# CS 412
# Introduction to Compilers

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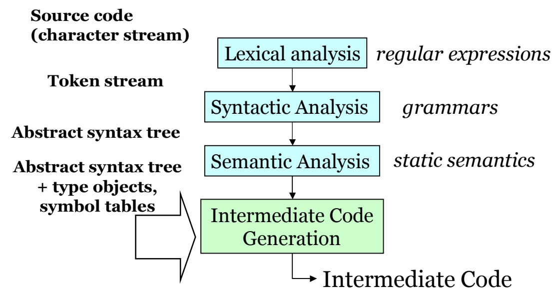
Lecture 13: Intermediate Code
21 Feb 01



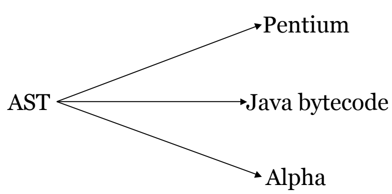
# Where we are






# Intermediate Code

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






# What makes a good IR?

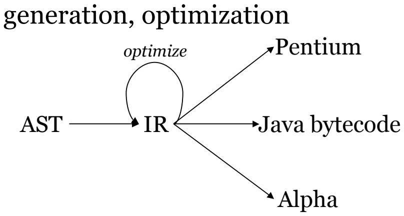
- Easy to translate from AST
- Easy to translate to assembly
- Narrow interface: small number of node types (instructions)
  - Easy to optimize
  - Easy to retarget

AST (>40 node types)
↓
IR (13 node types)
↓
Pentium (>200 opcodes)



# Intermediate Code

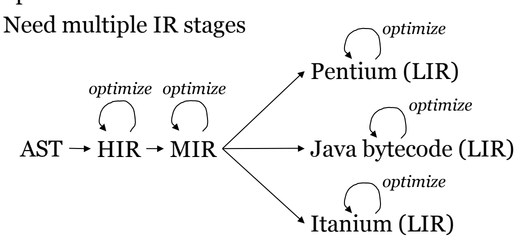
- Abstract machine code (**I**ntermediate **R**epresentation)
- Allows machine-independent code generation, optimization






# 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)
  - UCODE: stack machine based (like Java bytecode)
  - advantage of tree IR: easier instruction selection
  - advantage of quadruples: easier dataflow analysis, optimization
  - advantage of UCODE: 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

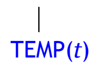
- CONST node represents an integer constant *i*

  |
  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

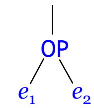





# OP

- Abstract machine supports a variety of different 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($e$)


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

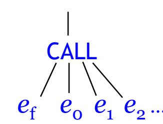


# CALL

- CALL node represents a function call

CALL($e_f$, $e_0$, $e_1$, $e_2$, ...)

function code address — arguments



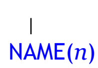

- No explicit representation of argument passing, stack frame setup, etc.
- Value of node is result of call



# 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($n$)






# 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)

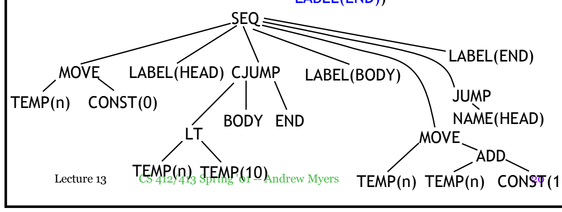


## Example

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

⇒

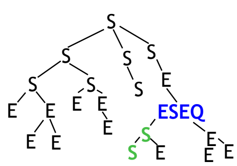
```
SEQ(MOVE(TEMP(n), CONST(0)),
    LABEL(HEAD),
    CJUMP(LT(TEMP(n), CONST(10)),
         BODY, END),
    LABEL(BODY),
    MOVE(TEMP(n), ADD(TEMP(n),
                      CONST(1))),
    JUMP(NAME(HEAD)),
    LABEL(END))
```






## Structure of IR tree

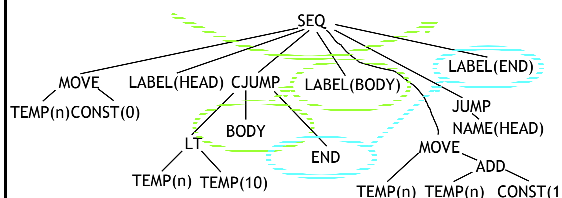
- Top of tree is a statement
- Expressions are under some statements
- Statements under expressions only if there is an ESEQ node






## 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?



## Syntax-directed Translation

- Technique: *syntax-directed translation*
- Abstract syntax tree ⇒ IR tree
- Each subtree of AST translated to subtree in IR tree with same value when executed
- Implemented as recursive traversal
  - like type checking, but makes a new tree
  - visitor impl. just complicates code unless several passes are needed

# Translation Code

- Like type-checking: add method to AST nodes that does the translation

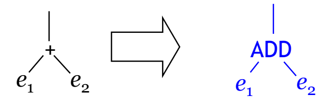
```
abstract class ASTNode {
    IRNode translate(SymTab A) { … }
}
```

- Implemented as recursive traversal
- How to express these translations precisely?



# Operators

- AST node corresponding to arithmetic becomes corresponding IR node

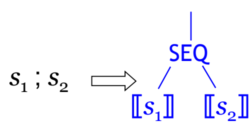



- Use $[\![e]\!]$ to represent result of translating AST expression tree $e$ to an IR expression tree



# Statements

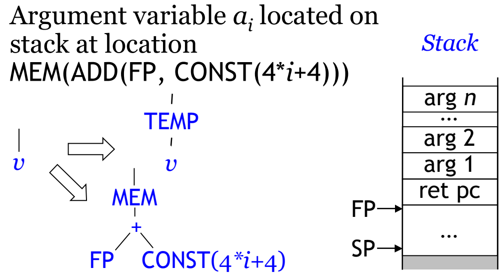
- A sequence of statements translates to a SEQ node:
- If $s_1$ translates to IR tree $[\![s_1]\!]$ and $s_2$ to $[\![s_2]\!]$
- Then $s_1$ ; $s_2$ translates to SEQ($[\![s_1]\!]$ , $[\![s_2]\!]$)






# Variables

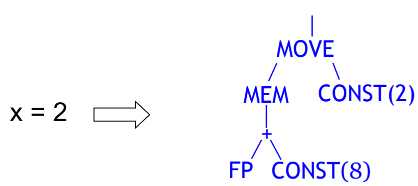
- Local variable $v$ translates to TEMP($v$)
- Argument variable $a_i$ located on stack at location MEM(ADD(FP, CONST(4*$i$+4)))






# Assignment

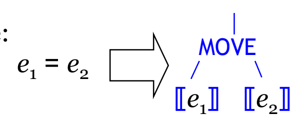
- Assignment $v = e$ translates to a MOVE(*dest*, $e$) node, where $e$ is the translation of expression $E$, and *dest* is the location of $v$.



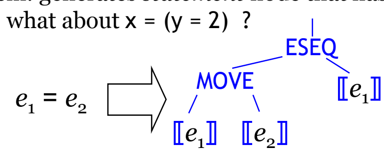



# Assignment rule

- General rule:

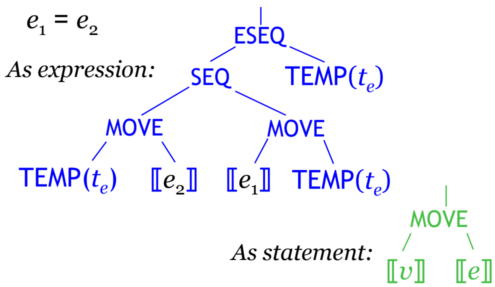



- Problem: generates *statement* node that has no value; what about x = (y = 2) ?



# Eliminating extra v

$e_1 = e_2$






# Example again

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