CS323: Compilers

Spring 2023

Week 6: Semantic Processing (contd..)

Intermediate Representation

- Compilers need to synthesize code based on the ‘interpretation’ of the syntactic structure
- Code can be generated with the help of AST or can directly do it in semantic actions (recall: SDTs augment grammar rules with program fragments. Program fragments contain semantic actions.)
- Generated code can be directly executed on the machine or an intermediate form such as 3-address code can be produced.

3 Address Code (3AC)

- **What is it?** sequence of elementary program instructions
  - Linear in structure (no hierarchy) unlike AST
  - Format:

```
op A, B, C    //means C = A op B.
//op: ADDI, MULI, SUBF, DIVF, GOTO, STOREF etc.
```

  - E.g.

program text	**3-address code**

`INT x;`
`FLOAT y, z;`
`z:=x+y;`
	`ADDF x y T1`
	`STOREF T1 z`

`INT a, b, c, d;`
`d = a-b/c;`
	`DIVI b c T1`
	`SUBI a T1 T2`
	`STOREI T2 d`

Comments:

```
d = a-b/c; is broken into:
t1 = b/c;
t2 = a-t1;
d = t2;
```

3 Address Code (3AC)

- **Why is it needed?** To perform *significant* optimizations such as:
  - common sub-expression elimination
  - statically analyze possible values that a variable can take etc.

  How?

  Break the long sequence of instructions into “basic blocks” and operate on/analyze a graph of basic blocks

3 Address Code (3AC)

- **How is it generated?** Choices available:
  1. Do a post-order walk of AST
  - Generate/Emit code as a string/data_object (seen later) when you visit a node
  - Pass the code to the parent node

    Parent generates code for self after the code for children is generated. The generated code is appended to code passed by children and passed up the tree

```
data_object generate_code() {
    //preprocessing code
    data_object lcode=left.generate_code();
    data_object rcode=right.generate_code();
    return generate_self(lcode, rcode);
}
```

  2. Can generate directly in semantic routines or after building AST

3 Address Code (3AC)

- Generating 3AC directly in semantic routines.

```
INT x;
x:=3*4+5+6+7;
```

```
MULI 3 4 T1
ADDI T1 5 T2
ADDI T2 6 T3
ADDI T3 7 T4
STOREI T4 x
```

Comments:

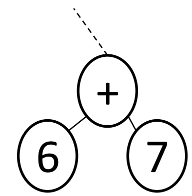
```
x = 3*4+5+6+7 is broken into:
t1 = 3*4;
t2 = 5+t1;
t3 = 6+t2;
t4 = 7+t3;
x = t4
```

- Walk the AST in post-order and infer at an internal node (labelled op) that it computes a constant expression

```
INT x;
x:=3*4+5+6+7;
```

```
STOREI 30 x
```

Comments:



L-values and R-values

- Need to distinguish between meaning of identifiers appearing on RHS and LHS of an assignment statement

```
i := 5;          //RHS specifies data that is computed/read.
i := i + 1;      LHS specifies address where data is stored.
```

- **L-values**: addresses which can be loaded from or stored into
- **R-values**: data often loaded from address
  - Expressions produce R-values
- Assignment statements: `L-value := R-value;`

```
a := a;
```

a refers to memory location named a. We are storing into that memory location (L-value)

a refers to data stored in the memory location named a. We are loading from that memory location to produce R-value

Temporaries

- Earlier saw the use of temporaries e.g.

```
INT x;
FLOAT y, z;
z:=x+y;
```

```
ADDF x y T1
STOREF T1 z
```

- Think of them as unlimited pool of registers with memory to be allocated later
- Optionally declare them in 3AC. Name should be unique and should not appear in program text

```
INT x
FLOAT y z T1
ADDF x y T1
STOREF T1 z
```

- Temporary can hold L-value or R-value

Temporaries and L-value

- Yes, a temporary can hold L-value. Consider:

```
a := &b;  //& is address-of operator. R-value
of a is set to L-value of b.
//expression on the RHS produces data that is
an address of a memory location.

Recall: L-Value = address which can be loaded
from or stored into, R-Value = data (often)
loaded from addresses.
```

Take L-value of b, don't load from it, treat it as an R-value and store the resulting data in a temporary

Dereference operator

- Consider:

```
*a := b;  //* is dereference operator. R-value
of a is set to R-value of b.
//expression on the LHS produces data that is
an address of a memory location.
```

a appearing on LHS is loaded from to produce R-value. That R-value is treated as an address that can be stored into.

Take R-value of a, treat it as an L-value (address of a memory location) and then store RHS data

*Summary: pointer operations & and * mess with meaning of L-value and R-values*

Observations

- Identifiers appearing on LHS are (normally) treated as L-values. Appearing on RHS are treated as R-values.
  - So, when you are visiting an `id` node in an AST, you cannot generate code (load-from or store-into) until you have seen how that identifier is used. => until you visit the parent.
- Temporaries are needed to store result of current expression
- a `data_object` should store:
  - Code
  - L-value or R-Value or constant
  - Temporary storing the result of the expression

Simple cases

- Generating code for constants/literals
  - Store constant in temporary
  - Optional: pass up flag specifying this is a constant
- Generating code for identifiers
  - Generated code depends on whether identifier is used as L-value or R-value
    - Is this an address? Or data?
  - One solution: just pass identifier up to next level
    - Mark it as an L-value (it's not yet data!)
    - Generate code once we see how variable is used

Slide courtesy: Milind Kulkarni

Generating code for expressions

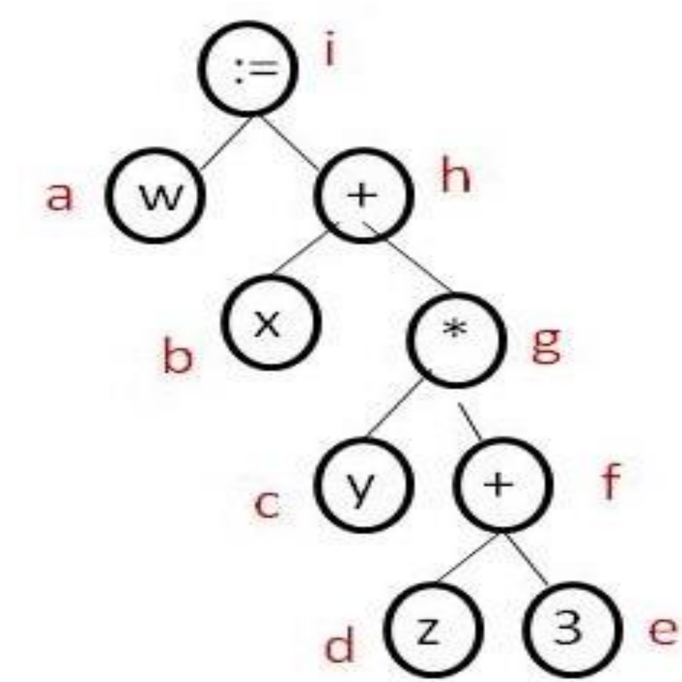
- Create a new temporary for result of expression
- Examine data-objects from subtrees
- If temporaries are L-values, load data from them into new temporaries
  - Generate code to perform operation
  - In project, no need to explicitly load (variables can be operands)
- If temporaries are constant, can perform operation immediately
  - No need to perform code generation!
- Store result in new temporary
  - Is this an L-value or an R-value?
- Return code for entire expression

Slide courtesy: Milind Kulkarni

Example - assignment statement

AST for

`w:=x+y*(z+3);`



Visit Node a:

Temp: w

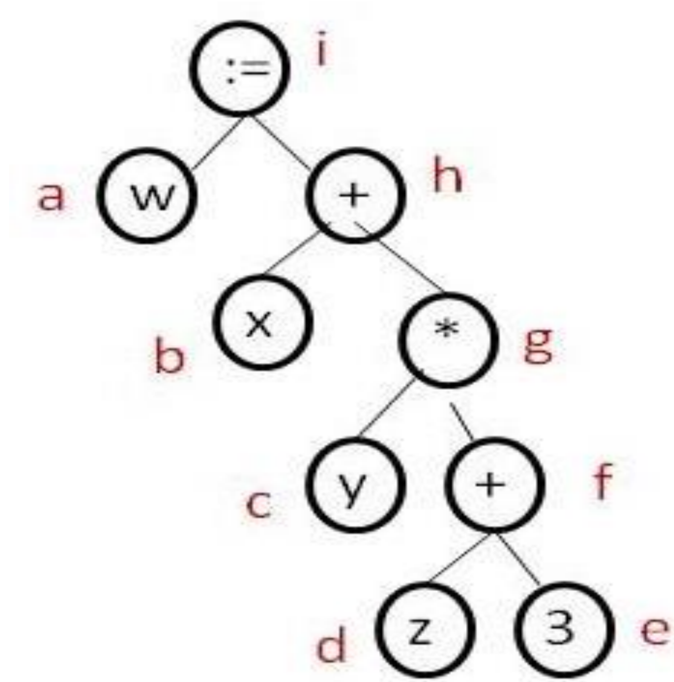
Type: l-value

Code: --

Example - assignment statement

AST for

`w:=x+y*(z+3);`



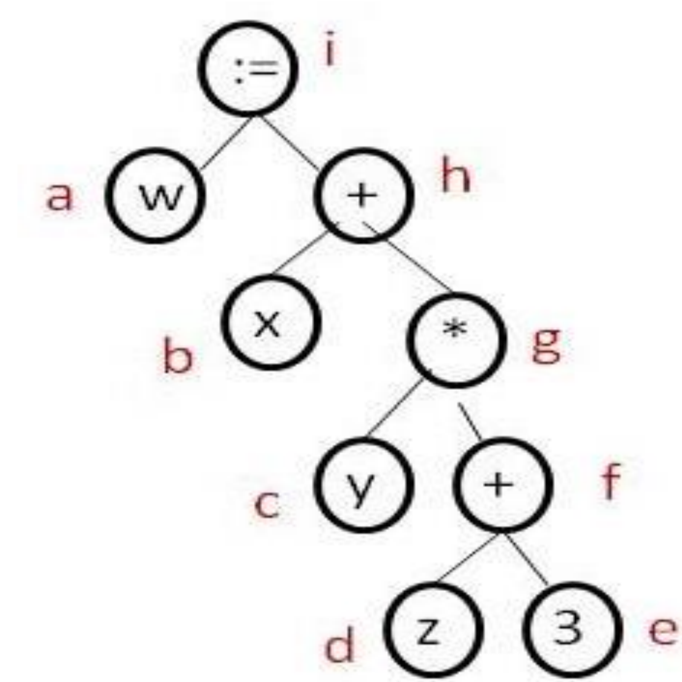
Visit Node b:

- Temp: x
- Type: l-value
- Code: --

Example - assignment statement

AST for

`w:=x+y*(z+3);`



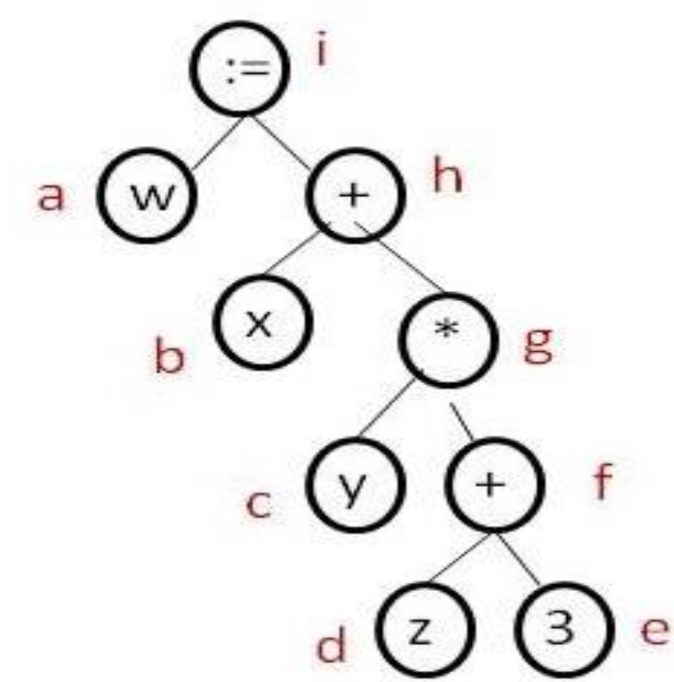
Visit Node c:

- Temp: y
- Type: l-value
- Code: --

Example - assignment statement

AST for

`w:=x+y*(z+3);`



Visit Node d:

Temp: z

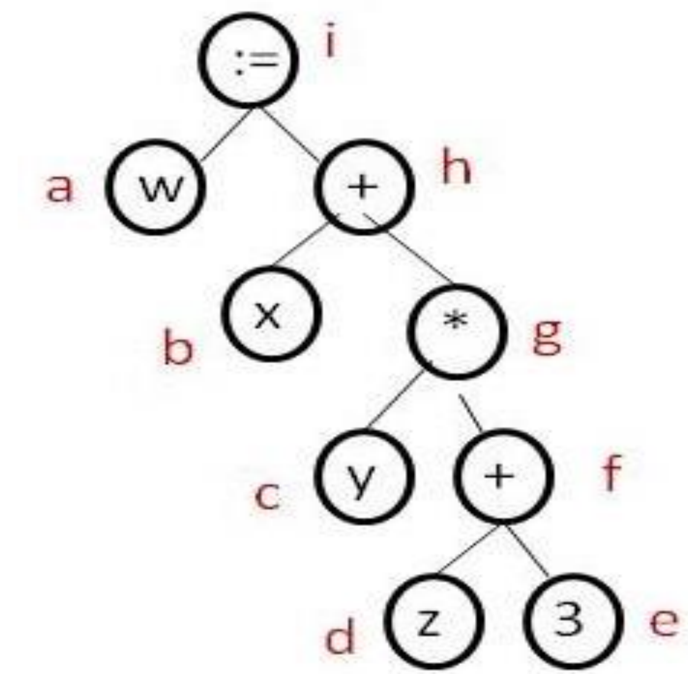
Type: l-value

Code: --

Example - assignment statement

AST for

`w:=x+y*(z+3);`



Visit Node e:

Temp: 3

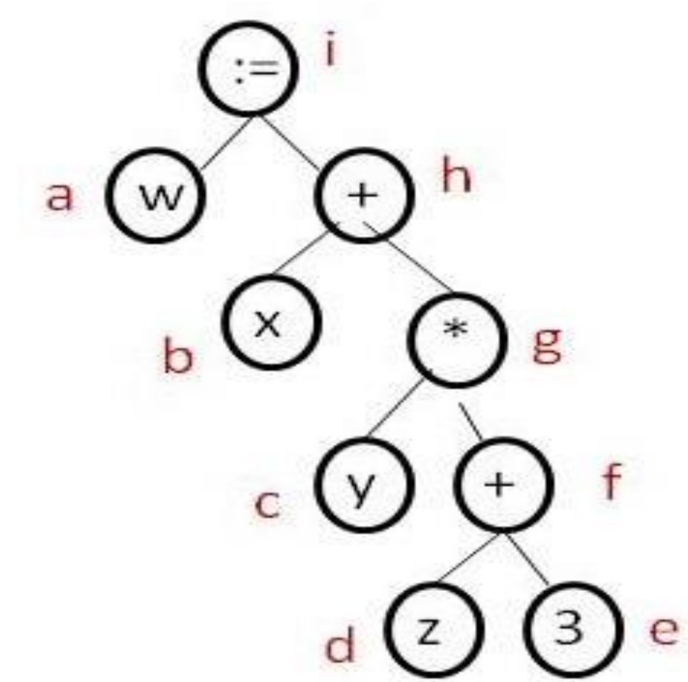
Type: constant

Code: --

Example - assignment statement

AST for

`w:=x+y*(z+3);`



Visit Node f:

Temp: T1

Type: R-value

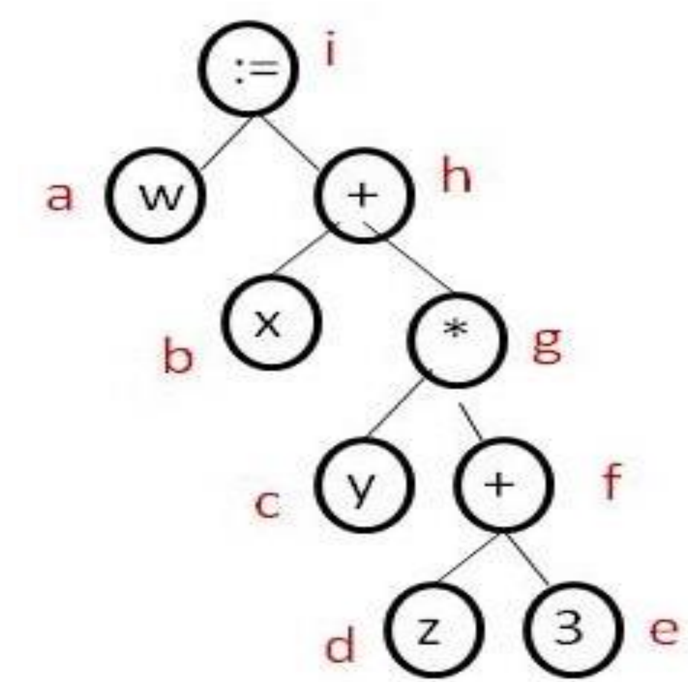
Code:

```
LD z T2
ADD T2 3 T1
```

Example - assignment statement

AST for

`w:=x+y*(z+3);`



Visit Node g:

Temp: T3

Type: R-value

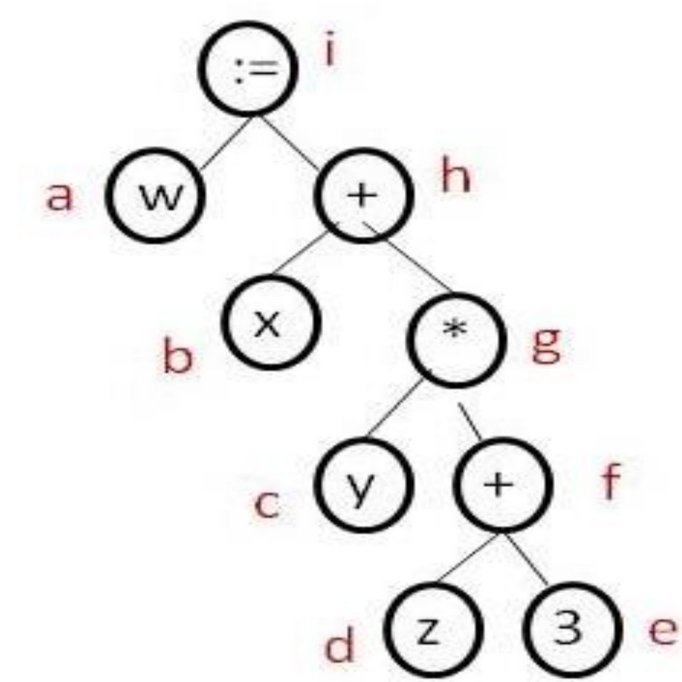
Code:

```
LD y T4
LD z T2
ADD T2 3 T1
MUL T4 T1 T3
```

Example - assignment statement

AST for

`w:=x+y*(z+3);`



Visit Node h:

Temp: T5

Type: R-value

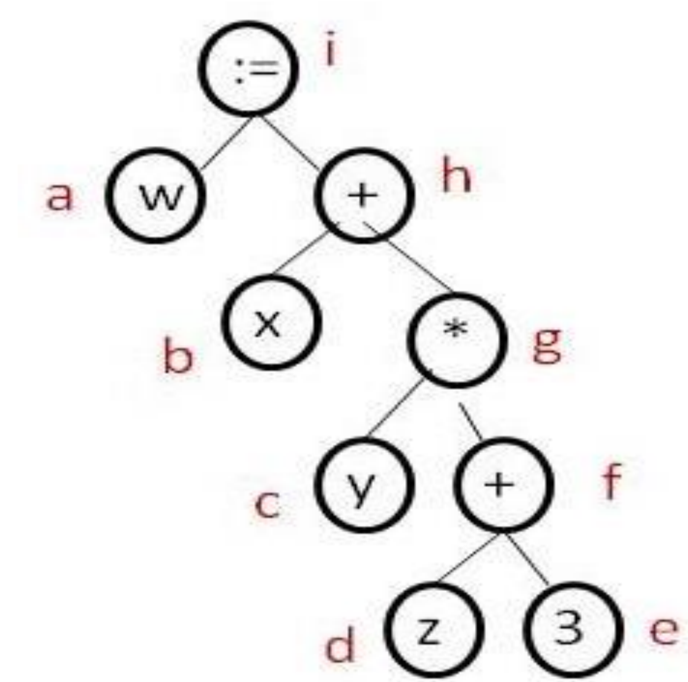
Code:

```
LD x T6
LD y T4
LD z T2

ADD T2 3 T1

MUL T4 T1 T3
ADD T6 T3 T5
```

Example - assignment statement

AST for

`w:=x+y*(z+3);`



Visit Node i:

Temp: NA

Type: NA

Code:

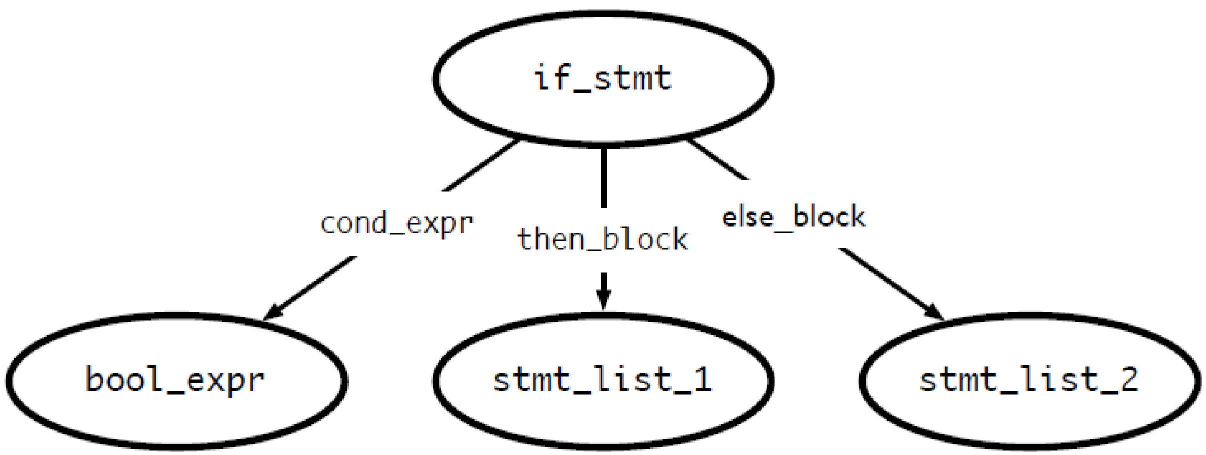
```
LD x T6
LD y T4
LD z T2

ADD T2 3 T1

MUL T4 T1 T3
ADD T6 T3 T5
ST T5 w
```

If statements

```
if <bool_expr_1>
  <stmt_list_1>
else
  <stmt_list_2>
endif
```


Slide courtesy: Milind Kulkarni

If statements



Slide courtesy: Milind Kulkarni

Generating code for ifs

```
if <bool_expr_1>
  <stmt_list_1>
else
  <stmt_list_2>
endif
```

```
  <code for bool_expr_1>
  j<!op> ELSE_1
  <code for stmt_list_1>
  jmp OUT_1
ELSE_1:
  <code for stmt_list_2>
OUT_1:
```


Slide courtesy: Milind Kulkarni

Notes on code generation

- The <op> in j<!op> is dependent on the type of comparison you are doing in <bool_expr>
- When you generate JUMP instructions, you should also generate the appropriate LABELs
- Remember: labels have to be unique!

Slide courtesy: Milind Kulkarni

Code-generation – if-statement

Program text	**3AC**
`INT a, b;`	

Code-generation – if-statement

Program text	**3AC**	
`INT a, b;`		Make entries in the symbol table

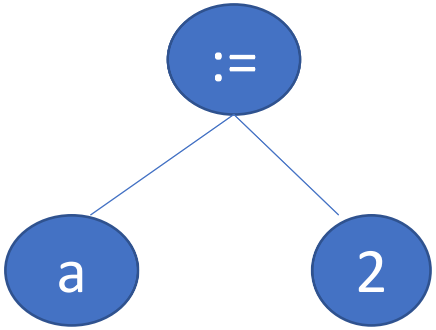
Code-generation – if-statement

Program text	**3AC**
`INT a, b;` `a := 2;`	

Code-generation – if-statement

Program text | **3AC**

```
INT a, b;
a := 2;
```

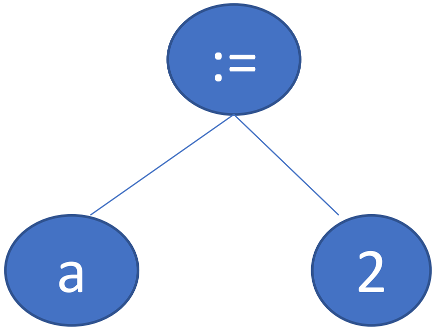


1. “a” is left-child, type=l-val. No code generated. *Return an object containing identifier details after verifying that “a” is present in the symbol table.*

Code-generation – if-statement

Program text | **3AC**

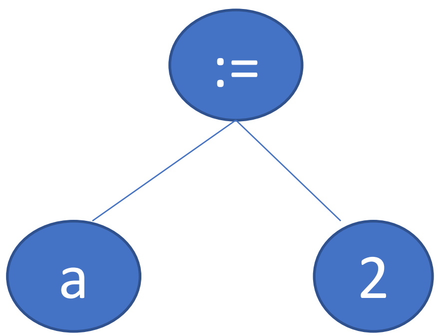
```
INT a, b;
a := 2;
```



1. “a” is left-child, type=l-val. No code generated. Pass up the identifier.
2. “2” is right-child, type=const. No code generated.

Code-generation – if-statement

Program text	**3AC**
`INT a, b;` `a := 2;`	

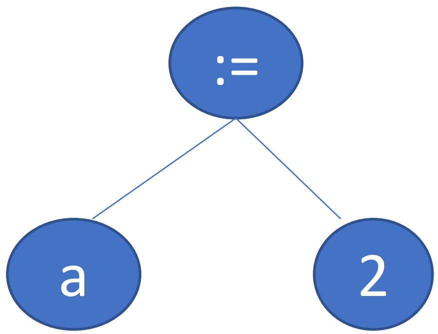


1. "a" is left-child, type=l-val. No code generated. Pass up the identifier.
2. "2" is right-child, type=const. No code generated.
3. Create a temporary T1 to store the result of the expression

Code-generation – if-statement

Program text | **3AC**

```
INT a, b;
a := 2;
```



1. "a" is left-child, type=l-val. No code generated. Pass up the identifier.
2. "2" is right-child, type=const. No code generated.
3. Current node stores the op ':='. A call to `process_op` stores the RHS data in LHS

Code-generation – if-statement

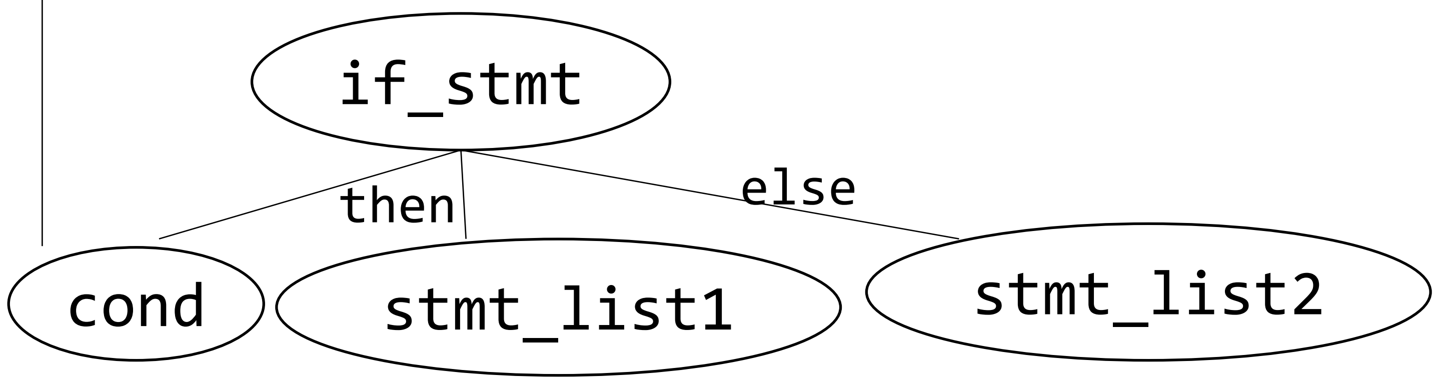
Program text	**3AC**
`INT a, b;`	`STOREI 2 T1`
`a := 2;`	`STOREI T1 a`

Code-generation – if-statement

Program text	**3AC**
`INT a, b;`	`STOREI 2 T1`
`a := 2;`	`STOREI T1 a`

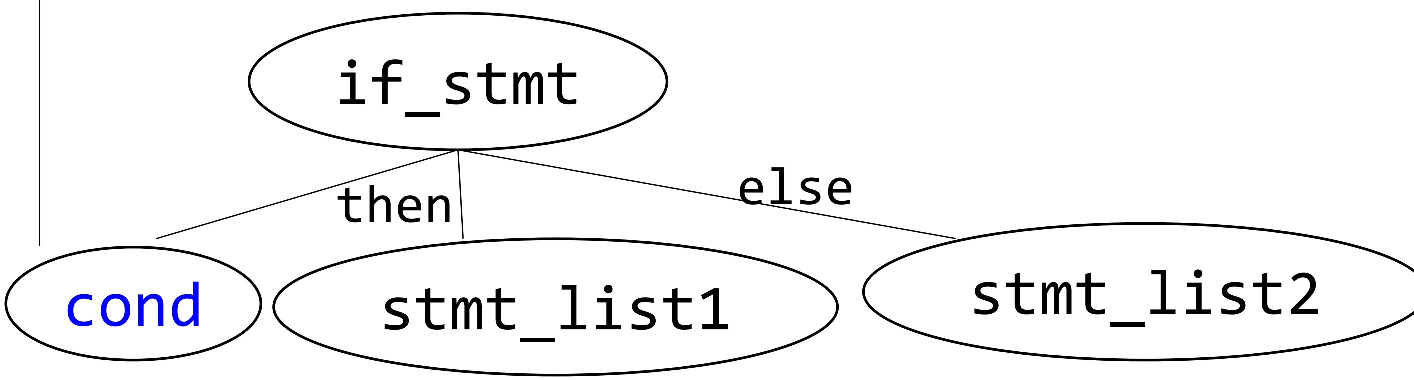
```
INT a, b;
a := 2;
IF (a = 1)
   b := 1;
ELSE
   b := 2;
ENDIF
```

```
STOREI 2 T1
STOREI T1 a
```



Code-generation – if-statement

Program text	**3AC**
`INT a, b;`	`STOREI 2 T1`
`a := 2;`	`STOREI T1 a`
`IF (a = 1)`	
`   b := 1;`	
`ELSE`	
`   b := 2;`	
`ENDIF`	



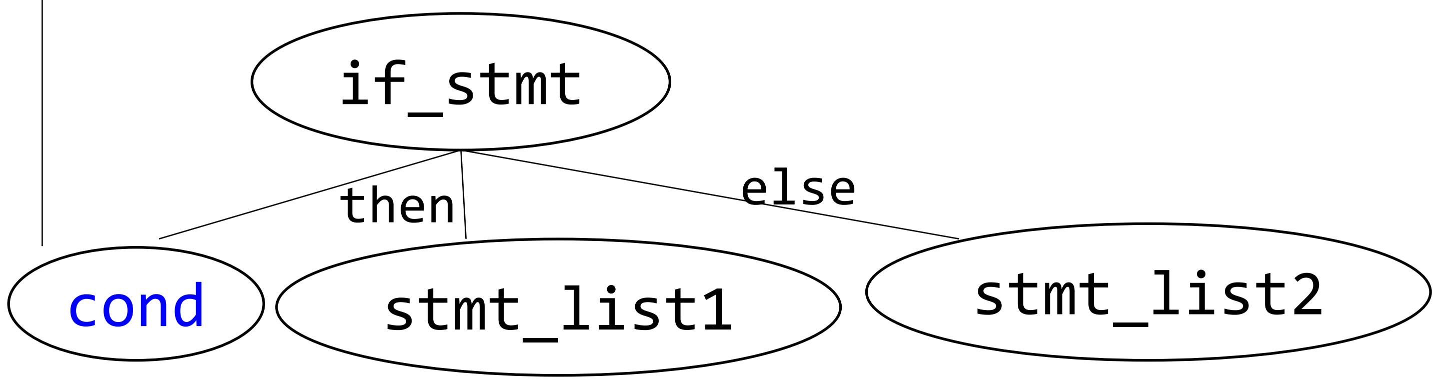
1. Generate code for cond

Code-generation – if-statement

Program text | **3AC**

```
INT a, b;
a := 2;
IF (a = 1)
   b := 1;
ELSE
   b := 2;
ENDIF
```

```
STOREI 2 T1
STOREI T1 a
```




```
STOREI 1 T2
NE a T2 label1
```

1. Generate code for cond

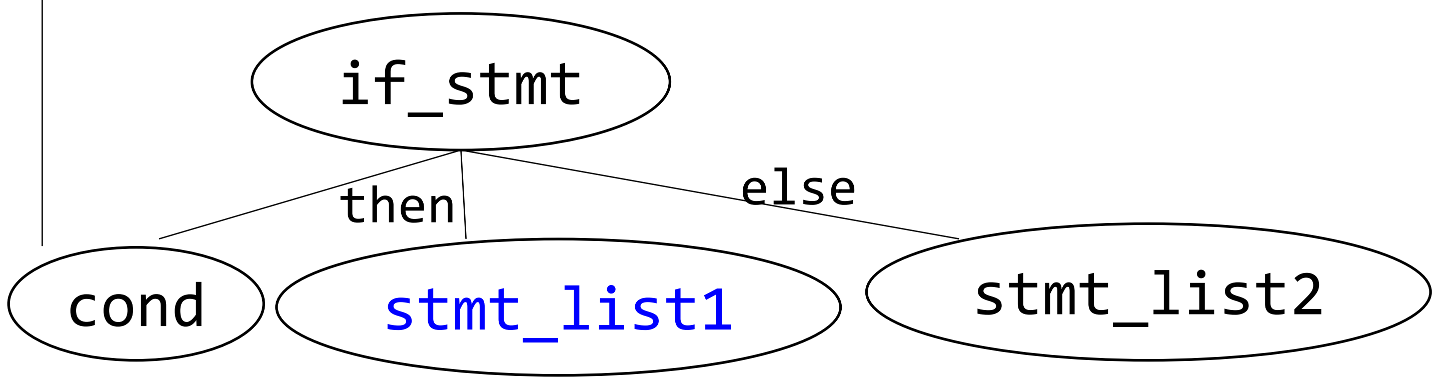
Note that to generate this instruction when cond node is visited, we need information about the label. This information can be passed on as a semantic record for the child node of the if construct. The record can be created by the IF construct (when the keyword IF is seen) and would be updated subsequently.

Code-generation – if-statement

Program text | **3AC**

```
INT a, b;
a := 2;
IF (a = 1)
   b := 1;
ELSE
   b := 2;
ENDIF
```

```
STOREI 2 T1
STOREI T1 a
```



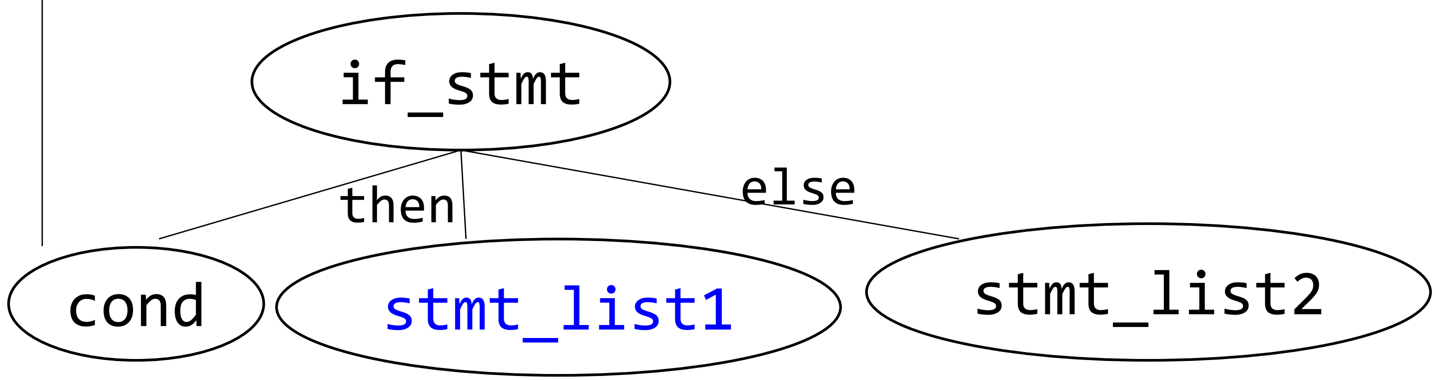
2. Generate code for stmt_list1

Code-generation – if-statement

Program text | **3AC**

```
INT a, b;
a := 2;
IF (a = 1)
   b := 1;
ELSE
   b := 2;
ENDIF
```

```
STOREI 2 T1
STOREI T1 a
```



2. Generate code for stmt_list1

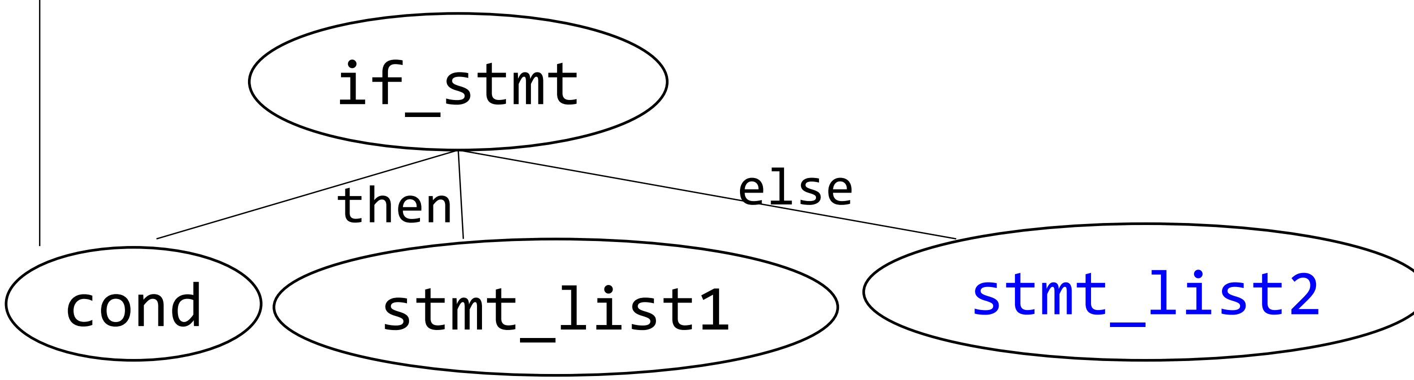
```
STOREI 1 T3
STOREI T3 b
```

Code-generation – if-statement

Program text | **3AC**

```
INT a, b;
a := 2;
IF (a = 1)
   b := 1;
ELSE
   b := 2;
ENDIF
```

```
STOREI 2 T1
STOREI T1 a
```



3. Generate code for stmt_list2

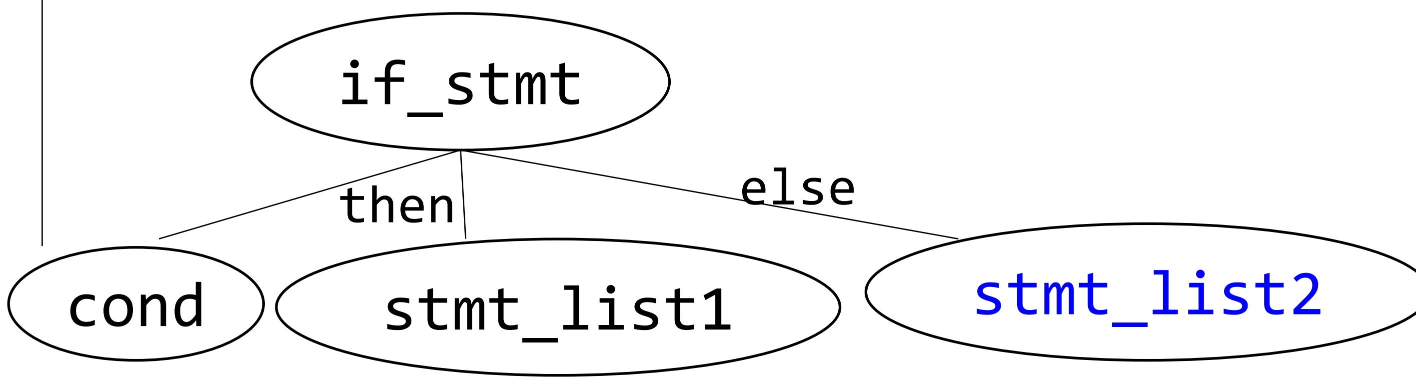
Code-generation – if-statement

Program text

```
INT a, b;
a := 2;
IF (a = 1)
   b := 1;
ELSE
   b := 2;
ENDIF
```

3AC

```
STOREI 2 T1
STOREI T1 a
```




```
JUMP label2
LABEL label1
STOREI 2 T4
STOREI T4 b
JUMP label2
```

3. Generate code for stmt_list2

The statements shown in red can be part of the semantic routines that correspond to handling the else part.

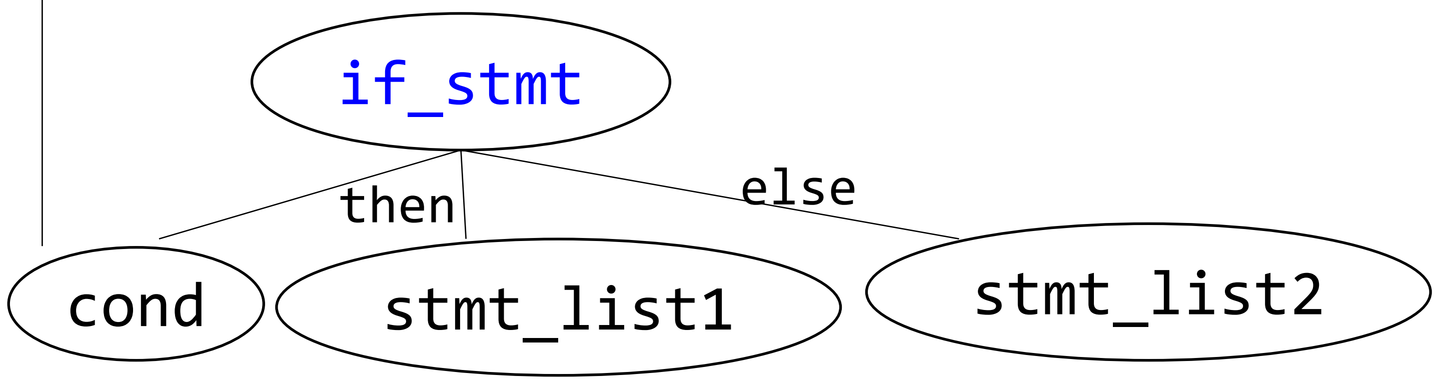
Code-generation – if-statement

Program text

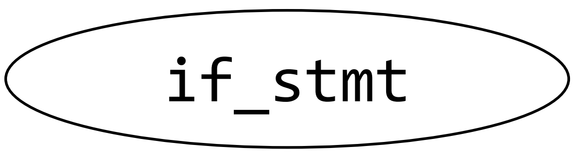
```
INT a, b;
a := 2;
IF (a = 1)
   b := 1;
ELSE
   b := 2;
ENDIF
```

3AC

```
STOREI 2 T1
STOREI T1 a
```



3. Generate code for




```
LABEL label2
```

Code-generation – if-statement

Program text	**3AC**
INT a, b;	
a := 2;	STOREI 2 T1 //a := 2 STOREI T1 a
IF (a = 1)	STOREI 1 T2 //a = 1? NE a T2 label1
b := 1;	STOREI 1 T3 //b := 1 STOREI T3 b
ELSE	
b := 2;	JUMP label2 //to out label LABEL label1 //else label begins here STOREI 2 T4 //b := 2 STOREI T4 b JUMP label2 //jump to out label
ENDIF	LABEL label2 //out label

Can also generate this code after seeing the token ENDIF (rather than as part of the routine that is executed when the whole production is matched)

Jumps and Labels?

- Who will generate labels?
- When will the labels be generated?
- To what addresses will the labels be associated with?

How are targets of jumps decided?

Suggested Reading

- Alfred V. Aho, Monica S. Lam, Ravi Sethi and Jeffrey D.Ullman: Compilers: Principles, Techniques, and Tools, 2/E, AddisonWesley 2007
  - Chapter 2 (2.3, 2.5, 2.7, 2.8), Chapter 4 (4.6), Chapter 5 (5.1, 5.2.3, 5.2.4, 5.4), Chapter 6(6.2-6.4)
- Fisher and LeBlanc: Crafting a Compiler with C
  - Chapter 6 (6.2-6.4), Chapter 7 (7.1, 7.3), Chapter 8 (8.2, 8.3), Chapter 11 (11.2)