

CS3300 - Compiler Design Semantic Analysis - IR Generation

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Intermediate representations

Why use an intermediate representation?

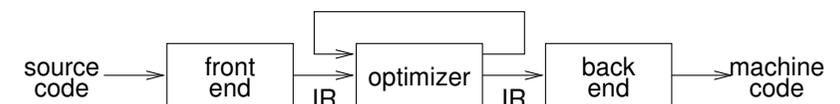
- 1 break the compiler into manageable pieces
– good software engineering technique
- 2 simplifies retargeting to new host
– isolates back end from front end
- 3 simplifies handling of “poly-architecture” problem
– m lang’s, n targets $\Rightarrow m + n$ components
- 4 enables machine-independent optimization
– general techniques, multiple passes

(myth)

An intermediate representation is a compile-time data structure



Intermediate representations



Generally speaking:

- front end produces IR
- optimizer transforms that representation into an equivalent program that may run more efficiently
- back end transforms IR into native code for the target machine



Intermediate representations

Representations talked about in the literature include:

- abstract syntax trees (AST)
- linear (operator) form of tree
- directed acyclic graphs (DAG)
- control flow graphs
- program dependence graphs
- static single assignment form
- 3-address code
- hybrid combinations



Intermediate representations - properties

Important IR Properties

- ease of generation
- ease of manipulation
- cost of manipulation
- level of abstraction
- freedom of expression
- size of typical procedure

Subtle design decisions in the IR have far reaching effects on the speed and effectiveness of the compiler.

Level of exposed detail is a crucial consideration.



IR design issues

- Is the chosen IR appropriate for the (analysis/ optimization/ transformation) passes under consideration?
- What is the IR level: close to language/machine.
- Multiple IRs in a compiler: for example, High, Medium and Low

$t1 \leftarrow a[i,j+2]$	$t1 \leftarrow j + 2$	$r1 \leftarrow [fp-4]$
	$t2 \leftarrow i * 20$	$r2 \leftarrow r1 + 2$
	$t3 \leftarrow t1 + t2$	$r3 \leftarrow [fp-8]$
	$t4 \leftarrow 4 * t3$	$r4 \leftarrow r3 * 20$
	$t5 \leftarrow \text{addr } a$	$r5 \leftarrow r4 + r2$
	$t6 \leftarrow t5 + t4$	$r6 \leftarrow 4 * r5$
	$t7 \leftarrow *t6$	$r7 \leftarrow fp - 216$
		$f1 \leftarrow [r7+r6]$

(a) High-, (b) medium-, and (c) low-level representations of a C array reference.

- In reality, the variables etc are also only pointers to other data structures.



Intermediate representations

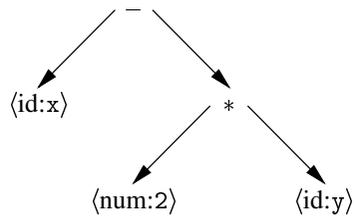
Broadly speaking, IRs fall into three categories:

- Structural
 - structural IRs are graphically oriented
 - examples include trees, DAGs
 - heavily used in source to source translators
 - nodes, edges tend to be large
- Linear
 - pseudo-code for some abstract machine
 - large variation in level of abstraction
 - simple, compact data structures
 - easier to rearrange
- Hybrids
 - combination of graphs and linear code
 - attempt to take best of each
 - e.g., control-flow graphs
 - Example: GCC Tree IR.



Abstract syntax tree

An abstract syntax tree (AST) is the procedure's parse tree with the nodes for most non-terminal symbols removed.



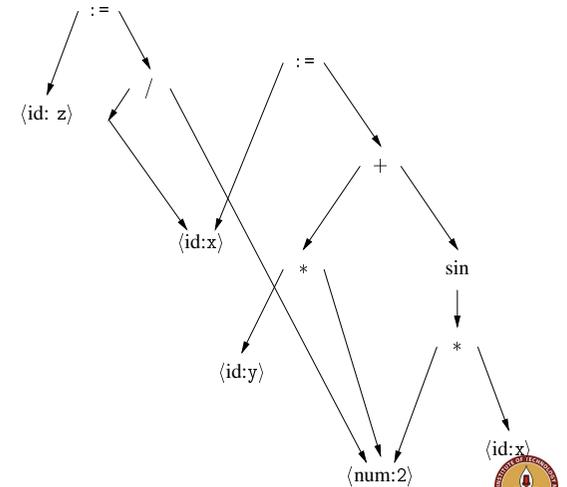
This represents “ $x - 2 * y$ ”.
 For ease of manipulation, can use a linearized (operator) form of the tree.
 e.g., in postfix form: $x \ 2 \ y \ * \ -$



Directed acyclic graph

A directed acyclic graph (DAG) is an AST with a unique node for each value.

```
x := 2 * y + sin (2*x)
z := x / 2
```



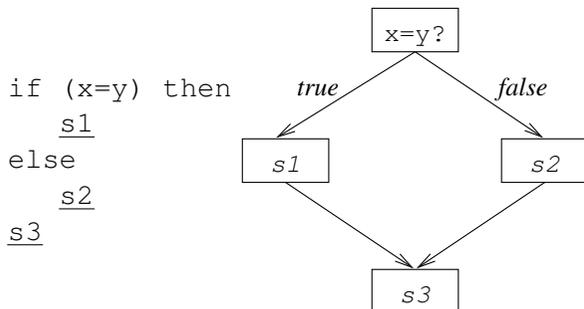
Q: What to do for matching names present across different functions



Control flow graph

The control flow graph (CFG) models the transfers of control in the procedure

- nodes in the graph are basic blocks
straight-line blocks of code
- edges in the graph represent control flow
loops, if-then-else, case, goto



3-address code

- At most one operator on the right side of an instruction.
- 3-address code can mean a variety of representations.
- In general, it allows statements of the form:

```
x ← y op z
```

with a single operator and, at most, three names.
 Simpler form of expression:

```
x ← 2 * y
```

becomes

```
t1 ← 2 * y
t2 ← x - t1
```

Advantages

- compact form (direct naming)
- names for intermediate values

Can include forms of prefix or postfix code



3-address code: Addresses

Three-address code is built from two concepts: addresses and instructions.

- An address can be
 - A name: source variable program name or pointer to the Symbol Table name.
 - A constant: Constants in the program.
 - Compiler generated temporary.



3-address code

Typical instructions types include:

- 1 assignments $x \leftarrow y \text{ op } z$
- 2 assignments $x \leftarrow \text{op } y$
- 3 assignments $x \leftarrow y[i]$
- 4 assignments $x \leftarrow y$
- 5 branches `goto L`
- 6 conditional branches
`if x goto L`
- 7 procedure calls
`param x1, param x2, ... param xn`
`and`
`call p, n`
- 8 address and pointer assignments

How to translate:

```
if (x < y) S1 else
S2
```

?



3-address code - implementation

Quadruples

- Has four fields: op, arg1, arg2 and result.
- Some instructions (e.g. unary minus) do not use arg2.
- For copy statement : the operator itself is =; for others it is implied.
- Instructions like `param` don't use neither arg2 nor result.
- Jumps put the target label in result.

	$x - 2 * y$			
	op	result	arg1	arg2
(1)	load	t1	y	
(2)	loadi	t2	2	
(3)	mult	t3	t2	t1
(4)	load	t4	x	
(5)	sub	t5	t4	t3

- simple record structure with four fields
- easy to reorder
- explicit names



3-address code - implementation

Triples

	$x - 2 * y$		
(1)	load	y	
(2)	loadi	2	
(3)	mult	(1)	(2)
(4)	load	x	
(5)	sub	(4)	(3)

- use table index as implicit name
- require only three fields in record
- harder to reorder



3-address code - implementation

Indirect Triples

$x - 2 * y$

	exec-order	stmt	op	arg1	arg2
(1)	(100)	(100)	load	y	
(2)	(101)	(101)	loadi	2	
(3)	(102)	(102)	mult	(100)	(101)
(4)	(103)	(103)	load	x	
(5)	(104)	(104)	sub	(103)	(102)

- simplifies moving statements (change the execution order)
- more space than triples
- implicit name space management



Indirect triples advantage

```
for i:=1 to 10 do
begin
  a=b*c
  d=i*3
end
(a)
```

Optimized version

```
a=b*c
for i:=1 to 10 do
begin
  d=i*3
end
(b)
```

(1) := 1 i
(2) nop
(3) * b c
(4) := (3) a
(5) * 3 i
(6) := (5) d
(7) + 1 i
(8) := (7) i
(9) LE i 10
(10) IFT goto (2)

Execution Order (a) : 1 2 3 4 5 6 7
8 9 10
Execution Order (b) : 3 4 1 2 5 6 7
8 9 10



Other hybrids

An attempt to get the best of both worlds.

- graphs where they work
- linear codes where it pays off

Unfortunately, there appears to be little agreement about where to use each kind of IR to best advantage.

For example:

- PCC and FORTRAN 77 directly emit assembly code for control flow, but build and pass around expression trees for expressions.
- Many people have tried using a control flow graph with low-level, three address code for each basic block.



Intermediate representations

But, this isn't the whole story

Symbol table:

- identifiers, procedures
- size, type, location
- lexical nesting depth

Constant table:

- representation, type
- storage class, offset(s)

Storage map:

- storage layout
- overlap information
- (virtual) register assignments



- Many kinds of IR are used in practice.
- There is no widespread agreement on this subject.
- A compiler may need several different IRs
- Choose IR with right level of detail
- Keep manipulation costs in mind



Translating expressions

```

S -> id = E; {gen(top.get(id.lexeme) '=' E.addr);}

E -> E1 + E2 {E.addr = new Temp();
              gen(E.addr '=' E1.addr '+' E2.addr);}

      | - E1  {E.addr = new Temp();
              gen(E.addr '=' - E2.addr);}

      | (E1)  {E.addr = E1.addr;}

      | id    {E.addr = top.get(id.lexeme);}

```

- Builds the three-address code for an assignment statement.
- addr: a synthesized-attr of E – denotes the address holding the val of E .
- Constructs a three-address instruction and appends the instruction to the sequence of instructions.
- top is the top-most (current) symbol table.



Gap between HLL and IR

- High level languages may allow complexities that are not allowed in IR (such as expressions with multiple operators).
- High level languages have many syntactic constructs, not present in the IR (such as if-then-else or loops)

Challenges in translation:

- Deep nesting of constructs.
- Recursive grammars.
- We need a systematic approach to IR generation.

Goal:

- A HLL to IR translator.
- Input: A program in HLL.
- Output: A program in IR (may be an AST or program text)



IR generation for flow-of-control statements

```

P->S          S.next = new Label();
              P.code = S.code || label(S.next)

S->assign     S.code = assign.code

S->if (B) S1   B.true = new Label();
              B.false = S1.next = S.next
              S.code = B.code || label(B.true) || S1.code

S->if (B) S1   B.true = new Label();
              else S2 B.false = new Label();
              S1.next = S2.next = S.next
              S.code = B.code || label(B.true) || S1.code
                  || gen ('goto' S.next)
                  || label (B.false) || S2.code

```

- *code* is an synthetic attribute: giving the code for that node.
- Assume: *gen* only creates an instruction.
- `||` concatenates the code.



IR generation for flow-of-control statements

```

S->while (B) S1      begin = new Label();
                    B.true = new Label();
                    B.false = S.next
                    S1.next = begin
                    S.code = begin || B.code
                        || label(B.true) || S1.code
                        || 'goto' || begin

S->S1 S2             S1.next = new Label()
                    S2.next = S.next
                    S.code = S1.code || label(S1.next) || S2.code
    
```

- *code* is an synthetic attribute: giving the code for that node.
- Assume: *gen* only creates an instruction.
- `||` concatenates the code.



IR generation for boolean expressions

```

B -> B1 || B2      B1.true = B.true
                  B1.false = new Label()
                  B2.true = B.true
                  B2.false = B.false
                  B.code = B1.code || label(B1.false) || B2.code

B -> B1 && B2      B1.true = new Label()
                  B1.false = B.false
                  B2.true = B.true
                  B2.false = B.false
                  B.code = B1.code || label(B1.true) || B2.code

B -> !B1           B1.true = B.false
                  B1.false = B.true
                  B.code = B1.code

B -> E1 rel E2     t = new Temp()
                  B.code=E1.code||E2.code|| t || '=' || E1.addr || rel.op || E2.addr
                  || 'if' || t || 'goto' || B.true
                  || 'goto' || B.false;

B -> true          B.code = 'goto' || B.true

B -> false         B.code = 'goto' || B.false
    
```



Array elements dereference (Recall)

- Elements are typically stored in a block of consecutive locations.
- If the width of each array element is w , then the i^{th} element of array A (say, starting at the address $base$), begins at the location: $base + i \times w$.
- For multi-dimensions, beginning address of $A[i_1][i_2]$ is calculated by the formula:
 $base + i_1 \times w_1 + i_2 \times w_2$
 where, w_1 is the width of the row, and w_2 is the width of one element.
- We declare arrays by the number of elements (n_j is the size of the j^{th} dimension) and the width of each element in an array is fixed (say w).
 The location for $A[i_1][i_2]$ is given by
 $base + (i_1 \times n_2 + i_2) \times w$
- Q: If the array index does not start at '0', then ?
- Q: What if the data is stored in column-major form?



Translation of Array references

- Extending the expression grammar with arrays:

```

S -> id = E;
    | L = E;

E -> E1 + E2      L -> id [E]
                  | L1 [E]
                  | id
                  | L
    
```



Translation of Array references (contd)

```
S -> id = E; {gen(top.get(id.lexeme) '=' E.addr)}
      | L = E; {gen(L.array.base['L.addr'] '=' E.addr);}
E -> E1 + E2 {E.addr = new Temp();
              gen(E.addr '=' E1.addr '+' E2.addr);}
      | id    {E.addr = top.get(id.lexeme);}
      | L     {E.addr = new Temp();
              gen(E.addr '=' L.array.base['L.addr'])};
```

Nonterminal L has three synthesized attributes

- 1 $L.addr$ denotes a temporary that is used while computing the offset for the array reference.
- 2 $L.array$ is a pointer to the ST entry for the array name. The field *base* gives the actual l-value of the array reference.



Translation of Array references (contd)

```
L -> Id [E] {L.array = top.get(id.lexeme);
             L.type = L.array.type.elem;
             L.addr = new Temp();
             gen(L.addr '=' E.addr '*' L.type.width);}
      | L1 [E] {L.array = L1.array;
              L.type = L1.type.elem;
              t = new Temp();
              L.addr = new Temp();
              gen(t '=' E.addr '*' L.type.width);
              gen(L.addr '=' L1.addr '+' t);}
```

- 3 $L.type$ is the type of the subarray generated by L .
 - For any type t : $t.width$ gives get the width of the type.
 - For any type t : $t.elem$ gives the element type.



Translation of Array references (contd)

Example:

- Let a denotes a 2×3 integer array.
- Type of a is given by $array(2, array(3, integer))$
- Width of $a = 24$ (size of $integer = 4$).
- Type of $a[i]$ is $array(3, integer)$, width = 12.
- Type of $a[i][j] = integer$

Exercise:

- Write three address code for $c + a[i][j]$

```
t1 = i * 12
t2 = j * 4
t3 = t1 + t2
t4 = a [t3]
t5 = c + t4
```



Q: What if we did not know the size of $integer$ (machine dependent)?

Some challenges/questions

- Avoiding redundant gotos. ??
- Multiple passes. ??
- How to translate implicit branches: `break` and `continue`?
- How to translate `switch` statements efficiently?
- How to translate procedure code?



What have we done in last few classes?

- Intermediate Code Generation.

To read

- Dragon Book. Sections 6.4, 6.5, 6.6, 6.7, 6.8, 6.9 and 2.8

