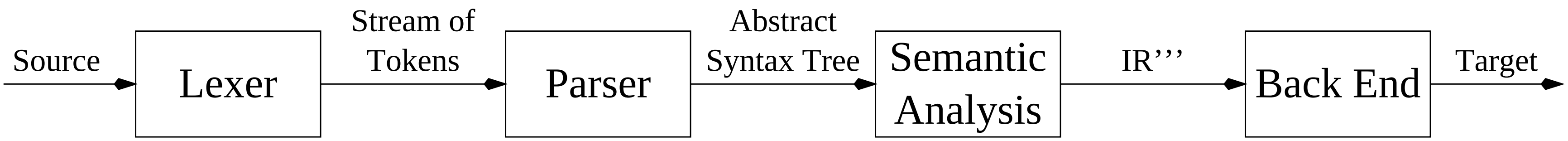
Intermediate Representation



Intermediate Representation (IR):

- An abstract machine language
- Expresses operations of target machine
- Not specific to any particular machine
- Independent of source language

IR code generation not necessary:

- Semantic analysis phase can generate real assembly code directly.
- Hinders portability and modularity.

Intermediate Representation

Suppose we wish to build compilers for n source languages and m target machines.

Case 1: no IR

- Need separate compiler for each source language/target machine combination.
- A total of $n * m$ compilers necessary.
- Front-end becomes cluttered with machine specific details, back-end becomes cluttered with source language specific details.

Case 2: IR present

- Need just n front-ends, m back ends.

Intermediate Representation

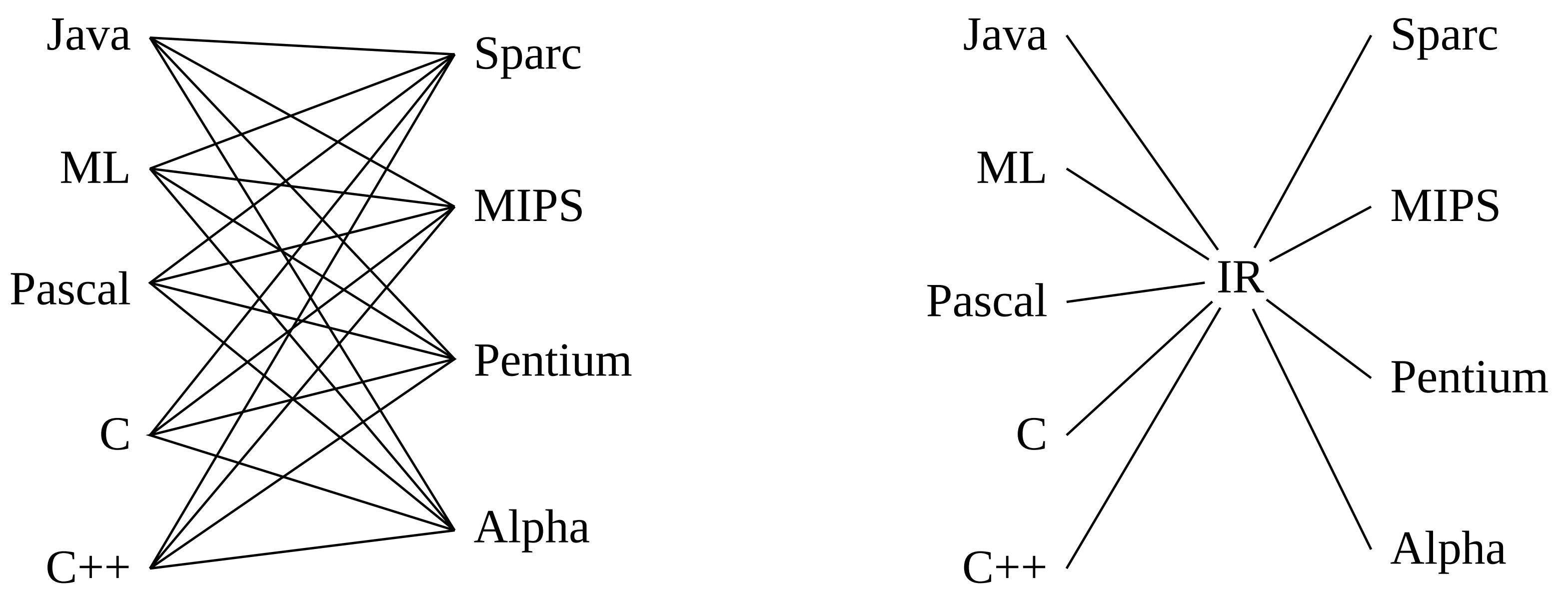


FIGURE 7.1. Compilers for five languages and four target machines: (left) without an IR, (right) with an IR.
From *Modern Compiler Implementation in ML,* Cambridge University Press, ©1998 Andrew W. Appel

IR properties

- Must be convenient for semantic analysis phase to produce.
- Must be convenient to translate into real assembly code for all desired target machines.
  - RISC processors execute operations that are rather simple.
    * Examples: load, store, add, shift, branch
    * IR should represent abstract load, abstract store, abstract add, etc.
  - CISC processors execute more complex operations.
    * Examples: multiply-add, add to/from memory
    * Simple operations in IR may be "clumped" together during instruction selection to form complex operations.

IR expression trees

The IR may be represented in many forms:

- Liberty, IMPACT, and Elcor compilers use *pseudo-assembly*.
- gcc and the class project use *expression trees*.
- Intel's Electron, and HP's production compiler use both.

Expression trees:

- `exp`: constructs that compute some value, possibly with side effects.
- `stm`: constructs that perform side effects and control flow.

```
signature TREE = sig
datatype exp   = CONST of int
                | NAME of Temp.label
                | TEMP of Temp.temp
                | BINOP of binop * exp * exp
                | MEM of exp
                | CALL of exp * exp list
                | ESEQ of stm * exp
```

IR expression trees

TREE **continued:**

```
     and stm   = MOVE of exp * exp
               | EXP of exp
               | JUMP of exp * Temp.label list
               | CJUMP of relop * exp * exp *
                           Temp.label * Temp.label
               | SEQ of stm * stm
               | LABEL of Temp.label
     and binop = PLUS|MINUS|MUL|DIV|AND|OR|
                 LSHIFT|RSHIFT|ARSHIFT|XOR
     and relop = EQ|NE|LT|GT|LE|GE|ULT|ULE|UGT|UGE
end
```

Expressions

Expressions compute some value, possibly with side effects.

`CONST(`i`)` integer constant i

`NAME(`n`)` symbolic constant n corresponding to assembly language label (abstract name for memory address)

`TEMP(`t`)` temporary t, or abstract/virtual register t

`BINOP(`op`, `e_1`, `e_2`)` e_1 op e_2, e_1 evaluated before e_2

- integer arithmetic operators: PLUS, MINUS, MUL, DIV
- integer bit-wise operators: AND, OR, XOR
- integer logical shift operators: LSHIFT, RSHIFT
- integer arithmetic shift operator: ARSHIFT

Expressions

`MEM(`e`)` contents of `wordSize` bytes of memory starting at address e

- `wordSize` is defined in `Frame` module.
- if `MEM` is used as left operand of `MOVE` statement $\Rightarrow$ store
- if `MEM` is used as right operand of `MOVE` statement $\Rightarrow$ load

`CALL(`f`, `l`)` application of function f to argument list l

- subexpression f is evaluated first
- arguments in list l are evaluated left to right

`ESEQ(`s`, `e`)` the statement s evaluated for side-effects, e evaluated next for result

Statements

Statements have side effects and perform control flow.

`MOVE(TEMP(`t`),` e`)` evaluate e and move result into temporary t.

`MOVE(MEM(`e_1`),` e_2`)` evaluate e_1, yielding address a; evaluate e_2, store result in `wordSize` bytes of memory stating at address a

`EXP(`e`)` evaluate expression e, discard result.

`JUMP(`e`,` $labs$`)` jump to address e

- e may be literal label (`NAME(`l`)`), or address calculated by expression
- $labs$ specifies all locations that e can evaluate to (used for dataflow analysis)
- jump to literal label l: `JUMP(NAME(`l`),[`l`])`

`CJUMP(`op`,` e_1`,` e_2`,` t`,` f`)` evaluate e_1, then e_2; compare results using op; if true, jump to t, else jump to f

- EQ, NE: signed/unsigned integer equality and non-equality
- LT, GT, LE, GE: signed integer inequality
- ULT, UGT, ULE, UGE: unsigned integer inequality

Statements

`SEQ(`s_1`,` s_2`)` statement s_1 followed by s_2

`LABEL(`l`)` label definition - constant value of l defined to be current machine code address

- similar to label definition in assembly language
- use `NAME(`l`)` to specify jump target, calls, etc.

- The statements and expressions in `TREE` can specify function bodies.
- Function entry and exit sequences are machine specific and will be added later.

Translation of Abstract Syntax

- if `Absyn.exp` computes value ⇒ `Tree.exp`
- if `Absyn.exp` does not compute value ⇒ `Tree.stm`
- if `Absyn.exp` has boolean value ⇒ `Tree.stm` and `Temp.label`s

```
datatype exp = Ex of Tree.exp
             | Nx of Tree.stm
             | Cx of Temp.label * Temp.label -> Tree.stm
```

- `Ex` "expression" represented as a `Tree.exp`
- `Nx` "no result" represented as a `Tree.stm`
- `Cx` "conditional" represented as a function. Given a false-destination label and a true-destination label, it will produce a `Tree.stm` which evaluates some conditionals and jumps to one of the destinations.

Translation of Abstract Syntax - Conditionals

Conditional:

```
x > y:
  Cx(fn (t, f) => CJUMP(GT, x, y, t, f))


a > b | c < d:
  Cx(fn (t, f) => SEQ(CJUMP(GT, a, b, t, z),
                      SEQ(LABEL z, CJUMP(LT, c, d, t, f))))
```

May need to convert conditional to value:

```
a := x > y:
```

`Cx` corresponding to "x $>$ y" must be converted into `Tree.exp` e.

```
  MOVE(TEMP(a), e)
```

Need three conversion functions:

```
  val unEx: exp -> Tree.exp
  val unNx: exp -> Tree.stm
  val unCx: exp -> (Temp.label * Temp.label -> Tree.stm)
```

Translation of Abstract Syntax - Conditionals

The three conversion functions:

```
val unEx: exp -> Tree.exp
val unNx: exp -> Tree.stm
val unCx: exp -> (Temp.label * Temp.label -> Tree.stm)
```

```
a := x > y:
  MOVE(TEMP(a), unEx(Cx(t,f) => ...)
```

`unEx` makes a `Tree.exp` even though e was `Cx`.

Translation of Abstract Syntax

Implementation of function `UnEx`**:**

```
structure T = Tree

fun unEx(Ex(e)) = e
  | unEx(Nx(s)) = T.ESEQ(s, T.CONST(0))
  | unEx(Cx(genstm)) =
      let val r = Temp.newtemp()
          val t = Temp.newlabel()
          val f = Temp.newlabel()
      in T.ESEQ(seq[T.MOVE(T.TEMP(r), T.CONST(1)),
                    genstm(t, f),
                    T.LABEL(f),
                    T.MOVE(T.TEMP(r), T.CONST(0)),
                    T.LABEL(t)],
                T.TEMP(r))
      end
```

Translation of Abstract Syntax

- Recall type and value environments `tenv`, `venv`.
- The function `transVar` return a record {exp, ty} of `Translate.exp` and `Types.ty`.
- `exp` is no longer a place-holder

Simple Variables

- **Case 1:** variable v declared in current procedure's frame

```
InFrame(k):
  MEM(BINOP(PLUS, TEMP(FP), CONST(k)))

k: offest in own frame
```

`FP` is declared in FRAME module.

- **Case 2:** variable v declared in temporary register

```
InReg(t_103):
  TEMP(t_103)
```

Simple Variables

- **Case 3:** variable v not declared in current procedure's frame, need to generate IR code to follow static links

```
InFrame(k_n):
  MEM(BINOP(PLUS, CONST(k_n),
      MEM(BINOP(PLUS, CONST(k_n-1),
           ...
           MEM(BINOP(PLUS, CONST(k_2),
               MEM(BINOP(PLUS, CONST(k_1), TEMP(FP))))))))

k_1, k_2,..., k_n-1: static link offsets
k_n: offset of v in own frame
```

Simple Variables

To construct simple variable IR tree, need:

- l_f: level of function f in which v used
- l_g: level of function g in which v declared
- `MEM` nodes added to tree with static link offsets (`k_1,..,k_n-1`)
- When l_g reached, offset `k_n` used.

Array Accesses

Given array variable `a`,

```
&(a[0]) = a
&(a[1]) = a + w, where w is the word-size of machine
&(a[2]) = a + (2 * w)
...
```

Let `e` be the IR tree for `a`:

```
a[i]:
  MEM(BINOP(PLUS, e, BINOP(MUL, i, CONST(w))))
```

Compiler must emit code to check whether `i` is out of bounds.

Record Accesses

```
type rectype = {f1:int, f2:int, f3:int}
                  |       |       |
        offset:   0       1       2

var a:rectype := rectype{f1=4, f2=5, f3=6}
```

Let `e` be IR tree for `a`:

```
a.f3:
  MEM(BINOP(PLUS, e, BINOP(MUL, CONST(3), CONST(w))))
```

Compiler must emit code to check whether `a` is `nil`.

Conditional Statements

`if` e_1 `then` e_2 `else` e_3

- Treat e_1 as `Cx` expression $\Rightarrow$ apply `unCx`.
- Treat e_2, e_3 as `Ex` expressions $\Rightarrow$ apply `unEx`.

```
Ex(ESEQ(SEQ(unCx(e1)(t, f),
         SEQ(LABEL(t),
          SEQ(MOVE(TEMP(r), unEx(e2)),
           SEQ(JUMP(NAME(join)),
            SEQ(LABEL(f),
             SEQ(MOVE(TEMP(r), unEx(e3)),
              LABEL(join)))))))
        TEMP(r)))
```