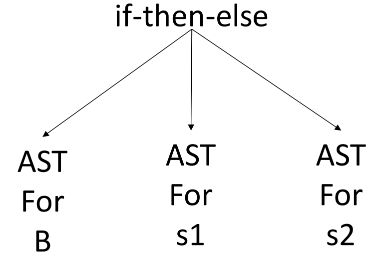
Compiler Design

AST

Amey Karkare
Department of Computer Science and Engineering
IIT Kanpur
karkare@iitk.ac.in

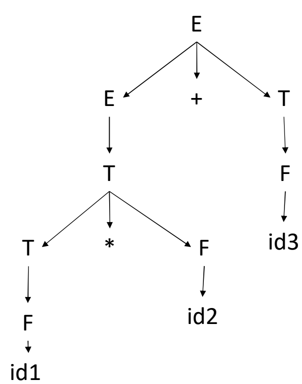
Abstract Syntax Tree

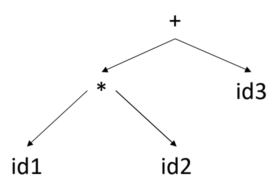
- Condensed form of parse tree
- useful for representing language constructs.
- The production S → if B then s1 else s2 may appear as



Abstract Syntax tree …

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





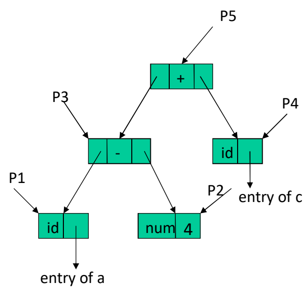
Constructing Abstract Syntax Tree for expression

- 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)



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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	

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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))

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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’)

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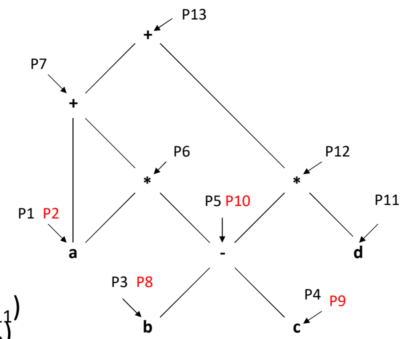
DAG for Expressions

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})



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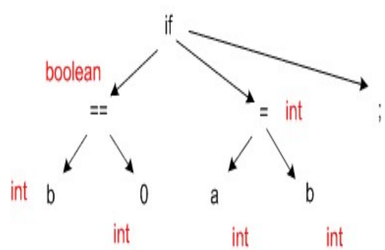
Compiler Design

Semantic Analysis

Amey Karkare
Department of Computer Science and Engineering
IIT Kanpur
karkare@iitk.ac.in

Semantic Analysis

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



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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 {wαw | w ϵ Σ*}
  - This language is not context free

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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

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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?

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- 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

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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

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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

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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

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Attribute Grammar Framework

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

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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

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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

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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

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Example

- Associate attributes with grammar symbols

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

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

production	Attribute rule
number → sign list	list.position ← 0 if sign.negative number.value ← -list.value else number.value ← list.value
sign → +	sign.negative ← false
sign → -	sign.negative ← true

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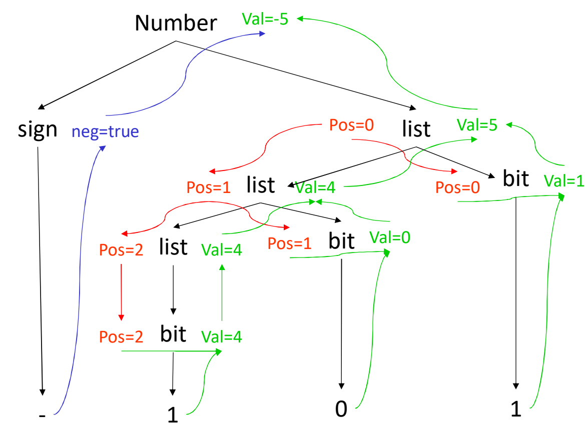
symbol	attributes
number	value
sign	negative
list	position, value
bit	position, value

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 → α 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, …, 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

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Syntax Directed Definitions for a desk calculator program

$L \rightarrow E\ \$$	Print (E.val)
$E \rightarrow E + T$	E.val = E.val + T.val
$E \rightarrow T$	E.val = T.val
$T \rightarrow T * F$	T.val = T.val * F.val
$T \rightarrow F$	T.val = F.val
$F \rightarrow (E)$	F.val = E.val
$F \rightarrow$ 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

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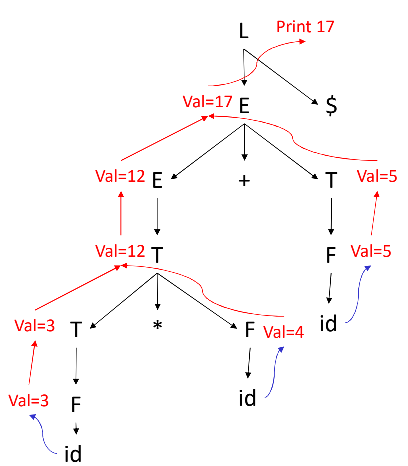
Parse tree for 3 * 4 + 5 $



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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

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Inherited Attributes

$D \rightarrow T\ L$

$T \rightarrow real$

$T \rightarrow\ int$

$L \rightarrow L_1,\ id$

$L \rightarrow id$

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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)

$D \rightarrow T\ L$

$T \rightarrow real$

$T \rightarrow\ int$

$L \rightarrow L_1,\ id$

$L \rightarrow id$

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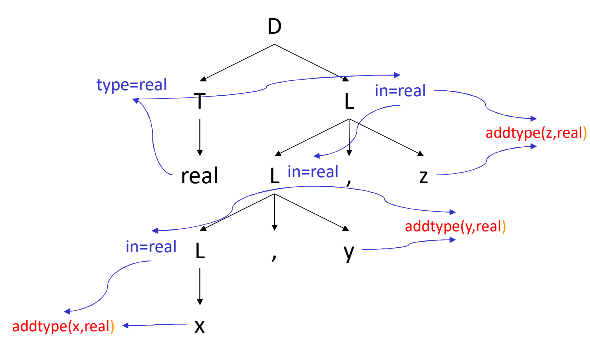
Parse tree for

real x, y, z



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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

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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 **$b = f(c_1, c_2, \ldots, c_k)$**
  associated with production at **n** {
    for i = 1 to k {
      construct an edge from **c_i** to **b**
    }
  }
}

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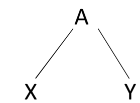
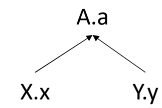
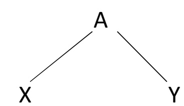
Example

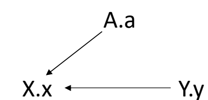
- Suppose A.a = f(X.x , Y.y) is a semantic rule for
  $A \rightarrow X\ Y$





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





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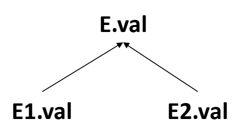
Example

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



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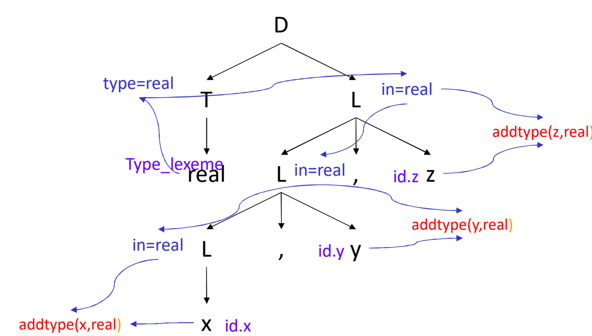
Example

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



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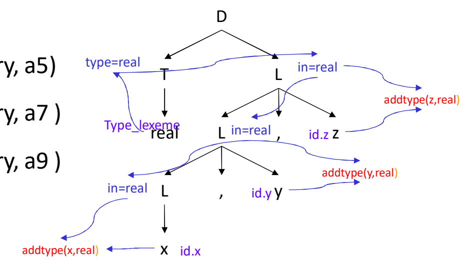
Evaluation Order

- 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)



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