Lecture 09 – IR (Backpatching)

THEORY OF COMPILATION

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www.cs.technion.ac.il/~yahave/tocs2011/compilers-lec09.pptx

Reference: Dragon 6.2,6.3,6.4,6.6

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Recap

- Lexical analysis
  - regular expressions identify tokens (“words”)
- Syntax analysis
  - context-free grammars identify the structure of the program (“sentences”)
- Contextual (semantic) analysis
  - type checking defined via typing judgments
  - can be encoded via attribute grammars
- Syntax directed translation (SDT)
  - attribute grammars
- Intermediate representation
  - many possible IRs
  - generation of intermediate representation
  - 3AC

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Journey inside a compiler

float position;
float initial;
float rate;
position = initial + rate * 60

⇨

Token Stream

<float> <ID,position> <;> <float> <ID,initial> <;> <float> <ID,rate> <;> <ID,1> <=> <ID,2> <+> <ID,3> <*> <60>

Lexical Analysis | Syntax Analysis | Sem. Analysis | Inter. Rep. | Code Gen.

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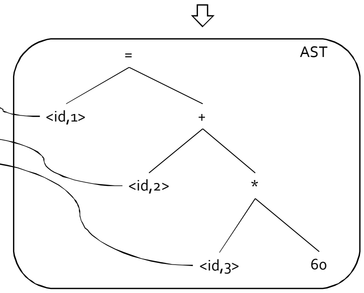
Journey inside a compiler

<ID,1> <=> <ID,2> <+> <ID,3> <*> <60>

symbol table

id	symbol	type	data
1	position	float	…
2	initial	float	…
3	rate	float	…



S → ID = E
E → ID
  | E + E
  | E * E
  | NUM

Lexical Analysis | Syntax Analysis | Sem. Analysis | Inter. Rep. | Code Gen.

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Problem 3.8 from [Appel]

A simple left-recursive grammar:
E → E + id
E → id

A simple right-recursive grammar accepting the same language:
E → id + E
E → id

Which has better behavior for shift-reduce parsing?

Answer

Input
id+id+id+id+id

left recursive
E → E + id
E → id

stack
id (reduce)
E
E +
E + id (reduce)
E
E +
E + id (reduce)
E
E +
E + id (reduce)
E
E +
E + id (reduce)
E

The stack never has more than three items on it. In general, with LR-parsing of left-recursive grammars, an input string of length O(n) requires only O(1) space on the stack.

Answer

Input
id+id+id+id+id

right recursive
E → id + E
E → id

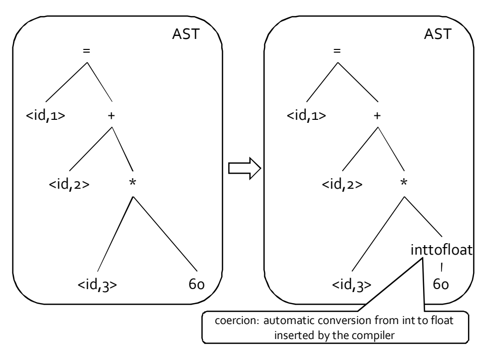
stack
id
id +
id + id
id + id +
id + id + id
id + id + id
id + id + id + id
id + id + id + id +
id + id + id + id + id (reduce)
id + id + id + id + E (reduce)
id + id + id + E (reduce)
id + id + E (reduce)
id + E (reduce)
E

The stack grows as large as the input string. In general, with LR-parsing of right-recursive grammars, an input string of length O(n) requires O(n) space on the stack.

Journey inside a compiler

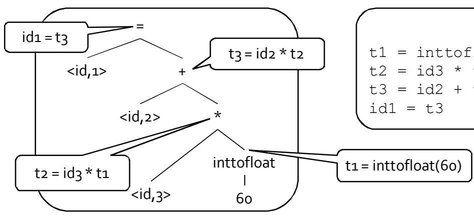
symbol table

id	symbol	type
1	position	float
2	initial	float
3	rate	float



Lexical Analysis | Syntax Analysis | Sem. Analysis | Inter. Rep. | Code Gen.

Journey inside a compiler



3AC

```
t1 = inttofloat(60)
t2 = id3 * t1
t3 = id2 + t2
id1 = t3
```

<table>
<tr><th>production</th><th>semantic rule</th></tr>
<tr><td>S → id = E</td><td>S.code := E. code || gen(id.var ‘:=‘ E.var)</td></tr>
<tr><td>E → E1 op E2</td><td>E.var := freshVar();
E.code = E1.code || E2.code || gen(E.var ‘:=‘ E1.var ‘op’ E2.var)</td></tr>
<tr><td>E → inttofloat(num)</td><td>E.var := freshVar();
E.code = gen(E.var ‘:=‘ inttofloat(num))</td></tr>
<tr><td>E → id</td><td>E.var := id.var; E.code = ‘’</td></tr>
</table>

(for brevity, bubbles show only code generated by the node and not all accumulated “code” attribute)

note the structure:
translate E1
translate E2
handle operator

Lexical Analysis | Syntax Analysis | Sem. Analysis | Inter. Rep. | Code Gen.

Journey inside a compiler

3AC

```
t1 = inttofloat(60)
t2 = id3 * t1
t3 = id2 + t2
id1 = t3
```

Optimized

```
t1 = id3 * 60.0
id1 = id2 + t1
```

value known at compile time
can generate code with converted value

eliminated temporary t3

Lexical Analysis | Syntax Analysis | Sem. Analysis | Inter. Rep. | Code Gen.

Journey inside a compiler

Optimized

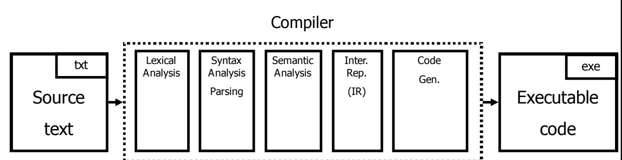
```
t1 = id3 * 60.0
id1 = id2 + t1
```

Code Gen

```
LDF R2, id3
MULF R2, R2, #60.0
LDF R1, id2
ADDF R1,R1,R2
STF id1,R1
```

Lexical Analysis | Syntax Analysis | Sem. Analysis | Inter. Rep. | Code Gen.

You are here



IR So Far…

- many possible intermediate representations
- 3-address code (3AC)
- Every instruction operates on at most three addresses
  - result = operand1 operator operand2
- gets us closer to code generation
- enables machine-independent optimizations
- how do we generate 3AC?

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Last Time: Creating 3AC

- Creating 3AC via syntax directed translation
- Attributes
  - code – code generated for a nonterminal
  - var – name of variable that stores result of nonterminal

- freshVar() – helper function that returns the name of a fresh variable

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Creating 3AC: expressions

production	semantic rule
S → id := E	S.code := E. code || gen(id.var ':=' E.var)
E → E1 + E2	E.var := freshVar(); E.code = E1.code || E2.code || gen(E.var ':=' E1.var '+' E2.var)
E → E1 * E2	E.var := freshVar(); E.code = E1.code || E2.code || gen(E.var ':=' E1.var '*' E2.var)
E → - E1	E.var := freshVar(); E.code = E1.code || gen(E.var ':=' 'uminu' E1.var)
E → (E1)	E.var := E1.var E.code = '(' || E1.code || ')'
E → id	E.var := id.var; E.code = ''

(we use || to denote concatenation of intermediate code fragments)

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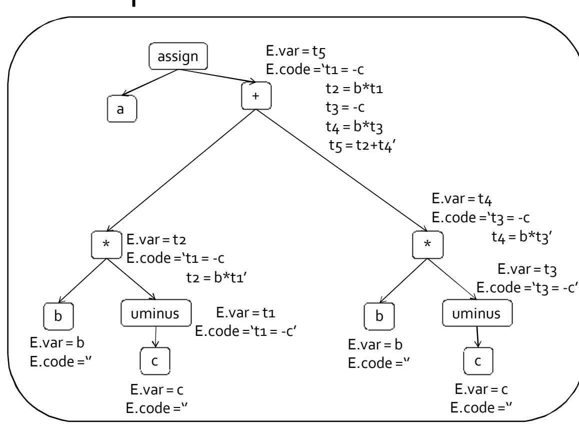
example



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Creating 3AC: control statements

- 3AC only supports conditional/unconditional jumps
- Add labels
- Attributes
  - begin – label marks beginning of code
  - after – label marks end of code
- Helper function freshLabel() allocates a new fresh label

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Expressions and assignments

production	semantic action
S → id := E	{ p:= lookup(id.name); if p ≠ null then **emit**(p ':=' E.var) else error }
E → E1 op E2	{ E.var := freshVar(); **emit**(E.var ':=' E1.var op E2.var) }
E → - E1	{ E.var := freshVar(); **emit**(E.var ':=' 'uminus' E1.var) }
E → (E1)	{ E.var := E1.var }
E → id	{ p:= lookup(id.name); if p ≠ null then E.var :=p else error }

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Boolean Expressions

production	semantic action
E → E1 op E2	{ E.var := freshVar(); **emit**(E.var ':=' E1.var op E2.var) }
E → not E1	{ E.var := freshVar(); **emit**(E.var ':=' 'not' E1.var) }
E → (E1)	{ E.var := E1.var }
E → true	{ E.var := freshVar(); **emit**(E.var ':=' '1') }
E → false	{ E.var := freshVar(); **emit**(E.var ':=' '0') }

- Represent true as 1, false as 0
- Wasteful representation, creating variables for true/false

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Boolean expressions via jumps

production	semantic action

E → id1 op id2	{
	E.var := freshVar();
	emit('if' id1.var relop id2.var 'goto' nextStmt+2);
	emit(E.var ':=' '0');
	emit('goto ' nextStmt + 1);
	emit(E.var ':=' '1')
	}

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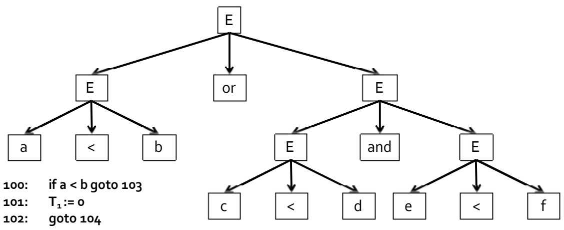
Example



100: if a < b goto 103
101: T_1 := 0
102: goto 104
103: T_1 := 1

104: if c < d goto 107
105: T_2 := 0
106: goto 108
107: T_2 := 1

108: if e < f goto 111
109: T_3 := 0
110: goto 112
111: T_3 := 1
112: T_4 := T_2 and T_3
113: T_5 := T_1 or T_4

Short circuit evaluation

- Second argument of a Boolean operator is only evaluated if the first argument does not already determine the outcome
- (x and y) is equivalent to if x then y else false;
- (x or y) is equivalent to if x then true else y

example

a < b or (c<d and e<f)

100: if a < b goto 103
101: T_1 := 0
102: goto 104
103: T_1 := 1
104: if c < d goto 107
105: T_2 := 0
106: goto 108
107: T_2 := 1
108: if e < f goto 111
109: T_3 := 0
110: goto 112
111: T_3 := 1
112: T_4 := T_2 and T_3
113: T_5 := T_1 and T_4

naive

100: if a < b goto 105
101: if !(c < d) goto 103
102: if e < f goto 105
103: T := 0
104: goto 106
105: T := 1
106:

Short circuit evaluation

Control Structures

```
S→ if B then S1
  | if B then S1 else S2
  | while B do S1
```

- For every Boolean expression B, we attach two properties
  - falseLabel – target label for a jump when condition B evaluates to false
  - trueLabel – target label for a jump when condition B evaluates to true
- For every statement S we attach a property
  - next – the label of the next code to execute after S
- Challenge
  - Compute falseLabel and trueLabel during code generation

Control Structures: next

<table>
<tr><th>production</th><th>semantic action</th></tr>
<tr><td>P → S</td><td>S.next = freshLabel();
P.code = S.code || label(S.next)</td></tr>
<tr><td>S → S1S2</td><td>S1.next = freshLabel();
S2.next = S.next;
S.code = S1.code || label(S1.next) || S2.code</td></tr>
</table>

- The label S.next is symbolic, we will only determine its value after we finish deriving S

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Control Structures: conditional

<table>
<tr><th>production</th><th>semantic action</th></tr>
<tr><td>S → if B then S1</td><td>B.trueLabel = freshLabel();
B.falseLabel = S.next;
S1.next = S.next;
S.code = B.code || gen (B.trueLabel ':') || S1.code</td></tr>
</table>

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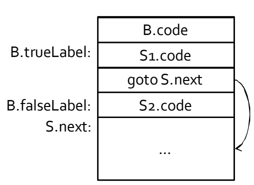
Control Structures: conditional

<table>
<tr><th>production</th><th>semantic action</th></tr>
<tr><td>S → if B then S1 else S2</td><td>B.trueLabel = freshLabel();
B.falseLabel = freshLabel();
S1.next = S.next;
S2.next = S.next;
S.code =
B.code || gen(B.trueLabel ':') || S1.code || gen('goto' S.next)
|| gen(B.falseLabel ':') || S2.code</td></tr>
</table>



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Boolean expressions

<table>
<tr><th>production</th><th>semantic action</th></tr>
<tr><td>B → B1 or B2</td><td>B1.trueLabel = B.trueLabel;
B1.falseLabel = freshLabel();
B2.trueLabel = B.trueLabel;
B2.falseLabel = B.falseLabel;
B.code = B1.code || gen (B1.falseLabel ':') || B2.code</td></tr>
<tr><td>B → B1 and B2</td><td>B1.trueLabel = freshLabel();
B1.falseLabel = B.falseLabel;
B2.trueLabel = B.trueLabel;
B2.falseLabel = B.falseLabel;
B.code = B1.code || gen (B1.trueLabel ':') || B2.code</td></tr>
<tr><td>B → not B1</td><td>B1.trueLabel = B.falseLabel;
B1.falseLabel = B.trueLabel;
B.code = B1.code;</td></tr>
<tr><td>B → (B1)</td><td>B1.trueLabel = B.trueLabel; B1.falseLabel = B.falseLabel; B.code = B1.code;</td></tr>
<tr><td>B → id1 relop id2</td><td>B.code=gen ('if' id1.var relop id2.var 'goto' B.trueLabel)||gen('goto' B.falseLabel);</td></tr>
<tr><td>B → true</td><td>B.code = gen('goto' B.trueLabel)</td></tr>
<tr><td>B → false</td><td>B.code = gen('goto' B.falseLabel);</td></tr>
</table>

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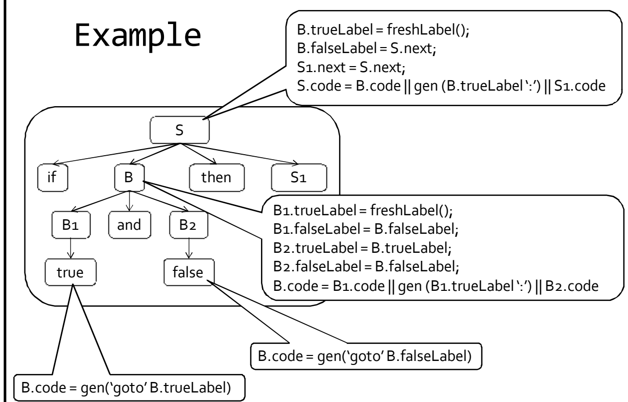
Boolean expressions

production	semantic action
B → B1 or B2	B1.trueLabel = B.trueLabel; B1.falseLabel = freshLabel(); B2.trueLabel = B.trueLabel; B.falseLabel = B.falseLabel; B.code = B1.code || gen (B1.falseLabel ':') || B2.code

- How can we determine the address of B1.falseLabel?
- Only possible after we know the code of B1 and all the code preceding B1

Example



Computing addresses for labels

- We used symbolic labels
- We need to compute their addresses
- We can compute addresses for the labels but it would require an additional pass on the AST
- Can we do it in a single pass?

Backpatching

- Goal: generate code in a single pass
- Generate code as we did before, but manage labels differently
- Keep labels symbolic until values are known, and then back-patch them
- New synthesized attributes for B
  - B.truelist – list of jump instructions that eventually get the label where B goes when B is true.
  - B.falselist – list of jump instructions that eventually get the label where B goes when B is false.

Backpatching

- Previous approach does not guarantee a single pass
  - The attribute grammar we had before is not S-attributed (e.g., next), and is not L-attributed.
- For every label, maintain a list of instructions that jump to this label
- When the address of the label is known, go over the list and update the address of the label

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Backpatching

- makelist(addr) – create a list of instructions containing addr
- merge(p1,p2) – concatenate the lists pointed to by p1 and p2, returns a pointer to the new list
- backpatch(p,addr) – inserts i as the target label for each of the instructions in the list pointed to by p

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Backpatching Boolean expressions

<table>
<tr><th>production</th><th>semantic action</th></tr>
<tr><td>B → B1 or M B2</td><td>backpatch(B1.falseList,M.instr);
B.trueList = merge(B1.trueList,B2.trueList);
B.falseList = B2.falseList;</td></tr>
<tr><td>B → B1 and M B2</td><td>backpatch(B1.trueList,M.instr);
B.trueList = B2.trueList;
B.falseList = merge(B1.falseList,B2.falseList);</td></tr>
<tr><td>B → not B1</td><td>B.trueList = B1.falseList;
B.falseList = B1.trueList;</td></tr>
<tr><td>B → (B1)</td><td>B.trueList = B1.trueList;
B.falseList = B1.falseList;</td></tr>
<tr><td>B → id1 relop id2</td><td>B.trueList = makeList(nextInstr);
B.falseList = makeList(nextInstr+1);
emit ('if' id1.var relop id2.var 'goto _') || emit('goto _');</td></tr>
<tr><td>B → true</td><td>B.trueList = makeList(nextInstr);
emit ('goto _');</td></tr>
<tr><td>B → false</td><td>B.falseList = makeList(nextInstr);
emit ('goto _');</td></tr>
<tr><td>M → ε</td><td>M.instr = nextinstr;</td></tr>
</table>

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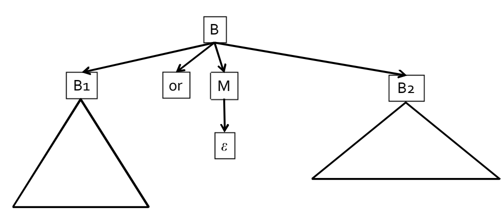
Marker



- { M.instr = nextinstr;}
- Use M to obtain the address just before B2 code starts being generated

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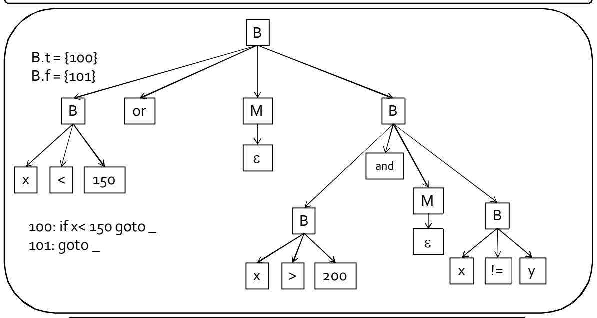
Example

X < 150 or x > 200 and x != y



B → id1 relop id2	**B.trueList = makeList(nextInstr);** **B.falseList = makeList(nextInstr+1);** **emit ('if' id1.var relop id2.var 'goto _') || emit('goto _');**

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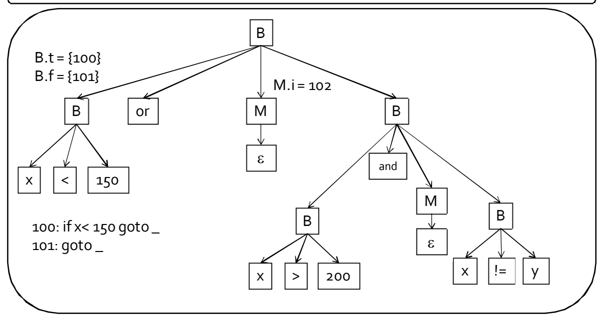
Example

X < 150 or x > 200 and x != y



M → ε	**M.instr = nextinstr;**

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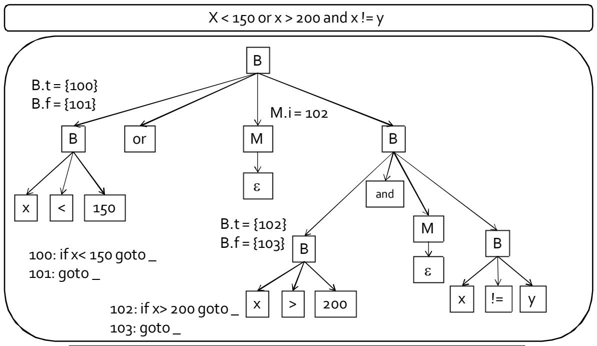
Example

X < 150 or x > 200 and x != y



B → id1 relop id2	**B.trueList = makeList(nextInstr);** **B.falseList = makeList(nextInstr+1);** **emit ('if' id1.var relop id2.var 'goto _') || emit('goto _');**

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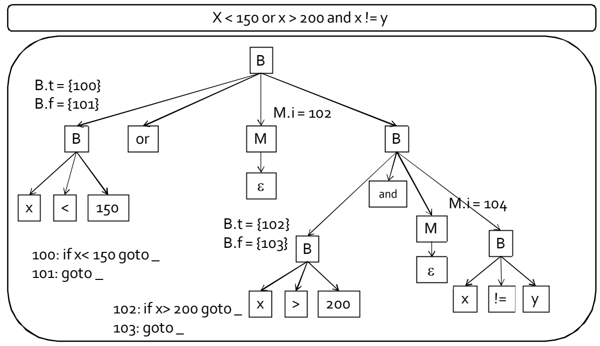
Example

X < 150 or x > 200 and x != y



M → ε	**M.instr = nextinstr;**

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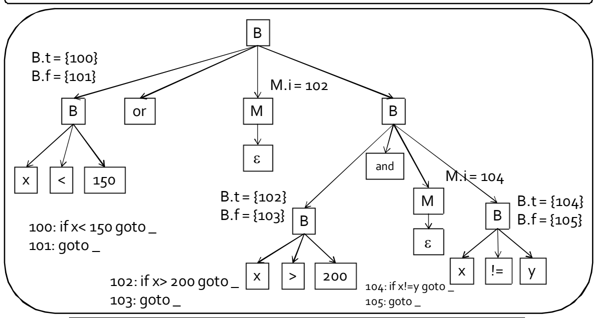
Example

X < 150 or x > 200 and x != y



B → id1 relop id2	**B.trueList = makeList(nextInstr);** **B.falseList = makeList(nextInstr+1);** **emit ('if' id1.var relop id2.var 'goto _') || emit('goto _');**

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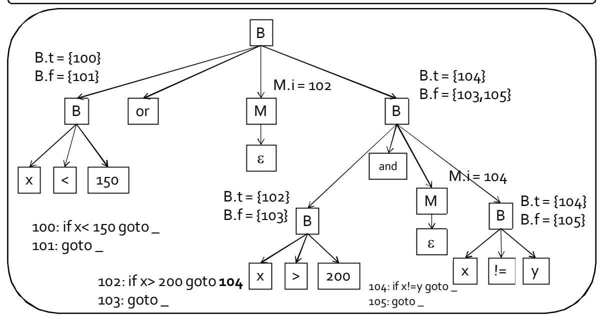
Example

X < 150 or x > 200 and x != y



B → B1 and M B2	**backpatch(B1.trueList,M.instr);** **B.trueList = B2.trueList;** **B.falseList = merge(B1.falseList,B2.falseList);**

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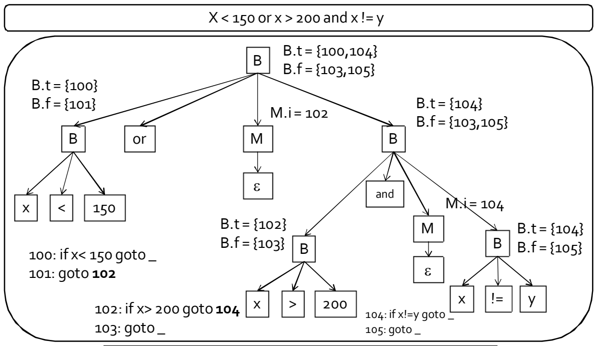
Example

X < 150 or x > 200 and x != y



B → B1 or M B2	**backpatch(B1.falseList,M.instr);** **B.trueList = merge(B1.trueList,B2.trueList);** **B.falseList = B2.falseList;**

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Example

100: if x<150 goto _
101: goto _
102: if x>200 goto _
103: goto _
104: if x!=y goto _
105: goto _

Before backpatching

100: if x<150 goto _
101: goto _
102: if x>200 goto **104**
103: goto _
104: if x!=y goto _
105: goto _

After backpatching by the production B → B1 and M B2

100: if x<150 goto _
101: goto **102**
102: if x>200 goto **104**
103: goto _
104: if x!=y goto _
105: goto _

After backpatching by the production B → B1 or M B2

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Backpatching for statements

production	semantic action
S → if (B) M S1	backpatch(B.trueList,M.instr); S.nextList = merge(B.falseList,S1.nextList);

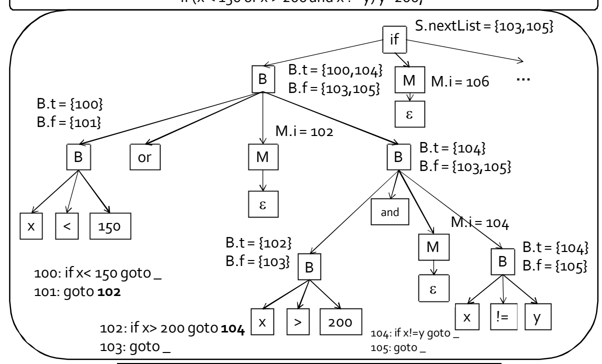
S → if (B) M1 S1 N else M2 S2	backpatch(B.trueList,M1.instr);
	backpatch(B.falseList,M2.instr);
	temp = merge(S1.nextList,N.nextList);
	S.nextList = merge(temp,S2.nextList);

S → while M1 (B) M2 S1	backpatch(S1.nextList,M1.instr);
	backpatch(B.trueList,M2.instr);
	S.nextList = B.falseList;
	emit('goto' M1.instr);

S → { L }	S.nextList = L.nextList;
S → A	S.nextList = null;
M → ε	M.instr = nextinstr;
N → ε	N.nextList = makeList(nextInstr); emit('goto _');
L → L1 M S	backpatch(L1.nextList,M.instr); L.nextList = S.nextList;
L → S	L.nextList = S.nextList

Example

if (x < 150 or x > 200 and x != y) y=200;



S → if (B) M S1	**backpatch(B.trueList,M.instr);** **S.nextList = merge(B.falseList,S1.nextList);**

Example

100: if x<150 goto _
101: goto **102**
102: if x>200 goto **104**
103: goto _
104: if x!=y goto _
105: goto _
106: y = 200

After backpatching
by the production
B → B1 or M B2

100: if x<150 goto **106**
101: goto **102**
102: if x>200 goto **104**
103: goto _
104: if x!=y goto **106**
105: goto _
106: y = 200

After backpatching
by the production
S → if (B) M S1

Procedures

n = f(a[i]);

t1 = i * 4
t2 = a[t1] // could have expanded this as well
param t2
t3 = call f, 1
n = t3

- we will see handling of procedure calls in much more detail later

Procedures

```
D → define T id (F) { S }
F → ε | T id, F
S → return E; | …
E → id (A) | …
A → ε | E, A
```

statements

expressions

- type checking
  - function type: return type, type of formal parameters
  - within an expression function treated like any other operator
- symbol table
  - parameter names

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Summary

- pick an intermediate representation
- translate expressions
- use a symbol table to implement declarations
- generate jumping code for boolean expressions
  - value of the expression is implicit in the control location
- backpatching
  - a technique for generating code for boolean expressions and statements in one pass
  - idea: maintain lists of incomplete jumps, where all jumps in a list have the same target. When the target becomes known, all instructions on its list are "filled in".

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Coming up next…

- Activation Records

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The End

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