Compiler Design

Samit Biswas

samit@cs.iiests.ac.in

Department of Computer Science and Technology,
Indian Institute of Engineering Science and Technology, Shibpur

October 29, 2017

Syntax Directed Translation

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- Values of this attributes are evaluated by semantic rules associated with the production rules.
- Evaluation of these semantic rules:
  - may generate intermediate code.
  - may put information into the symbol table.
  - may perform type checking.
- An attribute may hold almost anything.
  - a string, a number, a memory location, a complex record

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Translation schemes:

- indicate the order of evaluation of semantic actions associated with a production rule.

Syntax Directed Translation

Conceptually with both Syntax Directed Translation and Translation Scheme

- Parse the input token stream.
- Build the parse tree.
- Traverse the tree to evaluate the semantic rules at the parse tree nodes.

Input Stream ⟶ Parse Tree ⟶ dependency Graph ⟶ evaluation order for semantic rules

Syntax Directed Definitions

- A syntax directed definition is a generalization of Context Free Grammar in which each:
  - Each grammar symbol is associated with a set of attribute.
  - This set of attributes can be classified into two:
    - Synthesized Attributes.
    - Inherited Attributes.
  - Each production rule is associated with a set of semantic rules.

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    - Synthesized Attributes.
    - Inherited Attributes.
  - Each production rule is associated with a set of semantic rules.
- The value of an attribute at a parse tree node is defined by the semantic rule associated with a production at that node.
- The value of a **Synthesized Attribute** at a node is computed from the values of attributes at the children in that node of the parse tree.
- The value of a **Inherited Attribute** at a node is computed from the values of attributes at the sibling and parents in that node of the parse tree.

Syntax Directed Definitions

Examples:

- Synthesized Attributes:
  $E \rightarrow E_1 + E_2 \qquad \{E.val = E_1.val + E_2.val\}$
- Inherited Attributes:
  $A \rightarrow XYZ \qquad \{Y.val = 2 * A.val\}$

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- Semantic rules setup and dependencies between attributes which can be represented by a dependency graph.
- Dependency graph determines the evaluation order of these semantic rules.
- Evaluation of a semantic rule defines the value of an attribute. A semantic rule may also have some side effects such as printing a value.

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- Values of attributes in nodes of annotated parse tree are either :
  - initialized to constant values or by the lexical analyzer.
  - determined by the semantic rules.
- The process of computing the attributes values at the nodes is called **annotating** or **decorating** of the parse tree.
- The order of these computations depends on the **dependency graph** induced by the semantic rules.

Syntax-Directed Definition

In a Syntax-Directed Definition, each production $A \rightarrow \alpha$ is associated with a set of semantic rules of the form

$$b = f(c_1, c_2, c_3, \ldots, c_k)$$

where f is a function and b can be one of the following:

- b is a **synthesized attribute** of A and $c_1, c_2, c_3, \ldots, c_k$ are attributes of the grammar symbols in α, or
- b is an **inherited attribute** of one of the grammar symbols on the right side of the production $A \rightarrow \alpha$ and $c_1, c_2, c_3, \ldots, c_k$ are attributes of the grammar symbols in $\{A, \alpha\}$.

Example with Synthesized attributes

- Grammar Symbols: $L, E, T, F, n, +, *, (,), digit$
- Non-Terminal : L, E, T, F have an attribute called *val*.
- Terminal *digit* have an attribute called *lexval*.
- The value for *lexval* is provided by the lexical analyser.

Table: Syntax-directed Definition

Productions	Semantic Rules
$L \rightarrow En$	print("E.val");
$E \rightarrow E + T$	$E.val = E.val + T.val$
$E \rightarrow T$	$E.val = T.val$
$T \rightarrow T * F$	$T.val = T.val * F.val$
$T \rightarrow F$	$T.val = F.val$
$F \rightarrow (E)$	$F.val = E.val$
$F \rightarrow digit$	$F.val = digit.lexval$

Draw the tree (Annotated parse Tree)

(Example: $3 * 5 + 4n$)

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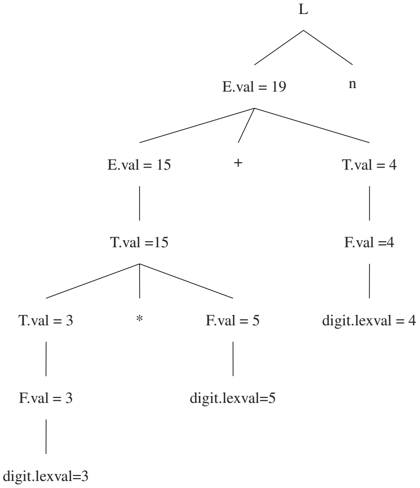

Example with Inherited attributes

A declaration generated by the non-terminal *D* in the Syntax directed Definition consists of keyword *int* or *real* followed by a list of Identifiers.

Table: Syntax-directed Definition

Productions	Semantic Rules
$D \rightarrow TL$	$L.in = T.type$
$T \rightarrow int$	$T.type = integer$
$T \rightarrow real$	$T.type = real$
$L \rightarrow L_1, id$	$L_1.in = L.in$ addtype(id.entry, L.in)
$L \rightarrow id$	addtype(id.entry, L.in)

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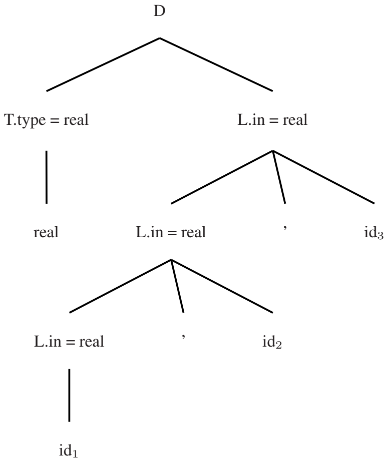

Dependency Graph

- Directed Graph.
- Shows Intermediate dependencies between attributes.
- Construction
  - Put each semantic rule into the form $b = f(c_1, \ldots, c_k)$ by introducing dummy synthesized attribute b for every semantic rule that consists of a **procedure call.**
  - Eg.

$L \rightarrow En$	print("E.val")
Becomes:	dummy = print("'E.val')
etc.	

Dependency Graph Construction

- **for** each node n in the parse tree **do**
  for each attribute a of the grammar symbol at node a **do**
  - construct a node in the dependency graph for a;

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- **for** each node n in the parse tree **do**
  - for each semantic rule $b = f(c_1, c_2, \ldots, c_k)$ associated with the production used at n **do**
    - **for** i = 1 to k do
      Construct an edge from the node for c_i to the node for b;

Example with Synthesized attributes

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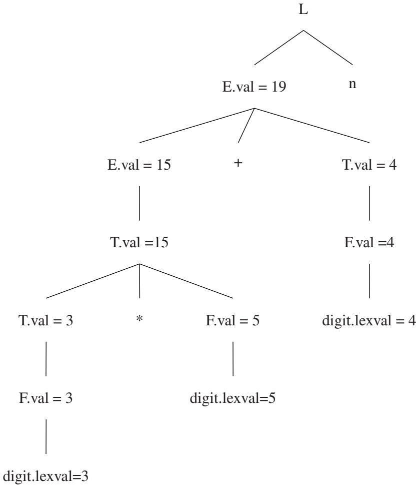
Table: Syntax-directed Definition

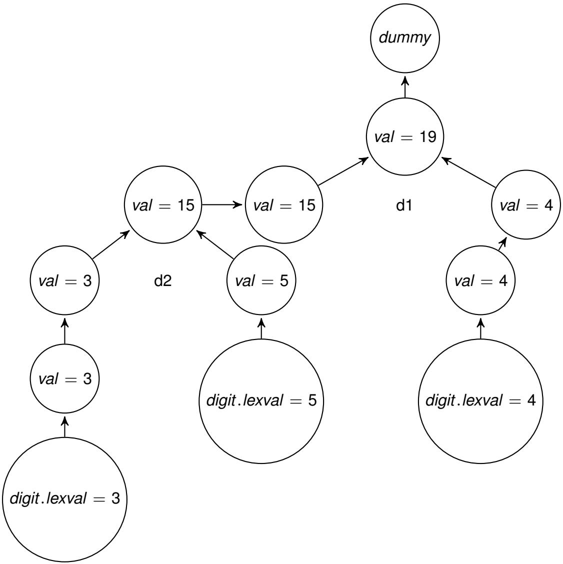
Productions	Semantic Rules
$L \to En$	print("E.val");
$E \to E_1 + T$	$E.val = E_1.val + T.val$
$E \to T$	$E.val = T.val$
$T \to T_1 * F$	$T.val = T_1.val * F.val$
$T \to F$	$T.val = F.val$
$F \to (E)$	$F.val = E.val$
$F \to digit$	$F.val = digit.lexval$

(Annotated parse Tree)

(Example: $3 * 5 + 4n$)



Example: Dependency Graph



Example with Inherited attributes

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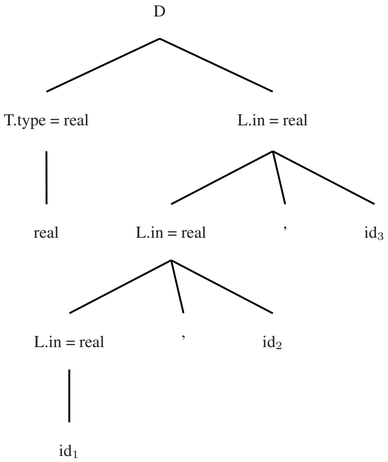
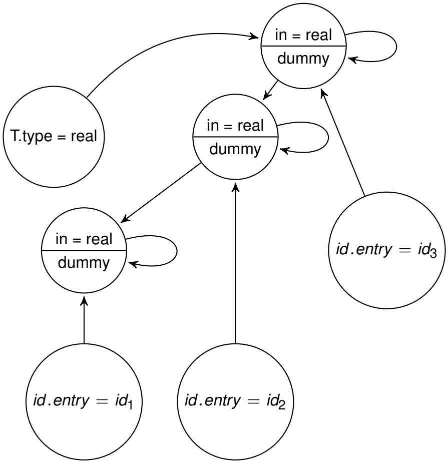
$T \rightarrow real$	$T.type = real$
$L \rightarrow L_1, id$	$L_1.in = L.in$ addtype(id.entry, L.in)
$L \rightarrow id$	addtype(id.entry, L.in)

Annotated parse Tree

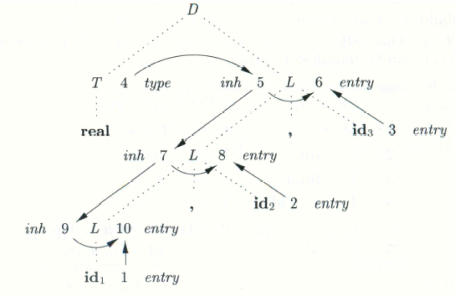
(Example: *real* id_1, id_2, id_3)



Example: Dependency Graph



Example: Evaluation Order



- $a_4 = real$
- $a_5 = a_4$
- $addtype(id_3.entry, a_5)$
- $a_7 = a_5$
- $addtype(id_2.entry, a_7)$
- $a_9 = a_7$
- $addtype(id_1.entry, a_9)$

Evaluation Order of Semantic Rules

Several methods have been proposed for the evaluation of semantic rules.

- Parse Tree Method:
  - At compile time evaluation order obtained from dependency graph constructed from the parse tree.
  - Fails if dependency graph contains a cycle.
- Rule Based methods:
  - Semantic rules analyzed by hand or specialized tools at compiler construction time.
  - Order of evaluation of attributes associated with a production is pre-determined at compiler construction time.
- Oblivious methods:
  - Evaluation order is chosen without considering the semantic rules.
  - Restricts the class of syntax directed definitions that can be implemented.
  - Order of evaluation is forced by parsing method.

Construction of Syntax tree

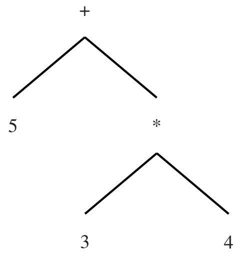
Syntax - Tree

- an intermediate representation of the **compiler's input.**
- A condensed form of parse tree.
- Syntax tree shows the syntactic structure of the programme while omitting the irrelevant details.
- Operators or keywords are associated with the interior nodes.
- Chains of simple productions are collapsed.

Syntax directed translation can be based on syntax tree as well as parse tree.

Syntax - Tree Example

5 + 3 * 4



- Leaves: identifiers or constants.
- Internal nodes: Labelled with operations.
- Children of a node are its operands.

Constructing Syntax trees for an Expression:

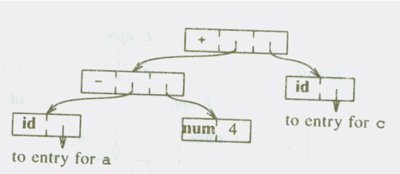
- Each node can be implemented as a record with several fields.
- Operator node: one field identifies the operator (called label of the node) and remaining fields contain pointers to operands.
- The nodes may also contain fields to hold the values (pointers to values) of attributes attached to the nodes.
- Functions used to create nodes of syntax tree for expressions with binary operator are given below
  - **mknode**(op, left, right)
  - **mkleaf**(id, entry)
  - **makeleaf** (num, val)

  Each function returns a pointer to a newly created node.

Example

a - 4 + c

1. $p_1 = mkleaf(id, entrya);$
2. $p_2 = mkleaf(num, 4);$
3. $p_3 = mknode('-', p_1, p_2);$
4. $p_4 = mkleaf(id, entryc);$
5. $p_5 = mknode('+', p_3, p_4);$

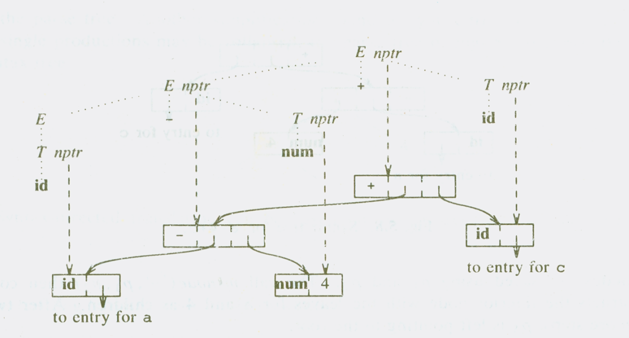


Syntax-Directed definition for Constructing Syntax Trees

Table: Syntax-directed definition for constructing a syntax tree.

Production	Semantic Rules
$E \rightarrow E_1 + T$	$E.nptr = mknode('+', E_1.nptr, T.nptr)$
$E \rightarrow E_1 - T$	$E.nptr = mknode('-', E_1.nptr, T.nptr)$
$E \rightarrow T$	$E.nptr = T.nptr$
$T \rightarrow (E)$	$T.nptr = E.nptr$
$T \rightarrow id$	$T.nptr = mkleaf(id, id.entry)$
$T \rightarrow num$	$T.nptr = mkleaf(num, num.val)$

Example: Construction of a Syntax-tree for a-4+c



Directed Acyclic Graphs for Expression

Bottom up Evaluation of S - Attributed Definitions

- A translator for an S-attributed definition can often be implemented with the help of an LR parser.
- From an S-attributed definition the parser generator can construct a translator that evaluates attributes as it parses the input.
- We put the values of the synthesized attributes of the grammar symbols a stack that has extra fields to hold the values of attributes.
-

Table: Implementation of a Calculator with an LR parser

Production	Code Fragment
$L \rightarrow En$	print(val[top]);
$E \rightarrow E_1 + T$	$val[ntop] = val[top-2] + val[top]$
$E \rightarrow T$	
$T \rightarrow T_1 * F$	$val[ntop] = val[top-2] * val[top]$
$T \rightarrow F$	
$F \rightarrow (E)$	$val[ntop] = val[top-1]$
$F \rightarrow digit$	

Table: Moves made by translator on Input 3*5+4n

Input	State	val	Production Used
3*5+4n	–	–	
*5+4n	3	3	
*5+4n	F	3	$F \rightarrow digit$
*5+4n	T	3	$T \rightarrow F$
5+4n	T *	3 _	
+4n	T * 5	3 _ 5	
+4n	F * F	3 _ 5	$F \rightarrow digit$
+4n	T	15	$T \rightarrow T * F$
+4n	E	15	$E \rightarrow T$
4n	E +	15 _	
n	E + 4	15 _ 4	
n	E + F	15 _ 4	$F \rightarrow digit$
n	E + T	15 _ 4	$T \rightarrow F$
n	E	19	$T \rightarrow F$
En	E n	19 _	
	L	19	$L \rightarrow En$

Bottom-Up Evaluation of Inherited Attributes

Type Checking

Type Checking

- Type checking is the process of verifying that each operation executed in a program respects the type system of the language.
- This generally means that all operands in any expression are of appropriate types and numbers.
- Mostly what we do in semantic analysis phase is type checking.

Designing a Type Checker

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- Identify the language construct that have types associated with them.
- Identify the semantic rules for the language.
- If a problem found, e.g. one tries to add a character to a double in C, we encounter a type error.
- A language is considered ***strongly-typed*** if each and every type error is detected during compilation.
- Type checking can be done in compile time or in execution time.

Static Type Checking

- Static type checking is done at compile time. The information type checker needs is obtained via declarations and stored in a master symbol table.
- After this information is collected, the types involved in each operation are checked.

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- After this information is collected, the types involved in each operation are checked.
- For example, if a and b are of type int and we assign very large values to them, $a * b$ may not be in the the acceptable range of ints, or an attempt to compute the ratio between two integers may raise a division by zero. These kind of type errors usually can not be detected at compile time.

Dynamic Type Checking

- Dynamic type checking is implemented by including type information for each data location at runtime.
- For example, a variable of type double would contain both the actual double value and some kind of tag indicating "double type".
- The execution of any operation begins by first checking these type tags. The operation is performed only if everything checks out. Otherwise, a type error occurs and usually halts execution.

Type Expressions

The type of a language construct will be denoted by a “type expression”.

The few basic type expressions are as follows:

- The basic types are boolean, char, integer, and real. A special basic type, type_error, will signal an error during type checking. Finally, a basic type void denoting “the absence of a value ” allows statements to be checked.
- Type expression may be named, a type name is a type expression.

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- Type expression may be named, a type name is a type expression.
- A type constructor applied to type expression is a type expression. Constructors include:
  - Arrays
  - Products
  - Records
  - Pointers
  - Functions

Arrays:

If T is a Type expression, then array(I, T) is a type expression denoting the type of an array with elements of type *T* and index set *I*. *I* is often a range of integers. For example

- var A: array[1..10] of integer;

Associates the type expression: **array(1..10, integer) with A**

Products

If T_1 and T_2 are type expressions, their Cartesian product $T_1 \times T_2$ is a type expression.

Records

The record type constructor will be applied to a tuple formed from field names and field types.

type	row =	record	
		address:	integer;
		lexeme:	array [1..15] of char
		end ;	
var	table:	array[1..10] of row;	

declares the name row representing the type expression **record((address $\times$ integer) $\times$ (lexeme $\times$ array(1 .. 15, char)))**

The variable *table* to be an array of records of this type.

Pointers:
If T is a type expression, then $pointer(T)$ is a type expression denoting the type “pointer to an object of type T”.
For example,
var p: $\uparrow$ row
declares variable p to have type pointer (row).

Functions:
Mathematically, a function maps elements of one set, the domain, to another set, the range. We may treat functions in programming languages as mapping a *domain type* D to a *range type* R. The type of such a function will be denoted by $D \rightarrow R$.
As for example,

function f(a, b : char): $\uparrow$ integer;

The type of f is denoted by the type expression

$$char \times char \rightarrow pointer(integer)$$

Specification of a simple Type Checker

The following grammar generate programs, represented by the nonterminal P, consisting of a sequence of declarations D followed by a single expression E.

$P \rightarrow D; E$

$D \rightarrow D; D | id : T$

$T \rightarrow char | integer | array[num] of\ T | \uparrow T$

$E \rightarrow literal\ | num |\ id |\ EmodE\ | E[E]\ | E \uparrow$

Table: Translation Scheme that saves the type of an identifier

Productions	Associated rules for type
$P \rightarrow D; E$	
$D \rightarrow D; D$	
$D \rightarrow id : T$	{ addtype(id.entry, T.type)}
$T \rightarrow char$	{ T.type = char }
$T \rightarrow integer$	{ T.type = integer }
$T \rightarrow \uparrow T_1$	{ T.type = pointer($T_{1.type}$) }
$T \rightarrow array[num]\ of\ T_1$	{ T.type = array($1 \ldots num.val$, $T_{1.type}$ }

Type Checking of Expressions

Table: Associated rules for Type Checking

Productions	Associated rules for type
$E \rightarrow literal$	E.type = char
$E \rightarrow num$	E.type = integer
$E \rightarrow id$	E.type = lookup(id.entry)
$E \rightarrow E_1 mod E_2$	E.type = **if** $E_1.type = integer$ **and** $E_2.type = integer$ **then** *integer* **else** *type_error*
$E \rightarrow E_1[E_2]$	E.type = **if** $E_{2.type} = integer$ **and** $E_{1.type} = array(s, t)$ **then** t **else** *type_error*
$E \rightarrow E_1 \uparrow$	E.type = if $E_{1.type}$=pointer(t) then t **else** *type_error*

Type Checking of Statements

The state statements we consider are assignment, conditional, and while statements.

Table: default

Productions	Associated rules for type
$S \to id = E$	{S.type = **if** id.type == E.type **then** void **else** *type_error* }
$S \to$ *if* E then S_1	{S.type = **if** E.type == Boolean **then** $S_1.type$ **else** *type_error* }
$S \to$ *while* E do S_1	{S.type = **if** E.type == Boolean **then** $S_1.type$ **else** *type_error* }
$S \to S_1 ; S_2$	{S.type = **if** S_1.type == void **and** S_2.type == void **then** void **else** *type_error* }

Type Checking of Functions

Productions	Associated actions
$T \rightarrow T_1 \, ' \rightarrow ' \, T_2$	$\{ T.type = T_1.type \rightarrow T_2.type \}$
$E \rightarrow E_1(E_2)$	{E.type = if $E_2.type$ == s and E_1.type == $s \rightarrow t$ **then** t **else** *type_error* }