

## CS3300 - Compiler Design

### Semantic Analysis - IR Generation

V. Krishna Nandivada

IIT Madras

## Acknowledgement

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## Intermediate representations

### Why use an intermediate representation?

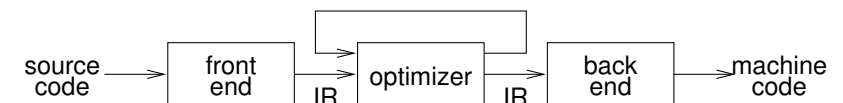
- 1 break the compiler into manageable pieces
  - good software engineering technique
- 2 simplifies retargeting to new host
  - isolates back end from front end
- 3 simplifies handling of “poly-architecture” problem
  - $m$  lang's,  $n$  targets  $\Rightarrow m + n$  components
- 4 enables machine-independent 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 ← a[i,j+2]	t1 ← j + 2	r1 ← [fp-4]
	t2 ← i * 20	r2 ← r1 + 2
	t3 ← t1 + t2	r3 ← [fp-8]
	t4 ← 4 * t3	r4 ← r3 * 20
	t5 ← addr a	r5 ← r4 + r2
	t6 ← t5 + t4	r6 ← 4 * r5
	t7 ← *t6	r7 ← fp - 216
		f1 ← [r7+r6]

(a) (b) (c)

(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

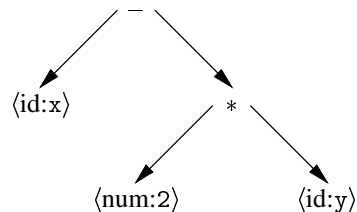
Broadly speaking, IRs fall into three categories:

- 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.

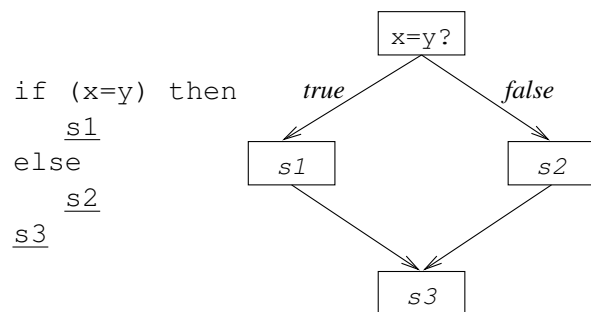
e.g., in postfix form:  $x \ 2 \ y \ * \ -$



## Control flow graph

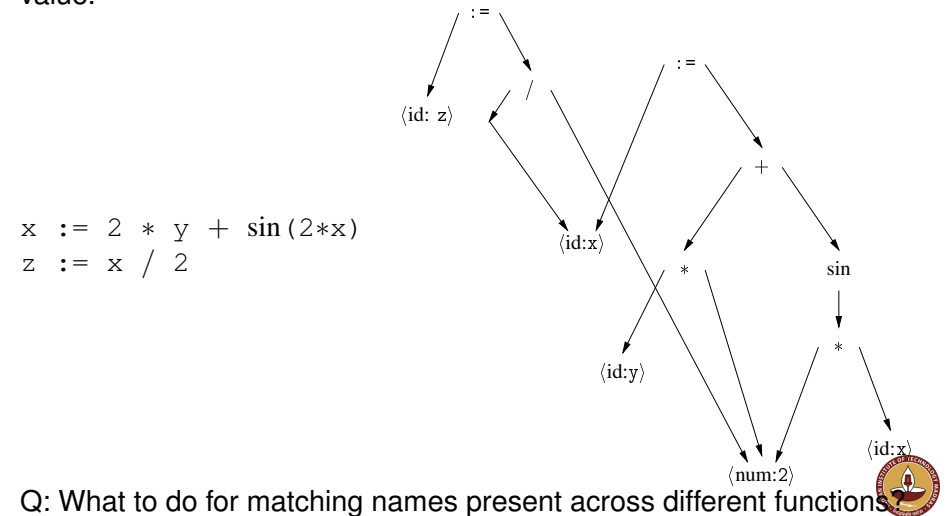
The control flow graph (CFG) models the transfers of control in the procedure

- 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



## Directed acyclic graph

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



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

## 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:

$$x \leftarrow y \ op \ z$$

with a single operator and, at most, three names.

Simpler form of expression:

$$x - 2 * y$$

becomes

$$t1 \leftarrow 2 * y$$

$$t2 \leftarrow x - t1$$

### 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.

$x - 2 * y$				
	<u>op</u>	<u>result</u>	<u>arg1</u>	<u>arg2</u>
(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



## 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.



## 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



## 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 synthetic-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

## 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

$P \rightarrow S$	$S.next = newlabel()$ $P.code = S.code \parallel label(S.next)$
$S \rightarrow \text{assign}$	$S.code = \text{assign.code}$
$S \rightarrow \text{if}(B) S_1$	$B.true = newlabel()$ $B.false = S_1.next = S.next$ $S.code = B.code \parallel label(B.true) \parallel S_1.code$
$S \rightarrow \text{if}(B) S_1 \text{ else } S_2$	$B.true = newlabel()$ $B.false = newlabel()$ $S_1.next = S_2.next = S.next$ $S.code = B.code$ $\parallel label(B.true) \parallel S_1.code$ $\parallel gen('goto' S.next)$ $\parallel label(B.false) \parallel S_2.code$

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



## IR generation for flow-of-control statements

$$\begin{array}{lcl}
 S \rightarrow \text{while} ( B ) S_1 & | & \begin{array}{l} \text{begin} = \text{newlabel}() \\ B.\text{true} = \text{newlabel}() \\ B.\text{false} = S.\text{next} \\ S_1.\text{next} = \text{begin} \\ S.\text{code} = \text{label}(\text{begin}) || B.\text{code} \\ \quad || \text{label}(B.\text{true}) || S_1.\text{code} \\ \quad || \text{gen}(\text{'goto' begin}) \end{array} \\
 \\
 S \rightarrow S_1 S_2 & | & \begin{array}{l} S_1.\text{next} = \text{newlabel}() \\ S_2.\text{next} = S.\text{next} \\ S.\text{code} = S_1.\text{code} || \text{label}(S_1.\text{next}) || S_2.\text{code} \end{array}
 \end{array}$$

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



## IR generation for boolean expressions

$$\begin{array}{lcl}
 B \rightarrow B_1 || B_2 & | & \begin{array}{l} B_1.\text{true} = B.\text{true} \\ B_1.\text{false} = \text{newlabel}() \\ B_2.\text{true} = B.\text{true} \\ B_2.\text{false} = B.\text{false} \\ B.\text{code} = B_1.\text{code} || \text{label}(B_1.\text{false}) || B_2.\text{code} \end{array} \\
 \\
 B \rightarrow B_1 \&\& B_2 & | & \begin{array}{l} B_1.\text{true} = \text{newlabel}() \\ B_1.\text{false} = B.\text{false} \\ B_2.\text{true} = B.\text{true} \\ B_2.\text{false} = B.\text{false} \\ B.\text{code} = B_1.\text{code} || \text{label}(B_1.\text{true}) || B_2.\text{code} \end{array} \\
 \\
 B \rightarrow ! B_1 & | & \begin{array}{l} B_1.\text{true} = B.\text{false} \\ B_1.\text{false} = B.\text{true} \\ B.\text{code} = B_1.\text{code} \end{array} \\
 \\
 B \rightarrow E_1 \text{ rel } E_2 & | & \begin{array}{l} B.\text{code} = E_1.\text{code} || E_2.\text{code} \\ \quad || \text{gen}(\text{'if' } E_1.\text{addr rel.op } E_2.\text{addr 'goto' } B.\text{true}) \\ \quad || \text{gen}(\text{'goto' } B.\text{false}) \end{array} \\
 \\
 B \rightarrow \text{true} & | & B.\text{code} = \text{gen}(\text{'goto' } B.\text{true}) \\
 \\
 B \rightarrow \text{false} & | & B.\text{code} = \text{gen}(\text{'goto' } B.\text{false})
 \end{array}$$


## 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  $i^{\text{th}}$  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  $j^{\text{th}}$  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:

$$S \rightarrow \text{id} = E ;$$

$$\begin{array}{lcl}
 | & L = E ; & L \rightarrow \text{id} [ E ]
 \end{array}$$

$$E \rightarrow E_1 + E_2$$

$$\begin{array}{lcl}
 | & \text{id} & | & L_1 [ E ]
 \end{array}$$

$$| \quad L$$


## Translation of Array references (contd)

$$\begin{aligned}
 S &\rightarrow \text{id} = E ; \quad \{ \text{gen}( \text{top.get}(\text{id.lexeme}) \neq E.\text{addr}); \} \\
 &\quad | \quad L = E ; \quad \{ \text{gen}(L.\text{addr.base} \neq L.\text{addr} \neq E.\text{addr}); \} \\
 E &\rightarrow E_1 + E_2 \quad \{ E.\text{addr} = \text{new Temp}(); \\
 &\quad \text{gen}(E.\text{addr} \neq E_1.\text{addr} + E_2.\text{addr}); \} \\
 &\quad | \quad \text{id} \quad \{ E.\text{addr} = \text{top.get}(\text{id.lexeme}); \} \\
 &\quad | \quad L \quad \{ E.\text{addr} = \text{new Temp}(); \\
 &\quad \text{gen}(E.\text{addr} \neq L.\text{array.base} \neq L.\text{addr}); \}
 \end{aligned}$$

Nonterminal  $L$  has three synthesized attributes

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



## Translation of Array references (contd)

$$\begin{aligned}
 L &\rightarrow \text{id} [ E ] \quad \{ L.\text{array} = \text{top.get}(\text{id.lexeme}); \\
 &\quad L.\text{type} = L.\text{array.type.elem}; \\
 &\quad L.\text{addr} = \text{new Temp}(); \\
 &\quad \text{gen}(L.\text{addr} \neq E.\text{addr} * L.\text{type.width}); \} \\
 &\quad | \quad L_1 [ E ] \quad \{ L.\text{array} = L_1.\text{array}; \\
 &\quad L.\text{type} = L_1.\text{type.elem}; \\
 &\quad t = \text{new Temp}(); \\
 &\quad L.\text{addr} = \text{new Temp}(); \\
 &\quad \text{gen}(t \neq E.\text{addr} * L.\text{type.width}); \} \\
 &\quad \text{gen}(L.\text{addr} \neq L_1.\text{addr} + t); \}
 \end{aligned}$$

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



## Translation of Array references (contd)

Example:

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

Exercise:

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

$$\begin{aligned}
 t_1 &= i * 12 \\
 t_2 &= j * 4 \\
 t_3 &= t_1 + t_2 \\
 t_4 &= a [ t_3 ] \\
 t_5 &= c + t_4
 \end{aligned}$$


Q: What if we did not know the size of  $\text{integer}$  (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?





## Closing remarks

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

