Compiler Design

Intermediate Code Generation

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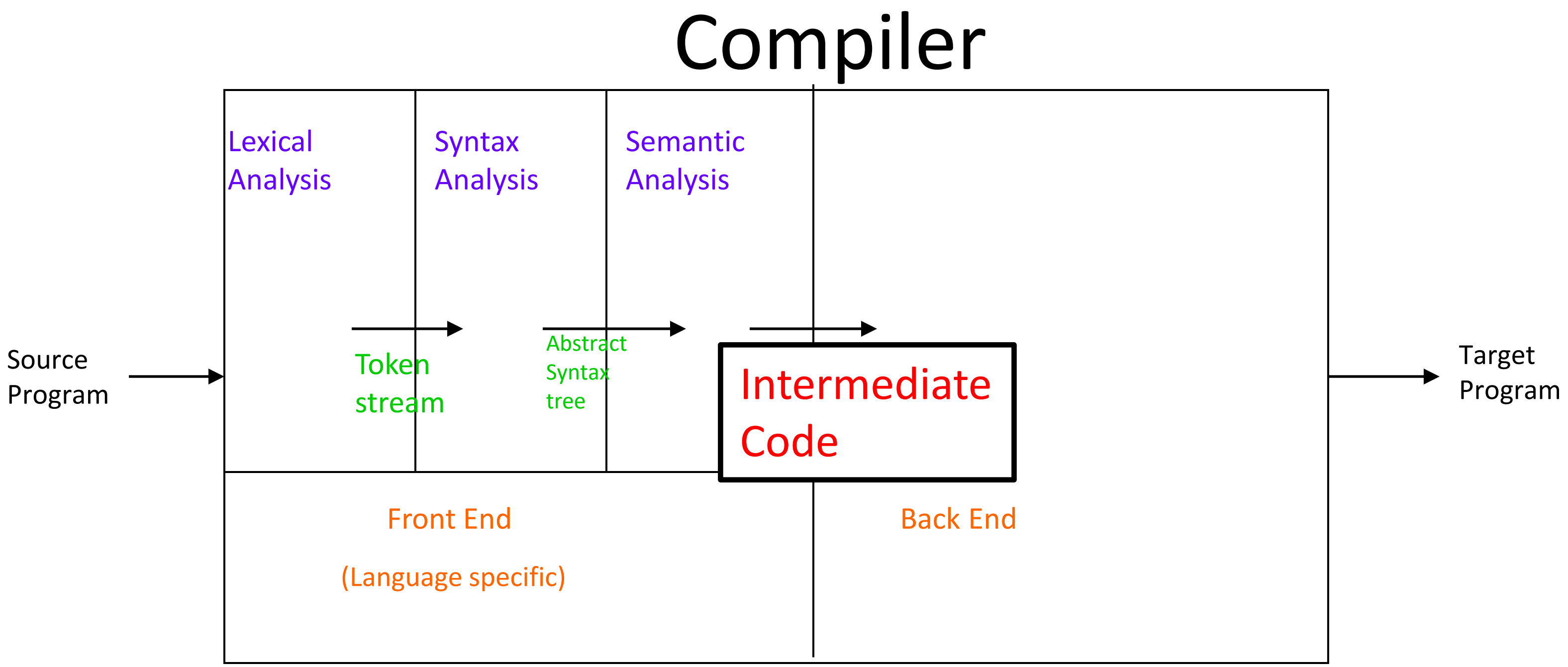
Principles of Compiler Design

Intermediate Representation



Intermediate Code Generation

- Code generation is a mapping from source level abstractions to target machine abstractions

- Abstraction at the source level

  identifiers, operators, expressions, statements, conditionals, iteration, functions (user defined, system defined or libraries)

- Abstraction at the target level

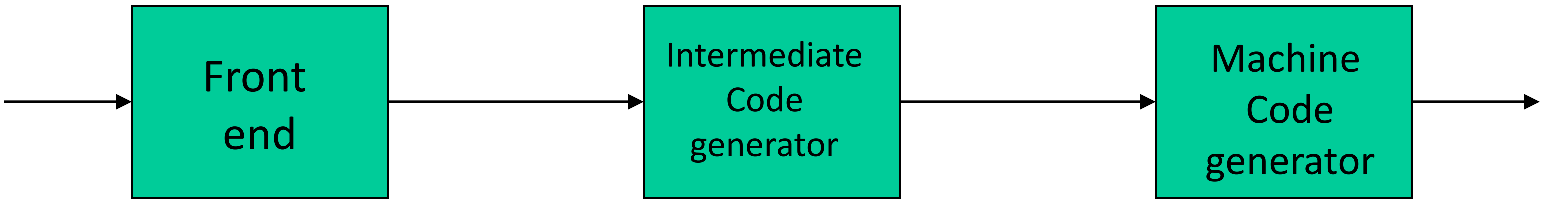
  memory locations, registers, stack, opcodes, addressing modes, system libraries, interface to the operating systems

Intermediate Code Generation ...

- Front end translates a source program into an intermediate representation

- Back end generates target code from intermediate representation

- Benefits
  - Retargeting is possible
  - Machine independent code optimization is possible



Three address code

- Assignment
  - x = y op z
  - x = op y
  - x = y
- Jump
  - goto L
  - if x relop y goto L
- Indexed assignment
  - x = y[i]
  - x[i] = y
- Function
  - param x
  - call p,n
  - return y
- Pointer
  - x = &y
  - x = *y
  - *x = y

Syntax directed translation of expression into 3-address code

- Two attributes
  - ***E.place***, a name that will hold the value of E,
  - ***E.code***, the sequence of three-address statements evaluating E.
- A function ***gen*(…)** to produce sequence of three address statements
  - The statements themselves are kept in some data structure, e.g. list
  - SDD operations described using pseudo code
  - *gen*(…) will be later replaced by a similar function ***emit***(…), to be discussed later.

Syntax directed translation of expression into 3-address code

$S \rightarrow id = E$

S.code := E.code ||

gen(id.place:= E.place)

$E \rightarrow E_1 + E_2$

E.place:= newtmp()

E.code:= E_1.code || E_2.code ||

gen(E.place := E_1.place + E_2.place)

$E \rightarrow E_1 * E_2$

E.place:= newtmp()

E.code := E_1.code || E_2.code ||

gen(E.place := E_1.place * E_2.place)

Syntax directed translation of expression …

$E \rightarrow -E_1$

E.place := newtmp

E.code := E_1.code ||

gen(E.place := - E_1.place)

$E \rightarrow (E_1)$

E.place := E_1.place

E.code := E_1.code

$E \rightarrow id$

E.place := id.place

E.code := ‘ ’ # empty code

Syntax directed translation of expression … (alternative way)

emit is like gen, but instead of returning code, it generates code as a side effect in a list of three address instructions.

$S \rightarrow id = E$

emit(id.place:= E.place)

$E \rightarrow E_1 + E_2$

E.place:= newtmp

emit(E.place := E_1.place + E_2.place)

$E \rightarrow E_1 * E_2$

E.place:= newtmp

emit(E.place := E_1.place * E_2.place)

Syntax directed translation of expression … (alternative way)

$E \rightarrow -E_1$

E.place := newtmp

emit(E.place := - E_1.place)

$E \rightarrow (E_1)$

E.place := E_1.place

$E \rightarrow id$

E.place := id.place

Example

For a = b * -c + b * -c

The following code is generated

t_1 = -c

t_2 = b * t_1

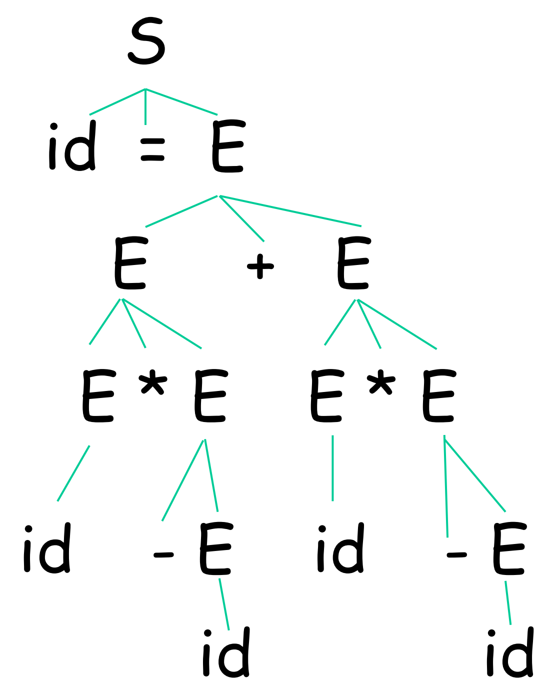
t_3 = -c

t_4 = b * t_3

t_5 = t_2 + t_4

a = t_5

S → id = E	emit(id.place:= E.place)
E → E_1 + E_2	E.place:= newtmp emit(E.place := E_1.place + E_2.place)
E → E_1 * E_2	E.place:= newtmp emit(E.place := E_1.place * E_2.place)
E → -E_1	E.place := newtmp emit(E.place := - E_1.place)
E → (E_1)	E.place := E_1.place
E → id	E.place := id.place



Names in the Symbol table

```
S → id := E
        {p = lookup(id.place);
        if p <> nil then emit(p := E.place)
                    else error}

E →  id
        {p = lookup(id.place);
        if p <> nil then E.place = p
                    else error}
```

Flow of Control

$S \rightarrow$ while E do S_1

Desired Translation is

S. begin :

E.code

if E.place = 0 goto S.after

S_1.code

goto S.begin

S.after :

S.begin := newlabel

S.after := newlabel

S.code := gen(S.begin:) | |
E.code | |
gen(if E.place = 0 goto S.after) | |
S_1.code | |
gen(goto S.begin) | |
gen(S.after:)

Flow of Control …

$S \rightarrow$ if E then S_1 else S_2

E.code

if E.place = 0 goto S.else

S_1.code

goto S.after

S.else:

S_2.code

S.after:

S.else := newlabel

S.after := newlabel

S.code = E.code ||

gen(if E.place = 0 goto S.else) ||

S_1.code ||

gen(goto S.after) ||

gen(S.else :) ||

S_2.code ||

gen(S.after :)

Type conversion within assignments

$E \rightarrow E_1 + E_2$

E.place= newtmp;

if E_1.type = integer and E_2.type = integer

then emit(E.place := E_1.place int+ E_2.place);

E.type = integer;

…

similar code if both E_1.type and E_2.type are real

…

else if E_1.type = int and E_2.type = real

then

u = newtmp;

emit(u := int2real E_1.place);

emit(E.place := u real+ E_2.place);

E.type = real;

…

similar code if E_1.type is real and E_2.type is integer

Example

real x, y;

int i, j;

x = y + i * j

generates code

t_1 = i int* j

t_2 = int2real t_1

t_3 = y real+ t_2

x = t_3

Boolean Expressions

- compute logical values
- change the flow of control
- boolean operators are: and or not

E → E or E
 | E and E
 | not E
 | (E)
 | id relop id
 | true
 | false

Numerical representation

- a or b and not c

  t_1 = not c
  t_2 = b and t_1
  t_3 = a or t_2

- relational expression a < b is equivalent to if a < b then 1 else 0

  1. if a < b goto 4.
  2. t = 0
  3. goto 5
  4. t = 1
  5.

Syntax directed translation of boolean expressions

$E \rightarrow E_1$ or E_2

E.place := newtmp

emit(E.place := E_1.place or E_2.place)

$E \rightarrow E_1$ and E_2

E.place:= newtmp

emit(E.place := E_1.place and E_2.place)

$E \rightarrow$ not E_1

E.place := newtmp

emit(E.place := not E_1.place)

$E \rightarrow (E_1)$ E.place = E_1.place

Syntax directed translation of boolean expressions

E → id1 relop id2
    E.place := newtmp
    emit(if id1.place relop id2.place goto nextstat+3)
    emit(E.place = 0)
    emit(goto nextstat+2)
    emit(E.place = 1)

E → true
    E.place := newtmp
    emit(E.place = 1)

E → false
    E.place := newtmp
    emit(E.place = 0)

"nextstat" is a global variable; a pointer to the statement to be emitted. emit also updates the nextstat as a side-effect.

Example:
Code for a < b or c < d and e < f

100: if a < b goto 103

101: $t_l = 0$

102: goto 104

103: $t_l = 1$

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: $t_5 = t_l$ or t_4

Short Circuit Evaluation of boolean expressions

- Translate Boolean expressions **without**:
  - × Generating code for Boolean operators
  - × Evaluating the entire expression
  - × Redundant labels
- Flow of control statements

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

Each Boolean expression E has two attributes, **true** and **false**. These attributes hold the label of the **target stmt** to jump to.

Control flow translation of boolean expression

if E is of the form: $a < b$

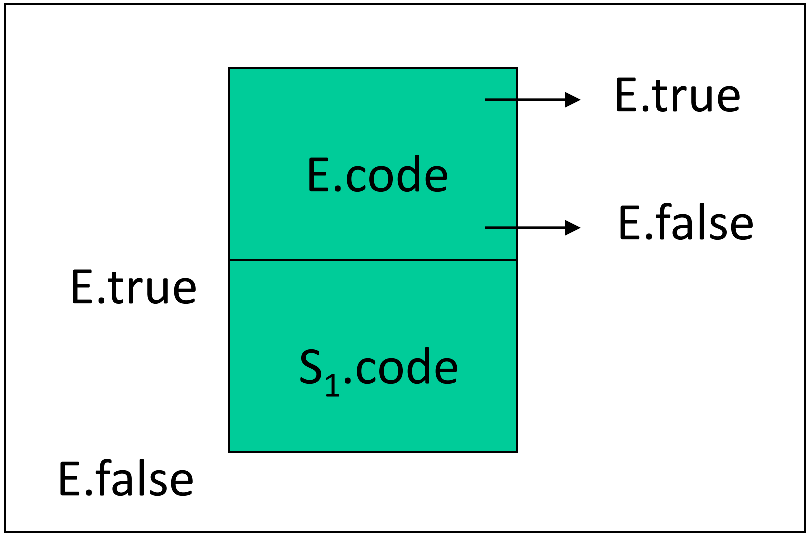
then code is of the form: if $a < b$ goto E.true
goto E.false

$E \rightarrow id_1$ relop id_2

E.code = gen(if id_1.place relop id_2.place goto E.true)
|| gen(goto E.false)

$E \rightarrow$ true E.code = gen(goto E.true)

$E \rightarrow$ false E.code = gen(goto E.false)



$S \rightarrow$ if E then S_1

E.true = newlabel

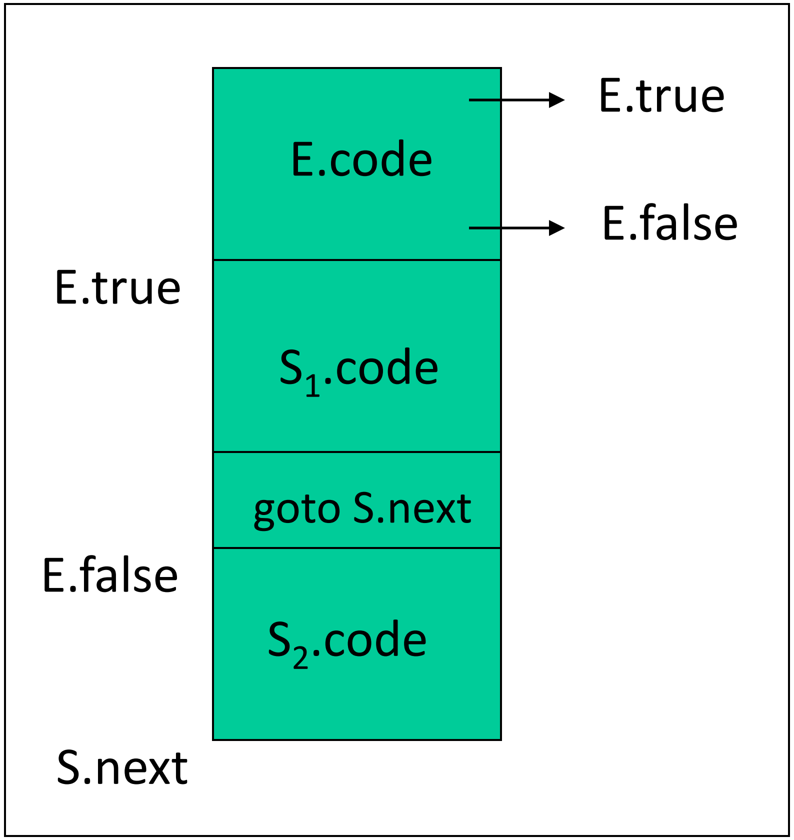
E.false = S.next

S_1.next = S.next

S.code = E.code ||

gen(E.true :) ||

S_1.code



$S \rightarrow$ if E then S_1 else S_2

E.true = newlabel

E.false = newlabel

S_1.next = S.next

S_2.next = S.next

S.code = E.code ||

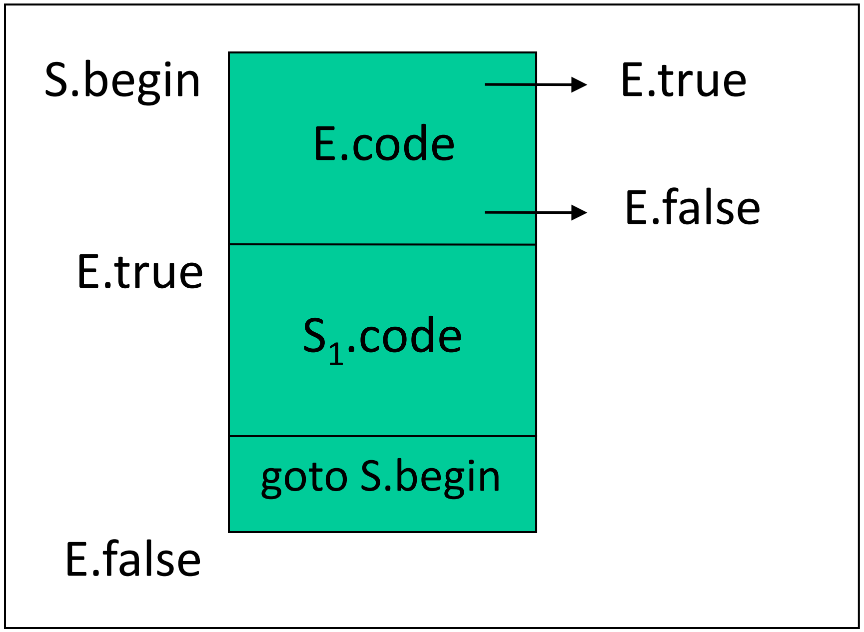
gen(E.true :) ||

S_1.code ||

gen(goto S.next) ||

gen(E.false :) ||

S_2.code



$S \rightarrow$ while E do S_1

S.begin = newlabel

E.true = newlabel

E.false = S.next

S_1.next = S.begin

S.code = gen(S.begin :) ||
E.code ||
gen(E.true :) ||
S_1.code ||
gen(goto S.begin)

Control flow translation of boolean expression

$E \rightarrow E_1$ or E_2

E_1.true := E.true
E_1.false := newlabel
E_2.true := E.true
E_2.false := E.false
E.code := E_1.code || gen(E_1.false) || E_2.code

$E \rightarrow E_1$ and E_2

E_1.true := newlabel
E_1 false := E.false
E_2.true := E.true
E_2 false := E.false
E.code := E_1.code || gen(E_1.true) || E_2.code

Control flow translation of boolean expression …

$E \rightarrow \text{not } E_1$	$E_1.\text{true} := E.\text{false}$
	$E_1.\text{false} := E.\text{true}$
	$E.\text{code} := E_1.\text{code}$
$E \rightarrow (E_1)$	$E_1.\text{true} := E.\text{true}$
	$E_1.\text{false} := E.\text{false}$
	$E.\text{code} := E_1.\text{code}$

Example

Code for a < b or c < d and e < f

```
        if a < b goto Ltrue
        goto L1
L1:     if c < d goto L2
        goto Lfalse
L2:     if e < f goto Ltrue
        goto Lfalse

Ltrue:
Lfalse:
```

Example …

Code for while a < b do

if c<d then x=y+z

else x=y-z

```
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:     t1 = Y - Z
        X= t1
        goto L1
Lnext:
```

Case Statement

- switch expression

```
begin
        case value: statement
        case value: statement
        ….
        case value: statement
        default: statement
end
```

- evaluate the expression
- find which value in the list of cases is the same as the value of the expression.
  - Default value matches the expression if none of the values explicitly mentioned in the cases matches the expression
- execute the statement associated with the value found

Translation

```
              code to evaluate E into t
              if t <> V1 goto L1
              code for S1
              goto next
L1            if t <> V2 goto L2
              code for S2
              goto next
L2:       ......
Ln-2          if t <> Vn-l goto Ln-l
              code for Sn-l
              goto next
Ln-1:         code for Sn
next:
```

```
              code to evaluate E into t
              goto test
L1: code for S1
              goto next
L2: code for S2
              goto next
              ......
Ln: code for Sn
              goto next
test:         if t = V1 goto L1
              if t = V2 goto L2
              ....
              if t = Vn-1 goto Ln-1
              goto Ln
next:
```

Efficient for n-way branch

BackPatching

- A way to implement Boolean expressions and flow of control statements in one pass
- Code is generated into an array (as quadruples, an implementation of 3 AC)
- Labels are indices into this array
- **makelist(i):** create a newlist containing only i, return a pointer to the list.
- **merge(p1, p2):** merge lists pointed to by p1 and p2 and return a pointer to the concatenated list
- **backpatch(p, i):** insert i as the target label for the statements in the list pointed to by p

Boolean Expressions

$$
\begin{aligned}
E \rightarrow\ & E_1 \text{ or } M\ E_2 \\
\mid\ & E_1 \text{ and } M\ E_2 \\
\mid\ & \text{not } E_1 \\
\mid\ & (E_1) \\
\mid\ & id_1 \text{ relop } id_2 \\
\mid\ & \text{true} \\
\mid\ & \text{false}
\end{aligned}
$$

$$M \rightarrow \epsilon$$

- Insert a marker non terminal M into the grammar to pick up index of next quadruple.
- attributes **truelist** and **falselist** are used to generate jump code for boolean expressions
- incomplete jumps are placed on lists pointed to by E.truelist and E.falselist

Boolean expressions …

- Consider $E \rightarrow E_1$ and M E_2
  - if E_1 is false then E is also false so statements in E_1.falselist become part of E.falselist
  - if E_1 is true then E_2 must be tested so target of E_1.truelist is beginning of E_2
  - target is obtained by marker M
  - attribute M.quad records the number of the first statement of E_2.code

$E \rightarrow E_1$ or M E_2

backpatch(E_1.falselist, M.quad)

E.truelist = merge(E_1.truelist, E_2.truelist)

E.falselist = E_2.falselist

$E \rightarrow E_1$ and M E_2

backpatch(E_1.truelist, M.quad)

E.truelist = E_2.truelist

E.falselist = merge(E_1.falselist, E_2.falselist)

$E \rightarrow$ not E_1

E.truelist = E_1 falselist

E.falselist = E_1.truelist

$E \rightarrow (E_1)$

E.truelist = E_1.truelist

E.falselist = E_1.falselist

$E \rightarrow id_1$ relop id_2

E.truelist = makelist(nextquad)

E.falselist = makelist(nextquad+ 1)

emit(if id_1 relop id_2 goto ---)

emit(goto ---)

$E \rightarrow$ true

E.truelist = makelist(nextquad)

emit(goto ---)

$E \rightarrow$ false

E.falselist = makelist(nextquad)

emit(goto ---)

$M \rightarrow \epsilon$

M.quad = nextquad

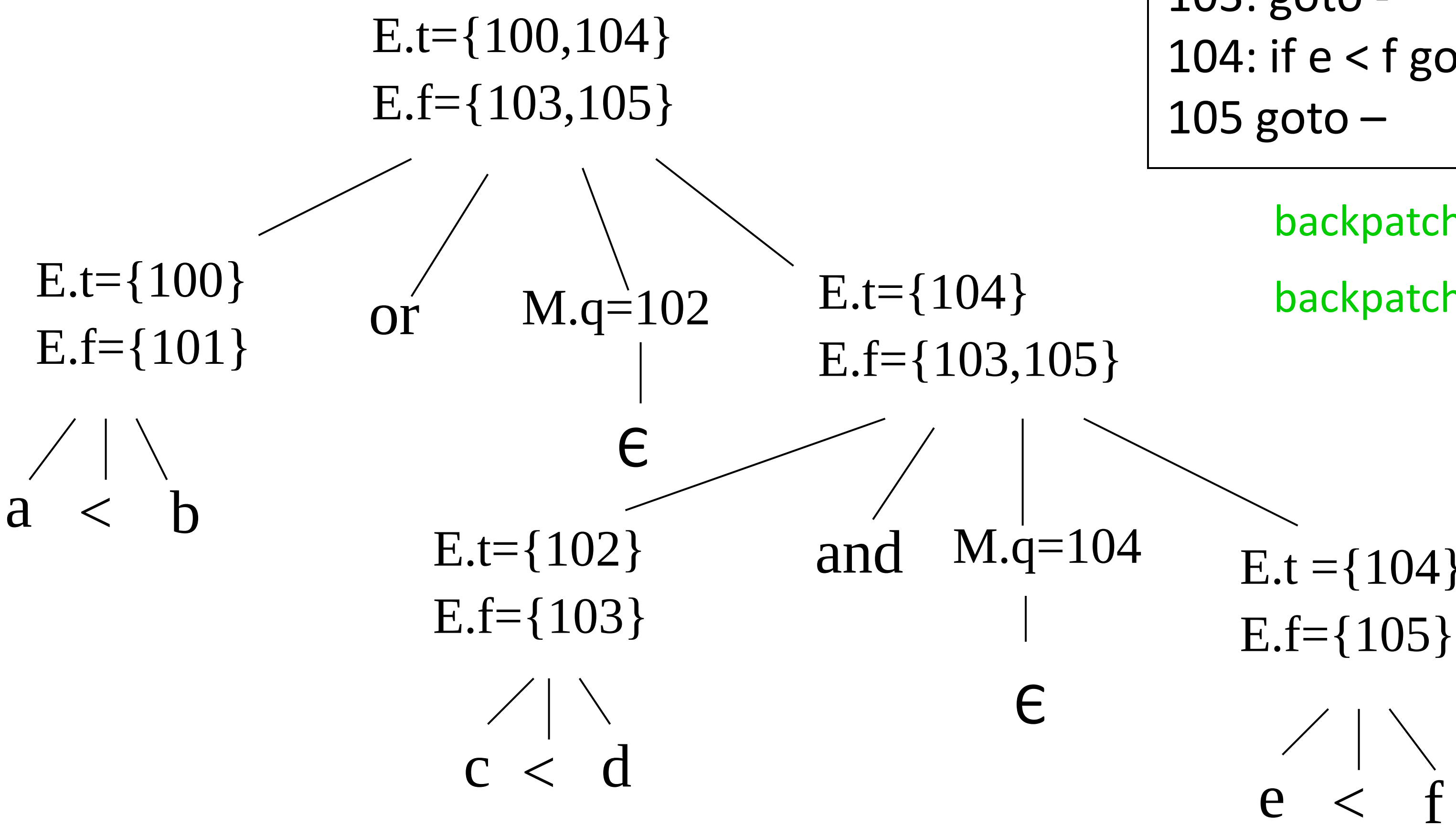
Generate code for
a < b or c < d and e < f

Initialize nextquad to 100

100: if a < b goto -
101: goto - 102
102: if c < d goto - 104
103: goto -
104: if e < f goto -
105 goto –

backpatch(102,104)

backpatch(101,102)



Flow of Control Statements

$S \rightarrow$ if E then S_1

| if E then S_1 else S_2

| while E do S_1

| begin L end

| A

$L \rightarrow L$; S

| S

S : Statement

A : Assignment

L : Statement list

Scheme to implement translation

- E has attributes truelist and falselist
- L and S have a list of unfilled quadruples to be filled by backpatching
- $S \rightarrow$ while E do S_1

  requires labels S.begin and E.true
  - markers M_1 and M_2 record these labels

    $S \rightarrow$ while M_1 E do M_2 S_1
  - when while. .. is reduced to S

    backpatch S_1.nextlist to make target of all the statements to M_1.quad
  - E.truelist is backpatched to go to the beginning of S_1 (M_2.quad)

Scheme to implement translation …

$S \rightarrow$ if E then M S_1

backpatch(E.truelist, M.quad)

S.nextlist = merge(E.falselist,
S_1.nextlist)

$S \rightarrow$ if E then M_1 S_1 N else M_2 S_2

backpatch(E.truelist, M_1.quad)

backpatch(E.falselist, M_2.quad)

S.nextlist = merge(S_1.nextlist,
N.nextlist,
S_2.nextlist)

Scheme to implement translation …

$S \rightarrow$ while M_1 E do M_2 S_1

backpatch(S_1.nextlist, M_1.quad)

backpatch(E.truelist, M_2.quad)

S.nextlist = E.falselist

emit(goto M_1.quad)

Scheme to implement translation …

$S \rightarrow \{ L \}$	S.nextlist = L.nextlist
$S \rightarrow A$	S.nextlist = makelist()
$L \rightarrow L_1 ; M S$	backpatch(L_1.nextlist, M.quad) L.nextlist = S.nextlist
$L \rightarrow S$	L.nextlist = S.nextlist
$N \rightarrow \in$	N.nextlist = makelist(nextquad) emit(goto ---)
$M \rightarrow \in$	M.quad = nextquad

Procedure Calls

$S \rightarrow$ call id (Elist)

$Elist \rightarrow Elist$, E

$Elist \rightarrow E$

- Calling sequence
  - allocate space for activation record
  - evaluate arguments
  - establish environment pointers
  - save status and return address
  - jump to the beginning of the procedure

Procedure Calls …

Example

- parameters are passed by reference
- storage is statically allocated
- use param statement as place holder for the arguments
- called procedure is passed a pointer to the first parameter
- pointers to any argument can be obtained by using proper offsets

Procedue Calls

- Generate three address code needed to evaluate arguments which are expressions
- Generate a list of param three address statements
- Store arguments in a list

S $\rightarrow$ call id (Elist)

for each item p on queue do emit(param p)

emit(call id.place)

Elist $\rightarrow$ Elist , E

append E.place to the end of queue

Elist $\rightarrow$ E

initialize queue to contain E.place

Procedure Calls

- Practice Exercise:

How to generate intermediate code for parameters passed by value?