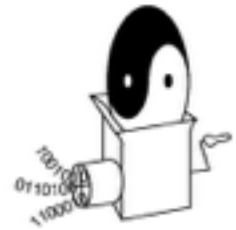
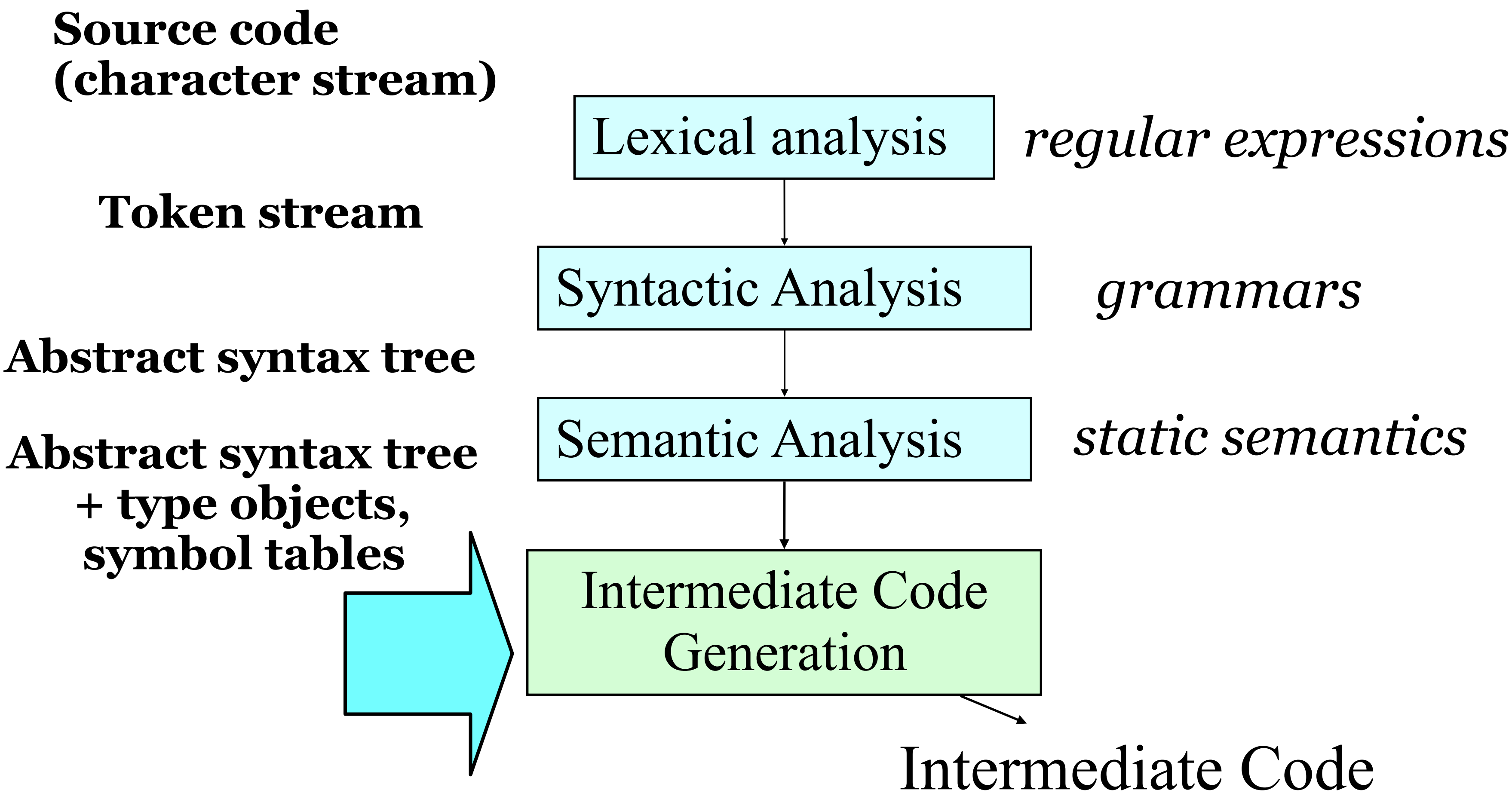


CS 4120
Introduction to Compilers

Andrew Myers

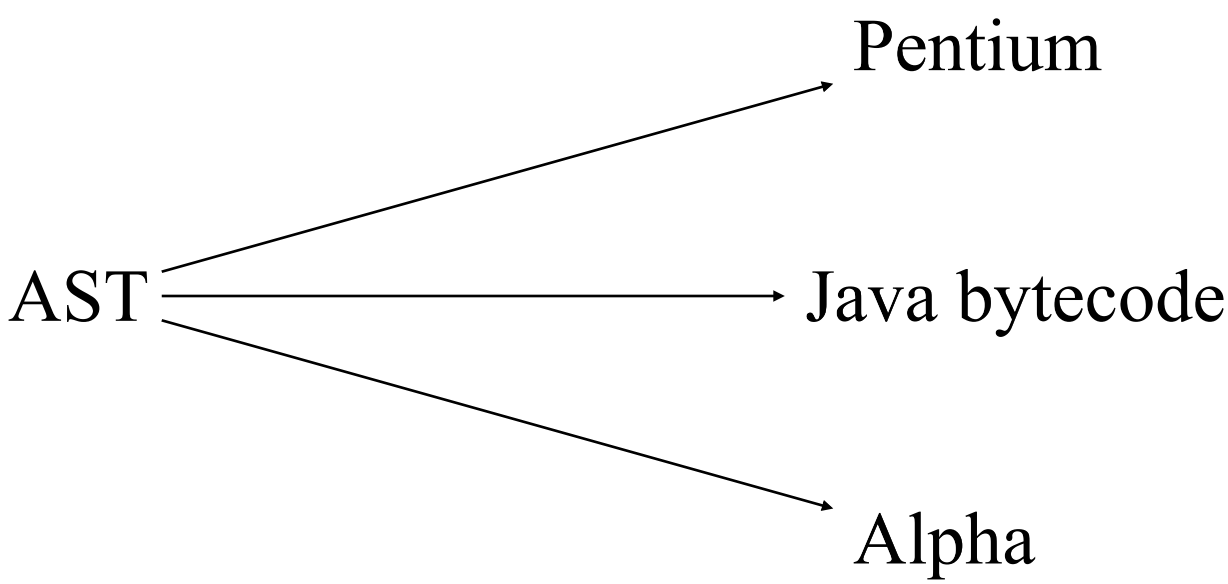
Cornell University

Where we are


Source code
(character stream)
Lexical analysis
regular expressions
Token stream
Syntactic Analysis
grammars
Abstract syntax tree
Semantic Analysis
static semantics
Abstract syntax tree
+ type objects,
symbol tables
Intermediate Code
Generation
Intermediate Code

Intermediate Code

- Abstract machine code - simpler
- Allows machine-independent code generation, optimization



What makes a good IR?

- Easy to translate from AST
- Easy to translate to assembly
- Narrow interface: small number of node types (instructions)
  - Easy to optimize
  - Easy to retarget

AST (>40 node types)

↓

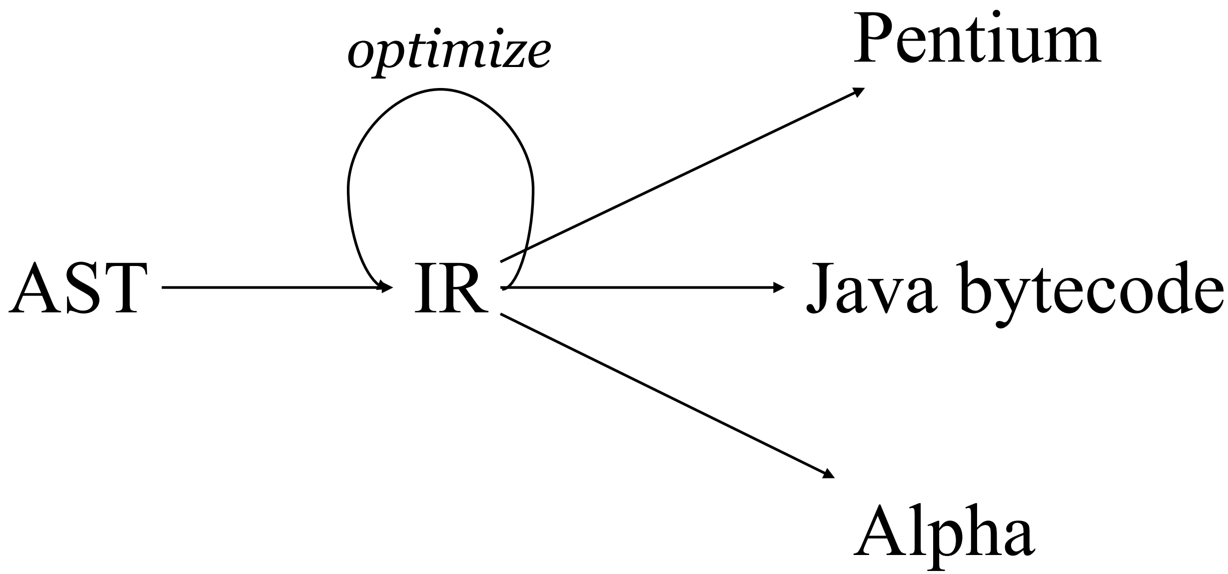
IR (13 node types)

↓

Pentium (>200 opcodes)

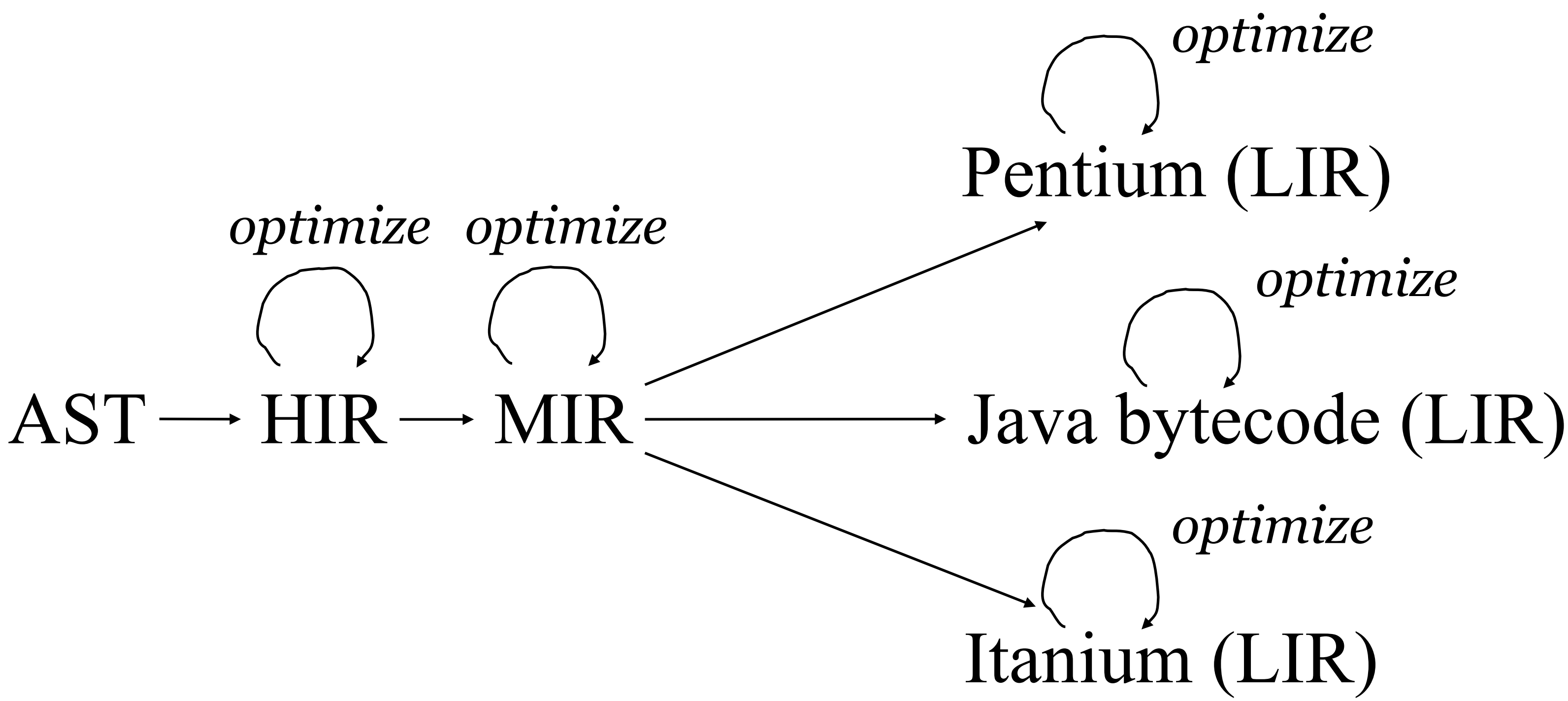
Intermediate Code

- Abstract machine code (**I**ntermediate **R**epresentation)
- Allows machine-independent code generation, optimization



Optimizing compilers

- Goal: get program closer to machine code without losing information needed to do useful optimizations
- Need multiple IR stages



High-level IR (HIR)

- AST + new node types not generated by parser
- Preserves high-level language constructs
  - structured flow, variables, methods
- Allows high-level optimizations based on properties of source language (*e.g.* inlining, reuse of constant variables)
- More passes: ideal for visitors

Medium-level IR (MIR)

- Intermediate between AST and assembly
- Appel's IR: tree structured IR (triples)
- Unstructured jumps, registers, memory loc'ns
- Convenient for translation to high-quality machine code
- Other MIRs:
  - quadruples: $a = b$ OP c ("a" is explicit, not arc)
  - JVM, UCODE: stack-machine based
  - LIRs for C: LLVM (clang), RTL (gcc)
  - advantage of tree IR: easier instruction selection
  - advantage of quadruples: easier dataflow analysis, optimization
  - stack machine code: slightly easier to generate

Low-level IR (LIR)

- Assembly code + extra pseudo-instructions
- Machine-dependent
- Translation to assembly code is trivial
- Allows optimization of code for low-level considerations: scheduling, memory layout

MIR tree

- **I**ntermediate **R**epresentation is a tree of nodes representing abstract machine instructions: can be interpreted
  - IR almost the same as Appel's (except CJUMP)
  - Statement nodes return no value, are executed in a particular order
  - *e.g.* MOVE, SEQ, CJUMP
    - Iota statement ≠ IR statement!
  - Expression nodes return a value, children are executed in no particular order
  - *e.g.* ADD, SUB
    - non-determinism gives flexibility for optimization

IR expressions

- CONST(i) : the integer constant i
- TEMP(t) : a temporary register t. The abstract machine has an infinite number of registers
- OP(e_1, e_2) : one of the following operations
  - arithmetic: ADD, SUB, MUL, DIV, MOD
  - bit logic: AND, OR, XOR, LSHIFT, RSHIFT, ARSHIFT
  - comparisons: EQ, NEQ, LT, GT, LEQ, GEQ
- MEM(e) : contents of memory locn w/ address e
- CALL(f, a_0, a_1, ...) : result of fcn f applied to arguments a_i
- NAME(n) : address of the statement or global data location labeled n (TBD)
- ESEQ(s, e) : result of e after stmt s is executed

CONST

- CONST node represents an integer constant i

CONST(i)

- Value of node is i

TEMP

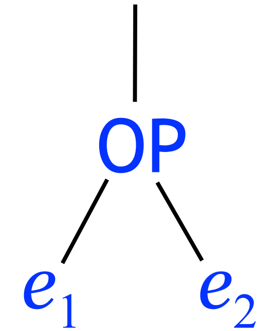
- TEMP node is one of the infinite number of registers (temporaries)
  - For brevity, FP = TEMP(FP)
  - Used for local variables and temporaries
  - Value of node is the current content of the named register at the time of evaluation

TEMP(t)

OP

  - Abstract machine supports a variety of arithmetic/logical/relational operations

OP(e_1, e_2)



  - Evaluates e_1 and e_2 and then applies operation to their results

- e_1 and e_2 must be expression nodes
  - Any order of evaluation of e_1 and e_2 is allowed

MEM

- MEM node is a memory location

MEM(e)

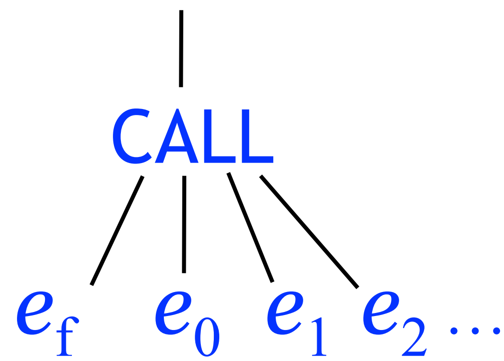
$$\begin{array}{c} | \\ \mathrm{MEM} \\ | \\ e \end{array}$$

- Computes value of e and looks up contents of memory at that address

CALL

- CALL node represents a function call

$$\mathrm{CALL}(\underbrace{e_f}_{\text{function code address}},\ \underbrace{e_0, e_1, e_2, \ldots}_{\text{arguments}})$$



  - No explicit representation of argument passing, stack frame setup, etc.
  - Value of node is result of call

NAME

- Address of memory location named n
- Two kinds of named locations
  - labeled statements in program (from LABEL statement)
  - global data definitions (not represented in IR)

NAME(n)

|
NAME(n)

ESEQ

- Evaluates an expression e **after** completion of a statement s that might affect result of e
- Result of node is result of e

ESEQ(s, e)

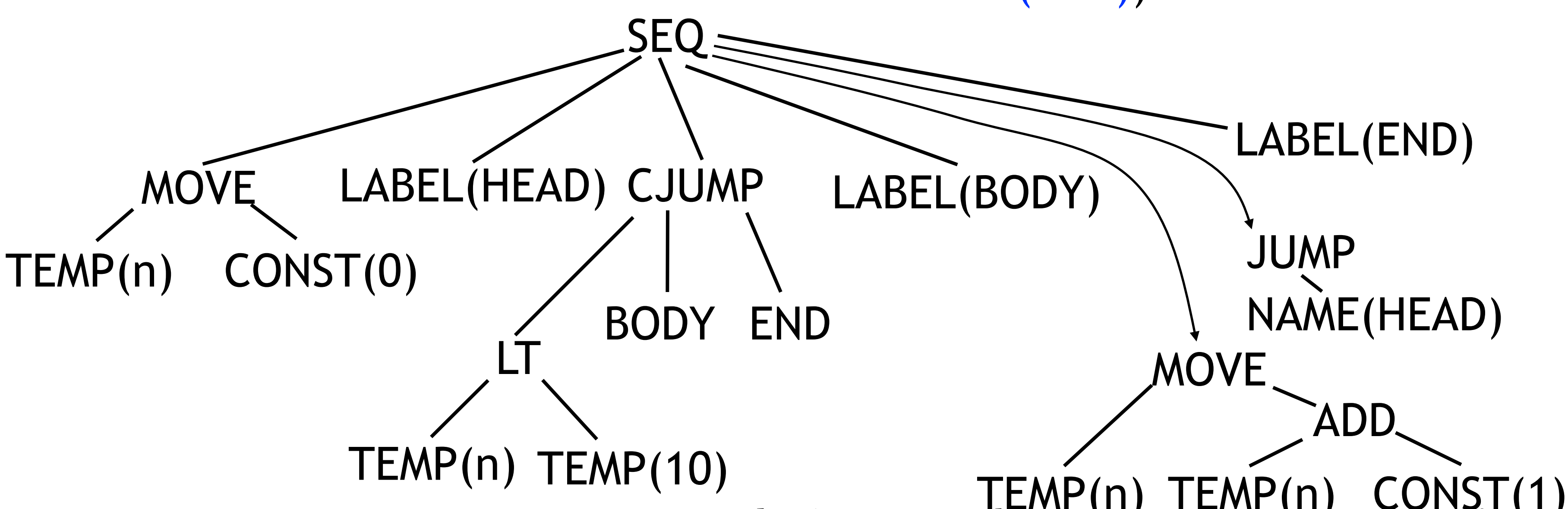
IR statements

- MOVE($dest$, e) : move result of e into $dest$
  - $dest$ = TEMP(t) : assign to temporary t
  - $dest$ = MEM(e) : assign to memory locn e
- EXP(e) : evaluate e for side-effects, discard result
- SEQ(s_1, …, s_n) : execute each stmt s_i in order
- JUMP(e) : jump to address e
- CJUMP(e, l_1, l_2) : jump to statement named l_1 or l_2 depending on whether e is true or false
- LABEL(n) : labels a statement (for use in NAME)
- RETURN: return from this function

Example

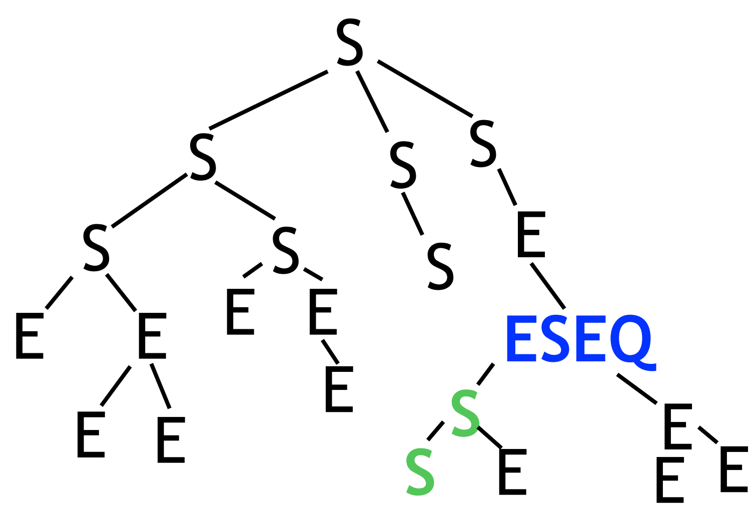
```
n = 0;
while (n < 10) {
   n = n + 1
}
```

```
SEQ(MOVE(TEMP(n), CONST(0)),
    LABEL(HEAD),
    CJUMP(LT(TEMP(n), CONST(10)),
          BODY, END),
    LABEL(BODY),
    MOVE(TEMP(n), ADD(TEMP(n),
                      CONST(1))),
    JUMP(NAME(HEAD)),
    LABEL(END))
```



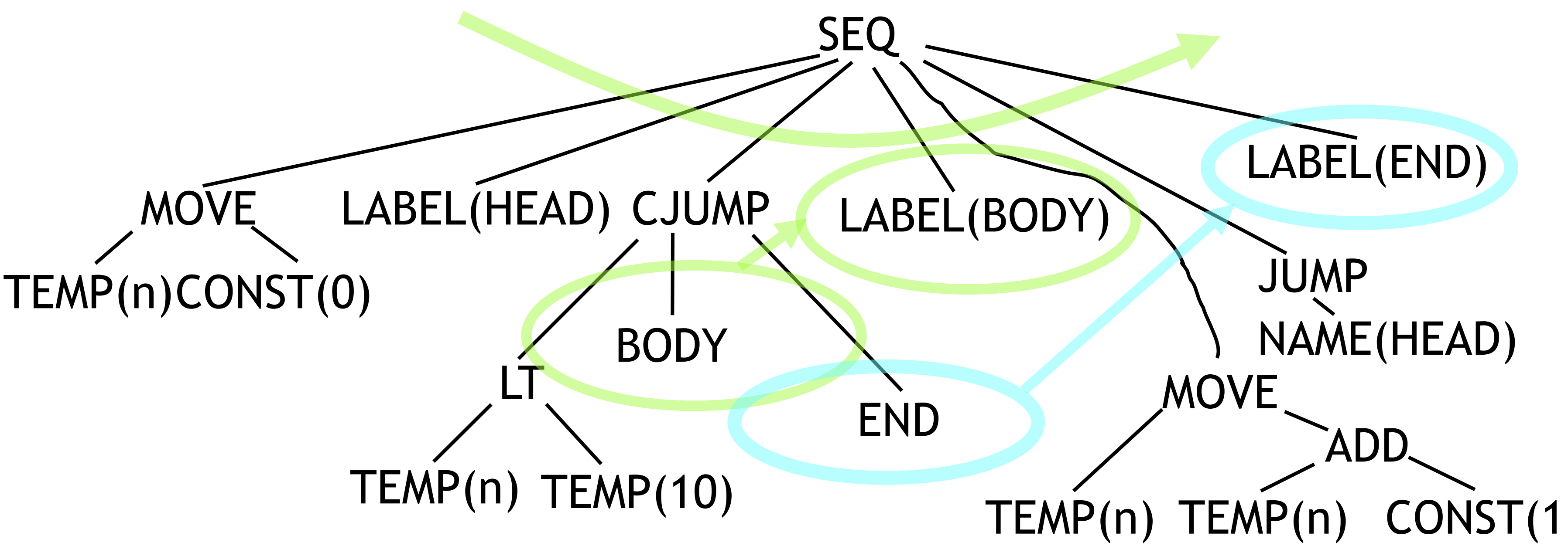
Structure of IR tree

- Top of tree is a statement
- Expressions are under some statements
- Statements under expressions only if there is an ESEQ node



Executing the IR

- IR tree is a program representation; can be executed directly by an interpreter
- Execution is tree traversal (exc. jumps)



How to translate?

- How do we translate an AST/High-level IR into this IR representation?
- Next: syntax-directed translation