Formal Languages and Compilers
Lecture IX—Intermediate Code Generation

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Formal Languages and Compilers — BSc course

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Summary of Lecture IX

- Three-Address Code
- Code for Assignments
- Code for Boolean Expressions and Flow-of-Control Statements

Intermediate Code Generation

- An intermediate code is generated as a program for an abstract machine.
  1. The intermediate code should be easy to translate into the target program.
  2. A machine-independent *Code Optimizer* can be applied before generating the target code.
- As intermediate code we consider the **three-address code**, similar to assembly: sequence of instructions with at most *three* operands such that:
  1. There is at most one operator, in addition to the assignment (we make explicit the operators precedence).
  2. The general form is: `x := y` *op* `z`
     where `x,y,z` are called addresses, i.e., either identifiers, constants or compiler-generated temporary names.
     - Temporary names must be generated to compute intermediate operations.
     - Addresses are implemented as pointers to their symbol-table entries.

Types of Three-Address Statements

Three-Address statements are akin to assembly code: Statements can have *labels* and there are statements for flow-of-control.

1. *Assignment Statements*: `x := y` *op* `z`.
2. *Unary Assignment Statements*: `x :=` *op* `y`.
3. *Copy Statements*: `x := y`.
4. *Unconditional Jump*: `goto L` (with `L` a label of a statement).
5. *Conditional Jump*: `if x` *relop* `y goto L`.

Types of Three-Address Statements (Cont.)

6. *Procedure Call*: `param x`, and `call p,n` for calling a procedure, `p`, with `n` parameters. With `return y` the returned value of the procedure is indicated.

```
param x1
param x2
...
param xn
call p,n
```

7. *Indexed assignments*: `x := y[i]` or `x[i] := y`.
   Note: `x[i]` denotes the value in the location `i` memory units beyond the location `x`.
8. *Pointer Assignmets*: `x := &y`, `x := *y`, or `*x := y`; where `&y` stands for the address of `y`, and `*y` for the value stored at `y`.

Summary

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Assignments and Symbol Tables: The Translation

The following S-attributed definition generates three-address code for assignments.

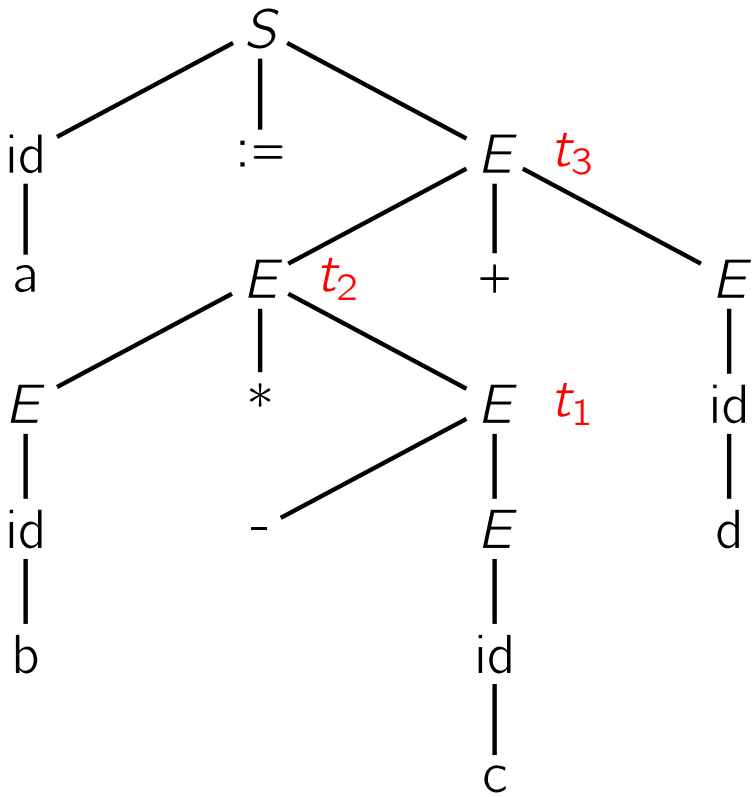
Production	**Semantic Rules**
$S \rightarrow \text{id} := E$	$p :=$ `lookup`(id.*name*); if $p \neq nil$ then `emit`($p\ ':='\ E.addr$) else *error*
$E \rightarrow E_1 + E_2$	$E.addr :=$ `newtemp`(); `emit`($E.addr\ ':='\ E_1.addr\ '+'\ E_2.addr$)
$E \rightarrow E_1 * E_2$	$E.addr :=$ `newtemp`(); `emit`($E.addr\ ':='\ E_1.addr\ '*'\ E_2.addr$)
$E \rightarrow -E_1$	$E.addr :=$ `newtemp`(); `emit`($E.addr\ ':='\ '\text{uminus}'\ E_1.addr$)
$E \rightarrow (E_1)$	$E.addr := E_1.addr$
$E \rightarrow \text{id}$	$p :=$ `lookup`(id.*name*); if $p \neq nil$ then $E.addr := p$ else *error*
$E \rightarrow \text{num}$	$E.addr :=$ `newtemp`(); $E.addr :=$ num.*val*

Assignments and Symbol Tables: Notes

- The function `emit()` output to a file a three-address code such that:
  1. Everything quoted is taken literally;
  2. The rest is evaluated.
- Temporary names are generated for intermediate computations.
  - The function `newtemp()` generates distinct temporary names $t_1, t_2, \ldots$.
- Expressions have a synthesized attribute:
  1. $E.addr$: Temporary name holding the value of E;
- Names/addresses stand for pointers to their symbol table entries: other info are needed for the final code generation (in particular, the storage address).
  - **Note.** Under this assumption Temporary Names must be also entered into the symbol table as they are created by the `newtemp()` function.
- The function `lookup`(id.*name*) return *nil* if the entry is not found in the symbol table, otherwise a pointer to the entry is returned.
  - The `lookup`(id.*name*) can be easily modified to account for scope: If *name* does not appear in the current symbol table the enclosing symbol table is checked (see the Lecture on "Symbol Table").

Code for Assignments: An Example

Given the assignment a := b ∗ −c + d the code generated by the above grammar is:



$$
\begin{aligned}
t_1 &:= \text{uminus } c \\
t_2 &:= b * t_1 \\
t_3 &:= t_2 + d \\
a &:= t_3
\end{aligned}
$$

Summary

- Three-Address Code
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- Code for Boolean Expressions and Flow-of-Control Statements

Boolean Expressions

- Boolean Expressions are used to either compute logical values or as conditional expressions in flow-of-control statements.
- We consider Boolean Expressions with the following grammar:

$$E \rightarrow E \text{ or } E \mid E \text{ and } E \mid \text{not } E \mid (E) \mid E \text{ relop } E \mid \text{true} \mid \text{false}$$

- There are two methods to evaluate Boolean Expressions
  1. Numerical Representation. Encode true with '1' and false with '0' and we proceed analogously to arithmetic expressions.
  2. Jumping Code. We represent the value of a Boolean Expression by a position reached in a program.

Numerical Representation of Boolean Expressions

- Expressions will be evaluated from left to right assuming that: **or** and **and** are left-associative, and that **or** has lowest precedence, then **and**, and finally **not**.
- **Example 1.** The translation for "a or (b and (not c))" is:
  t_1 := not c
  t_2 := b and t_1
  t_3 := a or t_2
- **Example 2.** A relational expression such as a<b is equivalent to the conditional statement if a<b then 1 else 0. Its translation involves *jumps to labeled statements*:

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

Numerical Representation: The Translation

- The following S-Attributed Definition makes use of the global variable `nextstat` that gives the index of the next three-address code statement and is incremented by *emit*.

Production	**Semantic Rules**
$E \rightarrow E_1$ or E_2	$E.addr :=$ `newtemp`(); `emit`($E.addr$ ':=' $E_1.addr$ 'or' $E_2.addr$)
$E \rightarrow E_1$ and E_2	$E.addr :=$ `newtemp`(); `emit`($E.addr$ ':=' $E_1.addr$ 'and' $E_2.addr$)
$E \rightarrow$ not E_1	$E.addr :=$ `newtemp`(); `emit`($E.addr$ ':=' 'not' $E_1.addr$)
$E \rightarrow (E_1)$	$E.addr := E_1.addr$
$E \rightarrow E_1$ relop E_2	$E.addr :=$ *newtemp*(); `emit`('if' $E_1.addr$ relop.*op* $E_2.addr$ 'goto' `nextstat` + 3); `emit`($E.addr$ ':=' '0'); `emit`('goto' `nextstat` + 2); `emit`($E.addr$ ':=' '1')
$E \rightarrow$ true	$E.addr :=$ `newtemp`(); `emit`($E.addr$ ':=' '1')
$E \rightarrow$ false	$E.addr :=$ `newtemp`(); `emit`($E.addr$ ':=' '0')

Jumping Code for Boolean Expressions

- The value of a Boolean Expression is represented by a position in the code.
- Consider Example 2: We can tell what value t will have by whether we reach statement 101 or statement 103.
- Jumping code is extremely useful when Boolean Expressions are in the context of flow-of-control statements.
- We start by presenting the translation for flow-of-control statements generated by the following grammar:

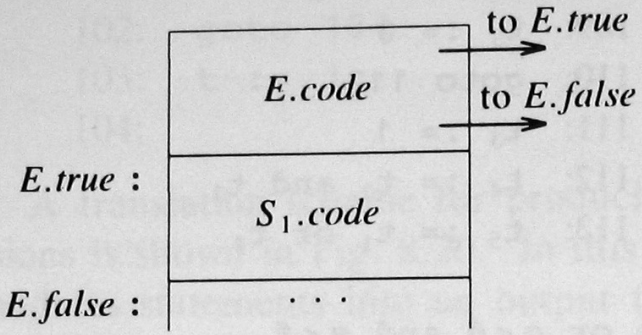
$$
\begin{array}{rcl}
S & \rightarrow & \text{if } E \text{ then } S \\
 & | & \text{if } E \text{ then } S_1 \text{ else } S_2 \\
 & | & \text{while } E \text{ do } S
\end{array}
$$

Flow-of-Control Statements

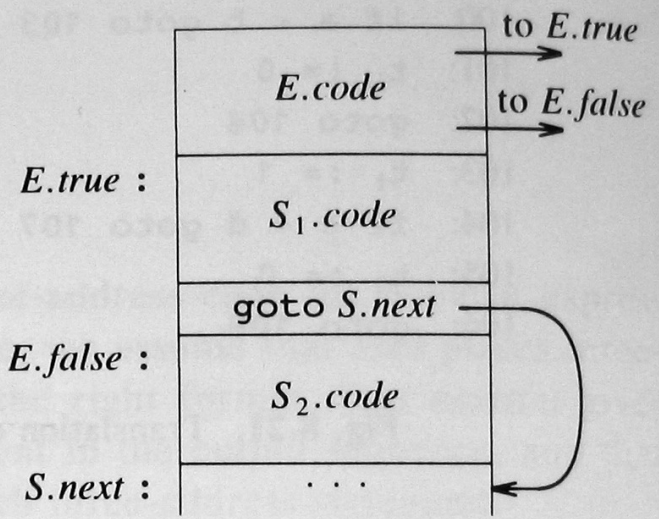
- In the translation, we assume that a three-address code statement can have a *symbolic label*, and that the function `newlabel()` generates such labels.
- We associate with E two labels using **inherited attributes**:
  1. $E.true$, the label to which control flows if E is true;
  2. $E.false$, the label to which control flows if E is false.
- We associate to S the inherited attribute $S.next$ that represents the label attached to the first statement after the code for S.
- **Note 1.** This method of generating symbolic labels can lead to a proliferation of label: The *backpatching* method (see the Book) creates labels only when needed and emits directly the code.
- **Note 2.** To substitute symbolic labels with actual addresses a second pass is needed: *backpatching* will avoid also the two-pass translation.

Flow-of-Control Statements (Cont.)

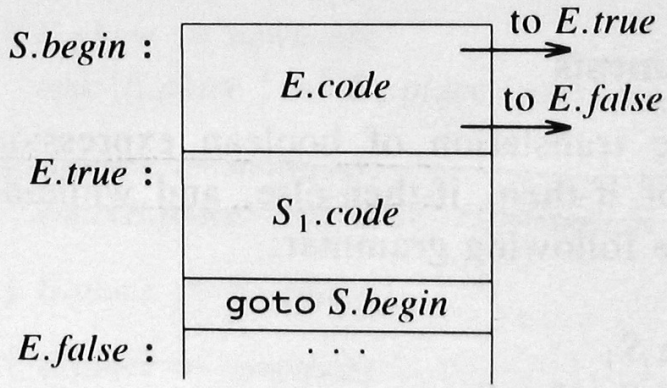
- The following figures show how the flow-of-control statements are translated.



(a) if-then



(b) if-then-else



(c) while-do

Flow-of-Control Statements: The Translation

Production	**Semantic Rules**
$P \rightarrow S$	$S.next = \texttt{newlabel}();$ $P.code := S.code \parallel \texttt{gen}(S.next\ ':')$
$S \rightarrow$ if E then S_1	$E.true := \texttt{newlabel}();\quad E.false := S.next;$ $S_1.next := S.next;$ $S.code := E.code \parallel \texttt{gen}(E.true\ ':') \parallel S_1.code$
$S \rightarrow$ if E then S_1 else S_2	$E.true := \texttt{newlabel}();\quad E.false := \texttt{newlabel}();$ $S_1.next := S.next;\quad S_2.next := S.next;$ $S.code := E.code \parallel \texttt{gen}(E.true\ ':') \parallel S_1.code \parallel$ $\texttt{gen}('\text{goto}'\ S.next) \parallel$ $\texttt{gen}(E.false\ ':') \parallel S_2.code$
$S \rightarrow$ while E do S_1	$E.begin := \texttt{newlabel}();$ $E.true := \texttt{newlabel}();\quad E.false := S.next;$ $S_1.next := E.begin;$ $S.code := \texttt{gen}(E.begin\ ':') \parallel E.code \parallel$ $\texttt{gen}(E.true\ ':') \parallel S_1.code \parallel$ $\texttt{gen}('\text{goto}'\ E.begin)$

Flow-of-Control Statements with Translation Schemes

Translation Scheme

$P \rightarrow \{S.next = \texttt{newlabel}();\}\ S\ \{P.code := S.code \parallel \texttt{gen}(S.next\ ':')\}$

$S \rightarrow \text{if}\ \{E.true := \texttt{newlabel}();\ E.false := S.next;\}\ E\ \text{then}$
$\{S_1.next := S.next;\}\ S_1 \{S.code := E.code \parallel \texttt{gen}(E.true\ ':') \parallel S_1.code\}$

$S \rightarrow \text{if}\ \{E.true := \texttt{newlabel}();\ E.false := \texttt{newlabel}();\}\ E\ \text{then}$
$\{S_1.next := S.next;\}\ S_1\ \text{else}\ \{\ S_2.next := S.next;\}\ S_2$
$\{S.code := E.code \parallel \texttt{gen}(E.true\ ':') \parallel S_1.code \parallel$
$\texttt{gen}('\text{goto}'\ S.next) \parallel \texttt{gen}(E.false\ ':') \parallel S_2.code\}$

Jumping Code for Boolean Expressions (Cont.)

- Boolean Expressions are translated in a sequence of conditional and unconditional jumps to either *E.true* or *E.false*.
- a < b. The code is of the form:
  if a < b goto *E.true*
  goto *E.false*
- E_1 or E_2. If E_1 is true then E is true, so $E_1.true = E.true$. Otherwise, E_2 must be evaluated, so $E_1.false$ is set to the label of the first statement in the code for E_2.
- E_1 and E_2. Analogous considerations apply.
- not E_1. We just interchange the true and false with that for E.
- **Note.** Both the *true* and *false* attributes are inherited and the translation is an L-attributed grammar.

Jumping Code for Boolean Expressions: The Translation

Production	**Semantic Rules**
$E \rightarrow E_1$ or E_2	$E_1.true := E.true$; $E_1.false :=$ `newlabel()`;
	$E_2.true := E.true$; $E_2.false := E.false$;
	$E.code := E_1.code \parallel \texttt{gen}(E_1.false\ ':') \parallel E_2.code$
$E \rightarrow E_1$ and E_2	$E_1.true :=$ `newlabel()`; $E_1.false := E.false$;
	$E_2.true := E.true$; $E_2.false := E.false$;
	$E.code := E_1.code \parallel \texttt{gen}(E_1.true\ ':') \parallel E_2.code$
$E \rightarrow$ not E_1	$E_1.true := E.false$; $E_1.false := E.true$;
	$E.code := E_1.code$
$E \rightarrow (E_1)$	$E_1.true := E.true$; $E_1.false := E.false$;
	$E.code := E_1.code$

(Follows $\rightarrow$)

Jumping Code for Boolean Expressions: The Translation

Production	**Semantic Rules**
$E \rightarrow E_1$ relop E_2	$E.code := E_1.code \parallel E_2.code \parallel$ $\texttt{gen}('\text{if}'\ E_1.addr\ \text{relop}.op\ E_2.addr\ '\text{goto}'\ E.true) \parallel$ $\texttt{gen}('\text{goto}'\ E.false)$
$E \rightarrow$ id	$p = \texttt{lookup}(\text{id}.name)$; if$(p.type = bool)$ then $\quad E.code := \texttt{gen}('\text{if}'\ p = true\ '\text{goto}'\ E.true) \parallel$ $\quad \texttt{gen}('\text{goto}'\ E.false)$ else if$(p \neq nil)$ then $\quad E.addr = p; E.code = '\ '$ $\quad$ else *error*
$E \rightarrow$ true	$E.code := \texttt{gen}('\text{goto}'\ E.true)$
$E \rightarrow$ false	$E.code := \texttt{gen}('\text{goto}'\ E.false)$

Flow-of-Control and Boolean Expressions: An Example

- **Example.** Translate the following statement:

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

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