

# CSE 4102

## Intermediate Code Generation

### Lecture 12

Compilers principles, techniques, & tools-ULLMAN  
Chapter 06

# Control Flow

- Translation of conditional statements is tied to translation of Boolean expressions.
- Boolean expressions are used to
  - Alter the flow of control, e.g. if (E) S
  - Compute logical values
- Evaluated in analogy to arithmetic expressions
- Intended use of Boolean expression is determined from its syntactic context
  - Expression follows the keyword **if**
    - Alter the flow of control
  - Expression on the right side of an assignment
    - Denote a logical value

# Boolean Expression

- Boolean operators
  - ‘&&’ (AND) , ‘||’ (OR) , ‘!’ (NOT)
- Relational expressions
  - $E_1 \text{ rel } E_2$ 
    - $E_1$  and  $E_2$  are arithmetic expressions
    - **rel.op** : <, <=, =, !=, >, >=
- Grammar for Boolean Expression

$B \rightarrow$  B || B  
| B && B  
| !B  
| (B)  
| E rel E  
| true  
| false

- We assume that || and && are left associative
  - || has the lowest precedence
  - then &&
  - then !

# Short-Circuit Code

- Boolean expressions are typically used in the flow of control statements, such as:
  - if, while and for statements, the effect of such boolean expression can be represented by the position of the program after the expression is evaluated.
- Jump code can be directly generated without evaluating the expressions explicitly.

# Short-Circuit Code

- IF  $B \rightarrow B_1 \parallel B_2$  and  $B_1$  is **true** then  $B$  is **true**
  - We can omit evaluation of  $B_2$
- IF  $B \rightarrow B_1 \&\& B_2$  and  $B_1$  is **false** then  $B$  is **false**
  - We can omit evaluation of  $B_2$
- Semantic definitions of language determines whether all parts of a Boolean expression must be evaluated

# 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:`

**NOTE:** Here all the Boolean operators `&&`, `||`, `!` are translated into jumps

# Short-Circuit Code

```
if (x < y)
    z = x;
else
    z = y;
z = z * z
```

```
t0 = x < y
if t0 goto L0
z = x
goto L1
L0:
    z = y
L1:
    z = z * z
```

# Short-Circuit Code

```
while (x < y) {  
  x = x * 2;  
}  
y = x;
```

```
L0:  
  t0 = x < y  
  IfF t0 goto L1  
  x = x * 2  
  Goto L0
```

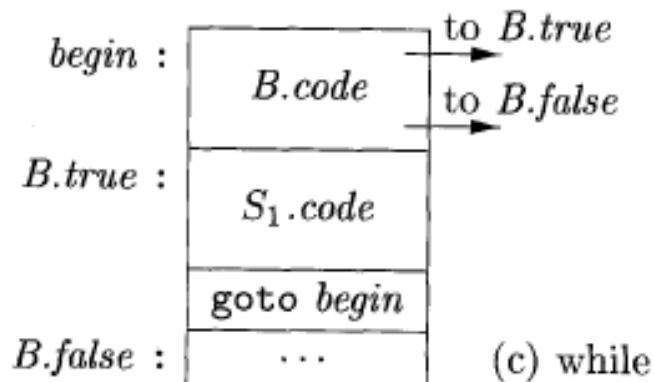
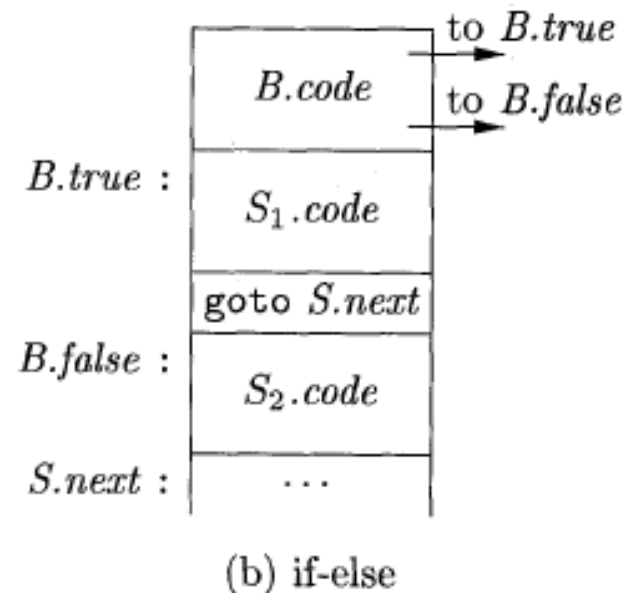
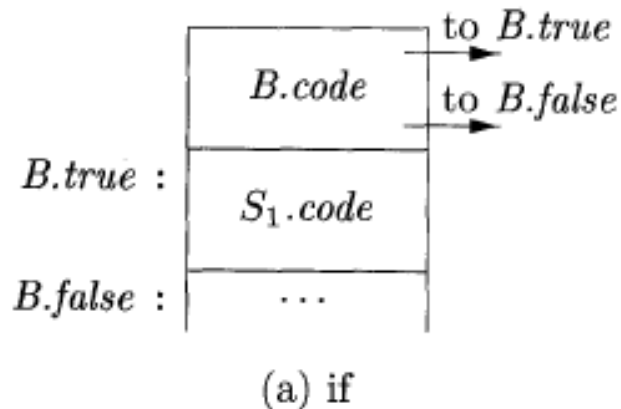
```
L1:
```



# Flow-of-Control Statements

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

- B and S has synthesized attribute *code*
- Within B.code jumps are based on value of B



# Syntax directed definition for flow-of-control statements

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

# Generating three-address code for booleans

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

# Example

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

$S \rightarrow \text{if } E \text{ then } S_1$

```
E.true := newlabel;
E.false := S.next;
S1.next := S.next;
S.code := E.code || gen(E.true ':') ||
          S1.code
```

$E \rightarrow E_1 \text{ or } E_2$

```
E1.true := E.true;
E1.false := newlabel;
E2.true := E.true;
E2.false := E.false;
E.code := E1.code || gen(E1.false ':') || E2.code
```

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

$E \rightarrow E_1 \text{ and } E_2$

```
E1.true := newlabel;
E1.false := E.false;
E2.true := E.true;
E2.false := E.false;
E.code := E1.code || gen(E1.true ':') || E2.code
```

```
L2: x = 0
L1:
```

$E \rightarrow \text{id}_1 \text{ relop id}_2$

```
E.code := gen('if id1.place
               relop.op id2.place 'goto'
               E.true) ||
          gen('goto' E.false)
```

# Example

```
while a < b do
  if c < d then
    x := y + z
  else
    x := y - z
```

$S \rightarrow \text{while } E \text{ do } S_1$

```
L1:    if a < b goto L2
        goto Lnext
L2:    if c < d goto L3
        goto L4
L3:    t1 := y + z
        x := t1
        goto L1
L4:    t2 := y - z
        x := t2
        goto L1
Lnext:
```

$S \rightarrow \text{if } E \text{ then } S_1 \text{ else } S_2$

$E \rightarrow \text{id}_1 \text{ relop id}_2$

```
S.begin := newlabel;
E.true := newlabel;
E.false := S.next;
S1.next := S.begin;
S.code := gen(S.begin ':') || E.code ||
          gen(E.true ':') || S1.code ||
          gen('goto' S.begin)
```

```
E.true := newlabel;
E.false := newlabel;
S1.next := S.next;
S2.next := S.next;
S.code := E.code || gen(E.true ':') ||
          S1.code || gen('goto' S.next) ||
          gen(E.false ':') || S2.code
```

```
E.code := gen('if' id.place
              relop.op id2.place 'goto'
              E.true) ||
          gen('goto' E.false)
```

# Avoiding Redundant Gotos

```
if x > 200 goto L4  
goto L1
```

L4

---

```
ifFalse x > 200 goto L1
```

# Avoiding Redundant Gotos

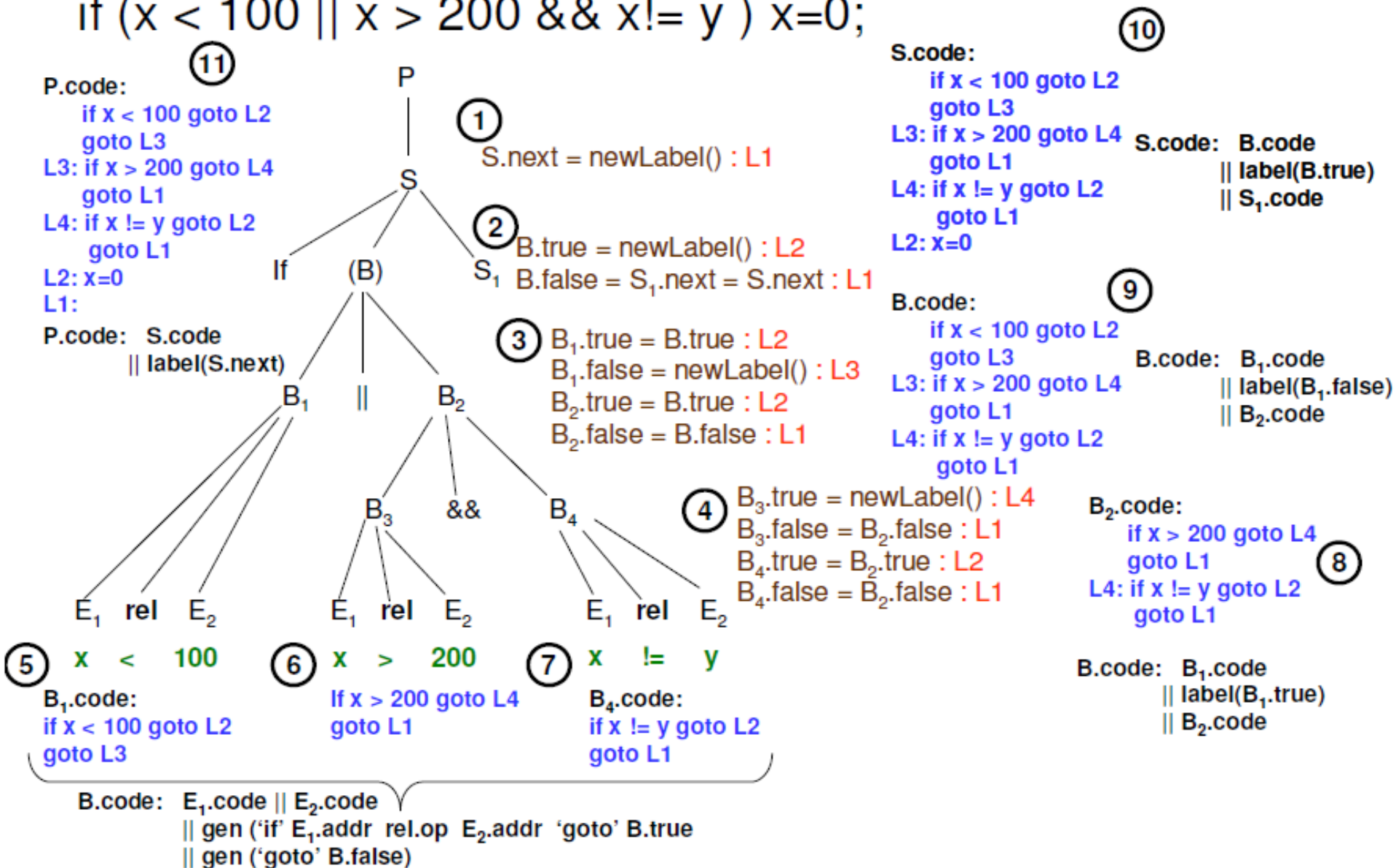
```
if( x < 100 || x > 200 && x != y ) x = 0;
```

```
    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:
```

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

# Example

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





- A key problem when generating code for *boolean expressions and flow-of-control statements* is that of **matching a jump instruction with the target of the jump**.
- For example, if ( B ) S
  - when B is false, to the instruction following the code for S
    - B must be translated before S is examined.
  - **what then is the target of the goto that jumps over the code for S?**
  - we addressed this problem by passing labels as inherited attributes to where the relevant jump instructions were generated.
  - **but a separate pass is then needed to bind labels to addresses.**

# Backpatching

- *Backpatching* can be used to generate code for Boolean expressions and flow of-control statements in one pass.
- Generate branching statements with the targets of the jumps *temporarily unspecified*
- Put each of these statements into a list which is then filled in when the proper label is determined

# Backpatching

108: t0 = true

109: if t0 goto 111

110: goto \_

Keep track of incomplete  
jump instructions

111: ...

122: goto 108

123: ...

– backpatch({110}, 123)

Backpatch when  
information is available

# Backpatching

- We maintain a list of statements that need patching by future statements
- Three lists are maintained:
  - **truelist**: for targets when evaluation is true
  - **falselist**: for targets when evaluation is false
  - **nextlist**: list of jumps to the instruction immediately following the code for S
- These lists can be implemented as a synthesized attribute
- Assume instructions are generated into an instruction arrays

Synthesized  
attributes of  
nonterminal B

# Back-patching

- For non-terminal 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

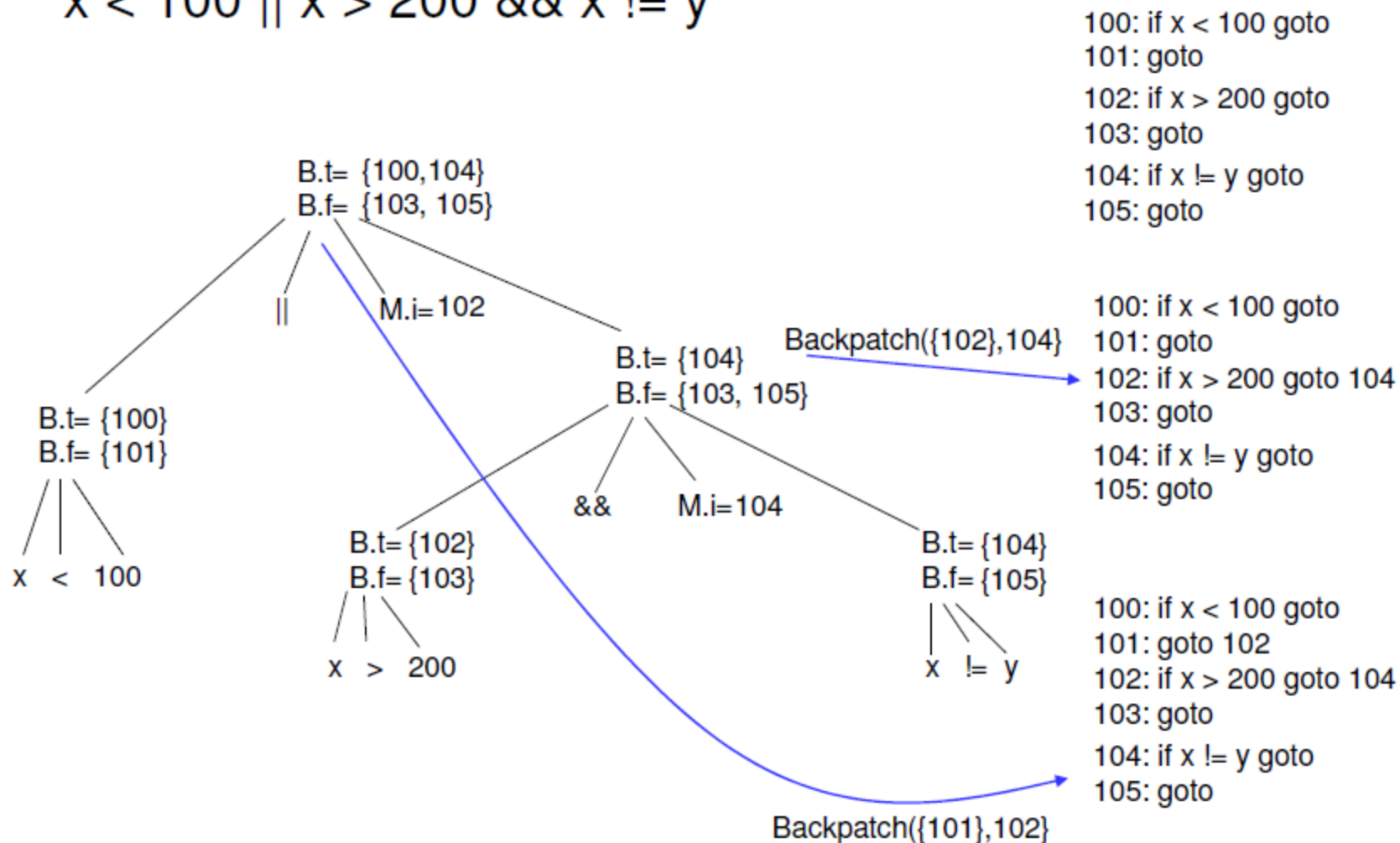
# Backpatching for Boolean Expressions

$B \rightarrow B_1 \parallel M B_2$	<pre>{backpatch(B<sub>1</sub>.falselist, M.instr); B.truelist = merge(B<sub>1</sub>.truelist,B<sub>2</sub>.truelist); B.falselist=B<sub>2</sub>.falselist;}</pre>
$B \rightarrow B_1 \&\& M B_2$	<pre>{backpatch(B<sub>1</sub>.truelist, M.instr); B.truelist = B<sub>2</sub>.truelist; B.falselist= merge(B<sub>1</sub>.falselist,B<sub>2</sub>.falselist);}</pre>
$B \rightarrow ! B_1$	<pre>{B.truelist = B<sub>1</sub>.falselist; B.falselist= B<sub>1</sub>.truelist;}</pre>
$B \rightarrow ( B_1 )$	<pre>{B.truelist = B<sub>1</sub>.truelist; B.falselist= B<sub>1</sub>.falselist;}</pre>
$B \rightarrow E_1 \text{ rel } E_2$	<pre>{B.truelist = makelist(nextinstr); B.falselist = makelist(nextinstr+1); emit('if' E<sub>1</sub>.addr rel.op E<sub>2</sub>.addr 'goto _') emit( 'goto _')}</pre>
$B \rightarrow \text{true}$	<pre>{B.truelist = makelist(nextinstr); emit ('goto _');}</pre>
$B \rightarrow \text{false}$	<pre>{B.false = makelist(nextinstr); emit ('goto _');}</pre>
$M \rightarrow \varepsilon$	<pre>{ M.instr = nextinstr;}</pre>

# Backpatching for Boolean Expressions

- Annotated parse tree for  $x < 100 \parallel x > 200 \&\& x \neq y$

$x < 100 \parallel x > 200 \&\& x \neq y$



# Back-patching for flow of control statements

$S \rightarrow \text{if } (B) \ M \ S_1$	$\{\text{backpatch}(B.\text{truelist}, M.\text{instr});$ $S.\text{nextlist} = \text{merge}(B.\text{falselist}, S_1.\text{nextlist});\}$
$S \rightarrow \text{if } (B) \ M_1 \ S_1 \ N$ $\quad \text{else } M_2 \ S_2$	$\{\text{backpatch}(B.\text{truelist}, M_1.\text{instr}); \text{backpatch}(B.\text{falselist}, M_2.\text{instr});$ $\text{temp} = \text{merge}(S_1.\text{nextlist}, N.\text{nextlist});$ $S.\text{nextlist} = \text{merge}(\text{temp}, S_2.\text{nextlist});\}$
$S \rightarrow \text{while } M_1 \ (B)$ $\quad M_2 \ S_1$	$\{\text{backpatch}(S_1.\text{nextlist}, M_1.\text{instr}); \text{backpatch}(B.\text{truelist}, M_2.\text{instr});$ $S.\text{nextlist} = B.\text{falselist};$ $\text{emit}('goto' \ M_1.\text{instr});\}$
$S \rightarrow \{ L \}$	$\{S.\text{nextlist} = L.\text{nextlist};\}$
$S \rightarrow A;$	$\{S.\text{nextlist} = \text{null};\}$
$M \rightarrow \epsilon$	$\{M.\text{instr} = \text{nextinstr};\}$
$N \rightarrow \epsilon$	$\{N.\text{nextlist} = \text{makelist}(\text{nextinstr}); \text{emit}('goto \_');\}$
$L \rightarrow L_1 \ M \ S$	$\{\text{backpatch}(L_1.\text{nextlist}, M.\text{instr});$ $L.\text{nextlist} = S.\text{nextlist};\}$
$L \rightarrow S$	$\{ L.\text{nextlist} = S.\text{nextlist};\}$



# Translation of a switch-statement

		code to evaluate $E$ into $t$	
		goto test	
	$L_1$ :	code for $S_1$	code to evaluate $E$ into $t$
		goto next	if $t \neq V_1$ goto $L_1$
switch ( $E$ ) {	$L_2$ :	code for $S_2$	code for $S_1$
case $V_1$ : $S_1$		goto next	goto next
case $V_2$ : $S_2$		...	$L_1$ :
...			if $t \neq V_2$ goto $L_2$
case $V_{n-1}$ : $S_{n-1}$	$L_{n-1}$ :	code for $S_{n-1}$	code for $S_2$
default: $S_n$		goto next	goto next
}	$L_n$ :	code for $S_n$	$L_2$ :
		goto next	...
	test:	if $t = V_1$ goto $L_1$	$L_{n-2}$ :
		if $t = V_2$ goto $L_2$	if $t \neq V_{n-1}$ goto $L_{n-1}$
		...	code for $S_{n-1}$
		if $t = V_{n-1}$ goto $L_{n-1}$	goto next
		goto $L_n$	$L_{n-1}$ :
			code for $S_n$
			next:
	next:		

# Back-patching Practice

```
if(m>2 && m<50 && m%3==0){  
    a=a+2;  
    b++;  
    m/=3  
}  
else{  
    a=a+5;  
    b--;  
}
```

$B \rightarrow B_1 \ \&\& \ M \ B_2$	$\left\{ \begin{array}{l} \text{backpatch}(B_1.\text{truelist}, M.\text{instr}); \\ B.\text{truelist} = B_2.\text{truelist}; \\ B.\text{falselist} = \text{merge}(B_1.\text{falselist}, B_2.\text{falselist}); \end{array} \right\}$
--------------------------------------	--

$S \rightarrow \text{if } (B) \ M_1 \ S_1 \ N$ $\quad \text{else } M_2 \ S_2$	$\left\{ \begin{array}{l} \text{backpatch}(B.\text{truelist}, M_1.\text{instr}); \text{backpatch}(B.\text{falselist}, M_2.\text{instr}); \\ \text{temp} = \text{merge}(S_1.\text{nextlist}, N.\text{nextlist}); \\ S.\text{nextlist} = \text{merge}(\text{temp}, S_2.\text{nextlist}); \end{array} \right\}$
--	--



Any Question?