Syntax-Directed Translation

Technique used to build semantic information for large structures, based on its syntax.

In a compiler, *Syntax-Directed Translation* is used for

- Constructing Abstract Syntax Tree
- Type checking
- Intermediate code generation

The Essence of Syntax-Directed Translation

The semantics (*i.e., meaning*) of the various constructs in the language is viewed as ***attributes*** of the corresponding grammar symbols.
Example:

sequence of characters 495
$\rightarrow$ *grammar symbol* `TOK_INT`
$\rightarrow$ *meaning* $\equiv$ *integer 495*
$\rightarrow$ *is an attribute of* `TOK_INT` *(*`yylval.int_val`*).*

Attributes are associated with **Terminal** as well as **Nonterminal** symbols.

An Example of Syntax-Directed Translation

$$
\boxed{\begin{array}{lcl}
E & \longrightarrow & E \mathtt{*} E \\
E & \longrightarrow & E \mathtt{+} E \\
E & \longrightarrow & \mathtt{id}
\end{array}}
$$

$$
\begin{array}{lcll}
E & \longrightarrow & E_1 \mathtt{*} E_2 & \{E.val := E_1.val * E_2.val\} \\
E & \longrightarrow & E_1 \mathtt{+} E_2 & \{E.val := E_1.val + E_2.val\} \\
E & \longrightarrow & \mathtt{int} & \{E.val := \mathtt{int}.val\}
\end{array}
$$

Another Example of Syntax-Directed Translation

$$
\begin{array}{|rcl|}
\hline
\mathit{Decl} & \longrightarrow & \mathit{Type}\ \mathit{VarList} \\
\mathit{Type} & \longrightarrow & \texttt{integer} \\
\mathit{Type} & \longrightarrow & \texttt{float} \\
\mathit{VarList} & \longrightarrow & \texttt{id}\ \texttt{,}\ \mathit{VarList} \\
\mathit{VarList} & \longrightarrow & \texttt{id} \\
\hline
\end{array}
$$

$$
\begin{array}{rcll}
\mathit{Decl} & \longrightarrow & \mathit{Type}\ \mathit{VarList} & \{\mathit{VarList.type} := \mathit{Type.type}\} \\
\mathit{Type} & \longrightarrow & \texttt{integer} & \{\mathit{Type.type} := \mathit{int}\} \\
\mathit{Type} & \longrightarrow & \texttt{float} & \{\mathit{Type.type} := \mathit{float}\} \\
\mathit{VarList} & \longrightarrow & \texttt{id}\ \texttt{,}\ \mathit{VarList}_1 & \{\mathit{VarList}_1.\mathit{type} := \mathit{VarList.type}; \\
 & & & \quad \texttt{id}.\mathit{type} := \mathit{VarList.type}\} \\
\mathit{VarList} & \longrightarrow & \texttt{id} & \{\texttt{id}.\mathit{type} := \mathit{VarList.type}\}
\end{array}
$$

Attributes

- **Synthesized:** Attribute of LHS symbol of a grammar rule, whose value depends on attributes of RHS symbols of the grammar rule.
  - Value flows from child to parent in the parse tree.
  - Example: *val* in Expression grammar
- **Inherited:** Attribute of an RHS symbol of a grammar rule, whose value depends on attributes of the LHS symbol and the other RHS symbols of the grammar rule.
  - Value flows into a node in the parse tree from parents and/or siblings.
  - Example: *type* of *VarList* in declaration grammar

Syntax-Directed Definition

Actions associated with each production in a grammar.

For a production $A \longrightarrow X\ Y$, actions may be of the form:

- $A.attr := f(X.attr', Y.attr'')$ for synthesized attributes
- $Y.attr := f(A.attr', X.attr'')$ for inherited attributes

If the function f does not have side effects, syntax directed definitions is also called as *attribute grammars*.

Attributes and Definitions

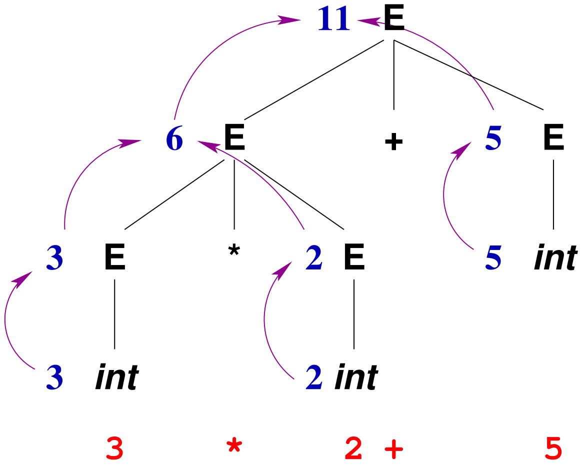
- **S-Attributed Definitions:** Where all attributes are *synthesized*.
- **L-Attributed Definitions:** Where all *inherited* attributes are such that their values depend only on
  - inherited attributes of the parent, and
  - attributes of left siblings

Synthesized Attributes: An Example

$$\boxed{\begin{array}{lcl} E & \longrightarrow & E \;\texttt{*}\; E \\ E & \longrightarrow & E \;\texttt{+}\; E \\ E & \longrightarrow & \texttt{int} \end{array}}$$

$$\begin{array}{lcll} E & \longrightarrow & E_1 \;\texttt{*}\; E_2 & \{E.val := E_1.val * E_2.val\} \\ E & \longrightarrow & E_1 \;\texttt{+}\; E_2 & \{E.val := E_1.val + E_2.val\} \\ E & \longrightarrow & \texttt{int} & \{E.val := \texttt{int}.val\} \end{array}$$

Information Flow for “Expression” Example

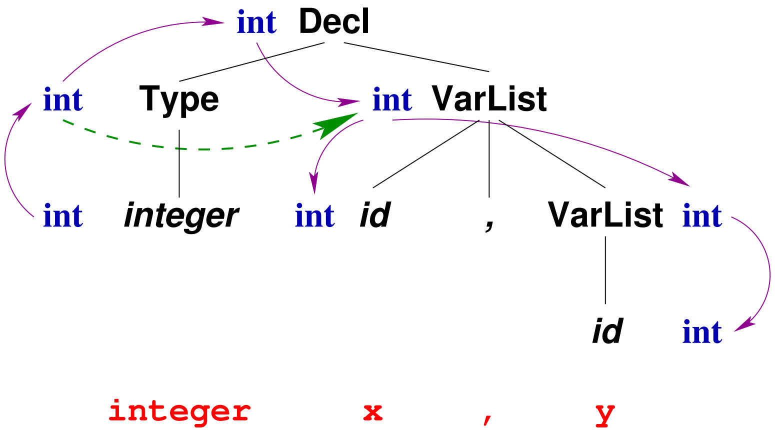


Another Example of Syntax-Directed Translation

$$\begin{array}{|rcl|}\hline
\textit{Decl} & \longrightarrow & \textit{Type}\ \textit{VarList} \\
\textit{Type} & \longrightarrow & \texttt{integer} \\
\textit{Type} & \longrightarrow & \texttt{float} \\
\textit{VarList} & \longrightarrow & \texttt{id}\ \texttt{,}\ \textit{VarList} \\
\textit{VarList} & \longrightarrow & \texttt{id} \\ \hline
\end{array}$$

$$\begin{array}{rcll}
\textit{Decl} & \longrightarrow & \textit{Type}\ \textit{VarList} & \{\textit{VarList.type} := \textit{Type.type}\} \\
\textit{Type} & \longrightarrow & \texttt{integer} & \{\textit{Type.type} := \textit{int}\} \\
\textit{Type} & \longrightarrow & \texttt{float} & \{\textit{Type.type} := \textit{float}\} \\
\textit{VarList} & \longrightarrow & \texttt{id}\ \texttt{,}\ \textit{VarList}_1 & \{\textit{VarList}_1\textit{.type} := \textit{VarList.type}; \\
 & & & \quad \texttt{id}\textit{.type} := \textit{VarList.type}\} \\
\textit{VarList} & \longrightarrow & \texttt{id} & \{\texttt{id}\textit{.type} := \textit{VarList.type}\}
\end{array}$$

Information Flow for “Type” Example



Syntax-Directed Definitions with yacc/Bison

$$\boxed{\begin{array}{lcll} E & \longrightarrow & E_1 \ \texttt{*} \ E_2 & \{E.val := E_1.val * E_2.val\} \\ E & \longrightarrow & E_1 \ \texttt{+} \ E_2 & \{E.val := E_1.val + E_2.val\} \\ E & \longrightarrow & \texttt{int} & \{E.val := \texttt{int}.val\} \end{array}}$$

$$\begin{array}{lcll} E & : & E \ \texttt{MULT} \ E & \{\$\$.val = \$1.val * \$3.val\} \\ E & : & E \ \texttt{PLUS} \ E & \{\$\$.val = \$1.val + \$3.val\} \\ E & : & \texttt{INT} & \{\$\$.val = \$1.val\} \end{array}$$

Syntax-Directed Definitions with PLY

$$
\boxed{
\begin{array}{lcll}
E & \longrightarrow & E_1 \; \texttt{*} \; E_2 & \{E.val := E_1.val * E_2.val\} \\
E & \longrightarrow & E_1 \; \texttt{+} \; E_2 & \{E.val := E_1.val + E_2.val\} \\
E & \longrightarrow & \texttt{int} & \{E.val := \texttt{int}.val\}
\end{array}
}
$$

```
def p_e_star(p):
    '''e : e '*' e'''
    p[0] = p[1] * p[3]

def p_e_plus(p):
    '''e : e '+' e'''
    p[0] = p[1] + p[3]

def p_e_int(p):
    '''e : int'''
    p[0] = p[1]
```

Synthesized Attributes and Bottom-up Parsing

Keep track of attributes of symbols while parsing.

- **Shift-reduce parsing:** Keep a stack of attributes corresponding to stack of symbols.
  Compute attributes of LHS symbol while performing reduction (*i.e.*, while pushing the symbol on symbol stack)

Synthesized Attributes & Shift-reduce parsing

$$E \longrightarrow E\texttt{+}E$$
$$E \longrightarrow E\texttt{*}E$$
$$E \longrightarrow \texttt{int}$$

STACK	INPUT STREAM	ATTRIBUTES
$	3 * 2 + 5 $	$
$ int	* 2 + 5 $	$ 3
$ *E*	* 2 + 5 $	$ 3
$ *E* *	2 + 5 $	$ 3 ⊥
$ *E* * int	+ 5 $	$ 3 ⊥ 2
$ *E*	+ 5 $	$ 6
$ *E* +	5 $	$ 6 ⊥
$ *E* + int	$	$ 6 ⊥ 5
$ *E* + *E*	$	$ 6 ⊥ 5
$ *E*	$	$ 11

Inherited Attributes

$$\boxed{\begin{array}{rcl} Ss & \longrightarrow & S \; \texttt{;} \; Ss \\ Ss & \longrightarrow & \epsilon \\ B & \longrightarrow & \texttt{\{} \; Ss \; \texttt{\}} \\ S & \longrightarrow & B \\ S & \longrightarrow & \texttt{other} \end{array}}$$

$$\begin{array}{rcll} Ss & \longrightarrow & S \; \texttt{;} \; Ss_1 & \{S.block = Ss.block; \\ & & & \; Ss_1.block = Ss.block;\} \\ Ss & \longrightarrow & \epsilon & \\ B & \longrightarrow & \texttt{\{} \; Ss \; \texttt{\}} & \{Ss.block = child(B.block);\} \\ S & \longrightarrow & B & \{B.block = S.block;\} \\ S & \longrightarrow & \texttt{other} & \{\texttt{other}.block = S.block;\} \end{array}$$

Top-down Parsing

```
parse_Ss() {
  /* production 1 */
    parse_S();
    parse_Ss();
    return;

  /* production 2 */
    return;
}
parse_B() {
  consume(OPEN_BRACE);
  parse_Ss();
  consume(CLOSE_BRACE);
}
```

Inherited Attributes and Top-down Parsing

```
parse_Ss(block) {
  /* production 1 */
    parse_S(block);
    parse_Ss(block);
    return;

  /* production 2 */
    return;
}
parse_B(block) {
  consume(OPEN_BRACE);
  parse_Ss(child(block));
  consume(CLOSE_BRACE);
}
```

Attributes and Top-down Parsing

- Inherited: analogous to function arguments
- Synthesized: analogous to return values

L-attributed definitions mean that argument to a parsing function is

- argument of the calling function, or
- return value/argument of a previously called function

Attributes and Bottom-up Parsing

- Synthesized: stored along with symbols on stack
- Inherited: **???**

Inherited Attributes and Bottom-up Parsing

Inherited attributes depend on the *context* in which a symbol is used.
For inherited attributes, we cannot assign an value to a node's attributes unless the parent's attributes are known.
When building parse trees bottom-up, parent of a node is not known when the node is created!

Solution:

- *Ensure that all attributes are inherited only from left siblings.*
- *Use "global" variables to capture inherited values,*
- *and introduce "marker" nonterminals to manipulate the global variables.*

Inherited Attributes & Bottom-up parsing

$$
\boxed{
\begin{array}{ccl}
Ss & \longrightarrow & S \; \texttt{;} \; Ss \\
Ss & \longrightarrow & \epsilon \\
B & \longrightarrow & \{ \;\; Ss \; \} \\
S & \longrightarrow & B \\
S & \longrightarrow & \texttt{other}
\end{array}
}
$$

$$
\begin{array}{cclcccccc}
B & \longrightarrow & \{ & M_1 & Ss & M_2 & \} & & \\
M_1 & \longrightarrow & \epsilon & & & & & & \{ \; current\_block{+}{+}; \} \\
M_2 & \longrightarrow & \epsilon & & & & & & \{ \; current\_block{-}{-}; \}
\end{array}
$$

M_1 and M_2 are marker non-terminals.