# Compiler Design

AST

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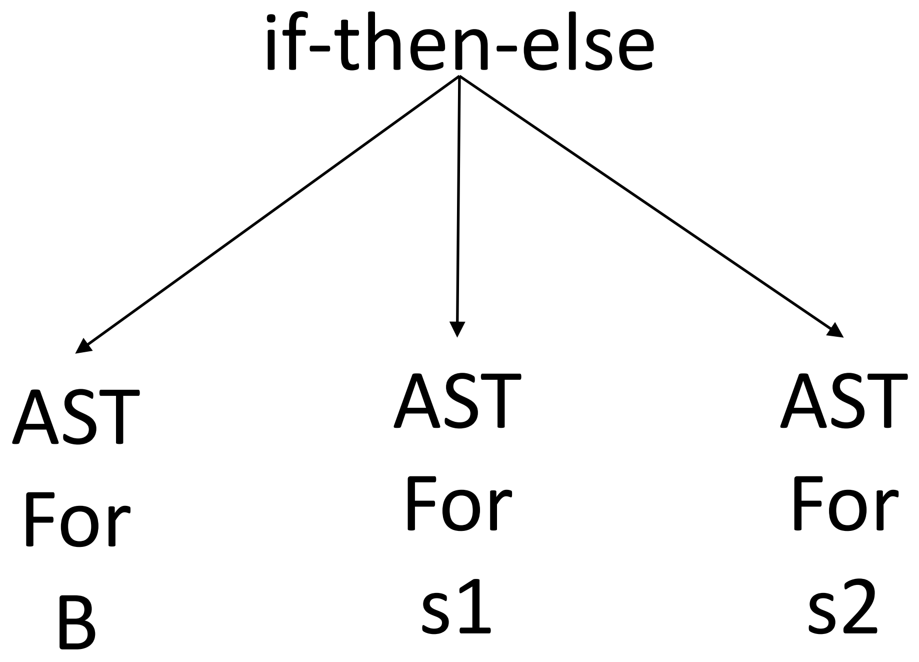
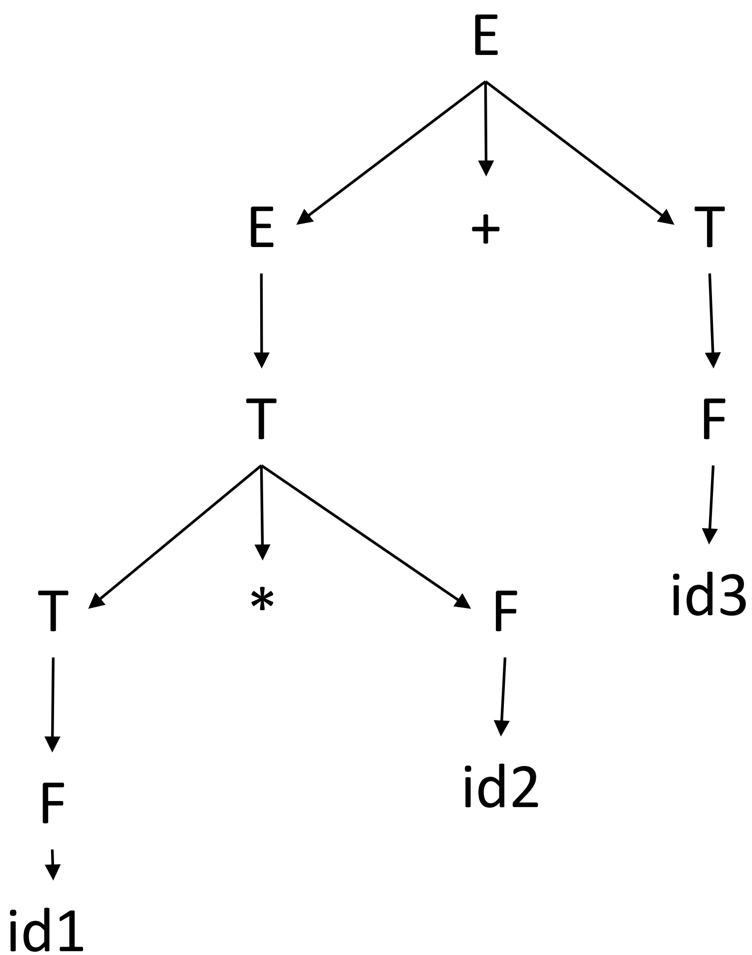
# Abstract Syntax Tree

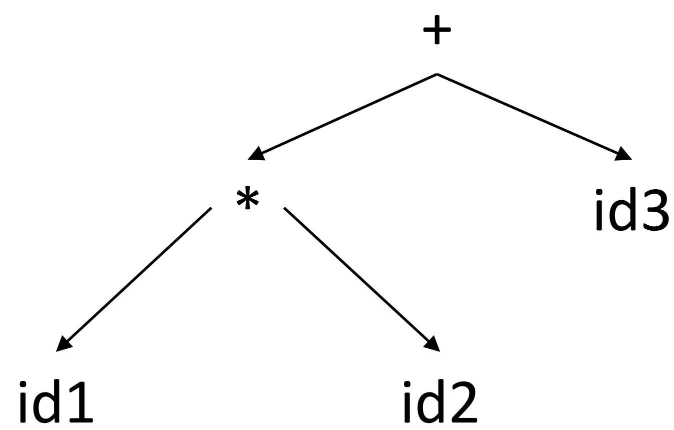
- Condensed form of parse tree
- useful for representing language constructs.
- The production $S \rightarrow$ if B then s1 else s2 may appear as



# Abstract Syntax tree …

- Chain of single productions may be collapsed, and operators move to the parent nodes



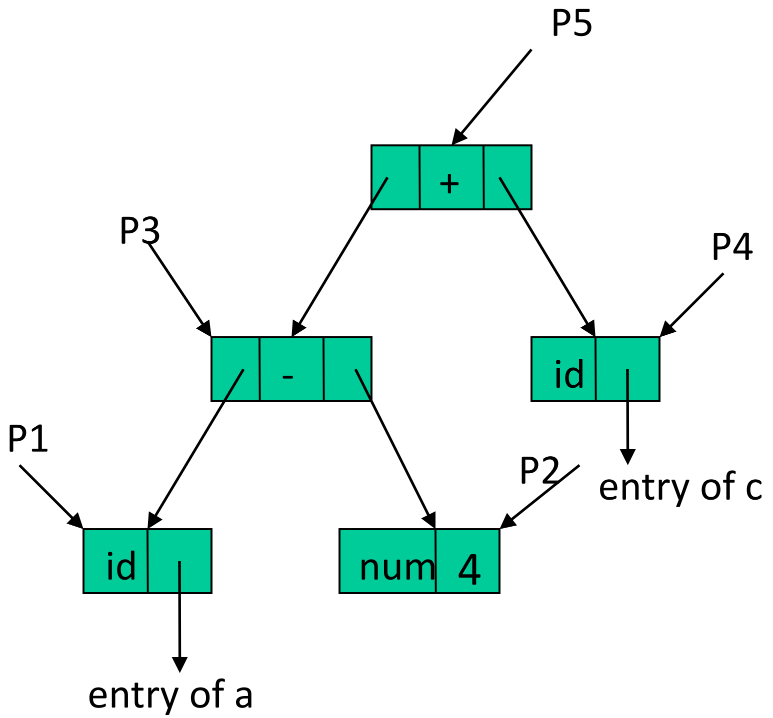
# Constructing Abstract Syntax Tree for expression

- Each node can be represented as a record
- *operators*: one field for operator, remaining fields ptrs to operands
  mknode(op,left,right )
- *identifier*: one field with label id and another ptr to symbol table
  mkleaf(id,entry)
- *number*: one field with label num and another to keep the value of the number
  mkleaf(num,val)

# Example

the following sequence of function calls creates a parse tree for a- 4 + c

$P_1$ = mkleaf(id, entry.a)
$P_2$ = mkleaf(num, 4)
$P_3$ = mknode(-, $P_1$, $P_2$)
$P_4$ = mkleaf(id, entry.c)
$P_5$ = mknode(+, $P_3$, $P_4$)



# Constructing syntax tree using YACC

| G. Rule | Action |
|---|---|
| $E \rightarrow E_1 + T$ | |
| $E \rightarrow T$ | |
| $T \rightarrow T_1 * F$ | |
| $T \rightarrow F$ | |
| $F \rightarrow (E)$ | |
| $F \rightarrow id$ | |
| $F \rightarrow num$ | |

# Constructing syntax tree using YACC

| G. Rule | Action |
| --- | --- |
| $E \rightarrow E + T$ | $$ = mknode(+, $1, $3) |
| $E \rightarrow T$ | $$ = $1 |
| $T \rightarrow T * F$ | $$ = mknode(*, $1, $3) |
| $T \rightarrow F$ | $$ = $1 |
| $F \rightarrow (E)$ | $$ = $1 |
| $F \rightarrow$ id | $$ := mkleaf($1, lookup(yylval)) |
| $F \rightarrow$ num | $$ := mkleaf($1, lookup(yylval)) |

# Other kind of statements/expressions

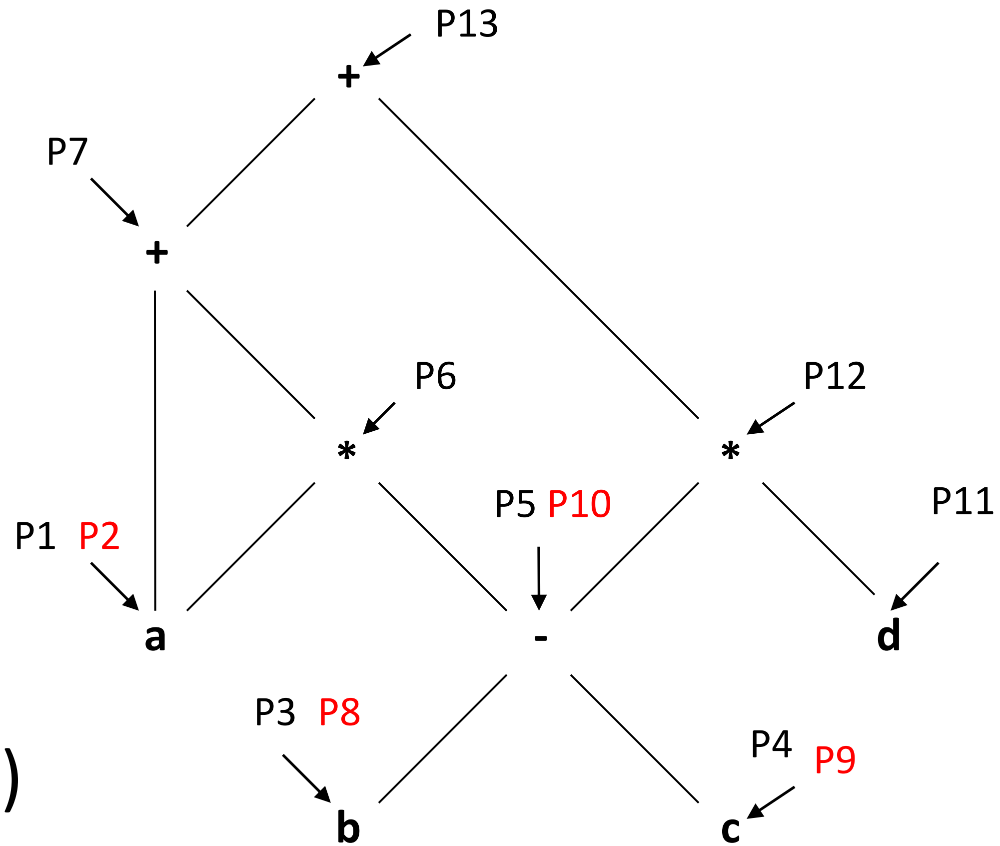
- Declarations do not contribute to AST
  - Modify the Symbol Table
- For other constructs, map to operator-operands format
  - A[20] ⇨ [ ] (A, 20)
  - if e1 then e2 else e3 ⇨ ite(e1’, e2’, e3’)

  Here e1’, e2’, e3, are the operator-operand form of e1, e2, e3.
  - x = e1 ⇨ = (x, e1’)

# DAG for Expressions

Expression a + a * ( b – c ) + ( b - c ) * d
make a leaf or node if not present,
otherwise return pointer to the existing node

$P_1$ = makeleaf(id,a)
$P_2$ = makeleaf(id,a)
$P_3$ = makeleaf(id,b)
$P_4$ = makeleaf(id,c)
$P_5$ = makenode(-,$P_3$,$P_4$)
$P_6$ = makenode(*,$P_2$,$P_5$)
$P_7$ = makenode(+,$P_1$,$P_6$)
$P_8$ = makeleaf(id,b)
$P_9$ = makeleaf(id,c)
$P_{10}$ = makenode(-,$P_8$,$P_9$)
$P_{11}$ = makeleaf(id,d)
$P_{12}$ = makenode(*,$P_{10}$,$P_{11}$)
$P_{13}$ = makenode(+,$P_7$,$P_{12}$)



Compiler Design

# Semantic Analysis

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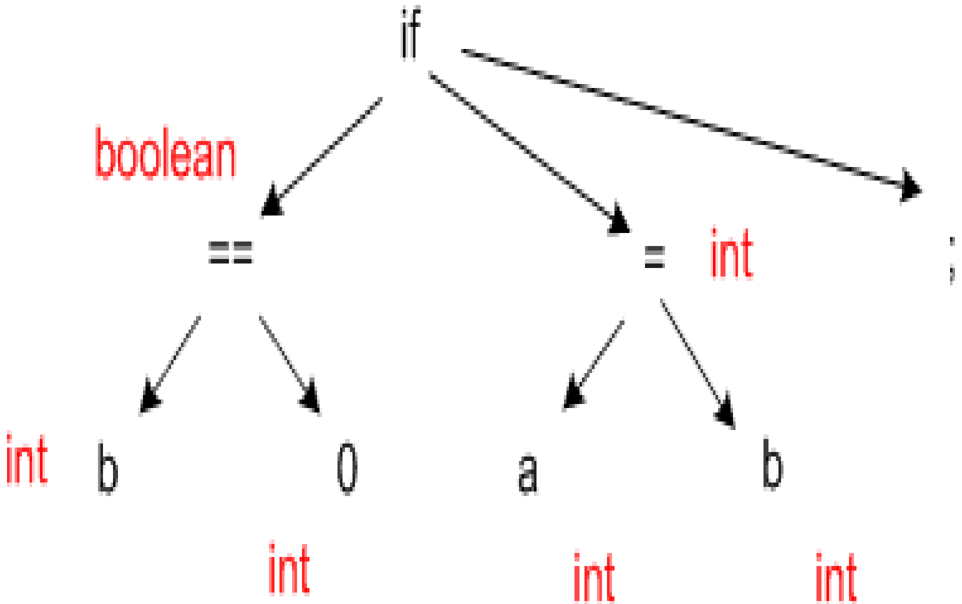
# Semantic Analysis

- Static checking
  - Type checking
  - Control flow checking
  - Uniqueness checking
  - Name checks
- Disambiguate overloaded operators
- Type coercion
- Error reporting



# Beyond syntax analysis

- Parser cannot catch all the program errors
- There is a level of correctness that is deeper than syntax analysis
- Some language features cannot be modeled using context free grammar formalism
  - Whether an identifier has been declared before use
  - This problem is of identifying a language $\{w\alpha w \mid w \in \Sigma^*\}$
  - This language is not context free

# Beyond syntax …

- Examples
  ```
  string x; int y;
  y = x + 3
  ```
  the use of x could be a type error
  ```
  int a, b;
  a = b + c
  ```
  c is not declared

- An identifier may refer to different variables in different parts of the program
- An identifier may be usable in one part of the program but not another

# Compiler needs to know?

- Whether a variable has been declared?
- Are there variables which have not been declared?
- What is the type of the variable?
- Whether a variable is a scalar, an array, or a function?
- What declaration of the variable does each reference use?
- If an expression is type consistent?
- If an array use like A[i,j,k] is consistent with the declaration? Does it have three dimensions?

- How many arguments does a function take?
- Are all invocations of a function consistent with the declaration?
- If an operator/function is overloaded, which function is being invoked?
- Inheritance relationship
- Classes not multiply defined
- Methods in a class are not multiply defined

- The exact requirements depend upon the language

# How to answer these questions?

- These issues are part of semantic analysis phase
- Answers to these questions depend upon values like type information, number of parameters etc.
- Compiler will have to do some computation to arrive at answers
- The information required by computations may be non local in some cases

# How to … ?

- Use formal methods
  - Context sensitive grammars
  - Extended attribute grammars
- Use ad-hoc techniques
  - Symbol table
  - Ad-hoc code
- Something in between !!!
  - Use attributes
  - Do analysis along with parsing
  - Use code for attribute value computation
  - However, code is developed systematically

# Why attributes ?

- For lexical analysis and syntax analysis formal techniques were used.
- However, we still had code in form of actions along with regular expressions and context free grammar
- The attribute grammar formalism is important
  - However, it is very difficult to implement
  - But makes many points clear
  - Makes “ad-hoc” code more organized
  - Helps in doing non local computations

# Attribute Grammar Framework

- Generalization of CFG where each grammar symbol has an associated set of attributes
- Values of attributes are computed by semantic rules

# Attribute Grammar Framework

- Two notations for associating semantic rules with productions
- Syntax directed definition
  - high level specifications
  - hides implementation details
  - explicit order of evaluation is not specified
- Translation scheme
  - indicate order in which semantic rules are to be evaluated
  - allow some implementation details to be shown

# Attribute Grammar Framework

- Conceptually both:
  - parse input token stream
  - build parse tree
  - traverse the parse tree to evaluate the semantic rules at the parse tree nodes
- Evaluation may:
  - save information in the symbol table
  - issue error messages
  - generate code
  - perform any other activity

# Example

- Consider a grammar for signed binary numbers

number → sign list
sign → + | -
list → list bit | bit
bit → 0 | 1

- Build attribute grammar that annotates number with the value it represents

# Example

- Associate attributes with grammar symbols

| **symbol** | **attributes** |
|---|---|
| number | value |
| sign | negative |
| list | position, value |
| bit | position, value |

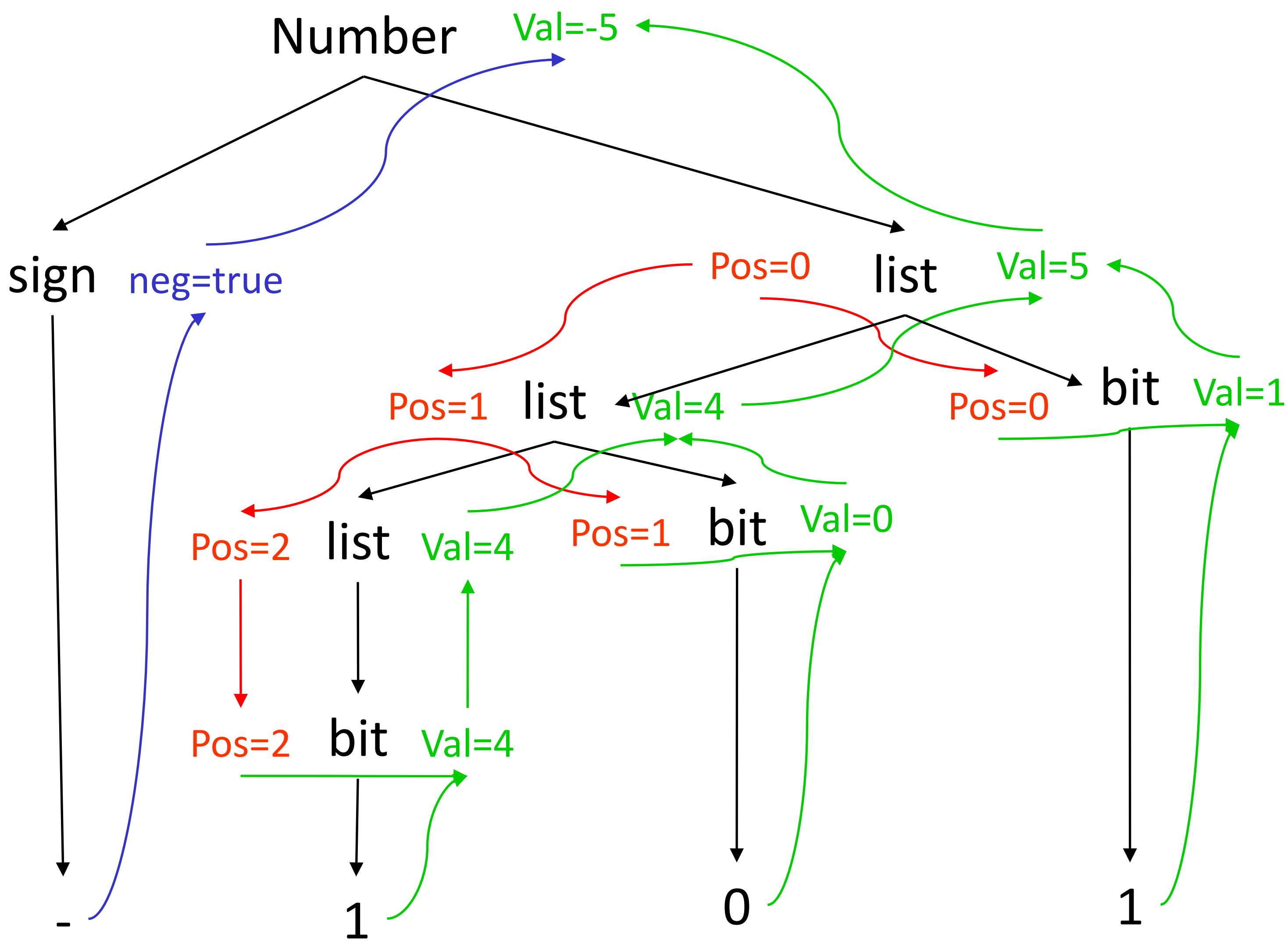
| symbol | attributes |
|---|---|
| number | value |
| sign | negative |
| list | position, value |
| bit | position, value |

| **production** | **Attribute rule** |
|---|---|
| number → sign list | list.position ← 0<br>if sign.negative<br>    number.value ← -list.value<br>else<br>    number.value ← list.value |
| sign → + | sign.negative ← false |
| sign → - | sign.negative ← true |

| symbol | attributes |
|---|---|
| number | value |
| sign | negative |
| list | position, value |
| bit | position, value |

| **production** | **Attribute rule** |
|---|---|
| list → bit | bit.position ← list.position |
| | list.value ← bit.value |
| $list_0$ → $list_1$ bit | $list_1$.position ← $list_0$.position + 1 |
| | bit.position ← $list_0$.position |
| | $list_0$.value ← $list_1$.value + bit.value |
| bit → 0 | bit.value ← 0 |
| bit → 1 | bit.value ← $2^{\text{bit.position}}$ |

# Parse tree and the dependence graph



# Attributes …

- Attributes fall into two classes: *Synthesized* and *Inherited*
- Value of a synthesized attribute is computed from the values of children nodes
  - Attribute value for LHS of a rule comes from attributes of RHS
- Value of an inherited attribute is computed from the sibling and parent nodes
  - Attribute value for a symbol on RHS of a rule comes from attributes of LHS and RHS symbols

# Attributes …

- Each grammar production $A \rightarrow \alpha$ has associated with it a set of semantic rules of the form

  $$b = f\,(c_1, c_2, \ldots, c_k)$$

  where f is a function, and
  - Either $b$ is a synthesized attribute of $A$
  - OR $b$ is an inherited attribute of one of the grammar symbols on the right
- Attribute $b$ depends on attributes $c_1, c_2, \ldots, c_k$

# Synthesized Attributes and S-attributed Definition

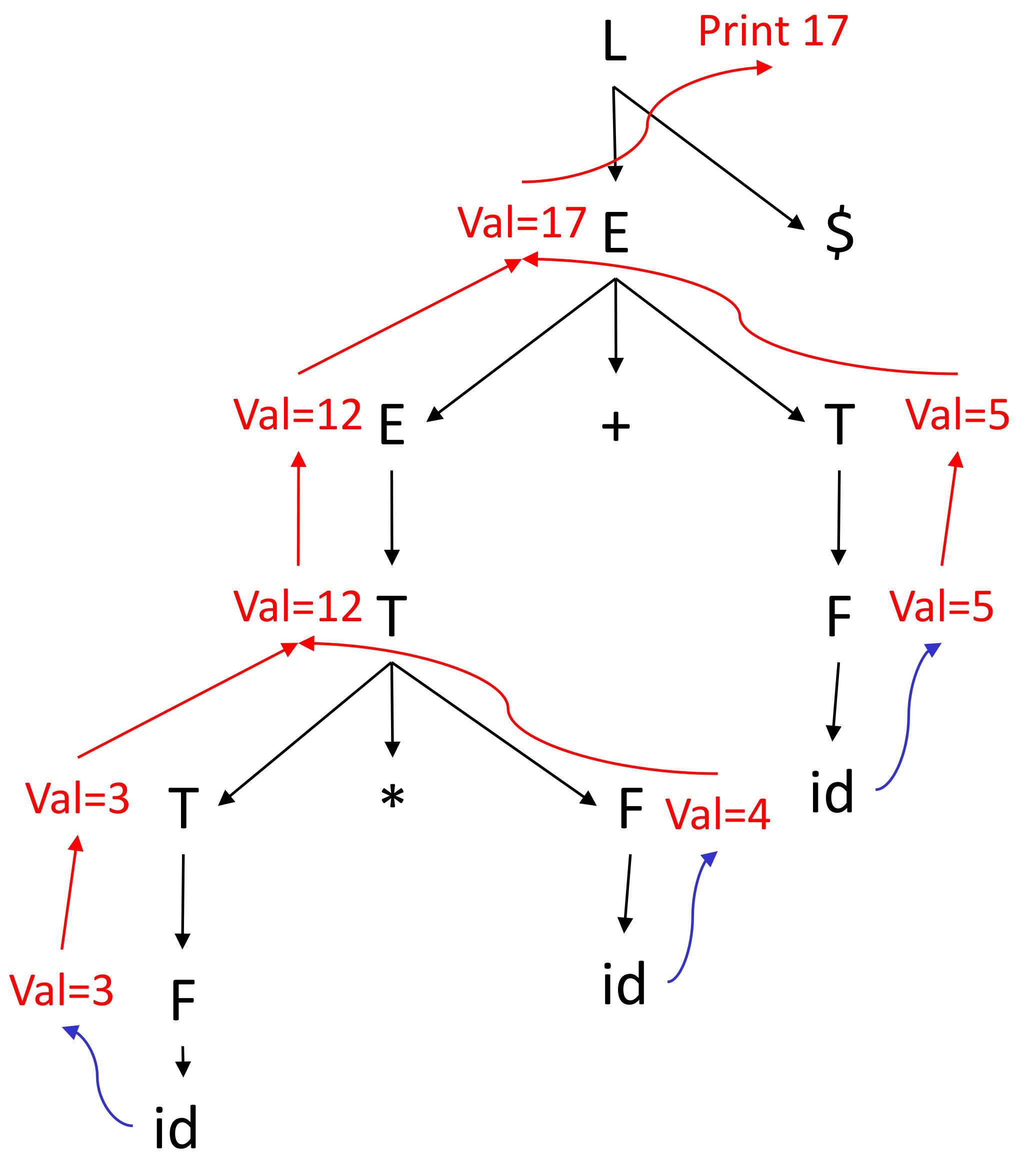
- A syntax directed definition that uses only synthesized attributes is said to be an S-attributed definition
- A parse tree for an S-attributed definition can be annotated by evaluating semantic rules for attributes

# Syntax Directed Definitions for a desk calculator program

| | |
|---|---|
| L -> E $ | Print (E.val) |
| E -> E + T | E.val = E.val + T.val |
| E -> T | E.val = T.val |
| T -> T * F | T.val = T.val * F.val |
| T -> F | T.val = F.val |
| F -> (E) | F.val = E.val |
| F -> digit | F.val = digit.lexval |

- terminals are assumed to have only synthesized attribute, values of which are supplied by lexical analyzer
- start symbol does not have any inherited attribute

# Parse tree for 3 * 4 + 5 $



# Inherited Attributes

- An inherited attribute is one whose value is defined in terms of attributes at the parent and/or siblings
- Used for finding out the context in which it appears
- It is possible to use only S-attributes but more natural to use inherited attributes

# Inherited Attributes

$D \rightarrow T\ L$

$T \rightarrow$ real

$T \rightarrow$ int

$L \rightarrow L_1$, id

$L \rightarrow$ id

# Inherited Attributes

| | |
|---|---|
| $D \rightarrow T\ L$ | $L.in = T.type$ |
| $T \rightarrow real$ | $T.type = real$ |
| $T \rightarrow int$ | $T.type = int$ |
| $L \rightarrow L_1, id$ | $L_1.in = L.in;$ addtype(id.entry, L.in) |
| $L \rightarrow id$ | addtype (id.entry,L.in) |

$D \rightarrow T\ L$

$T \rightarrow real$

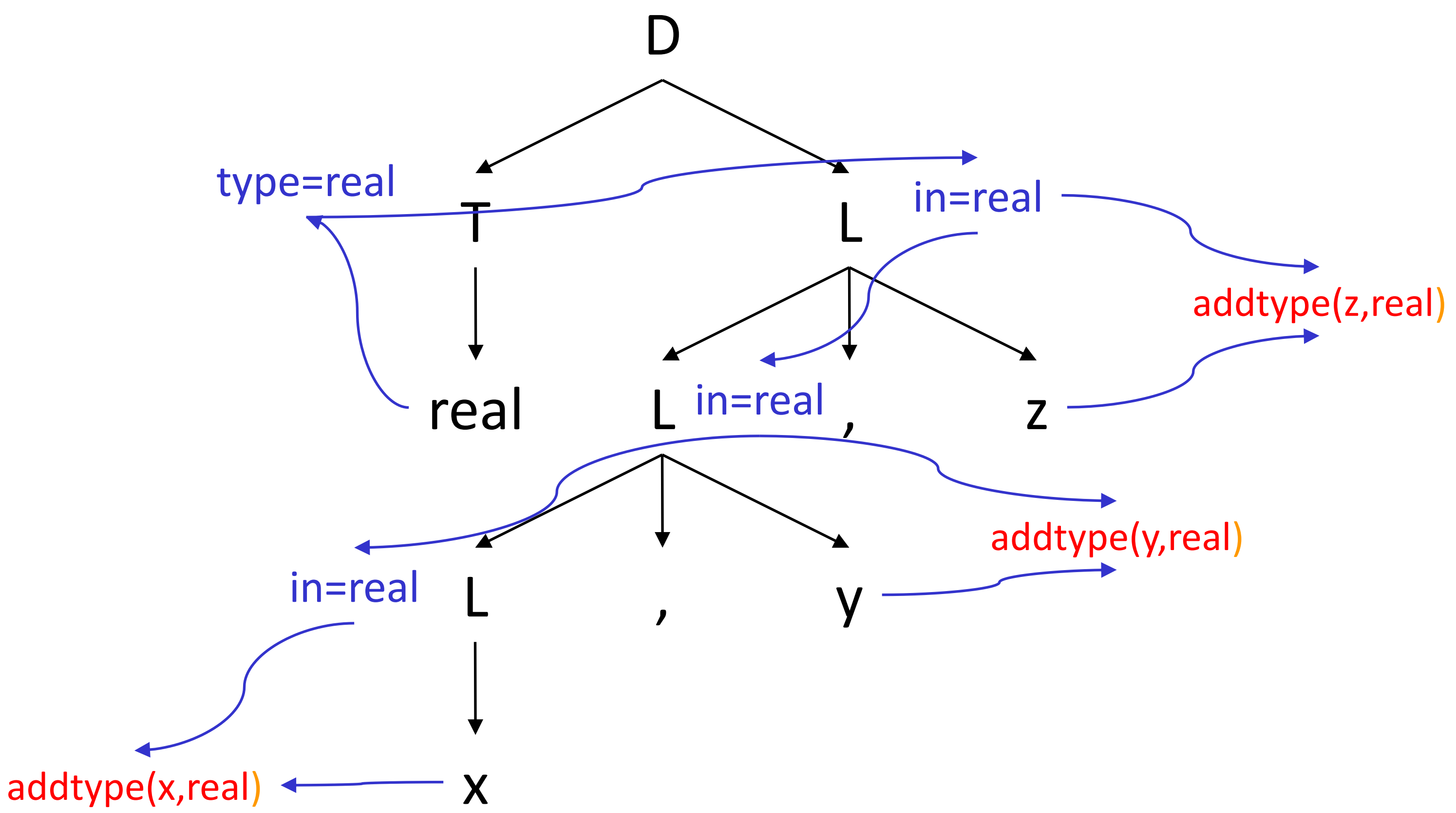
$T \rightarrow int$

$L \rightarrow L_1, id$

$L \rightarrow id$

# Parse tree for

# real x, y, z



# Dependence Graph

- If an attribute b depends on an attribute c then the semantic rule for b must be evaluated after the semantic rule for c
- The dependencies among the nodes can be depicted by a directed graph called dependency graph

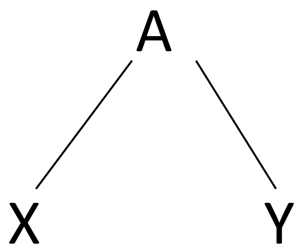
# Algorithm to construct dependency graph

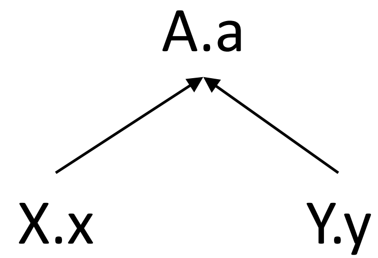
```
for each node n in the parse tree {
   for each attribute a of the grammar symbol {
        construct a node in the dependency graph
        for a
   }
}

for each node n in the parse tree {
   for each semantic rule b = f (c1, c2 , …, ck)
   associated with production at n {
        for i = 1 to k {
                construct an edge from ci to b
        }
   }
}
```

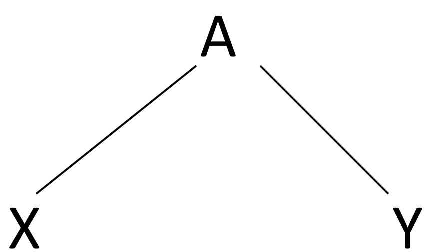
# Example

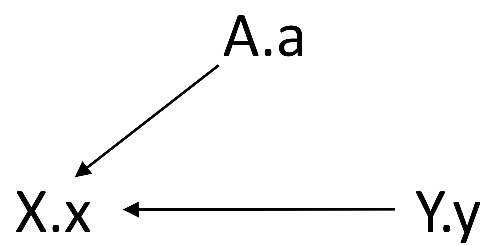
- Suppose A.a = f(X.x , Y.y) is a semantic rule for $A \rightarrow X\ Y$



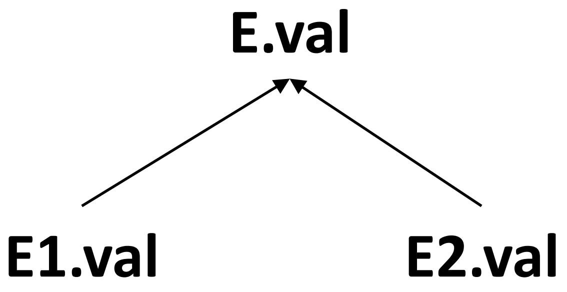

- If production $A \rightarrow X\ Y$ has the semantic rule X.x = g(A.a, Y.y)



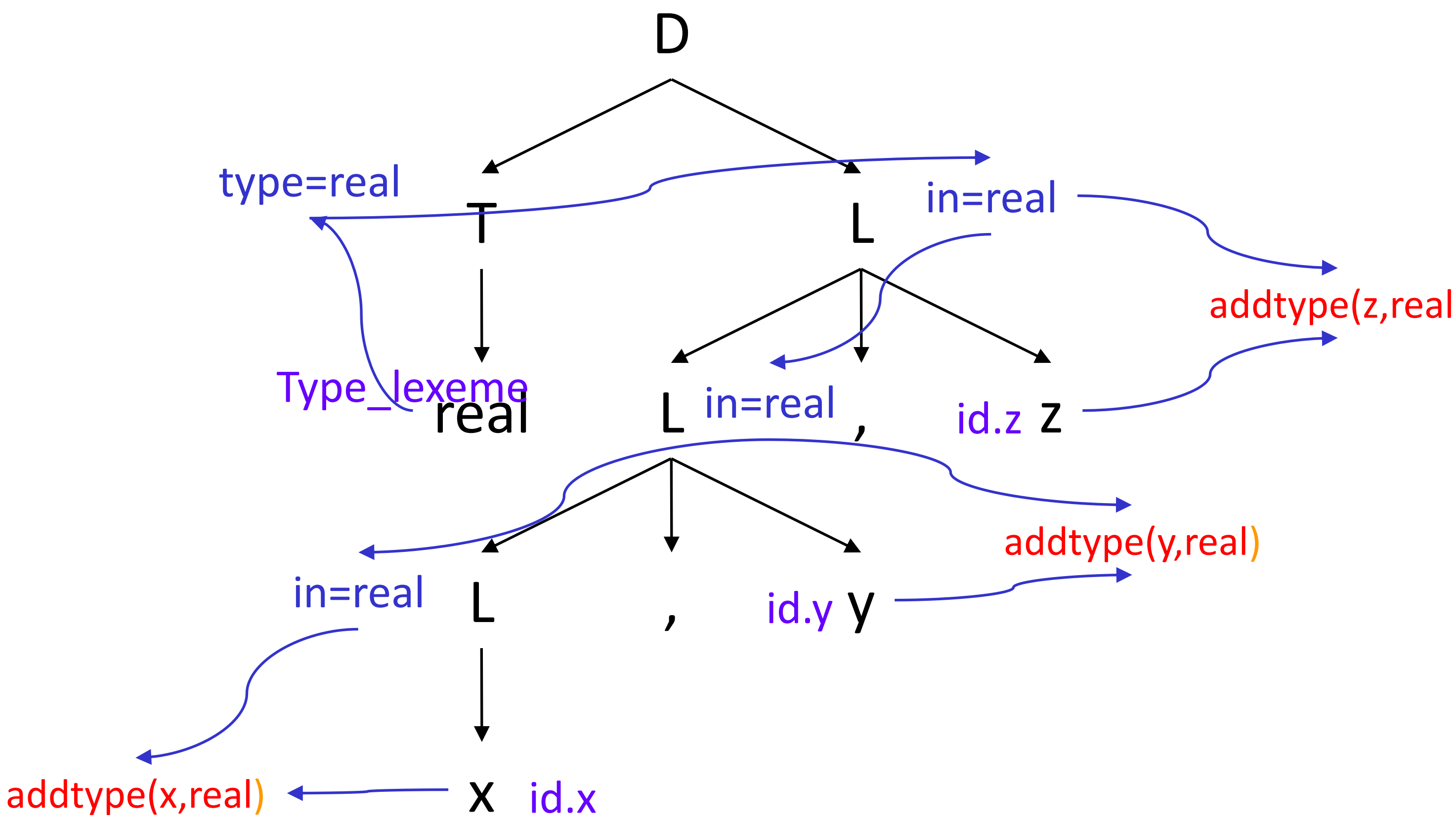
# Example

- Whenever following production is used in a parse tree
  $E \rightarrow E_1 + E_2$ $\qquad\qquad$ $E.val = E_1.val + E_2.val$
  we create a dependency graph



# Example

- dependency graph for real id1, id2, id3
- put a dummy node for a semantic rule that consists of a procedure call



# Evaluation Order

- Any topological sort of dependency graph gives a valid order in which semantic rules must be evaluated

a4 = real
a5 = a4
addtype(id3.entry, a5)
a7 = a5
addtype(id2.entry, a7 )
a9 := a7
addtype(id1.entry, a9 )