Compiler course

Chapter 6

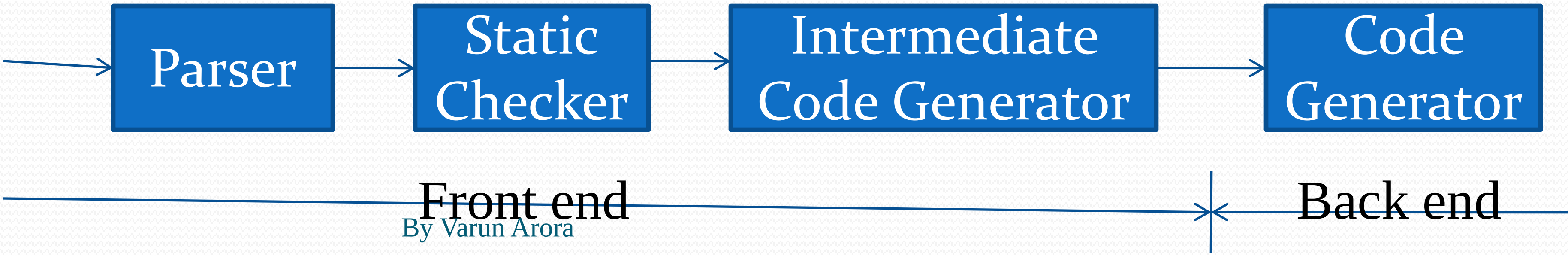
Intermediate Code Generation

Outline

- Variants of Syntax Trees
- Three-address code
- Types and declarations
- Translation of expressions
- Type checking
- Control flow
- Backpatching

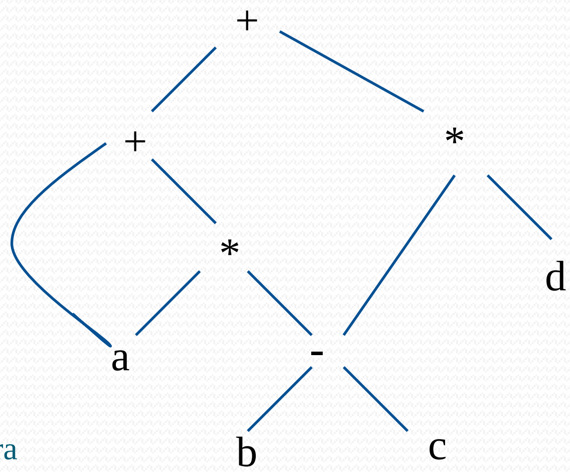
Introduction

- Intermediate code is the interface between front end and back end in a compiler
- Ideally the details of source language are confined to the front end and the details of target machines to the back end (a m*n model)
- In this chapter we study intermediate representations, static type checking and intermediate code generation



Variants of syntax trees

- It is sometimes beneficial to crate a DAG instead of tree for Expressions.
- This way we can easily show the common sub-expressions and then use that knowledge during code generation
- Example: a+a*(b-c)+(b-c)*d



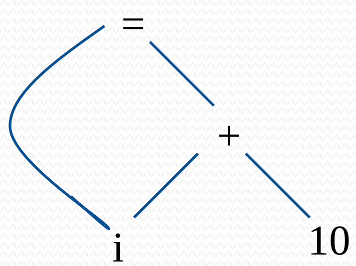
SDD for creating DAG's

Production	Semantic Rules
1) E -> E1+T	E.node= new Node('+', E1.node,T.node)
2) E -> E1-T	E.node= new Node('-', E1.node,T.node)
3) E -> T	E.node = T.node
4) T -> (E)	T.node = E.node
5) T -> id	T.node = new Leaf(id, id.entry)
6) T -> num	T.node = new Leaf(num, num.val)

Example:

1) p1=Leaf(id, entry-a)
2) P2=Leaf(id, entry-a)=p1
3) p3=Leaf(id, entry-b)
4) p4=Leaf(id, entry-c)
5) p5=Node('-',p3,p4)
6) p6=Node('*',p1,p5)
7) p7=Node('+',p1,p6)
8) p8=Leaf(id,entry-b)=p3
9) p9=Leaf(id,entry-c)=p4
10) p10=Node('-',p3,p4)=p5
11) p11=Leaf(id,entry-d)
12) p12=Node('*',p5,p11)
13) p13=Node('+',p7,p12)

Value-number method for constructing DAG's

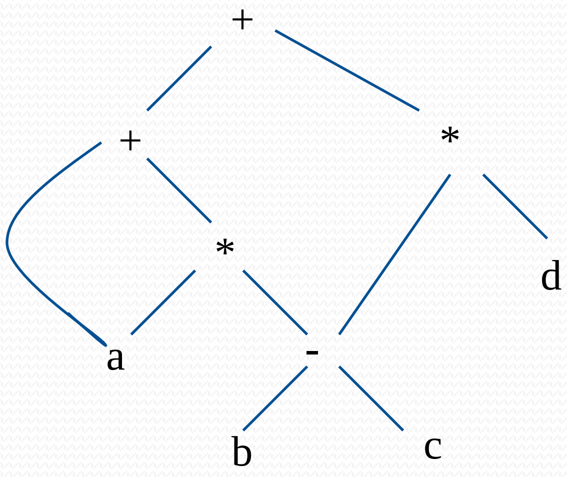


id	→ To entry for i	
num	10	
+	1	2
3	1	3

- Algorithm
  - Search the array for a node M with label op, left child l and right child r
  - If there is such a node, return the value number M
  - If not create in the array a new node N with label op, left child l, and right child r and return its value
- We may use a hash table

Three address code

- In a three address code there is at most one operator at the right side of an instruction
- Example:



t1 = b – c
t2 = a * t1
t3 = a + t2
t4 = t1 * d
t5 = t3 + t4

Forms of three address instructions

- x = y op z
- x = op y
- x = y
- goto L
- if x goto L and ifFalse x goto L
- if x relop y goto L
- Procedure calls using:
  - param x
  - call p,n
  - y = call p,n
- x = y[i] and x[i] = y
- x = &y and x = *y and *x =y

Example

- do i = i+1; while (a[i] < v);

Symbolic labels		Position numbers	
L:	t1 = i + 1	100:	t1 = i + 1
	i = t1	101:	i = t1
	t2 = i * 8	102:	t2 = i * 8
	t3 = a[t2]	103:	t3 = a[t2]
	if t3 < v goto L	104:	if t3 < v goto 100

Symbolic labels

Position numbers

Data structures for three address codes

- Quadruples
  - Has four fields: op, arg1, arg2 and result
- Triples
  - Temporaries are not used and instead references to instructions are made
- Indirect triples
  - In addition to triples we use a list of pointers to triples

Example

- b * minus c + b * minus c

Three address code

t1 = minus c
t2 = b * t1
t3 = minus c
t4 = b * t3
t5 = t2 + t4
a = t5

Quadruples

op	arg1	arg2	result
minus	c		t1
*	b	t1	t2
minus	c		t3
*	b	t3	t4
+	t2	t4	t5
=	t5		a

Triples

	op	arg1	arg2
0	minus	c	
1	*	b	(0)
2	minus	c	
3	*	b	(2)
4	+	(1)	(3)
5	=	a	(4)

Indirect Triples

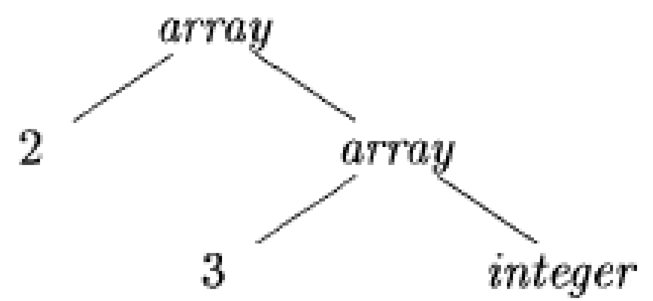
	op
35	(0)
36	(1)
37	(2)
38	(3)
39	(4)
40	(5)

	op	arg1	arg2
0	minus	c	
1	*	b	(0)
2	minus	c	
3	*	b	(2)
4	+	(1)	(3)
5	=	a	(4)

Type Expressions

Example: int[2][3]

array(2,array(3,integer))



- A basic type is a type expression
- A type name is a type expression
- A type expression can be formed by applying the array type constructor to a number and a type expression.
- A record is a data structure with named field
- A type expression can be formed by using the type constructor → for function types
- If s and t are type expressions, then their Cartesian product s**t* is a type expression
- Type expressions may contain variables whose values are type expressions

Type Equivalence

- They are the same basic type.
- They are formed by applying the same constructor to structurally equivalent types.
- One is a type name that denotes the other.

Declarations

$$
\begin{array}{lcl}
D & \rightarrow & T\ \textbf{id}\ ;\ D \mid \epsilon \\
T & \rightarrow & B\ C \mid \textbf{record}\ '\{'\ D\ '\}' \\
B & \rightarrow & \textbf{int} \mid \textbf{float} \\
C & \rightarrow & \epsilon \mid [\ \textbf{num}\ ]\ C
\end{array}
$$

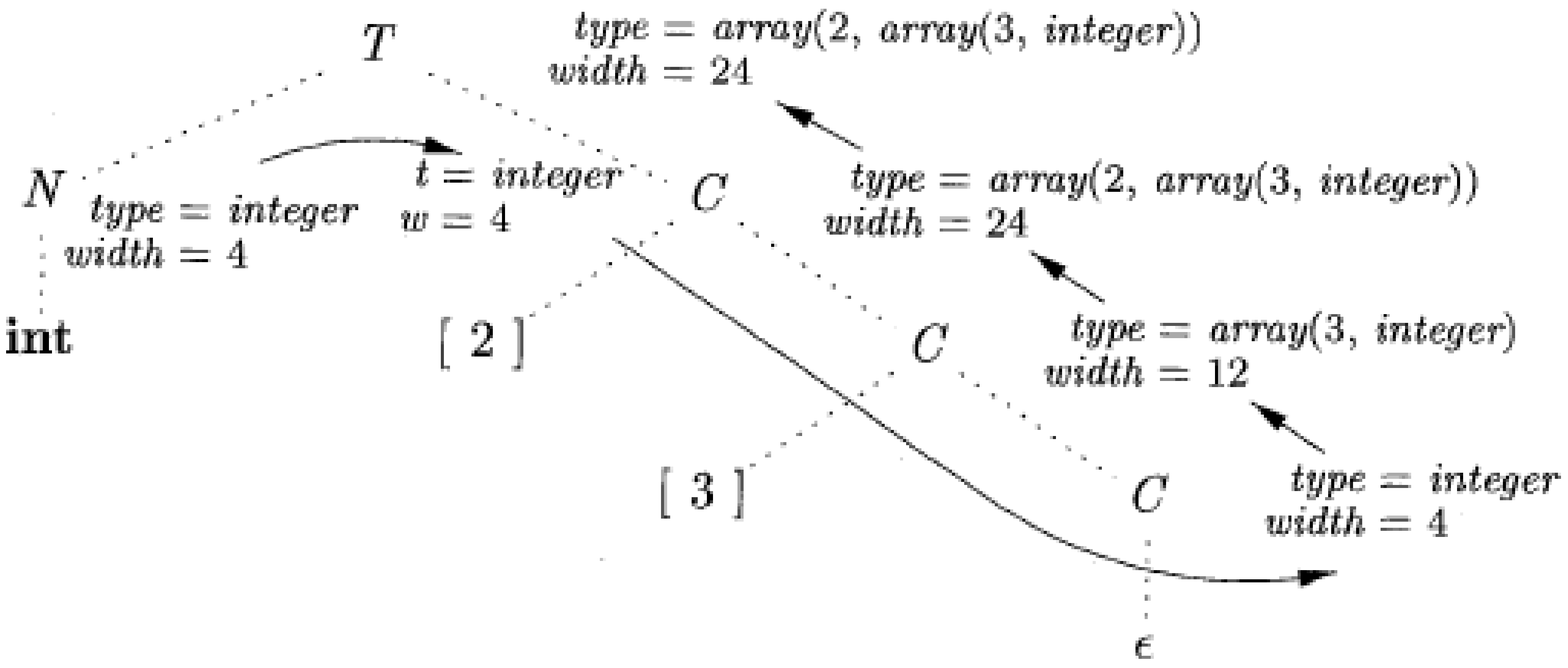
Storage Layout for Local Names

- Computing types and their widths

$$
\begin{array}{llll}
T & \rightarrow & B & \{\ t = B.type;\ w = B.width;\ \} \\
 & & C & \\
B & \rightarrow & \textbf{int} & \{\ B.type = integer;\ B.width = 4;\ \} \\
B & \rightarrow & \textbf{float} & \{\ B.type = float;\ B.width = 8;\ \} \\
C & \rightarrow & \epsilon & \{\ C.type = t;\ C.width = w;\ \} \\
C & \rightarrow & [\ \textbf{num}\ ]\ C_1 & \{\ array(\textbf{num}.value,\ C_1.type); \\
 & & & \quad C.width = \textbf{num}.value \times C_1.width;\ \}
\end{array}
$$

Storage Layout for Local Names

- Syntax-directed translation of array types



Sequences of Declarations

- $$\begin{array}{lll} P & \rightarrow & \{\ offset = 0;\ \} \\ & & D \\ D & \rightarrow & T\ \mathbf{id}\ ;\quad \{\ top.put(\mathbf{id}.lexeme,\ T.type,\ offset); \\ & & \quad offset = offset + T.width;\ \} \\ & & D_1 \\ D & \rightarrow & \epsilon \end{array}$$

- Actions at the end:

- $$\begin{array}{llll} P & \rightarrow & M\ D & \\ M & \rightarrow & \epsilon & \{\ offset = 0;\ \} \end{array}$$

Fields in Records and Classes

- ```
  float x;
  record { float x; float y; } p;
  record { int tag; float x; float y; } q;
  ```

- $$\begin{array}{llll} T & \rightarrow & \textbf{record}\ '\{' & \{\ Env.push(top);\ top = \textbf{new}\ Env(); \\ & & & \quad Stack.push(offset);\ offset = 0;\ \} \\ & & D\ '\}' & \{\ T.type = record(top);\ T.width = offset; \\ & & & \quad top = Env.pop();\ offset = Stack.pop();\ \} \end{array}$$
  ```

Translation of Expressions and Statements

- We discussed how to find the types and offset of variables
- We have therefore necessary preparations to discuss about translation to intermediate code
- We also discuss the type checking

Three-address code for expressions

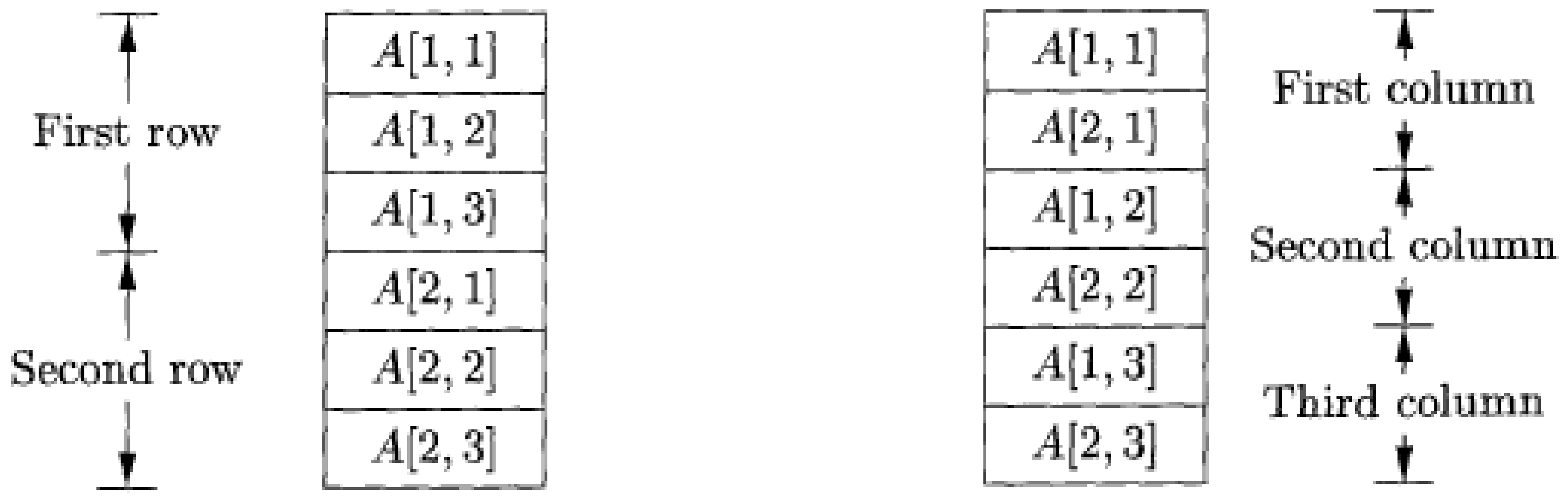
PRODUCTION	SEMANTIC RULES
$S \rightarrow \textbf{id} = E\ ;$	$S.code = E.code \ \|\|$ $gen(top.get(\textbf{id}.lexeme)\ '='\ E.addr)$
$E \rightarrow E_1 + E_2$	$E.addr = \textbf{new}\ Temp\,()$ $E.code = E_1.code \ \|\|\ E_2.code \ \|\|$ $gen(E.addr\ '='\ E_1.addr\ '+'\ E_2.addr)$
$\mid\ - E_1$	$E.addr = \textbf{new}\ Temp\,()$ $E.code = E_1.code \ \|\|$ $gen(E.addr\ '='\ '\textbf{minus}'\ E_1.addr)$
$\mid\ (\ E_1\ )$	$E.addr = E_1.addr$ $E.code = E_1.code$
$\mid\ \textbf{id}$	$E.addr = top.get(\textbf{id}.lexeme)$ $E.code = ''$

Incremental Translation

$$
\begin{array}{lcll}
S & \rightarrow & \textbf{id} = E\ ; & \{\ gen(\ top.get(\textbf{id}.lexeme)\ '='\ E.addr);\ \} \\
E & \rightarrow & E_1 + E_2 & \{\ E.addr = \textbf{new}\ Temp();\\
 & & & \quad gen(E.addr\ '='\ E_1.addr\ '+'\ E_2.addr);\ \} \\
 & | & -\ E_1 & \{\ E.addr = \textbf{new}\ Temp();\\
 & & & \quad gen(E.addr\ '='\ '\textbf{minus}'\ E_1.addr);\ \} \\
 & | & (\ E_1\ ) & \{\ E.addr = E_1.addr;\ \} \\
 & | & \textbf{id} & \{\ E.addr = top.get(\textbf{id}.lexeme);\ \}
\end{array}
$$

Addressing Array Elements

- Layouts for a two-dimensional array:



(a) Row Major

(b) Column Major

Semantic actions for array reference

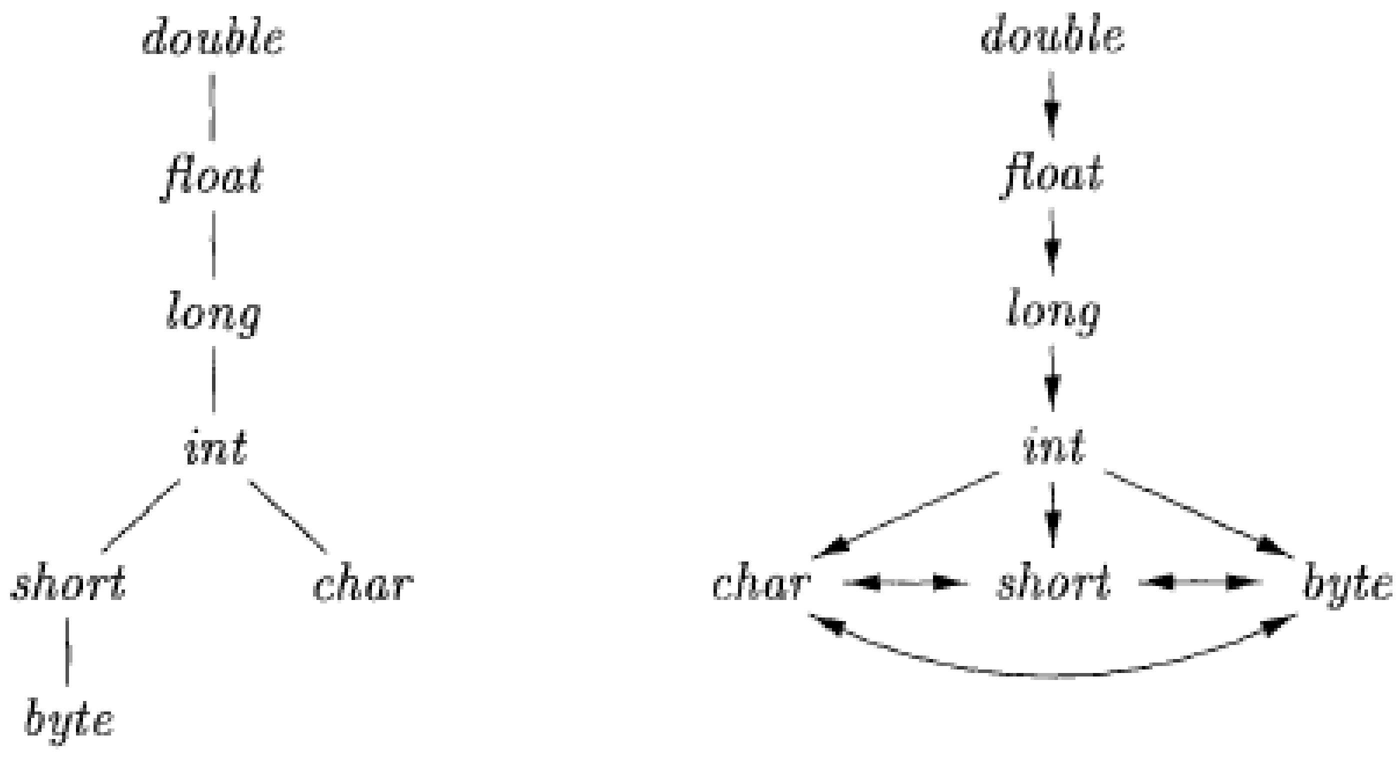
$S \rightarrow \textbf{id} = E \;;$	$\{ \; gen(\; top.get(\textbf{id}.lexeme) \; '=' \; E.addr); \; \}$
$\quad \mid \; L = E \;;$	$\{ \; gen(L.addr.base \; '[' \; L.addr \; ']' \; '=' \; E.addr); \; \}$
$E \rightarrow E_1 + E_2$	$\{ \; E.addr = \textbf{new} \; Temp\,();$ $gen(E.addr \; '=' \; E_1.addr \; '+' \; E_2.addr); \; \}$
$\quad \mid \; \textbf{id}$	$\{ \; E.addr = top.get(\textbf{id}.lexeme); \; \}$
$\quad \mid \; L$	$\{ \; E.addr = \textbf{new} \; Temp\,();$ $gen(E.addr \; '=' \; L.array.base \; '[' \; L.addr \; ']'); \; \}$
$L \rightarrow \textbf{id} \; [\; E \;]$	$\{ \; L.array = top.get(\textbf{id}.lexeme);$ $L.type = L.array.type.elem;$ $L.addr = \textbf{new} \; Temp\,();$ $gen(L.addr \; '=' \; E.addr \; '*' \; L.type.width); \; \}$
$\quad \mid \; L_1 \; [\; E \;]$	$\{ \; L.array = L_1.array;$ $L.type = L_1.type.elem;$ $t = \textbf{new} \; Temp\,();$ $L.addr = \textbf{new} \; Temp\,();$ $gen(t \; '=' \; E.addr \; '*' \; L.type.width); \; \}$ $gen(L.addr \; '=' \; L_1.addr \; '+' \; t); \; \}$

Translation of Array References

Nonterminal *L* has three synthesized attributes:

- *L.addr*
- L.array
- L.type

Conversions between primitive types in Java



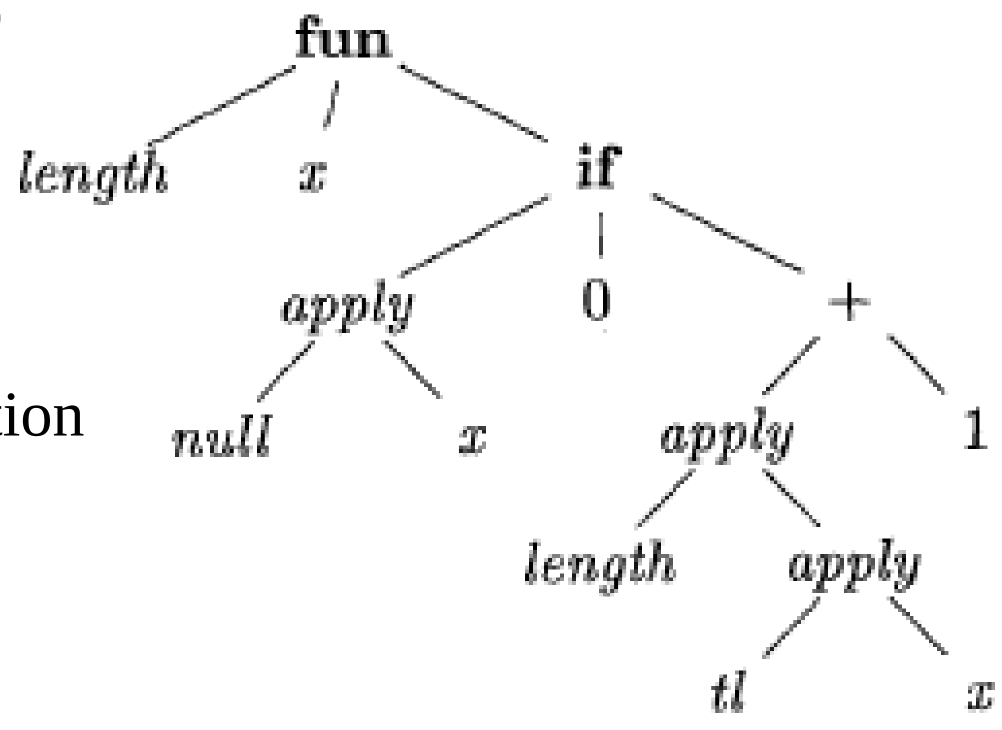
(a) Widening conversions (b) Narrowing conversions

Introducing type conversions into expression evaluation

$$
\begin{aligned}
E \;\rightarrow\; E_1 + E_2 \quad \{ \; & E.type \;=\; max(E_1.type, E_2.type); \\
& a_1 \;=\; widen(E_1.addr, E_1.type, E.type); \\
& a_2 \;=\; widen(E_2.addr, E_2.type, E.type); \\
& E.addr = \textbf{new}\; Temp\,(); \\
& gen(E.addr\; '=' \; a_1 \; '+' \; a_2); \; \}
\end{aligned}
$$

Abstract syntax tree for the function definition

fun length(x) =
  if null(x) then 0 else length(tl(x)+1)



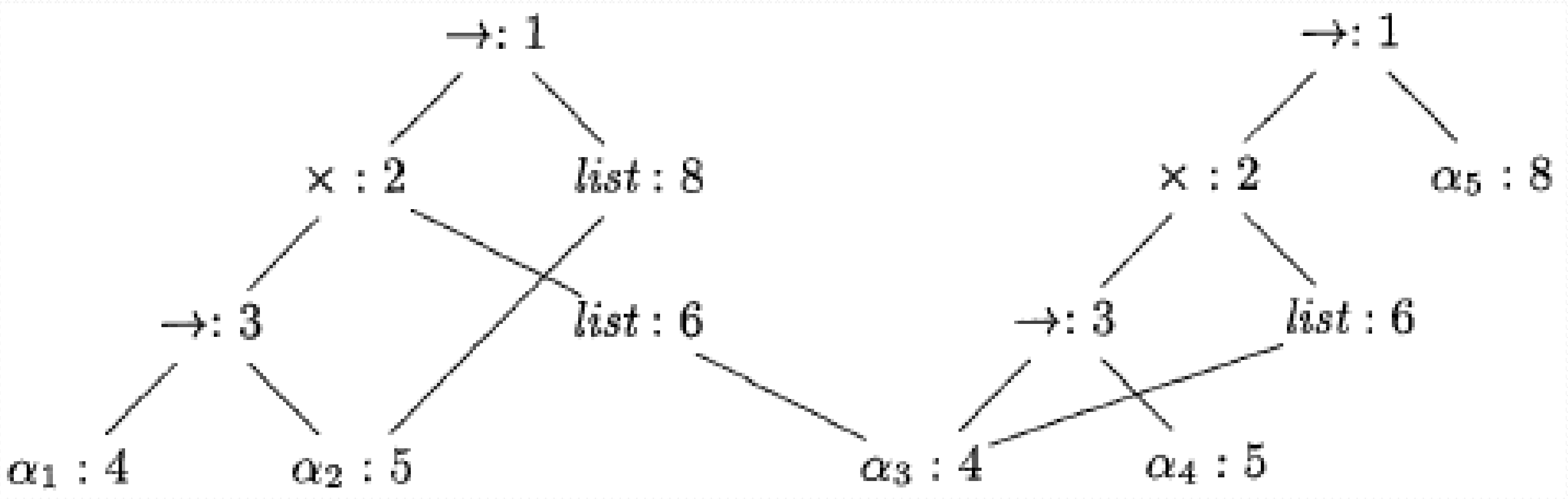
This is a polymorphic function in ML language

Inferring a type for the function *length*

LINE	EXPRESSION : TYPE	UNIFY
1)	$length : \beta \to \gamma$	
2)	$x : \beta$	
3)	$\textbf{if} : boolean \times \alpha_i \times \alpha_i \to \alpha_i$	
4)	$null : list(\alpha_n) \to boolean$	
5)	$null(x) : boolean$	$list(\alpha_n) = \beta$
6)	$0 : integer$	$\alpha_i = integer$
7)	$+ : integer \times integer \to integer$	
8)	$tl : list(\alpha_t) \to list(\alpha_t)$	
9)	$tl(x) : list(\alpha_t)$	$list(\alpha_t) = list(\alpha_n)$
10)	$length(tl(x)) : \gamma$	$\gamma = integer$
11)	$1 : integer$	
12)	$length(tl(x)) + 1 : integer$	
13)	$\textbf{if}(\cdots) : integer$	

Algorithm for Unification

$$((\alpha_1 \to \alpha_2) \times list(\alpha_3)) \to list(\alpha_2)$$
$$((\alpha_3 \to \alpha_4) \times list(\alpha_3)) \to \alpha_5$$



Unification algorithm

```
boolean unify (Node m, Node n) {
    s = find(m); t = find(n);
    if ( s = t ) return true;
    else if ( nodes s and t represent the same basic type ) return true;
    else if (s is an op-node with children s1 and s2 and
             t is an op-node with children t1 and t2) {
             union(s , t) ;
             return unify(s1, t1) and unify(s2, t2);
    }
    else if s or t represents a variable {
             union(s, t) ;
             return true;
    }
    else return false;
}
```

Control Flow

boolean expressions are often used to:

- *Alter the flow of control.*
- *Compute logical values.*

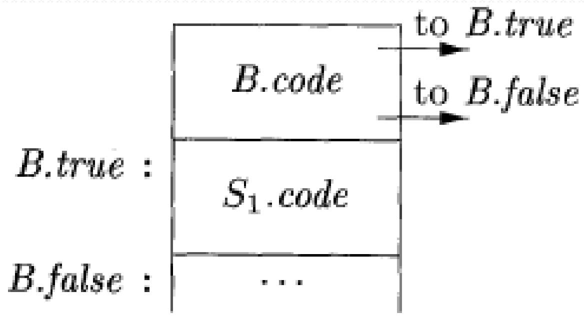
Short-Circuit Code

- ```
  if ( x < 100 || x > 200 && x != y ) x = 0;
  ```

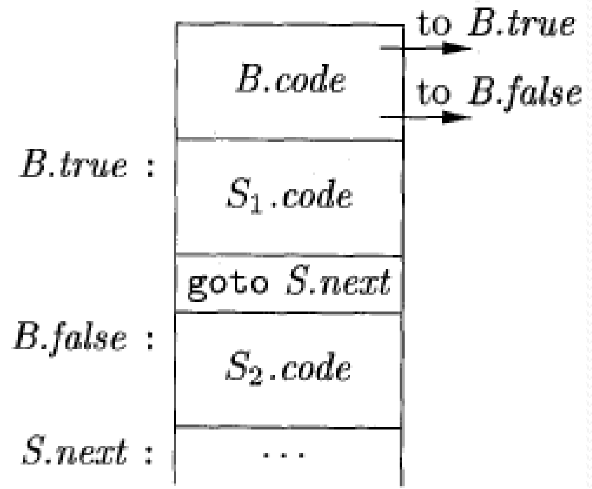
- ```
          if x < 100 goto L2
          ifFalse x > 200 goto L1
          ifFalse x != y goto L1
  L2:     x = 0
  L1:
  ```

Flow-of-Control Statements

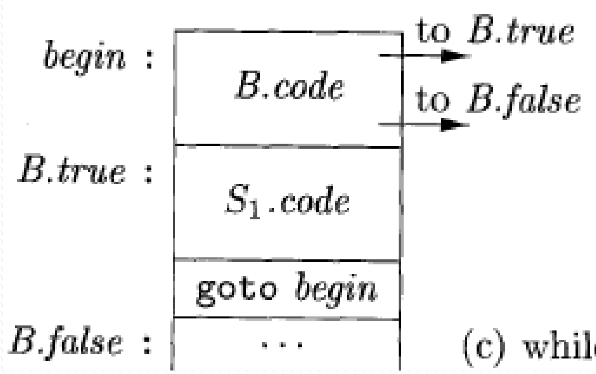
$$S \rightarrow \textbf{if}\ (\ B\ )\ S_1$$
$$S \rightarrow \textbf{if}\ (\ B\ )\ S_1\ \textbf{else}\ S_2$$
$$S \rightarrow \textbf{while}\ (\ B\ )\ S_1$$



(a) if



(b) if-else



(c) while

Syntax-directed definition

PRODUCTION	SEMANTIC RULES
$P \rightarrow S$	$S.next = newlabel()$ $P.code = S.code \;\|\|\; label(S.next)$
$S \rightarrow \textbf{assign}$	$S.code = \textbf{assign}.code$
$S \rightarrow \textbf{if}\ (\ B\ )\ S_1$	$B.true = newlabel()$ $B.false = S_1.next = S.next$ $S.code = B.code \;\|\|\; label(B.true) \;\|\|\; S_1.code$
$S \rightarrow \textbf{if}\ (\ B\ )\ S_1\ \textbf{else}\ S_2$	$B.true = newlabel()$ $B.false = newlabel()$ $S_1.next = S_2.next = S.next$ $S.code = B.code$ $\|\|\; label(B.true) \;\|\|\; S_1.code$ $\|\|\; gen('\texttt{goto}'\ S.next)$ $\|\|\; label(B.false) \;\|\|\; S_2.code$
$S \rightarrow \textbf{while}\ (\ B\ )\ S_1$	$begin = newlabel()$ $B.true = newlabel()$ $B.false = S.next$ $S_1.next = begin$ $S.code = label(begin) \;\|\|\; B.code$ $\|\|\; label(B.true) \;\|\|\; S_1.code$ $\|\|\; gen('\texttt{goto}'\ begin)$
$S \rightarrow S_1\ S_2$	$S_1.next = newlabel()$ $S_2.next = S.next$ $S.code = S_1.code \;\|\|\; label(S_1.next) \;\|\|\; S_2.code$

Generating three-address code for booleans

PRODUCTION	SEMANTIC RULES
$B \rightarrow B_1 \mid\mid B_2$	$B_1.true = B.true$ $B_1.false = newlabel()$ $B_2.true = B.true$ $B_2.false = B.false$ $B.code = B_1.code \mid\mid label(B_1.false) \mid\mid B_2.code$
$B \rightarrow B_1 \; \&\& \; B_2$	$B_1.true = newlabel()$ $B_1.false = B.false$ $B_2.true = B.true$ $B_2.false = B.false$ $B.code = B_1.code \mid\mid label(B_1.true) \mid\mid B_2.code$
$B \rightarrow \; ! \; B_1$	$B_1.true = B.false$ $B_1.false = B.true$ $B.code = B_1.code$
$B \rightarrow E_1 \; \mathbf{rel} \; E_2$	$B.code = E_1.code \mid\mid E_2.code$ $\mid\mid gen('\texttt{if}' \; E_1.addr \; \mathbf{rel}.op \; E_2.addr \; '\texttt{goto}' \; B.true)$ $\mid\mid gen('\texttt{goto}' \; B.false)$
$B \rightarrow \mathbf{true}$	$B.code = gen('\texttt{goto}' \; B.true)$
$B \rightarrow \mathbf{false}$	$B.code = gen('\texttt{goto}' \; B.false)$

translation of a simple if-statement

- `if( x < 100 || x > 200 && x != y ) x = 0;`

-
```
      if x < 100 goto L2
      goto L3
L3:   if x > 200 goto L4
      goto L1
L4:   if x != y goto L2
      goto L1
L2:   x = 0
L1:
```

Backpatching

- Previous codes for Boolean expressions insert symbolic labels for jumps
- It therefore needs a separate pass to set them to appropriate addresses
- We can use a technique named backpatching to avoid this
- We assume we save instructions into an array and labels will be indices in the array
- For nonterminal B we use two attributes B.truelist and B.falselist together with following functions:
  - makelist(i): create a new list containing only I, an index into the array of instructions
  - Merge(p1,p2): concatenates the lists pointed by p1 and p2 and returns a pointer to the concatenated list
  - Backpatch(p,i): inserts i as the target label for each of the instruction on the list pointed to by p

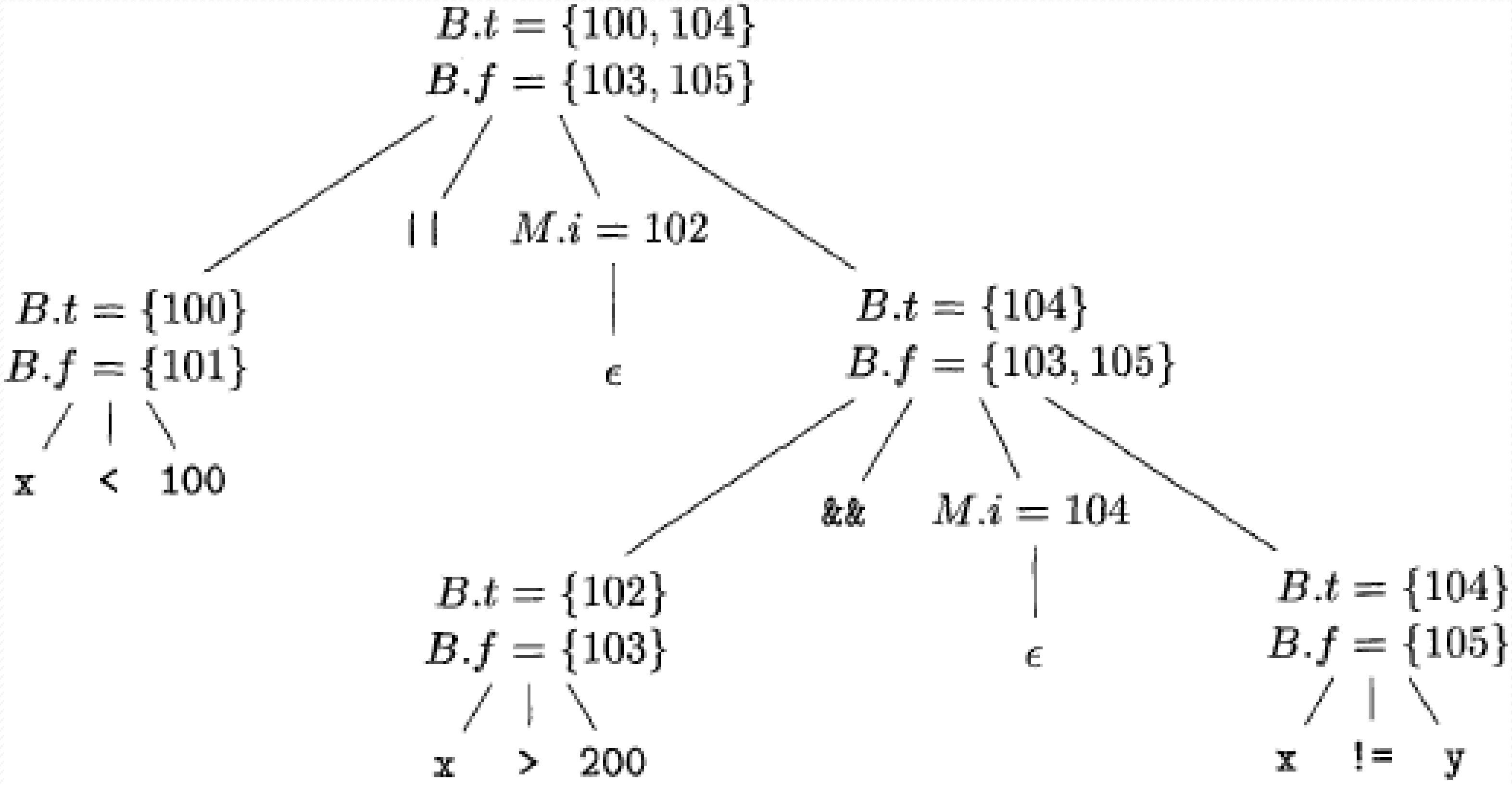
Backpatching for Boolean Expressions

- $B \rightarrow B_1 \;||\; M\, B_2 \mid B_1 \;\&\&\; M\, B_2 \mid !\, B_1 \mid (\, B_1\,) \mid E_1 \;\mathbf{rel}\; E_2 \mid \mathbf{true} \mid \mathbf{false}$
  $M \rightarrow \epsilon$
-

1)	$B \rightarrow B_1 \;||\; M\; B_2$	$\{$ $backpatch(B_1.falselist, M.instr);$ $B.truelist = merge(B_1.truelist, B_2.truelist);$ $B.falselist = B_2.falselist;\ \}$
2)	$B \rightarrow B_1 \;\&\&\; M\; B_2$	$\{$ $backpatch(B_1.truelist, M.instr);$ $B.truelist = B_2.truelist;$ $B.falselist = merge(B_1.falselist, B_2.falselist);\ \}$
3)	$B \rightarrow\ !\ B_1$	$\{$ $B.truelist = B_1.falselist;$ $B.falselist = B_1.truelist;\ \}$
4)	$B \rightarrow (\ B_1\ )$	$\{$ $B.truelist = B_1.truelist;$ $B.falselist = B_1.falselist;\ \}$
5)	$B \rightarrow E_1\ \mathbf{rel}\ E_2$	$\{$ $B.truelist = makelist(nextinstr);$ $B.falselist = makelist(nextinstr + 1);$ $emit(\text{'if'}\ E_1.addr\ \mathbf{rel}.op\ E_2.addr\ \text{'goto \_'});$ $emit(\text{'goto \_'});\ \}$
6)	$B \rightarrow \mathbf{true}$	$\{$ $B.truelist = makelist(nextinstr);$ $emit(\text{'goto \_'});\ \}$
7)	$B \rightarrow \mathbf{false}$	$\{$ $B.falselist = makelist(nextinstr);$ $emit(\text{'goto \_'});\ \}$
8)	$M \rightarrow \epsilon$	$\{$ $M.instr = nextinstr;\ \}$

Backpatching for Boolean Expressions

- Annotated parse tree for x < 100 || x > 200 && x ! = y



Flow-of-Control Statements

$S \rightarrow$ **while** M_1 (B) M_2 S_1

1) $S \rightarrow$ **if** (B) M S_1 { $backpatch(B.truelist,\ M.instr);$
$S.nextlist = merge(B.falselist,\ S_1.nextlist);$ }

2) $S \rightarrow$ **if** (B) M_1 S_1 N **else** M_2 S_2
{ $backpatch(B.truelist,\ M_1.instr);$
$backpatch(B.falselist,\ M_2.instr);$
$temp = merge(S_1.nextlist,\ N.nextlist);$
$S.nextlist = merge(temp,\ S_2.nextlist);$ }

3) $S \rightarrow$ **while** M_1 (B) M_2 S_1
{ $backpatch(S_1.nextlist,\ M_1.instr);$
$backpatch(B.truelist,\ M_2.instr);$
$S.nextlist = B.falselist;$
$emit($'goto' $M_1.instr);$ }

4) $S \rightarrow$ { L } { $S.nextlist = L.nextlist;$ }

5) $S \rightarrow A$; { $S.nextlist =$ **null**; }

6) $M \rightarrow \epsilon$ { $M.instr = nextinstr;$ }

7) $N \rightarrow \epsilon$ { $N.nextlist = makelist(nextinstr);$
$emit($'goto _'$);$ }

8) $L \rightarrow L_1\ M\ S$ { $backpatch(L_1.nextlist,\ M.instr);$
$L.nextlist = S.nextlist;$ }

9) $L \rightarrow S$ { $L.nextlist = S.nextlist;$ }

Translation of a switch-statement

switch (E) {
    case V_1: S_1
    case V_2: S_2
    ...
    case V_{n-1}: S_{n-1}
    default: S_n
}

	code to evaluate E into t
	goto test
L_1:	code for S_1
	goto next
L_2:	code for S_2
	goto next
	...
L_{n-1}:	code for S_{n-1}
	goto next
L_n:	code for S_n
	goto next
test:	if t = V_1 goto L_1
	if t = V_2 goto L_2
	...
	if t = V_{n-1} goto L_{n-1}
	goto L_n
next:	

	code to evaluate E into t
	if t != V_1 goto L_1
	code for S_1
	goto next
L_1:	if t != V_2 goto L_2
	code for S_2
	goto next
L_2:	
	...
L_{n-2}:	if t != V_{n-1} goto L_{n-1}
	code for S_{n-1}
	goto next
L_{n-1}:	code for S_n
next:	

Readings

- Chapter 6 of the book