Principles of Compiler Construction

Lecturer: 常会友

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Lecture 9. Semantic Analysis and Intermediate Code Generation

1. Introduction
2. Types and Declarations
3. Assignments and Expressions
4. Type Checking
5. Boolean Expressions
6. Backpatching and Flow-of-Control Statements

1. Introduction

- Review
  - Front end vs. back end
    - $m \times n$: m front ends and n back ends.
  - Interface between front ends and back ends
    - Intermediate representation
    - Why IR ? Extendability and optimization.
  - Semantic (static) analysis
    - The most common analysis
      - Type checking
    - Other static checking
      - Unreachable code
      - Use of uninitialized variables
      - etc.

Static Checking

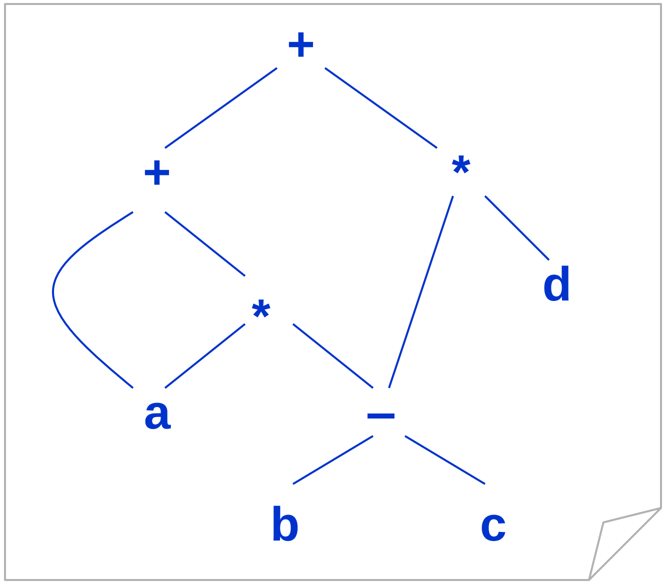
- Semantic analysis also focuses on the well-formness of source code
  - Due to the expressiveness power of Context-Free Grammars.
  - For example,
    - Number matching of actual parameters.
      - Context sensitive requirements cannot be specified using a context free grammar.
    - **break** statement must be in a loop or **switch**.
      - Requires a complicated and unnatural context free grammar.

Intermediate Representation

- High level intermediate representations
  - AST and DAG
  - Suitable for tasks like static type checking
- Low level intermediate representations
  - 3-address code: x = y **op** z
  - Suitable for machine-dependent tasks, such as register allocation and instruction selection.
- IR choice/design are application specific
  - C language is commonly used (AT&T Bell Lab Advanced C++)

Three-Address Code

- Compiler-generated temporary variables
  - $x + y * z$
  - $t_1 = y * z$
    $t_2 = x + t_1$
- An example
  - $t_1 = b - c$
    $t_2 = a * t_1$
    $t_3 = a + t_2$
    $t_4 = t_1 * d$
    $t_5 = t_3 + t_4$



Addresses

- Addresses in 3-address code
  - Name (variables in source code)
    - May be implemented as a pointer or reference to its entry in the symbol table.
  - Constant
    - Type conversions must be considered.
  - Compiler-generated temporary
    - Useful for optimization.
    - Register allocation.

Instructions

- Common 3-address instructions
  - x = y *op* z // arithmetic and logical
    x = *op* y // negation and conversion
    x = y // copy
  - **goto** L // unconditional jump
    if x **goto** L // conditional jump
    ifFalse x **goto** L // conditional jump
    if x *op* y **goto** L // relational operation
  - **param** x_1 // parameter passing
    param x_2
    ...
    param x_n
    call p, n // procedure call
    y = **call** p, n // function call
    return y // return a value

Instructions (cont')

- Common 3-address instructions
  - x = y[i] // indexed copy, i is the offset
    x[i] = y
  - x = &y // address and pointer assignment
    x = *y
    *x = y

Three-Address Code: Example

- Source code
  - **do** i = i + 1;
    while (a[i] < v);
- Translation to 3-address code (symbolic labels)
  - L: t_1 = i + 1
    i = t_1
    t_2 = i * 8
    t_3 = a[t_2]
    if t_3 < v **goto** L
- Another translation form (position numbers)
  - 100: t_1 = i + 1
    101: i = t_1
    102: t_2 = i * 8
    103: t_3 = a[t_2]
    104: **if** t_3 < v **goto** 100

Implementations of Three-Address Code

- Quadruples (quads)
  - Pros and cons ?
- Triples
  - Pros and cons ?
- Indirect triples
  - Pros and cons ?

Space consuming
Flexibility to optimizations

1) Quadruples

- Source code
  - $a = b * - c + b * - c$
- Three-address code
  - t_1 = **minus** c
    $t_2 = b * t_1$
    t_3 = **minus** c
    $t_4 = b * t_3$
    $t_5 = t_2 + t_4$
    $a = t_5$
- Quads

	op	arg_1	arg_2	result
0	**minus**	c		t_1
1	*	b	t_1	t_2
2	**minus**	c		t_3
3	*	b	t_3	t_4
4	+	t_2	t_4	t_5
5	=	t_5		a
…	…			

2) Triples

- Three-address code
  - t_1 = **minus** c
    t_2 = b * t_1
    t_3 = **minus** c
    t_4 = b * t_3
    t_5 = t_2 + t_4
    a = t_5

	op	arg_1	arg_2
0	**minus**	c	
1	*	b	(0)
2	**minus**	c	
3	*	b	(2)
4	+	(1)	(3)
5	=	a	(4)
...	...		

3) Indirect Triples

- Three-address code
  - t_1 = **minus** c
    t_2 = b * t_1
    t_3 = **minus** c
    t_4 = b * t_3
    t_5 = t_2 + t_4
    a = t_5

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

	op	arg_1	arg_2
0	**minus**	c	
1	*	b	(0)
2	**minus**	c	
3	*	b	(2)
4	+	(1)	(3)
5	=	a	(4)
…	…		

In Java, array of instruction objects

Static Single-Assignment Form

$$
\begin{aligned}
p &= a + b \\
q &= p - c \\
p &= q * d \\
p &= e - p \\
q &= p + q
\end{aligned}
$$

$$
\begin{aligned}
p_1 &= a + b \\
q_1 &= p_1 - c \\
p_2 &= q_1 * d \\
p_3 &= e - p_2 \\
q_2 &= p_3 + q_1
\end{aligned}
$$

Static Single-Assignment Form

```
if ( flag ) x = -1; else x = 1;
y = x * a;
```

$$\texttt{if (flag) } x_1 = -1;\ \texttt{else } x_2 = 1;$$
$$x_3 = \phi(x_1, x_2);$$

2. Types and Declarations

- Declaration
  - Literals: implicitly
  - Variables: explicitly
  - Other names: explicitly
- Type checking in strong-typing languages
  - Type compatibility
  - Type inference
  - Implicit type conversion
  - Resolving overloading operators

Relative address

Type Expressions

- Declare only one name at a time

  Basic Type;

  Type name;

  Array type constructor;

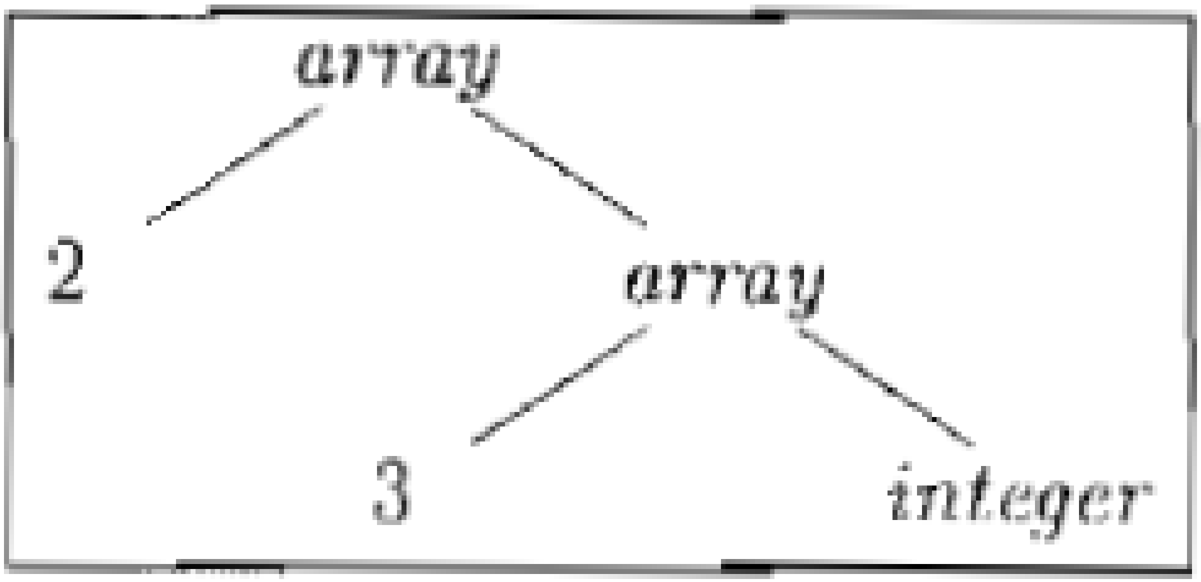
  Record; (Struct , Union)

  Type constructor ->;

  Cartesian product;

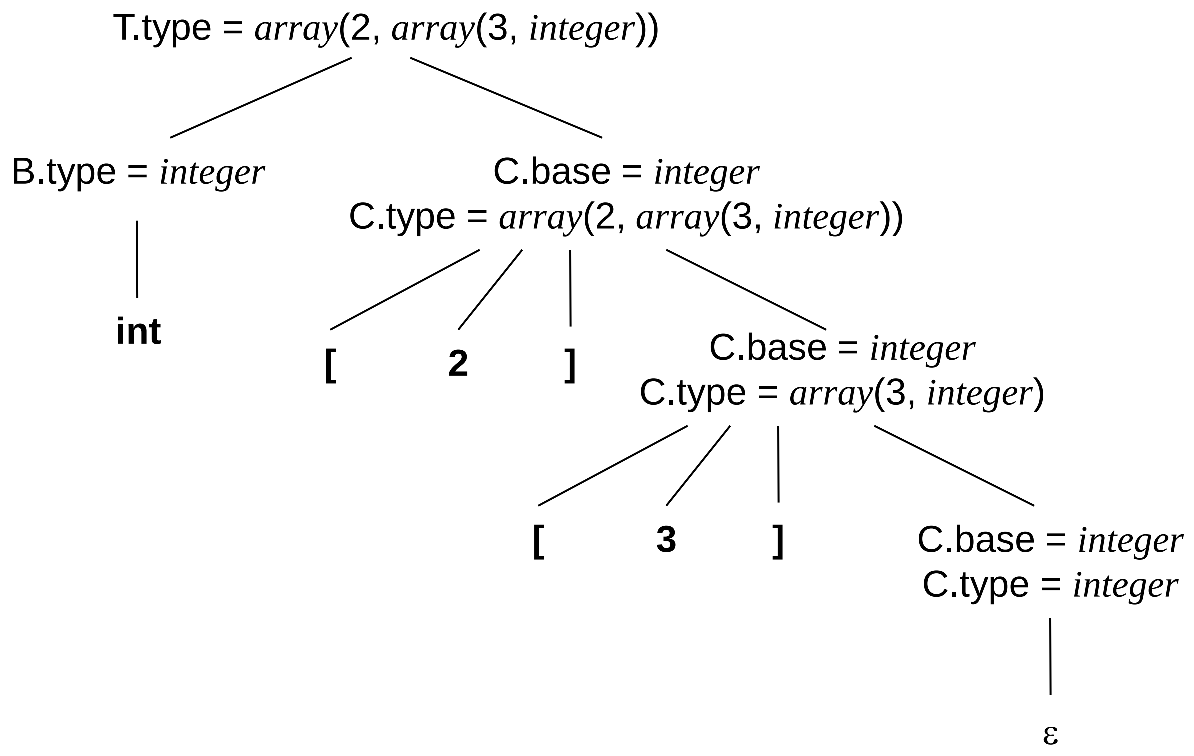
  Type expression contain variables whose values are type expressions.

Type Expressions



Type Structures (cont')

- Type structure for **int[2][3]**



Type Equivalence

- The same basic type;
- Formed by applying the same constructor to structurally equivalent types;
- One is a type name that denotes the other.

Simplified Grammar

- Declare only one name at a time

$$
\begin{aligned}
D &\rightarrow T\ \mathbf{id}\ \mathbf{;}\ D \mid \varepsilon \\
T &\rightarrow B\ C \mid \mathbf{record}\ \mathbf{\{}\ D\ \mathbf{\}} \\
B &\rightarrow \mathbf{int} \mid \mathbf{double} \\
C &\rightarrow \mathbf{[}\ \mathbf{num}\ \mathbf{]}\ C \mid \varepsilon
\end{aligned}
$$

Translation of Type Declarations

- Computing types and their widths

$T \rightarrow B$		{ t = B.type; w = B.width }
C		{ T.type = C.type; T.width = C.width }
$B \rightarrow$ **int**		{ B.type = INTEGER; B.width = 4 }
$B \rightarrow$ **double**		{ B.type = DOUBLE; B.width = 8 }
$C \rightarrow$ **[num]** C_1		{ C.type = array(**num**.value, C_1.type); C.width = **num**.value $\times$ C_1.width }
$C \rightarrow \varepsilon$		{ C.type = t; C.width = w }

Type expression

Just try it: **int[2][3]**
What is T.type and T.width ?

Translation of Type Declarations (cont')

- Computing relative addresses

$P \rightarrow$ { offset = 0 }
  D

top denotes the current symbol table

$D \rightarrow$ T **id ;** { top.put(**id**.lexeme, T.type, offset);
  offset += T.width }
  D_1

$D \rightarrow \varepsilon$

Embedded actions can be removed with markers

Another Example

- Enter types and their widths

P	$\rightarrow$		{ offset = 0 }
		D	
D	$\rightarrow$	D **;** D	
D	$\rightarrow$	**id :** T	{ table.enter(id.name, T.type, offset); offset += T.width }
T	$\rightarrow$	**integer**	{ T.type = INTEGER; T.width = 4 }
T	$\rightarrow$	**real**	{ T.type = REAL; T.width = 8 }
T	$\rightarrow$	**array [num] of** T_1	{ T.type = array(**num**.value, T_1.type); T.width = **num**.value $\times$ T_1.width }
T	$\rightarrow$	**^** T_1	{ T.type = pointer(T_1.type); T.width = 4 }

Just try it: **k: array [5] of ^real**
What are the side effects ?

DBv1

Another Example (cont')

- Field names in records

$T \rightarrow$ **record** { tableStack.push(**new** Table(**null**));
offsetStack.push(0) }
D **end** { T.type = record(tableStack.top());
T.width = offsetStack.top();
tableStack.pop();
offsetStack.pop() }

3. Assignments and Expressions

- Intermediate code generation
  - Code concatenation
    - gen(...)
    - ||
    - No side effects
  - Incremental generation
    - DBv1: emit(...)
    - DBv2: overloading gen(...)
    - Side effects

Example:

$$a = b + -c$$

$$\downarrow$$

t_1 = minus c

$t_2 = b + t_1$

$a = t_2$

Translation of Expressions

- Code concatenation (syntax-directed definition)

	Productions	Semantic Rules
1	S $\rightarrow$ **id = E ;**	S.code = E.code || gen(top.get(**id**.lexeme) '=' E.addr)
2	E $\rightarrow$ E_1 + E_2	E.addr = **new** Temp(); E.code = E_1.code || E_2.code || gen(E.addr '=' E_1.addr '+' E_2.addr)
3	E $\rightarrow$ **−** E_1	E.addr = **new** Temp(); E.code = E_1.code || gen(E.addr '=' '**minus**' E_1.addr)
4	E $\rightarrow$ **(** E_1 **)**	E.addr = E_1.addr; E.code = E_1.code
5	E $\rightarrow$ **id**	E.addr = top.get(**id**.lexeme); E.code = ' '

Translation of Expressions (cont')

- Incremental translation (translation scheme)

$S \rightarrow \mathbf{id} = E\ ;$	{ gen(top.get(**id**.lexeme) '=' E.addr) }
$E \rightarrow E_1 + E_2$	{ E.addr = **new** Temp(); gen(E.addr '=' E_1.addr '+' E_2.addr) }
$E \rightarrow - E_1$	{ E.addr = **new** Temp(); gen(E.addr '=' '**minus**' E_1.addr) }
$E \rightarrow (E_1)$	{ E.addr = E_1.addr }
$E \rightarrow \mathbf{id}$	{ E.addr = top.get(**id**.lexeme) }

Another Example

- Declared variables

$S \rightarrow$ **id :=** E **;** { p = symbolTable.lookup(**id**.name);
if (p == **null**) **throw new** SomeException();
emit(p '=' E.place) }

$E \rightarrow E_1$ **+** E_2 { E.place = **new** Temp();
emit(E.place '=' E_1.place '+' E_2.place) }

$E \rightarrow$ **–** E_1 { E.place = **new** Temp();
emit(E.place '=' '**minus**' E_1.place) }

$E \rightarrow$ **(** E_1 **)** { E.place = E_1.place }

$E \rightarrow$ **id** { p = symbolTable.lookup(**id**.name);
if (p == **null**) **throw new** SomeException();
E.place = p }

Addressing Array Elements

- 2-dimensional array layout
  - Row major vs. column major

1st row	A[1, 1]
	A[1, 2]
	A[1, 3]
2nd row	A[2, 1]
	A[2, 2]
	A[2, 3]

1st column	A[1, 1]
	A[2, 1]
2nd column	A[1, 2]
	A[2, 2]
3rd column	A[1, 3]
	A[2, 3]

Addressing Array Elements

- Relative address of array elements
  - A[i]
    - base + (i – low) × w
    - i × w + (base – low × w)
  - $A[i_1, i_2]$
    - $base + ((i_1 - low_1) \times n_2 + i_2 - low_2) \times w$
    - $((i_1 \times n_2) + i_2) \times w + (base - (low_1 \times n_2 + low_2) \times w)$
  - $A[i_1, i_2, \ldots, i_k]$
    - $((\ldots((i_1 \times n_2 + i_2) \times n_3 + i_3)\ldots) \times n_k + i_k) \times w +$
      $base - ((\ldots((low_1 \times n_2 + low_2) \times n_3 + low_3)\ldots) \times n_k + low_k) \times w$

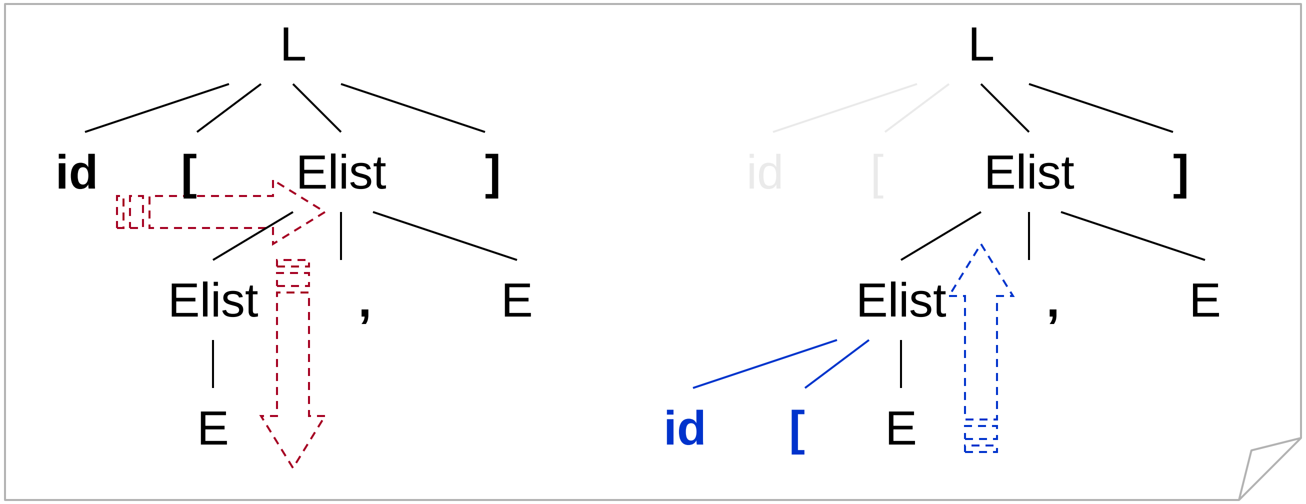
Constant for optimization

Addressing Tips

- For each increment of a new dimension, addressing is calculated recursively, e.g. from k to k + 1
  - For variable part V: $V \times n_{k+1} + i_{k+1}$
  - For constant part C: $C \times n_{k+1} + low_{k+1}$

Grammar for Array References

- Array references in Pascal: a[2, 3]
  - L → **id [** Elist **]** | **id**
  - Elist → Elist **,** E | E
- Grammar transformation (why ?)
  - L → Elist **]** | **id**
  - Elist → Elist **,** E | **id [** E



Translation Scheme

- Addressing array elements in Pascal

(1) S → L **:=** E { **if** (L.offset == **null**) emit(L.place '=' E.place)
else emit(L.place '[' L.offset ']' '=' E.place) }

(2) E → E_1 **+** E_2 { E.place = **new** Temp();
emit(E.place '=' E_1.place '+' E_2.place) }

(3) E → **(** E_1 **)** { E.place = E_1.place }

(4) E → L { **if** (L.offset == **null**) E.place = L.place
else {
E.place = **new** Temp();
emit(E.place '=' L.place '[' L.offset ']')
} }

(5) L → Elist **]** { L.place = **new** Temp();
emit(L.place '=' constant(Elist.array));
L.offset = **new** Temp();
emit(L.offset '=' Elist.place '*' width(Elist.array) }

(6) L → **id** { L.place = **id**.place;
L.offset = **null** }

L is a simple id (if L.offset is null)
or an array reference

L.place = base – C * w
L.offset = V * w

DBv1

Translation Scheme (cont')

- Addressing array elements in Pascal (cont')

(7) Elist $\rightarrow$ $Elist_1$ **,** E {t = **new** Temp();
m = $Elist_1$.ndim + 1;
emit(t '=' $Elist_1$.place '*' limit($Elist_1$.array, m));
emit(t '+=' E.place);
Elist.array = $Elist_1$.array;
Elist.place = t;
Elist.ndim = m }

(8) Elist $\rightarrow$ **id [** E {Elist.array = **id**.place;
Elist.place = E.place;
Elist.ndim = 1 }

Elist.array = base
Elist.place = V
Elist.ndim = dimensions

Another Translation Scheme

- Array references in C/C++: a[2][3]
  - For all n, $low_n = 0$
  - Addressing formula
    - A[i]
      - $base + i \times w$
    - $A[i_1][i_2]$
      - $base + i_1 \times w_1 + i_2 \times w_2$
      - w_1 is the width of a row
      - w_2 is the width of an element in a row
    - $A[i_1][i_2]\ldots[i_k]$
      - $base + i_1 \times w_1 + i_2 \times w_2 + \ldots + i_k \times w_k$

Java does NOT use
row-major storage for arrays

Another Translation Scheme (cont')

- Translation scheme

S	$\rightarrow$	**id = E ;**	{ gen(top.get(**id**.lexeme) '=' E.addr) }
S	$\rightarrow$	L **=** E **;**	{ gen(L.array.base '[' L.addr ']' '=' E.addr) }
E	$\rightarrow$	E_1 **+** E_2	{ E.addr = **new** Temp(); gen(E.addr '=' E_1.addr '+' E_2.addr) }
E	$\rightarrow$	**id**	{ E.addr = top.get(**id**.lexeme) }
E	$\rightarrow$	L	{ E.addr = **new** Temp(); gen(E.addr '=' L.array.base '[' L.addr ']') }
L	$\rightarrow$	**id [** E **]**	{ L.array = top.get(**id**.lexeme); L.type = L.array.type.element; L.addr = **new** Temp(); gen(L.addr '=' E.addr '*' L.type.width) }

L	$\rightarrow$	L_1 **[** E **]**	{ L.array = L_1.array;
			L.type = L_1.type.element;
			t = **new** Temp();
			L.addr = **new** Temp();
			gen(t '=' E.addr '*' L.type.width);
			gen(L.addr '=' L_1.addr '+' t) }

L only for array reference
E.addr = E.place
L.array.base = L.place
L.addr = L.offset

4. Type Checking

- Strong typing vs. weak typing
  - Strongness is relative
- Type definitions
  - Primitive types: enumeration of constant
  - Composite types: type expressions
  - Type of functions: signatures
    - **if** f has type $s \rightarrow t$ **and** x has type s **then** expression f(x) has type t

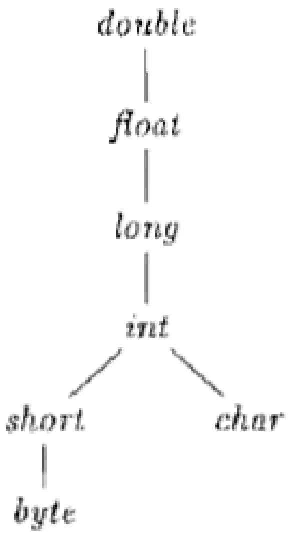
Translation Scheme: An Example

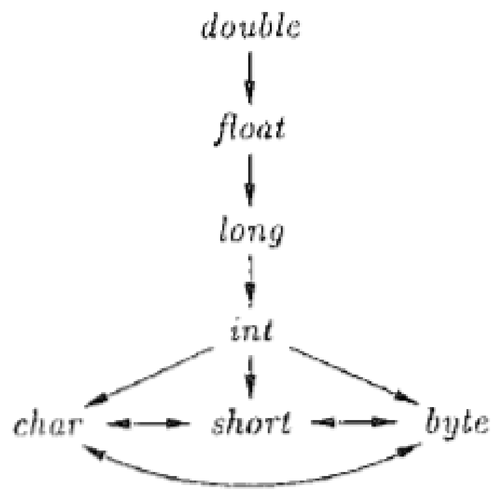
- Type checking, inference and implicit casting

```
E  → E1 * E2  { E.place := new Temp();
                if (E1.type == TK_INT && E2.type == TK_INT) {
                   emit(E.place '=' E1.place '*int' E2.place);
                   E.type = TK_INT;
                } elsif (E1.type == TK_REAL && E2.type == TK_REAL) {
                   emit(E.place '=' E1.place '*real' E2.place);
                   E.type = TK_REAL;
                } elsif (E1.type == TK_INT && E2.type == TK_REAL) {
                   t := new Temp();
                   emit(t '=' 'int2real' E1.place);
                   emit(E.place '=' t '*real' E2.place);
                   E.type = TK_REAL;
                } elsif (...) { ... }
              }
```

- *Type synthesis*
- *Type inference*

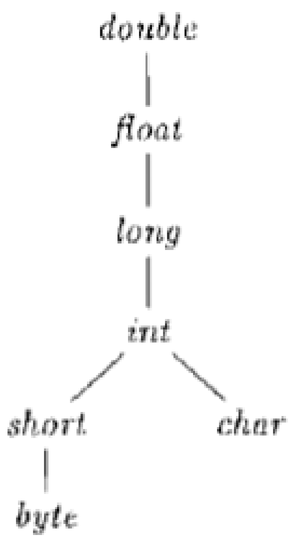
Type Conversion

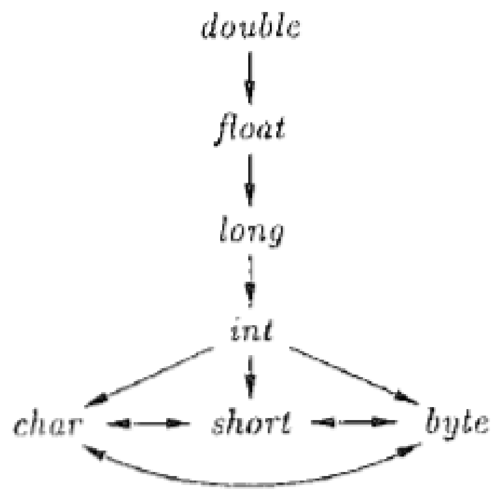





```
Addr widen(Addr a, Type t, Type w)
        if ( t = w ) return a;
        else if ( t = integer and w = float ) {
                temp = new Temp();
                gen(temp '=' '(float)' a);
                return temp;
        }
        else error;
}
```

Type Conversion





$$
\begin{array}{llll}
E \rightarrow E_1 + E_2 & \{ & E.type & = max(E_1.type, E_2.type); \\
 & & a_1 & = widen(E_1.addr, E_1.type, E.type); \\
 & & a_2 & = widen(E_2.addr, E_2.type, E.type); \\
 & & \multicolumn{2}{l}{E.addr = \textbf{new}\ Temp\,();} \\
 & & \multicolumn{2}{l}{gen(E.addr\ '='\ a_1\ '+'\ a_2);\ \}}
\end{array}
$$

Overloading of Functions and Operators

```
void err() { ··· }
void err(String s) { ··· }
```

if f 可能的类型为 $s_i \rightarrow t_i (1 \leqslant i \leqslant n)$，其中，$s_i \neq s_j (i \neq j)$

and x 的类型为 $s_k (1 \leqslant k \leqslant n)$

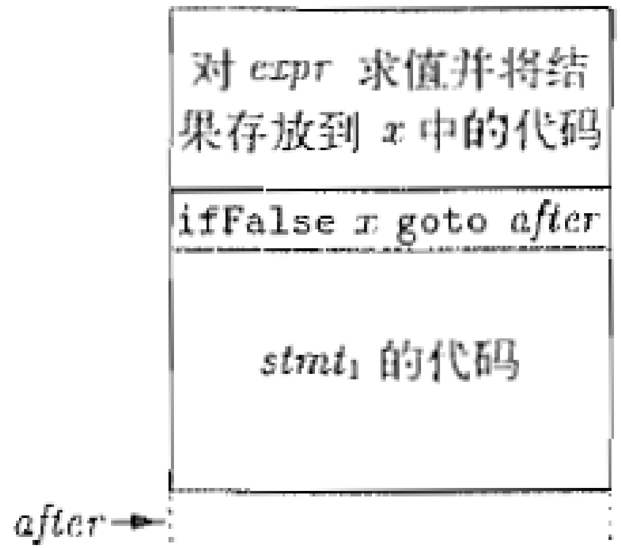
then 表达式 $f(x)$ 的类型为 t_k

5. Boolean Expressions

- Boolean expressions are used in
  - Flows of control
  - Computing logical values

Example

ifFalse *x* goto *after*




```
class If extends Stmt {
    Expr E; Stmt S;
    public If(Expr x, Stmt y) { E = x; S = y; after = newlabel(); }
    public void gen() {
        Expr n = E.rvalue();
        emit( "ifFalse " + n.toString() + " goto " + after);
        S.gen();
        emit(after + ":");
    }
}
```

Computing Logical Values

- **a < b** equals to **if (a < b) then 1 else 0**

$E \rightarrow E_1$ **or** E_2 { E.place = **new** Temp();
emit(E.place '=' E_1.place '**or**' E_2.place) }

$E \rightarrow E_1$ **and** E_2 { E.place = **new** Temp();
emit(E.place '=' E_1.place '**and**' E_2.place) }

$E \rightarrow$ **not** E_1 { E.place = **new** Temp();
emit(E.place '=' '**not**' E_1.place) }

$E \rightarrow$ **(** E_1 **)** { E.place = E_1.place }

$E \rightarrow$ **id_1 relop id_2** { E.place = **new** Temp();
emit('**if**' **id_1**.place **relop**.op **id_2**.place '**goto**' currentStmt+3);
emit(E.place '=' '**0**');
emit('**goto**' currentStmt+2);
emit(E.place '=' '**1**') }

$E \rightarrow$ **true** { E.place = **new** Temp();
emit(E.place '=' '**1**') }

$E \rightarrow$ **false** { E.place = **new** Temp();
emit(E.place '=' '**0**') }

DBv1

Computing Logical Values: An Example

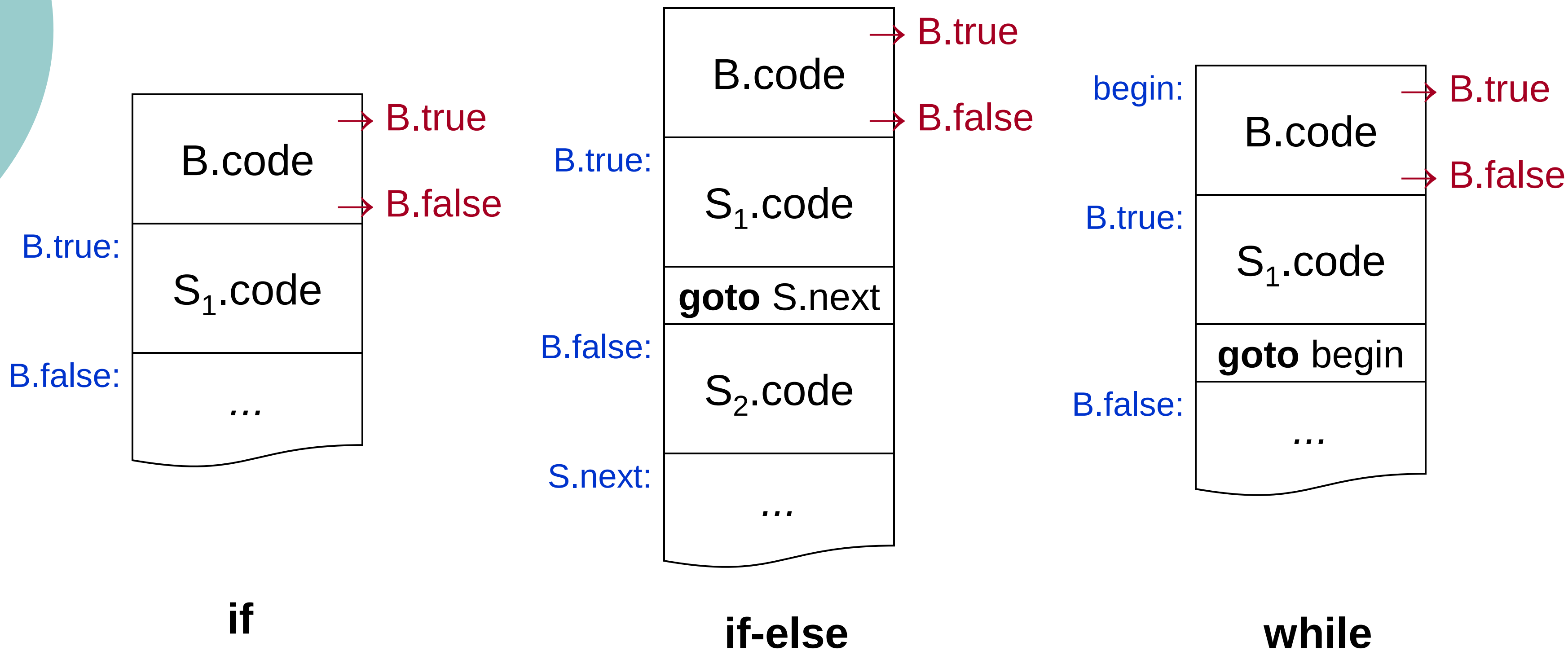
- Source code
  - a < b **or** c < d **and** e < f
- Intermediate code

100:	**if** a < b **goto** 103	108:	**if** e < f **goto** 111
101:	t_1 = 0	109:	t_3 = 0
102:	**goto** 104	110:	**goto** 112
103:	t_1 = 1	111:	t_3 = 1
104:	**if** c < d **goto** 107	112:	t_4 = t_2 **and** t_3
105:	t_2 = 0	113:	t_5 = t_1 **or** t_4
106:	**goto** 108	114:	…
107:	t_2 = 1		

Short-Circuit Evaluation

- Flow-of-Control Statements
  - $S \rightarrow$ **if** **(** B **)** S_1
  - $S \rightarrow$ **if** **(** B **)** S_1 **else** S_2
  - $S \rightarrow$ **while** **(** B **)** S_1
- Short-circuit evaluation for **&&** and **||**
  - For higher evaluation efficiency
  - And ...

Generated Code Illustration



Syntax-Directed Definition for Flow-of-Control Statements

Where does **S.next** come from ?

Productions	Semantic Rules
P → S	S.next = **new** Label(); P.code = S.code || label(S.next)
S → **assign**	S.code = **assign**.code
S → S_1 S_2	S_1.next = **new** Label(); S_2.next = S.next; S.code = S_1.code || label(S_1.next) || S_2.code
S → **if (** B **)** S_1	B.true = **new** Label(); B.false = S_1.next = S.next; S.code = B.code || label(B.true) || S_1.code
S → **if (** B **)** S_1 **else** S_2	B.true = **new** Label(); B.false = **new** Label(); S_1.next = S_2.next = S.next; S.code = B.code || label(B.true) || S_1.code || gen('**goto**' S.next) || label(B.false) || S_2.code
S → **while (** B **)** S_1	begin = **new** Label(); B.true = **new** Label(); B.false = S.next; S_1.next = begin; S.code = label(begin) || B.code || label(B.true) || S_1.code || gen('**goto**' begin)

Avoid redundant **goto**s

Syntax-Directed Definition for Booleans

Short-Circuit Evaluation

Productions	Semantic Rules
$B \to B_1$ **||** B_2	B_1.true = B.true; B_1.false = **new** Label(); B_2.true = B.true; B_2.false = B.false; B.code = B_1.code || label(B_1.false) || B_2.code
$B \to B_1$ **&&** B_2	B_1.true = **new** Label(); B_1.false = B.false; B_2.true = B.true; B_2.false = B.false; B.code = B_1.code || label(B_1.true) || B_2.code
$B \to$ **!** B_1	B_1.true = B.false; B_1.false = B.true; B.code = B_1.code
$B \to E_1$ **relop** E_2	B.code = E_1.code || E_2.code || gen('**if**' E_1.addr **relop**.op E_2.addr '**goto**' B.true) || gen('**goto**' B.false)
$B \to$ **true**	B.code = gen('**goto**' B.true)
$B \to$ **false**	B.code = gen('**goto**' B.false)

Syntax-Directed Translation: An Example

- Source code
  - **if** (x < 100 || x > 200 && x != y) x = 0
- Intermediate code

	if x < 100 **goto** L_2
	goto L_3
L_3:	**if** x > 200 **goto** L_4
	goto L_1
L_4:	**if** x != y **goto** L_2
	goto L_1
L_2:	x = 0
L_1:	…

6. Backpatching and Flow-of-Control Statements

- In SDD for Flow-of-Control Statements
  - Where does **S.next** come from ?
  - Only after all intermediate code are generated, can **S.next** be computed.
- In SDD for Booleans
  - Where do **B.true** and **B.false** come from ?
  - Must be provided by the context of the boolean expressions.
  - The context depends on the result of **S.next**.

Design Motivation and Solution

- Motivation
  - One-pass code generation

If(B) S.

- Solution
  - Using backpatching
- It is a general approach to dealing with initial values which must be computed at the end.

Backpatching for Boolean Expressions

- Translation scheme

$B \rightarrow B_1$ **||** $M\ B_2$	{ backpatch(B_1.falseList, M.instruction); B.trueList = merge(B_1.trueList, B_2.trueList); B.falseList = B_2.falseList; }
$B \rightarrow B_1$ **&&** $M\ B_2$	{ backpatch(B_1.trueList, M.instruction); B.trueList = B_2.trueList; B.falseList = merge(B_1.falseList, B_2.falseList); }
$B \rightarrow$ **!** B_1	{ B.trueList = B_1.falseList; B.falseList = B_1.trueList; }
$B \rightarrow$ **(** B_1 **)**	{ B.trueList = B_1.trueList; B.falseList = B_1.falseList; }
$B \rightarrow E_1$ **relop** E_2	{ B.trueList = **new** List(nextInstruction); B.falseList = **new** List(nextInstruction + 1); emit('**if**' E_1.addr relop.op E_2.addr '**goto** __'); emit('**goto** __'); }
$B \rightarrow$ **true**	{ B.trueList = **new** List(nextInstruction); emit('**goto** __'); }
$B \rightarrow$ **false**	{ B.falseList = **new** List(nextInstruction); emit('**goto** __'); }
$M \rightarrow \varepsilon$	{ M.instruction = nextInstruction; }

Backpatching for Flow-of-Control Statements

- Translation scheme

$S \rightarrow$ **if (** B **)** M S_1 { backpatch(B.trueList, M.instruction);
S.nextList = merge(B.falseList, S_1.nextList); }

$S \rightarrow$ **if (** B **)** M_1 S_1 N **else** M_2 S_2
{ backpatch(B.trueList, M_1.instruction);
backpatch(B.falseList, M_2.instruction);
S.nextList = merge(S_1.nextList, N.nextList, S_2.nextList); }

$S \rightarrow$ **while** M_1 **(** B **)** M_2 S_1
{ backpatch(B.trueList, M_2.instruction);
backpatch(S_1.nextList, M_1.instruction);
S.nextList = B.falseList;
emit('**goto**' M_1.instruction); }

$S \rightarrow$ **{** L **}** { S.nextList = L.nextList; }

$S \rightarrow$ A **;** { S.nextList = **new** List(); // Assignment or Atom }

$M \rightarrow \varepsilon$ { M.instruction = nextInstruction; }

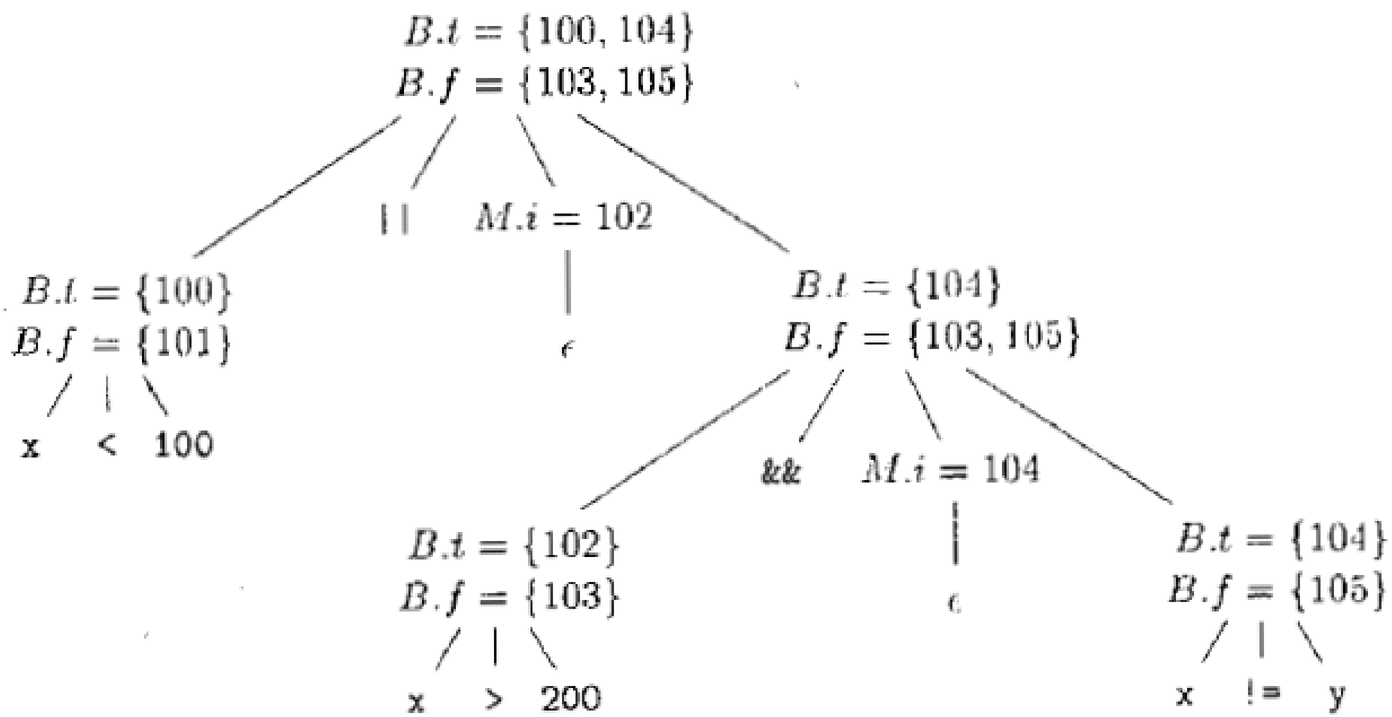
$N \rightarrow \varepsilon$ { N.nextList = **new** List(nextInstruction);
emit('**goto** __'); }

$L \rightarrow L_1$ M S { backpatch(L_1.nextList, M.instruction);
L.nextList = S.nextList; }

$L \rightarrow$ S { L.nextList = S.nextList; }

Example:

$$x < 100 \; || \; x > 200 \; \&\& \; x \; != \; y$$



Example:

$$x < 100 \mid\mid x > 200 \ \&\& \ x \ != y$$

```
100:  if x < 100 goto _
101:  goto _
102:  if x > 200 goto 104
103:  goto _
104:  if x != y goto _
105:  goto _
```

```
100:  if x < 100 goto _
101:  goto 102
102:  if x > 200 goto 104
103:  goto _
104:  if x != y goto _
105:  goto _
```

Example:

```
package inter;                    // 文件 If.java
import symbols.*;
public class If extends Stmt {
    Expr expr; Stmt stmt;
    public If(Expr x, Stmt s) {
        expr = x;  stmt = s;
        if( expr.type != Type.Bool ) expr.error("boolean required in if");
    }
    public void gen(int b, int a) {
        int label = newlabel(); // stmt 的代码的标号
        expr.jumping(0, a);     // 为真时控制流穿越，为假时转向a
        emitlabel(label); stmt.gen(label, a);
    }
}
```

Exercise 9.1

- What is the translation result of input token string: **x := A[y, z]** ?
  - Tips: use the translation scheme for Pascal.

Exercise 9.2

- What is the translation result of input token string: **c + a[i][j]** ?
  - Tips: use the translation scheme for C/C++.

Exercise 9.3

- What is the translation result of input token string: **x < 100 || x > 200 && x != y** ?
  - Tips: use the translation scheme for boolean expressions with backpatching.
  - Suppose that the start position of the generated code is 100.

Enjoy the Course!