CS412/413

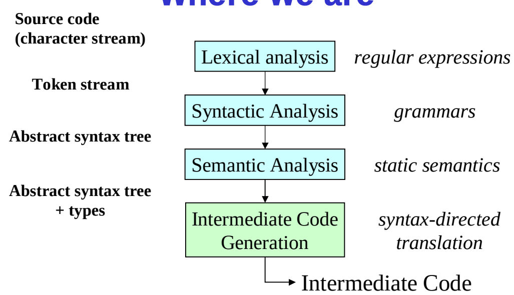
Introduction to
Compilers and Translators
Cornell University
Spring '00

Lecture 12: Intermediate Representations

Administration

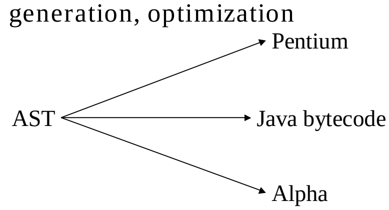
- PA2 due Monday
- Prelim 1 March 1

Where we are



Intermediate Code

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



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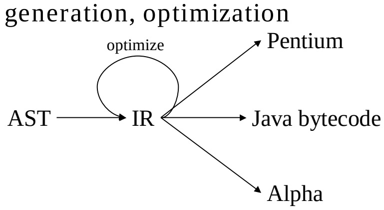
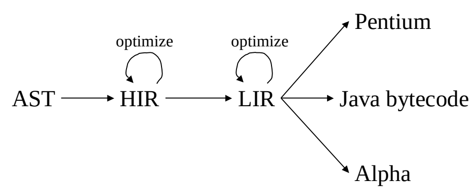


Optimizing compilers

- 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)
- Translation ideal for visitor impl.

Medium-level IR (MIR)

- Intermediate between AST and assembly
- Appel's IR: tree structured IR (triples)
- other MIRs exist
  - quadruples: a = b OP c ("a" is explicit, not arc)
  - UCODE: stack machine based (like Java bytecode)
  - advantage of tree IR: easy to generate, easier to do reasonable instruction selection
  - advantage of quadruples: easier optimization
- Unstructured jumps, registers, memory loc'ns
- Convenient for translation to high-quality machine code

Low-level IR (LIR)

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

MIR tree

- **I**ntermediate **R**epresentation (or IL) 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 non-deterministically
  - *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 these
- 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)
- 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 different operations

OP(e_1, e_2)

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
- Order of evaluation of e_1 and e_2 is non-deterministic

MEM

- MEM node is a memory location

MEM(e)

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

CALL

e_f e_0 e_1 e_2 …

- No explicit representation of argument passing, stack frame creation, 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)

ESEQ

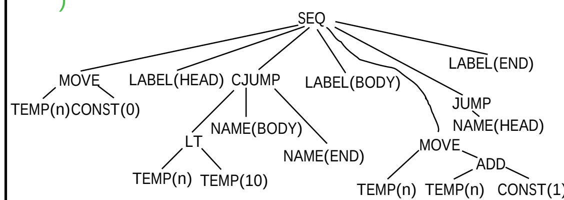
s e

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*, 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*) : a labeled statement (may be used in NAME, CJUMP)

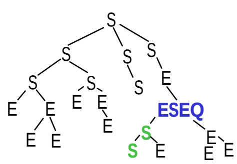
Example

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



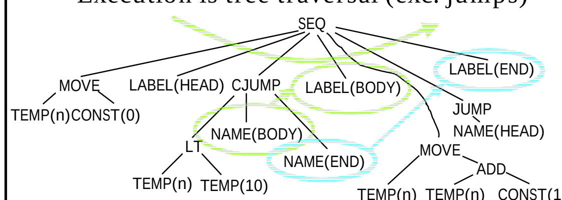
Structure of IR tree

- Top of tree is a statement
- Expressions are under some statement
- 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 (typically)
- Implemented as recursive traversal
  - like type checking, but makes a new tree
  - visitor impl. just complicates traversal unless split into several passes

Translation Code

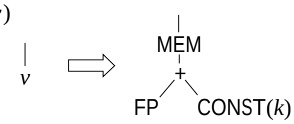
- Like type-checking: add method to AST nodes that does the translation

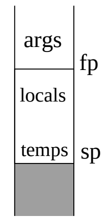
```
abstract class Node {
    IRNode translate(SymTab A) { … }
}
```

- Next: how to express these translations precisely

Variables

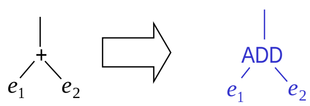
- AST expression node translated to IR expression node that has same value
- Local variable v located at offset k -- reference to v in AST becomes IR expression MEM(PLUS(FP, k)) or TEMP(v)





Operators

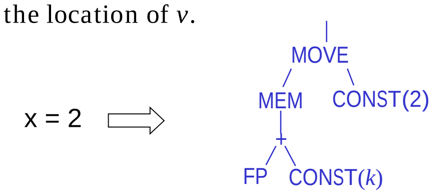
- AST node corresponding to arithmetic becomes corresponding IR node



- Use ⟦e⟧ to represent result of translating AST expression tree e to an IR expression tree

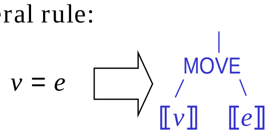
Assignment

- 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.

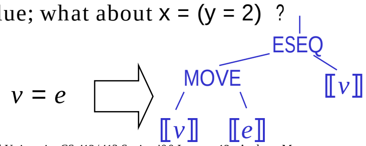


Assignment rule

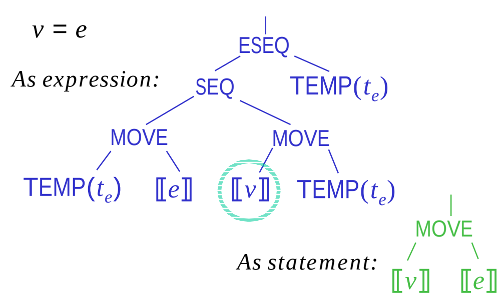
- General rule:



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

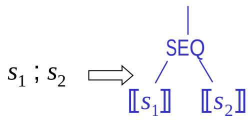


Eliminating extra v



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($[\![s_1]\!]$, $[\![s_2]\!]$)



Example again

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