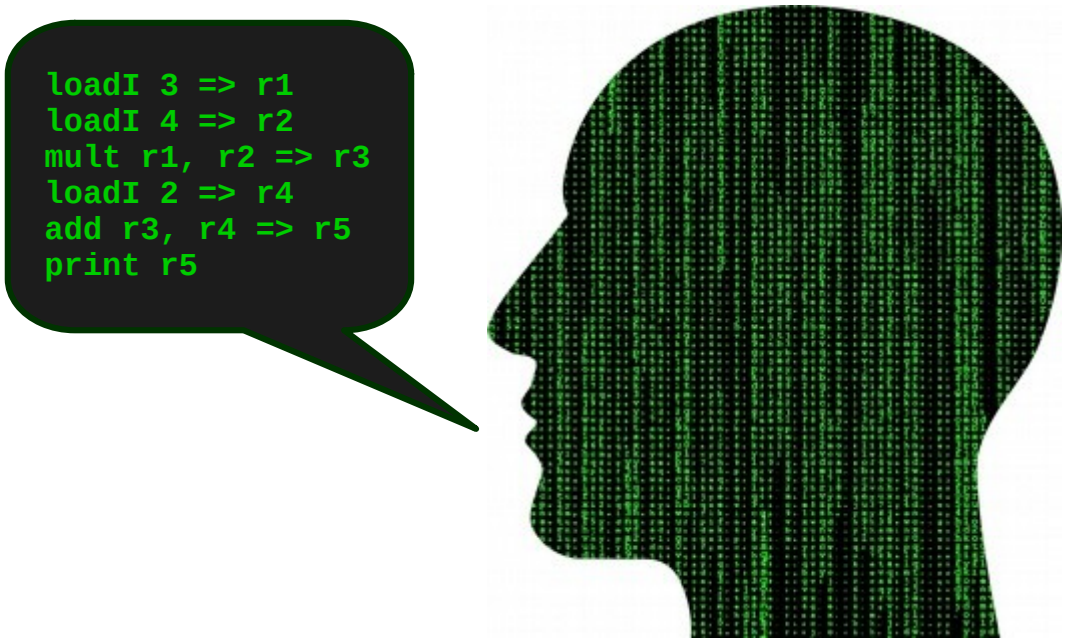
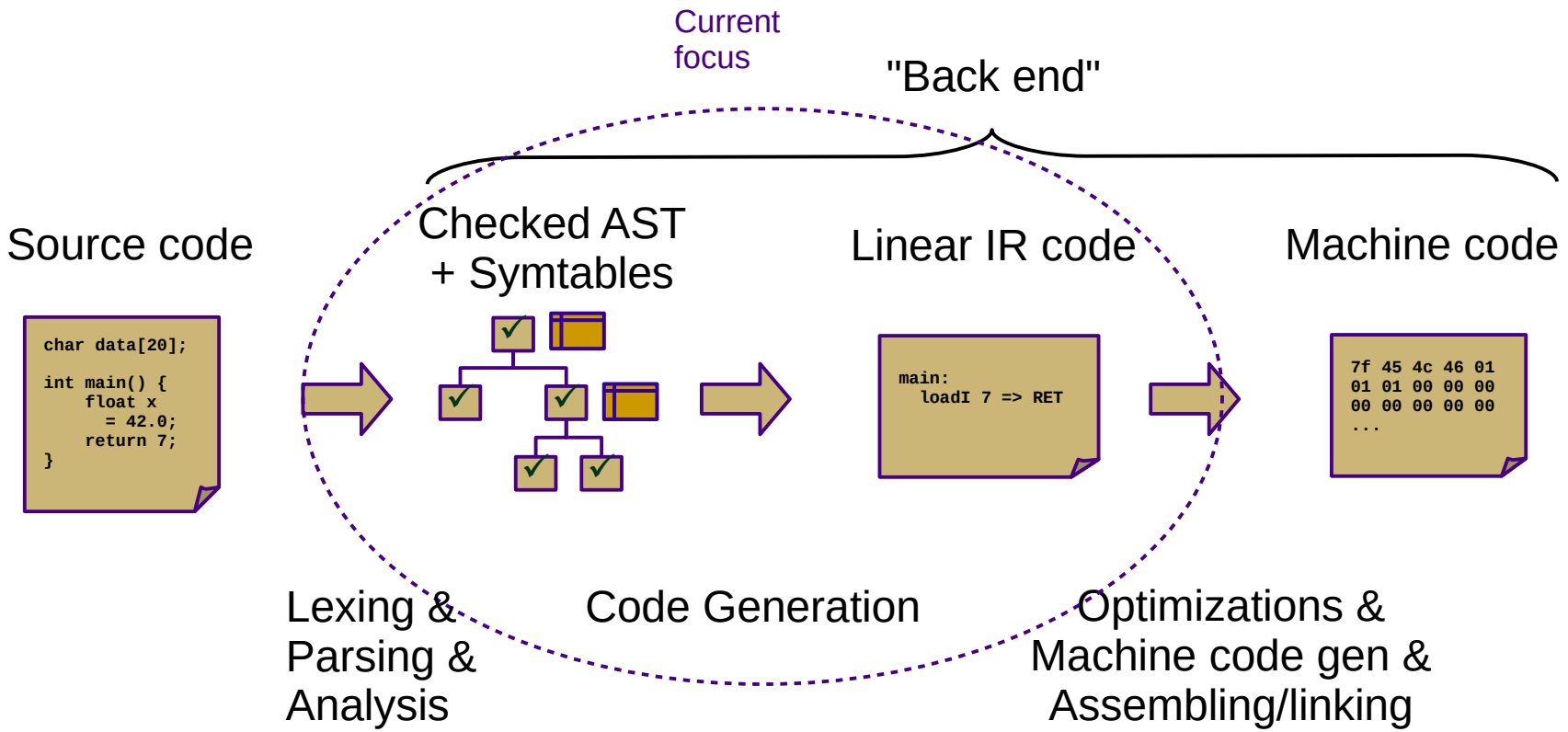
CS 432
Fall 2022

Mike Lam, Professor



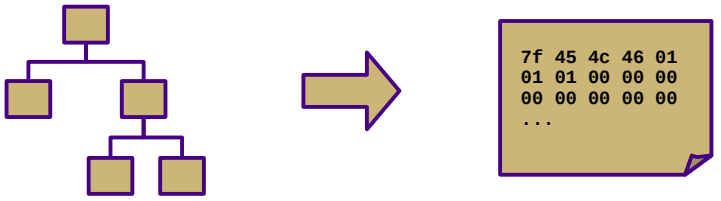
Code Generation

Compilers


Current
focus
"Back end"
Source code
Checked AST
+ Symtables
Linear IR code
Machine code
char data[20];
int main() {
float x
= 42.0;
return 7;
}
main:
loadI 7 => RET
7f 45 4c 46 01
01 01 00 00 00
00 00 00 00 00
...
Lexing &
Parsing &
Analysis
Code Generation
Optimizations &
Machine code gen &
Assembling/linking

Compilers

- Current status: type-checked AST
- Next step: convert to ILOC
  - This step is called *code generation*
  - Convert from a tree-based IR to a linear IR
    - Or directly to machine code (uncommon)
    - Use a tree traversal to “linearize” the program



Goals

- Linear codes
  - Stack code (`push a, push b, multiply, pop c`)
  - Three-address code (`c = a + b`)
  - Machine code (`movq a, %eax; addq b, %eax; movq %eax, c`)
- Code generator requirements
  - Must preserve semantics
  - Should produce efficient code
  - Should run efficiently

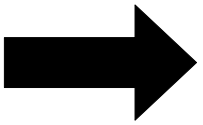
Obstacles

- Generating **optimal** code is undecidable
  - Unlike front-end transformations
    - (e.g., lexing & parsing)
  - Must use heuristics and approximation algorithms
    - **Systems design involves trade-offs** (e.g., speed for code size)
    - Sometimes “best” choice depends on target architecture (ISA, cache sizes, etc.)
  - This is why most compilers research since 1960s has been on the back end

ILOC

- Linear IR based on research compiler from Rice
- “Intermediate Language for an Optimizing Compiler”

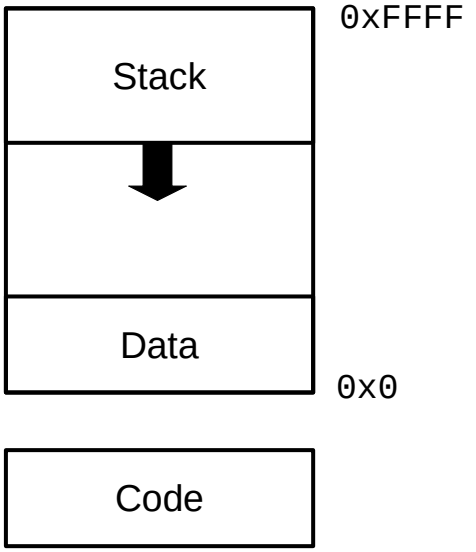
```
def int main()
{
    return 3+4;
}
```



```
main:
  loadI 3 => r0
  loadI 4 => r1
  add r0, r1 => r2
  i2i r2 => RET
  return
```

ILOC

- Simple von Neumann architecture
  - Not an actual hardware architecture, but useful for teaching
  - 64-bit words w/ 64K address space
  - Read-only code region indexed by instruction
  - Unlimited 64-bit integer virtual registers (r1, r2, …)
  - Four special-purpose registers:
    - IP: instruction pointer
    - SP: stack pointer
    - BP: base pointer
    - RET: return value



ILOC

- See Appendix A (and P4 code/documentation)
- I have made some modifications to simplify P4
  - Removed most immediate instructions (i.e., `subI`)
  - Removed binary shift instructions
  - Removed character-based instructions
  - Removed jump tables
  - Removed comparison-based conditional jumps
  - Added stack operations `push` and `pop`
  - Added labels and function call instructions `call` and `return`
  - Added binary `not` and arithmetic `neg`
  - Added `print` and `nop` instructions

ILOC

Form	Op1	Op2	Op3	Comment
Integer Arithmetic				
add op1, op2 => op3	reg	reg	reg	addition
sub op1, op2 => op3	reg	reg	reg	subtraction
mult op1, op2 => op3	reg	reg	reg	multiplication
div op1, op2 => op3	reg	reg	reg	division
addI op1, op2 => op3	reg	imm	reg	addition w/ constant
multI op1, op2 => op3	reg	imm	reg	multiplication w/ constant
neg op1 => op2	reg	reg		arithmetic negation
Boolean Arithmetic				
and op1, op2 => op3	reg	reg	reg	boolean AND
or op1, op2 => op3	reg	reg	reg	boolean OR
not op1 => op2	reg	reg		boolean NOT
Data Movement				
i2i op1 => op2	reg	reg		register copy
loadI op1 => op2	imm	reg		load integer constant
load [op1] => op2	reg	reg		load from address
loadAI [op1+op2] => op3	reg	imm	reg	load from base + immediate
loadAO [op1+op2] => op3	reg	reg	reg	load from base + offset
store op1 => [op2]	reg	reg		store to address
storeAI op1 => [op2+op3]	reg	reg	imm	store to base + immediate
storeAO op1 => [op2+op3]	reg	reg	reg	store to base + offset
push op1	reg			push onto stack
pop op1	reg			pop from stack

ILOC

Comparison				
cmp_LT op1, op2 => op3	reg	reg	reg	less-than comparison
cmp_LE op1, op2 => op3	reg	reg	reg	less-than-or-equal-to comparison
cmp_EQ op1, op2 => op3	reg	reg	reg	equality comparison
cmp_GE op1, op2 => op3	reg	reg	reg	greater-than-or-equal-to comparison
cmp_GT op1, op2 => op3	reg	reg	reg	greater-than comparison
cmp_NE op1, op2 => op3	reg	reg	reg	inequality comparison
Control Flow				
label (“op1:”)	lbl			control flow label
jump op1	lbl			unconditional branch
cbr op1 => op2, op3	reg	lbl	lbl	conditional branch
call	fun			call function
return				return to caller
Miscellaneous				
print	reg			print integer to standard out
print	str			print string to standard out
nop				no-op (do nothing)
phi	reg	reg	reg	φ-function (for SSA only)

x86-64:

```
cmpq %r2, %r1
jl L1
jmp L2
```

ILOC:

```
cmp_LT r1, r2 => rE
cbr rE => L1, L2
```

Syntax-Directed Translation

- Similar to attribute grammars (Figure 4.15)
- Create code-gen routine for each production
  - Each routine generates code based on a template
  - Save intermediate results in temporary registers
- In our project, we will use a visitor
  - Still syntax-based (actually AST-based)
  - Not dependent on original grammar
  - Generate code as a synthesized attribute ("`code`")
  - Save temporary registers as another attribute ("`reg`")
  - Operational semantics rules describe this process formally

$$\text{SBlock}\ \frac{s_1 \rightarrow C_1 \quad s_2 \rightarrow C_2 \quad \ldots \quad s_n \rightarrow C_n}{\text{`\{`}\ s_1, s_2, \ldots, s_n\ \text{`\}`} \rightarrow C_1;\ C_2;\ \ldots\ C_n}$$

Operational Semantics

- Expressions vs. statements
  - Former need a temporary register to store results
  - Denoted in semantics using <C, r> pairs
    - C = "`code`" attribute
    - r = "`reg`" attribute (temporary register)

$$\text{SInt}\ \frac{}{\texttt{INT} \rightarrow \langle \texttt{loadI INT => } r, \ r \rangle}$$

$$\text{SAdd}\ \frac{e_1 \rightarrow \langle C_1, \ r_1 \rangle \quad e_2 \rightarrow \langle C_2, \ r_2 \rangle}{e_1 \ \text{`+`} \ e_2 \ \rightarrow \ \langle C_1; \ C_2; \ \texttt{add } r_1\texttt{,}r_2 \texttt{ => } r_3, \ r_3 \rangle}$$

$$\text{SBlock}\ \frac{s_1 \rightarrow C_1 \quad s_2 \rightarrow C_2 \quad \ldots \quad s_n \rightarrow C_n}{\text{`\{`} \ s_1, s_2, \ldots, s_n \ \text{`\}`} \ \rightarrow \ C_1; \ C_2; \ \ldots \ C_n}$$

Example

- Sample code:

```
loadI 2 => r1
loadI 3 => r2
loadI 4 => r3
mult r2, r3 => r4
add r1, r4 => r5
print r5
```

Decaf equivalent:

```
print_int(2+3*4);
```

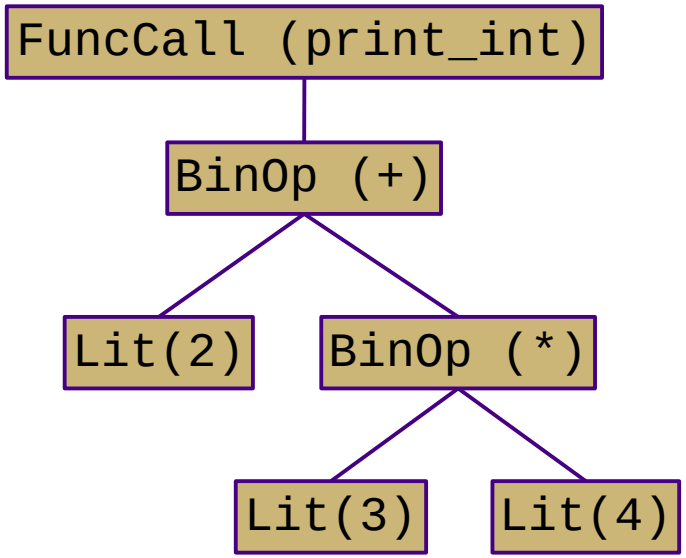
Example

- Sample code:

Decaf equivalent:

```
print_int(2+3*4);
```

```
loadI 2 => r1                  // Literal (2)
loadI 3 => r2                  // Literal (3)
loadI 4 => r3                  // Literal (4)
mult r2, r3 => r4              // BinaryOp (*)
add r1, r4 => r5               // BinaryOp (+)
print r5                       // FuncCall (print_int)
```

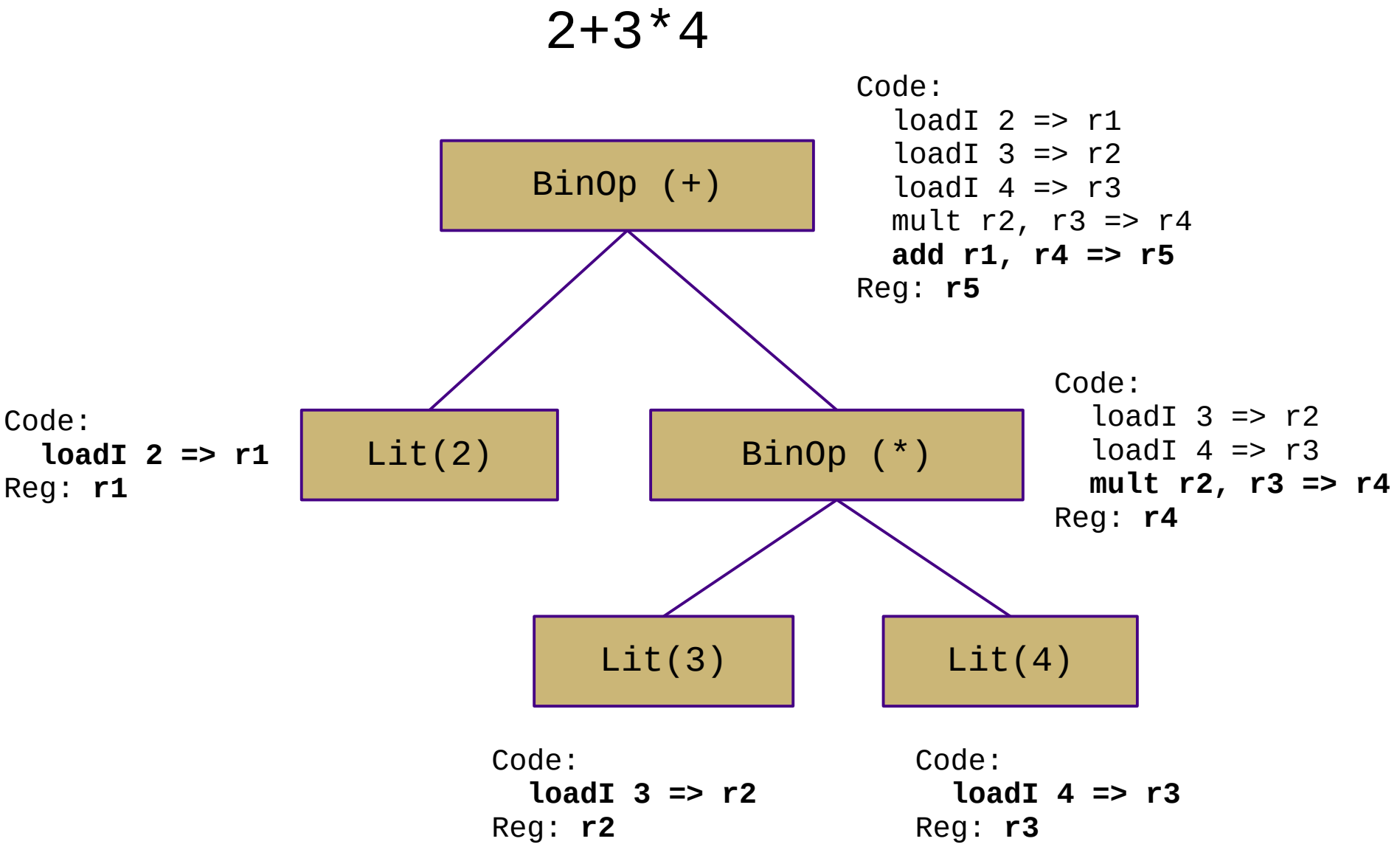


$$\text{SInt}\ \frac{}{\texttt{INT} \rightarrow \langle \texttt{loadI INT => } r,\ r \rangle}$$

$$\text{SAdd}\ \frac{e_1 \rightarrow \langle C_1,\ r_1 \rangle \quad e_2 \rightarrow \langle C_2,\ r_2 \rangle}{e_1\ \texttt{`+`}\ e_2 \rightarrow \langle C_1;\ C_2;\ \texttt{add } r_1\texttt{,}r_2\ \texttt{=>}\ r_3,\ r_3 \rangle}$$

(similar for SSub (`-`), SMul (`*`), SDiv (`/`), SAnd (`&&`), and SOr (`||`))

Example


2+3*4
BinOp (+)
Code:
loadI 2 => r1
loadI 3 => r2
loadI 4 => r3
mult r2, r3 => r4
add r1, r4 => r5
Reg: r5
Lit(2)
Code:
loadI 2 => r1
Reg: r1
BinOp (*)
Code:
loadI 3 => r2
loadI 4 => r3
mult r2, r3 => r4
Reg: r4
Lit(3)
Code:
loadI 3 => r2
Reg: r2
Lit(4)
Code:
loadI 4 => r3
Reg: r3

Boolean Encoding

- Integers: 0 for false, 1 for true
- Difference from book
  - No comparison-based conditional branches
  - Conditional branching uses boolean values instead
  - This enables simpler code generation
- Short-circuiting
  - Not in Decaf!

$$\text{STrue}\ \frac{}{\texttt{true} \rightarrow \langle \texttt{loadI 1 =>}\ r,\ r \rangle} \qquad \text{SFalse}\ \frac{}{\texttt{false} \rightarrow \langle \texttt{loadI 0 =>}\ r,\ r \rangle}$$

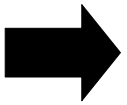
String Handling

- Arrays of chars vs. encapsulated type
  - Former is faster, latter is easier/safer
  - C uses the former, Java uses the latter
- Mutable vs. immutable
  - Former is more intuitive, latter is (sometimes) faster
  - C uses the former, Java uses the latter
- Decaf: immutable string constants only
  - No string variables

Variables

- Global: access using static address
  - Load address into temporary **base** register first (zero **offset**)
- Local: access using offset from base pointer (BP)
  - For ILOC, 8-byte slots starting at `[bp-8]` (so `[bp-16]`, `[bp-24]`, etc.)
  - Assume we can look up **base** register and constant **offset**

```
int a; int b; int c;
…
c = a + b;
```



```
loadAI [bp-8] => r1
loadAI [bp-16] => r2
add r1, r2 => r3
storeAI r3 => [bp-24]
```

$$\text{SLoc}\ \frac{r_b = \textbf{base}(\texttt{ID}) \quad x_o = \textbf{offset}(\texttt{ID})}{\texttt{ID} \rightarrow \langle \texttt{loadAI [}r_b\texttt{+}x_o\texttt{] => }r, r\rangle}$$

$$\text{SAssign}\ \frac{e \rightarrow \langle C_e, r_e\rangle \quad r_b = \textbf{base}(\texttt{ID}) \quad x_o = \textbf{offset}(\texttt{ID})}{\texttt{ID} = \texttt{e} \rightarrow C_e\texttt{; storeAI }r_e\texttt{ => [}r_b\texttt{+}x_o\texttt{]}}$$

Array Accesses

- 1-dimensional case: `base + size * i`
- Generalization for multiple dimensions:
  - `base + (i_1 * n_1) + (i_2 * n_2) + ... + (i_k * n_k)`
- Alternate definition:
  - 1d: `base + size * (i_1)`
  - 2d: `base + size * (i_1 * n_2 + i_2)`
  - nd: `base + size * (( ... ((i_1 * n_2 + i_2) * n_3 + i_3) ... ) * n_k + i_k)`
- Row-major vs. column-major
- In Decaf: row-major one-dimensional global arrays

$$\text{SArrLoc}\ \frac{e \rightarrow \langle C_e, r_e \rangle \quad x_s = \textbf{size}(\texttt{ID}) \quad r_b = \textbf{base}(\texttt{ID})}{\texttt{ID[}e\texttt{]} \ \rightarrow\ \langle C_e;\ \texttt{multI}\ r_e, x_s\ \texttt{=>}\ r_o;\ \texttt{loadAO}\ \texttt{[}r_b\texttt{+}r_o\texttt{]}\ \texttt{=>}\ r,\ r \rangle}$$

Struct and Record Types

- Access fields using static offsets from base of struct
- OO adds another level of complexity
  - Must include storage for inherited fields
  - Must handle dynamic dispatch for method calls
  - Class instance records and virtual method tables
  - Some of this complexity is covered in CS 430
- In Decaf: no structs or classes

Control Flow

- Introduce labels
  - Named locations in the program
  - Generated sequentially using static `newlabel`() call
- Generate jumps/branches using code templates
  - Similar to *do-while*, *jump-to-middle*, and *guarded-do* from CS 261
  - In ILOC: "`cbr`" instruction (no fallthrough!)
    - So the CS 261 templates won't work verbatim
  - Templates are composable
  - Operational semantics rules describe these templates
  - Concatenate code, labels, and jumps

Control Flow

if statement: **if (E) B1**

```
        rE = << E code >>
        cbr rE → b1, skip
    b1:
        << B1 code >>
    skip:
```

$$\text{SIf}\ \frac{e \to \langle C_e,\ r_e \rangle \qquad b \to C_b}{\texttt{if `(` } e \texttt{ `)` } b \ \to\ C_e;\ \texttt{cbr}\ r_e\ \texttt{=>}\ l_1, l_2;\ l_1\texttt{:};\ C_b;\ l_2\texttt{:}}$$

Control Flow

if statement: **if (E) B1 else B2**

```
        rE = << E code >>
        cbr rE → b1, b2
    b1:
        << B1 code >>
        jmp done
    b2:
        << B2 code >>
    done:
```

$$\text{SIfElse}\ \frac{e \rightarrow \langle C_e,\ r_e \rangle \qquad b_1 \rightarrow C_1 \qquad b_2 \rightarrow C_2}{\texttt{if `(` } e \texttt{ `)` } b_1 \texttt{ else } b_2 \ \rightarrow\ C_e;\ \texttt{cbr}\ r_e\ \texttt{=>}\ l_1\texttt{,}l_2;\ l_1\texttt{:};\ C_1;\ \texttt{jump}\ l_3;\ l_2\texttt{:};\ C_2;\ l_3\texttt{:}}$$

Control Flow

while loop: **while (E) B**

Control Flow

while loop: **while (E) B**

```
cond:
    rE = << E code >>
    cbr rE → body, done
body:
    << B code >>
    jmp cond
done:
```

Control Flow

while loop: **while (E) B**

```
    cond:                                   ; CONTINUE target
        rE = << E code >>
        cbr rE → body, done
    body:
        << B code >>
        jmp cond
    done:                                   ; BREAK target
```

$$\text{SWhile}\ \frac{e \to \langle C_e,\ r_e \rangle \qquad b \to C_b}{\texttt{while `(`}\ e\ \texttt{`)`}\ b\ \to\ l_1\texttt{:};\ C_e;\ \texttt{cbr}\ r_e\ \texttt{=>}\ l_2\texttt{,}l_3\texttt{;}\ l_2\texttt{:};\ C_b;\ \texttt{jump}\ l_1;\ l_3\texttt{:}}$$

Control Flow

for loop: **for V in E1, E2 B**

NOT CURRENTLY IN DECAF

```
        rX = << E1 code >>
        rY = << E2 code >>
        rV = rX
    cond:
        cmp_GE rV, rY → rC
        cbr rC → done, body
    body:
        << B code >>
        rV = rV + 1                    ; CONTINUE target
        jmp cond
    done:                              ; BREAK target
```

Control Flow

switch statement:

switch (E) {
case V1: B1
case V2: B2
default: BD
}

```
        rE = << E code >>
        if rE == V1 goto b1
        if rE == V2 goto b2
        << BD code >>
        jmp end
    b1:
        << B1 code >>
        jmp end
    b2:
        << B2 code >>
        jmp end
    l3:
```

NOT CURRENTLY IN DECAF

Control Flow

For sequential values starting with constant:

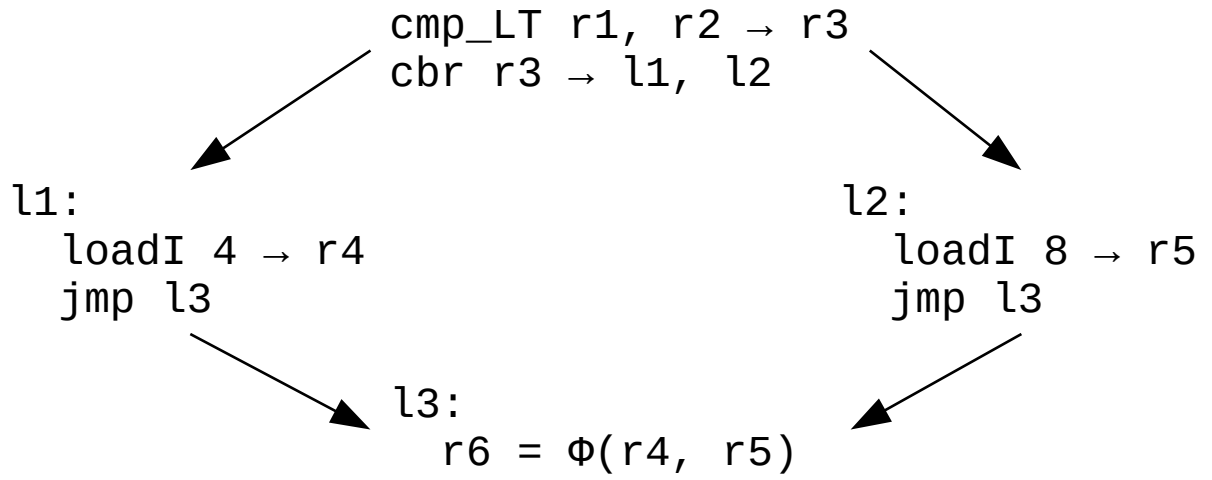
("jump table")

```
        rE = << E code >>
        jmp (jt+rE)
jt:     jmp l1
        jmp l2
(...)
```

SSA Form

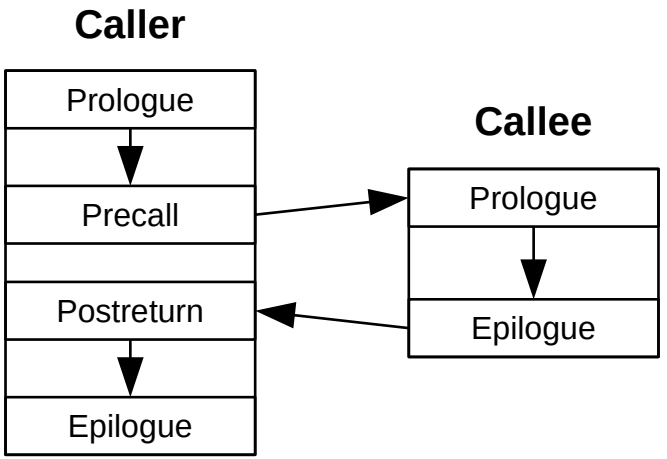
- Static single-assignment
  - Unique name for each newly-calculated value
  - Values are collapsed at control flow points using Φ-functions
    - Useful for various types of analysis
    - Φ-functions have no actual effect at runtime
  - We'll generate ILOC in SSA for P4
    - Unique temporary register for each newly-calculated value
    - No need for Φ-functions because we'll store to memory at every assignment

```
if (a < b) {
    c = 4;
} else {
    c = 8;
}
```



Procedure Calls

- Procedures are harder
  - (recall x86-64 calling conventions from CS 261)
  - Need rules for control transfer, parameter passing, return values, and register usage
    - Usually specified by an application binary interface (ABI)
  - We'll cover all of this next week



Reading Topics

- 4.4: Ad hoc syntax-directed translation
  - General concept of AST-based translation
- 5.3: Linear IRs
- 5.4: Mapping values to names
  - Intro to static single-assignment (SSA) form
- 7.1-7.5, 7.8: Basic code generation
  - Data storage, arithmetic, booleans/conditionals, arrays
  - Control flow constructs
  - Parts needed for Decaf
- 7.6-7.7: Code gen for strings and structures
  - Not needed for Decaf

Allocating Symbols (pre-P4)

- Walk the AST, allocating memory for symbols
  - Each symbol has a location and offset field
    - This is a form of static coordinates
    - `STATIC_VAR` and static offset for global variables
    - `STACK_LOCAL` and BP offset for local variables
    - `STACK_PARAM` and BP offset for function parameters
  - Track allocated memory
    - `localSize` attribute for each FuncDecl
    - `staticSize` attribute for the Program

Code Generation (P4)

- Walk the AST, generating code
  - Build ILOC instructions for all nodes
    - Refer to operational semantics (section 7 of language reference)
    - Store in “`code`” attribute
    - May require copying “`code`” attribute of children
  - Store expression results in temporary registers
    - Use “`reg`” attribute
    - Need state information to track the next temporary ID
    - Location loads and stores will require static coordinate info