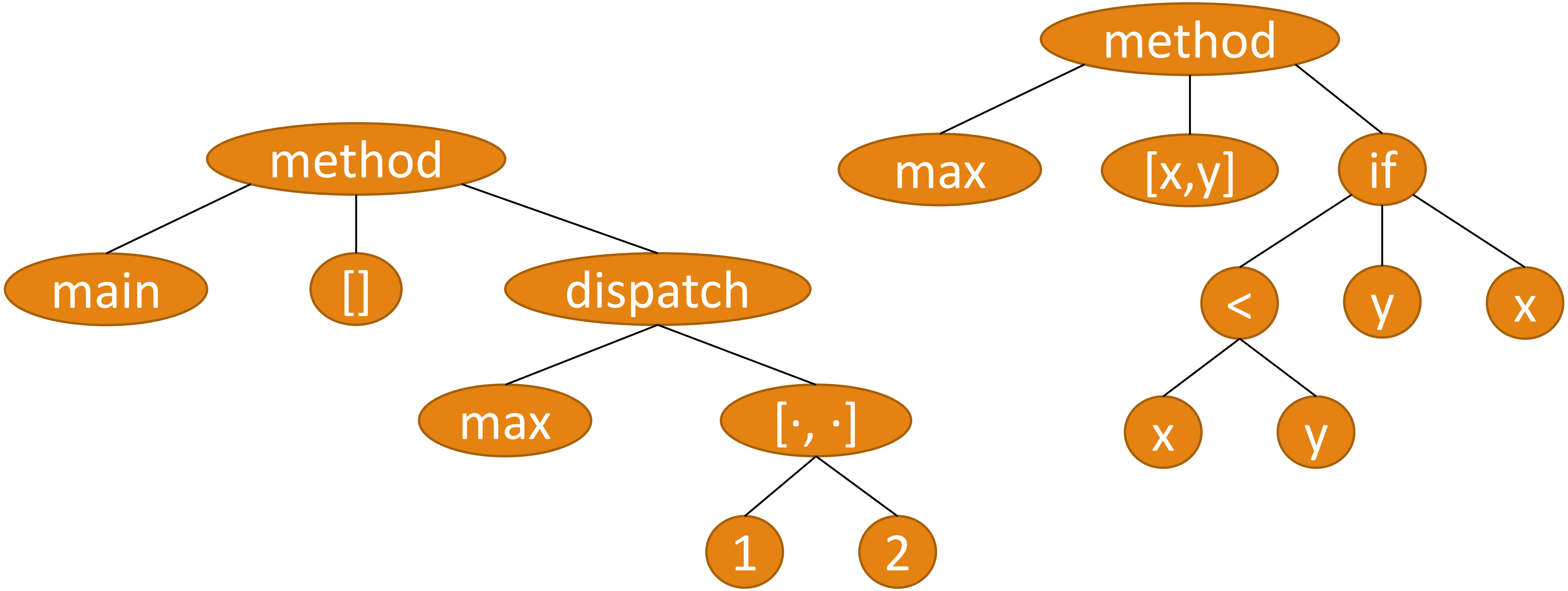
Cool virtual machine.

Calling conventions:

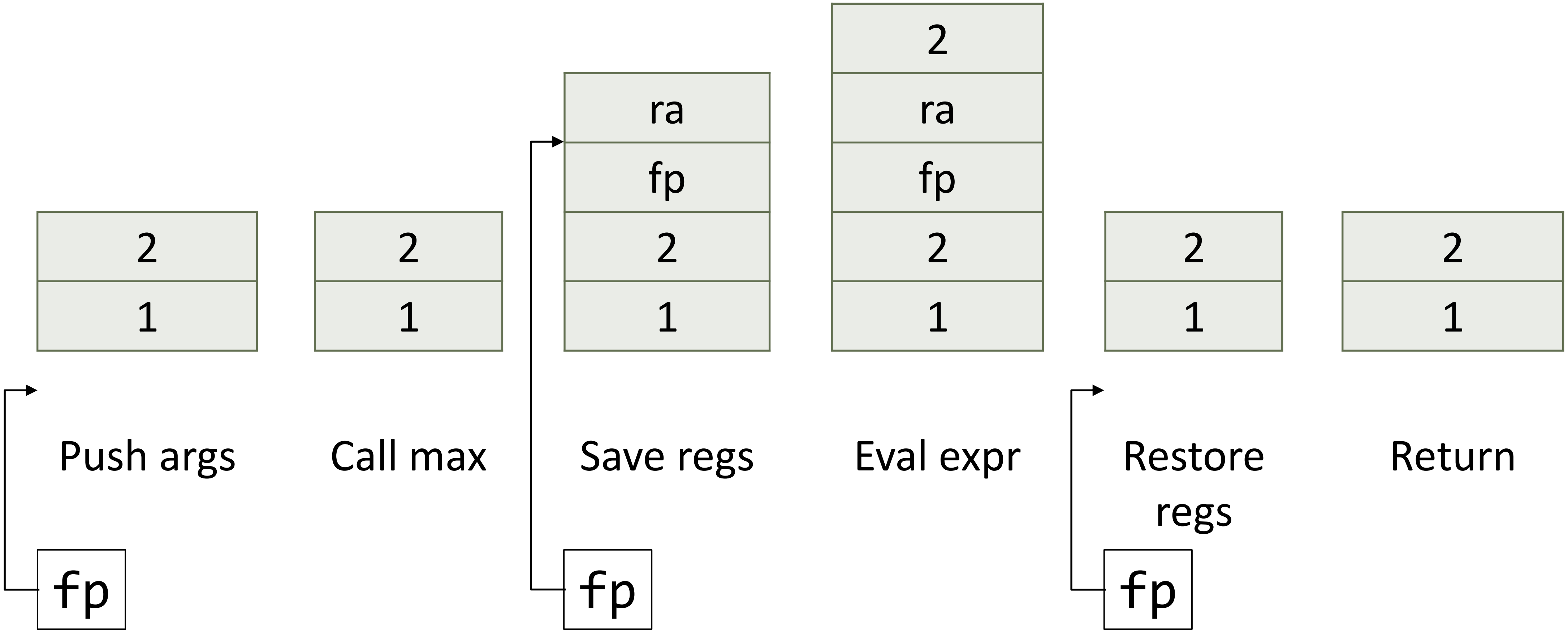
- Arguments are passed on stack. Arg 1 is below arg N.
- Return value in `r1`.
- All other registers are callee-saved.

```
max(Int x, Int y) : Int {
  if (x < y) then y else x fi
}
main() : Object {
  max(1,2)
}
```

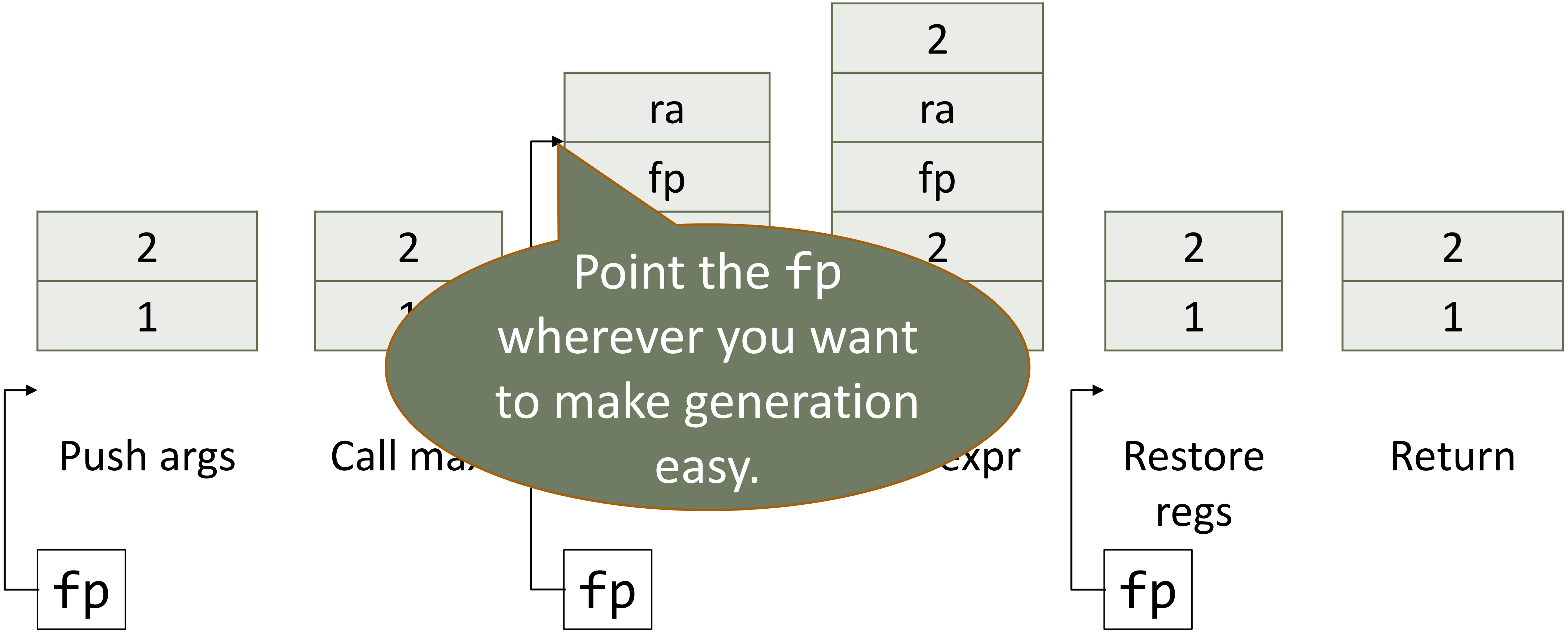
# Function Call Example: Syntax Trees



# Function Call Example: Stack Discipline



# Function Call Example: Stack Discipline



2
1
Push args
fp

2
1
Call ma

ra
fp
fp

2
ra
fp
2
xpr

2
1
Restore regs
fp

2
1
Return

Point the `fp` wherever you want to make generation easy.

# Closing Thoughts

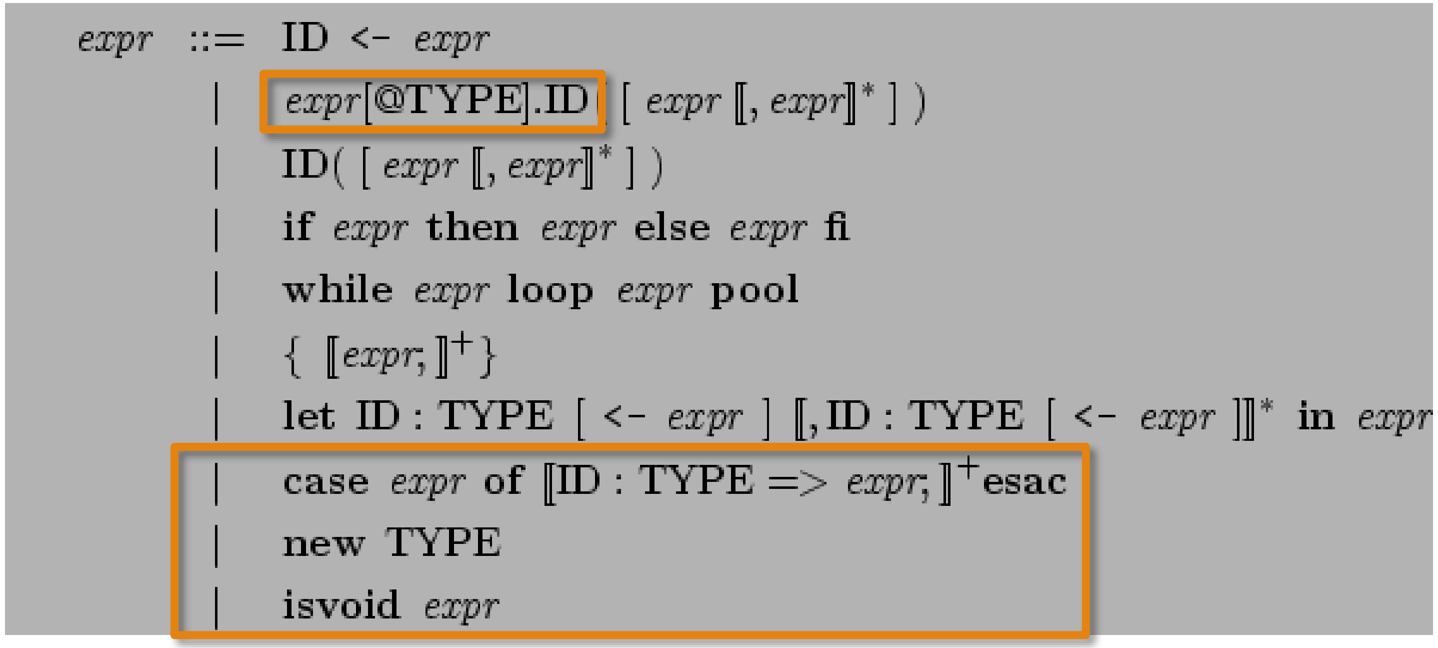
Simple functions (like `max`) do not need a stack frame.

- Avoids saving and restoring registers.
- Avoids updating and restoring `fp`.
- More complicated code generation.

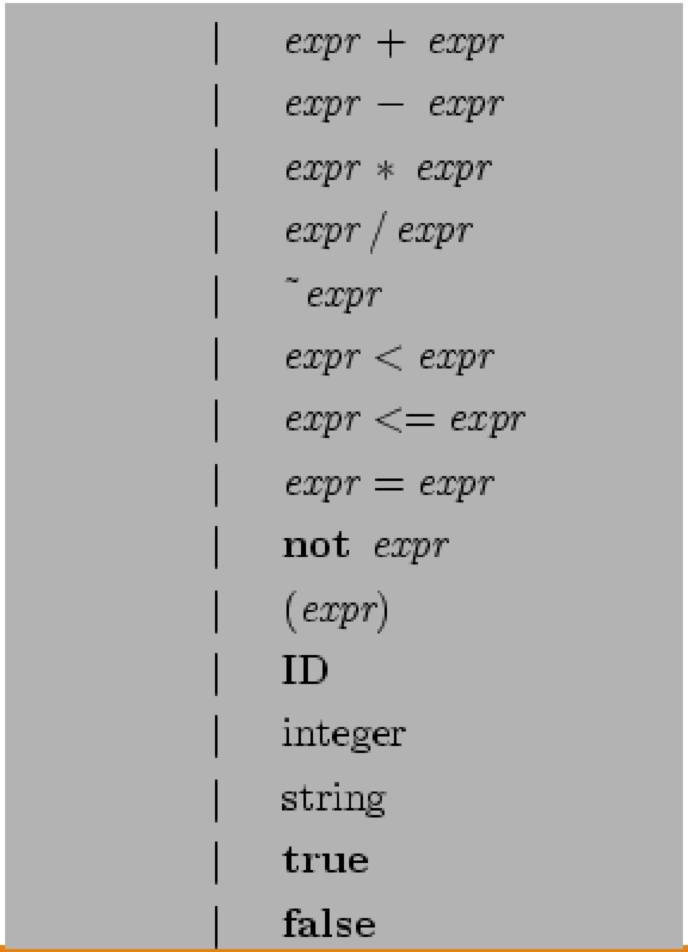
For performance, update `sp` once at start.

- Access temporaries and locals via explicit offsets from `fp`.

# Objects



```
expr ::= ID <- expr
       | expr[@TYPE].ID( [ expr [[, expr]]* ] )
       | ID( [ expr [[, expr]]* ] )
       | if expr then expr else expr fi
       | while expr loop expr pool
       | { [[expr; ]]+ }
       | let ID : TYPE [ <- expr ] [[,ID : TYPE [ <- expr ]]]* in expr
       | case expr of [[ID : TYPE => expr; ]]+esac
       | new TYPE
       | isvoid expr
```



```
       | expr + expr
       | expr − expr
       | expr ∗ expr
       | expr / expr
       | ~expr
       | expr < expr
       | expr <= expr
       | expr = expr
       | not expr
       | (expr)
       | ID
       | integer
       | string
       | true
       | false
```

# Implementation Considerations

How to lay out object in memory?

How to implement inheritance?

How to implement dynamic dispatch?

# Struct Layout

Lay out fields contiguously.

- Each field at fixed offset.

Insert padding where needed for ***alignment***.

| Field | Offset |
|---|---|
| Attribute 1 | 0 |
| Attribute 2 | 1 |
| … | … |
| Attribute N | N |

# Alignment?

Data may only be read from some subset of addresses.

On x86_64 address must be multiple of data size.

- 8-byte pointers must have address divisible by 8.
- 4-byte ints must have address divisible by 4.
- Object tend to have alignment of largest field.

Not a concern for Cool.

# Inheritance

***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.

The fields B inherits from A must have the same offsets.

| Field | Offset |
|---|---|
| Attribute A.1 | 0 |
| Attribute A.2 | 1 |
| … | … |
| Attribute A.N | N |
| Attribute B.1 | N+1 |
| Attribute B.2 | N+2 |
| … | … |

# Static Dispatch

Like function calls with two modifications:

1. Pass “self” as implicit parameter.
2. Place fields in “self” object into symbol table.

# Dynamic Dispatch

```
Class A {
  f(): Object {
    out_string(“A”)
  }
  g(): Object {
    f()
  }
}
```

```
Class B inherits A {
  f(): Object {
    out_string(“B”)
  }
}
```

# Dynamic Dispatch

What does `e.g()` print?

- If `e` is an A: “A”
- If `e` is a B: “B”

`g()` must work for ***both***.

Need to look up method label in object at ***run time***, not compile time.

How?

More fields.

# Implementing Dynamic Dispatch

Methods are same for all instances of class.

- Carrying copies of labels in all objects is redundant.

Instead use one ***virtual function table*** (vtable) per class instead.

| Object Layout | Offset |
|---|---|
| vtable | 0 |
| Attribute 1 | 1 |
| … | … |

| vtable Layout | Offset |
|---|---|
| Method 1 | 0 |
| … | … |

# Dynamic Dispatch Example

Calling conventions:

- Self object pointer passed on stack before arguments.
- Arguments passed on stack. Arg 1 is below arg N.
- Return value in r1.
- All other registers are callee saved.

| Dispatch Tables | | |
|---|---|---|
| Offset | A | B |
| 0 | A.f | B.f |
| 1 | A.g | A.g |

# Dynamic Dispatch Example

```
A.g:
    push ra
    ld r1 <- sp[1] ; get self obj
    push r1        ; pass self arg
    ld r1 <- r1[0] ; get vtable
    ld r1 <- r1[0] ; get f() label
    call r1
    ; return value now in r1
```

```
    pop ra ; self obj
    pop ra ; return addr
    return
```