SEMANTIC ANALYSIS

PRINCIPLES OF PROGRAMMING LANGUAGES

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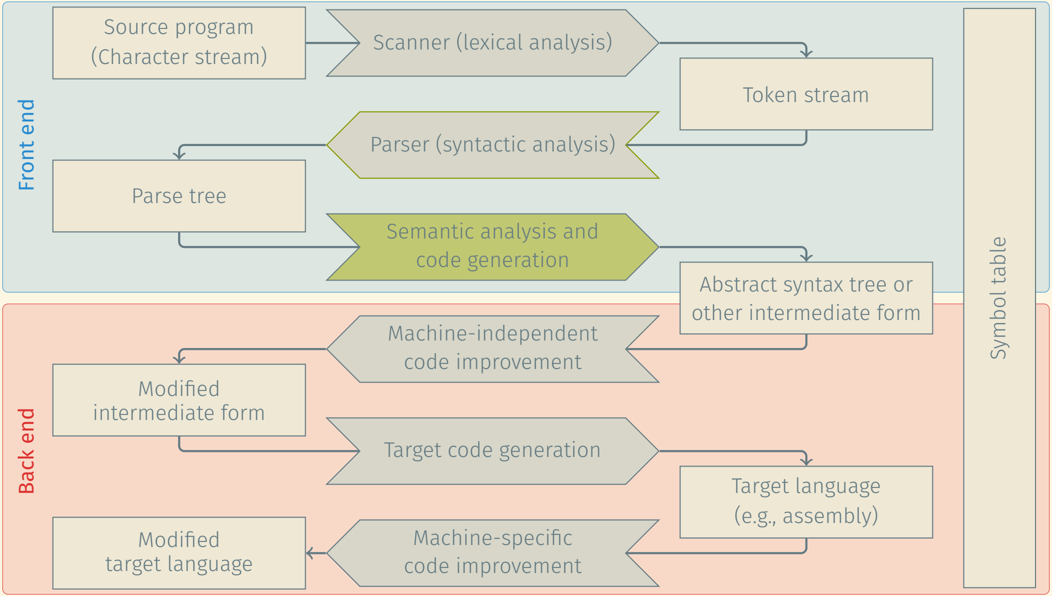
Dalhousie University

PROGRAM TRANSLATION FLOW CHART



ROAD MAP

- Syntax, semantics, and semantic analysis
- Attribute grammars
- Action routines
- Abstract syntax trees

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Some constraints that may appear syntactic are enforced by semantic analysis!

Example: Use of identifier only after its declaration

Semantic analysis

- Enforces semantic rules
- Builds intermediate representation (e.g., abstract syntax tree)
- Fills symbol table
- Passes results to intermediate code generator

SEMANTIC ANALYSIS

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Two approaches

- Interleaved with syntactic analysis
- As a separate phase

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Formal mechanism

- Attribute grammars

ENFORCING SEMANTIC RULES

Static semantic rules

- Enforced by compiler at compile time
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Dynamic semantic rules

- Compiler generates code for enforcement at runtime.
- **Examples:** Division by zero, array index out of bounds
- Some compilers allow these checks to be disabled.

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Attribute grammar

An augmented context-free grammar:

- Each symbol in a production has a number of attributes.
- Each production is augmented with semantic rules that
  - Copy attribute values between symbols,
  - Evaluate attribute values using semantic functions,
  - Enforce constraints on attribute values.

ATTRIBUTE GRAMMAR: EXAMPLE

$E \to E + T$

$E \to E - T$

$E \to T$

$T \to T * F$

$T \to T \,/\, F$

$T \to F$

$F \to -F$

$F \to (\,E\,)$

$F \to \text{const}$

ATTRIBUTE GRAMMAR: EXAMPLE

$E \to E + T$	$E_1 \to E_2 + T$	$\{\, E_1.val = \mathrm{add}(E_2.val, T.val) \,\}$
$E \to E - T$	$E_1 \to E_2 - T$	$\{\, E_1.val = \mathrm{sub}(E_2.val, T.val) \,\}$
$E \to T$	$E \to T$	$\{\, E.val = T.val \,\}$
$T \to T * F$	$T_1 \to T_2 * F$	$\{\, T_1.val = \mathrm{mul}(T_2.val, F.val) \,\}$
$T \to T \,/\, F$	$T_1 \to T_2 \,/\, F$	$\{\, T_1.val = \mathrm{div}(T_2.val, F.val) \,\}$
$T \to F$	$T \to F$	$\{\, T.val = F.val \,\}$
$F \to -F$	$F_1 \to -F_2$	$\{\, F_1.val = \mathrm{neg}(F_2.val) \,\}$
$F \to (E)$	$F \to (E)$	$\{\, F.val = E.val \,\}$
$F \to \mathrm{const}$	$F \to \mathrm{const}$	$\{\, F.val = \mathrm{const}.val \,\}$

Synthesized attributes

Attributes of LHS of production are computed from attributes of RHS of production.

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Inherited attributes

Attributes flow from left to right:

- From LHS to RHS,
- From symbols on RHS to symbols later on the RHS.

SYNTHESIZED ATTRIBUTES: EXAMPLE

The language

$$\mathcal{L} = \{\mathrm{a}^n\mathrm{b}^n\mathrm{c}^n \mid n > 0\} = \{\mathrm{abc}, \mathrm{aabbcc}, \mathrm{aaabbbccc}, \ldots\}$$

is not context-free but can be defined using an attribute grammar:

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is not context-free but can be defined using an attribute grammar:

$$
\begin{array}{ll}
S \rightarrow A\;B\;C & \{\text{Condition: } A.count = B.count = C.count\} \\
A \rightarrow \mathtt{a} & \{A.count = 1\} \\
A_1 \rightarrow A_2\;\mathtt{a} & \{A_1.count = A_2.count + 1\} \\
B \rightarrow \mathtt{b} & \{B.count = 1\} \\
B_1 \rightarrow B_2\;\mathtt{b} & \{B_1.count = B_2.count + 1\} \\
C \rightarrow \mathtt{c} & \{C.count = 1\} \\
C_1 \rightarrow C_2\;\mathtt{c} & \{C_1.count = C_2.count + 1\}
\end{array}
$$

SYNTHESIZED ATTRIBUTES: PARSE TREE DECORATION (1)

Input: aaabbbccc

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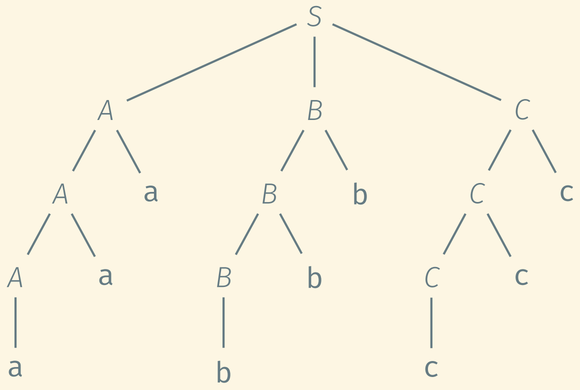
Parse tree:



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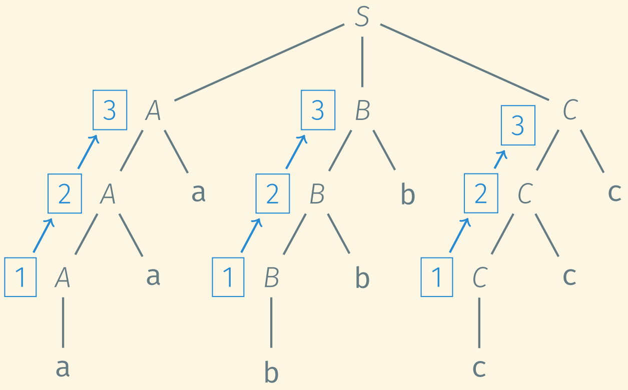

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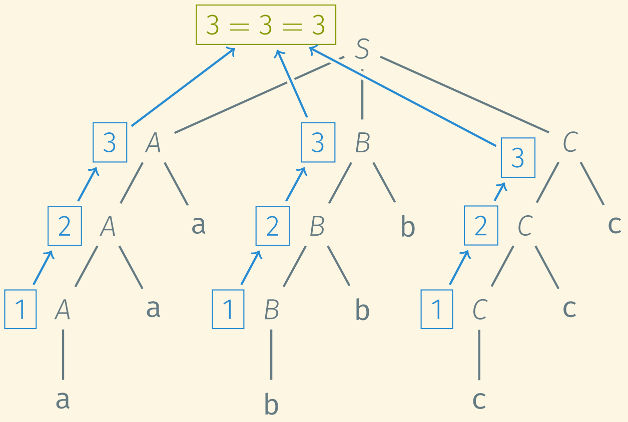

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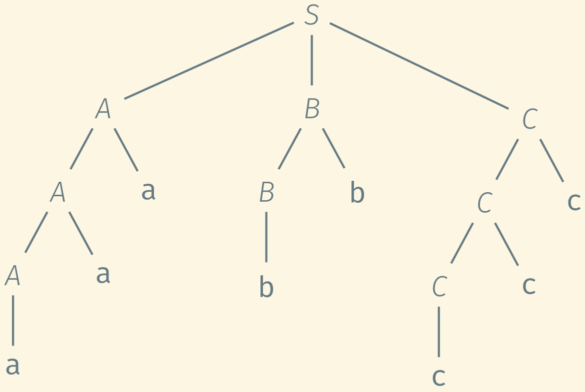

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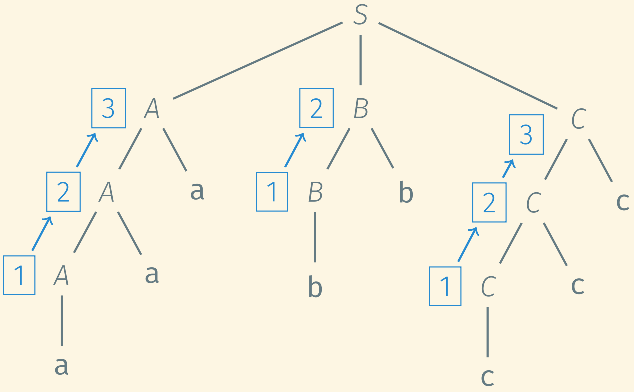

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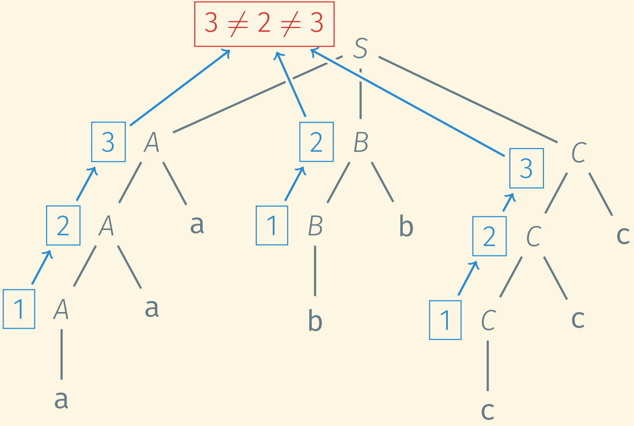

INHERITED ATTRIBUTES: EXAMPLE

Again, we consider the language

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$$
\begin{aligned}
S &\to A\, B\, C && \{B.inhCount = A.count; C.inhCount = A.count\} \\
A &\to \mathtt{a} && \{A.count = 1\} \\
A_1 &\to A_2\, \mathtt{a} && \{A_1.count = A_2.count + 1\} \\
B &\to \mathtt{b} && \{Condition : B.inhCount = 1\} \\
B_1 &\to B_2\, \mathtt{b} && \{B_2.inhCount = B_1.inhCount - 1\} \\
C &\to \mathtt{c} && \{Condition : C.inhCount = 1\} \\
C_1 &\to C_2\, \mathtt{c} && \{C_2.inhCount = C_1.inhCount - 1\}
\end{aligned}
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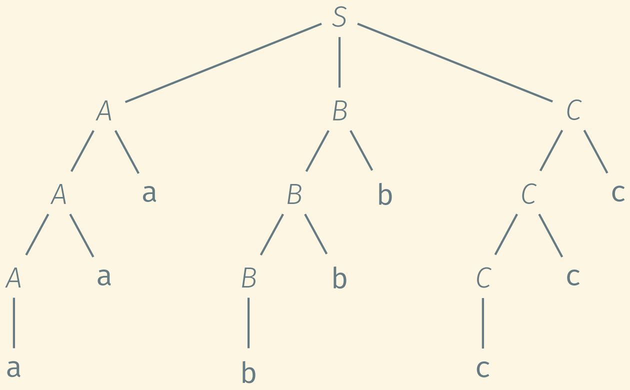

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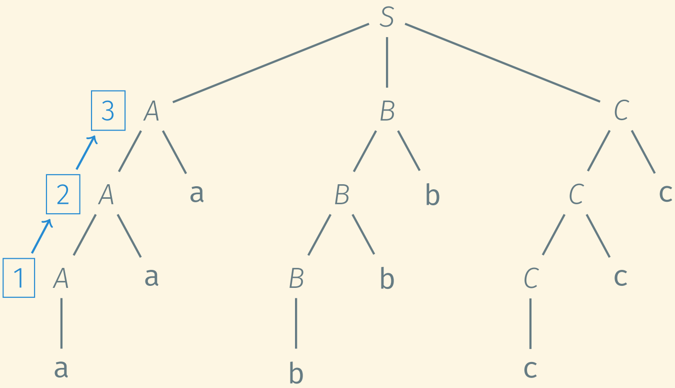

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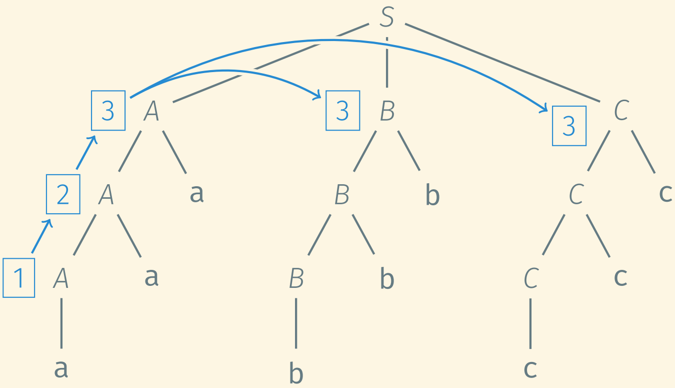

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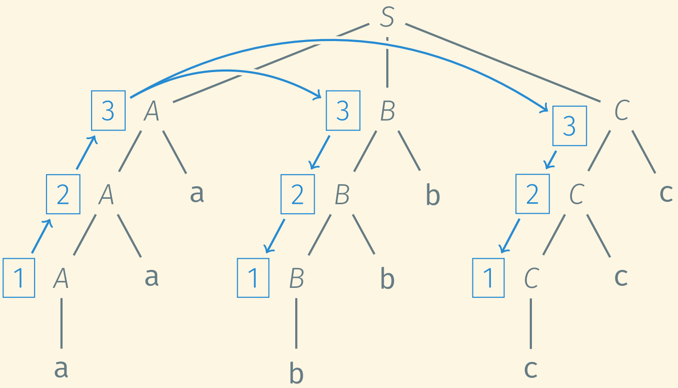

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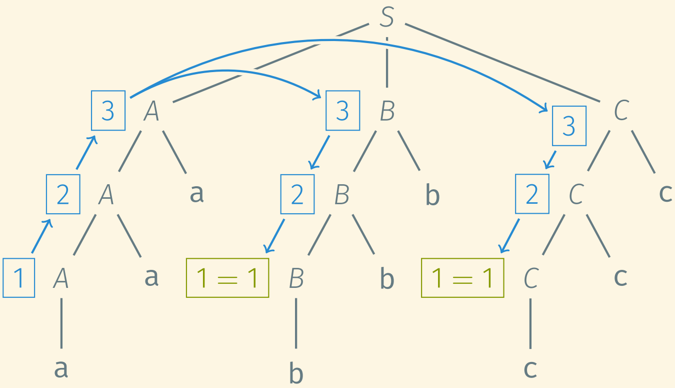

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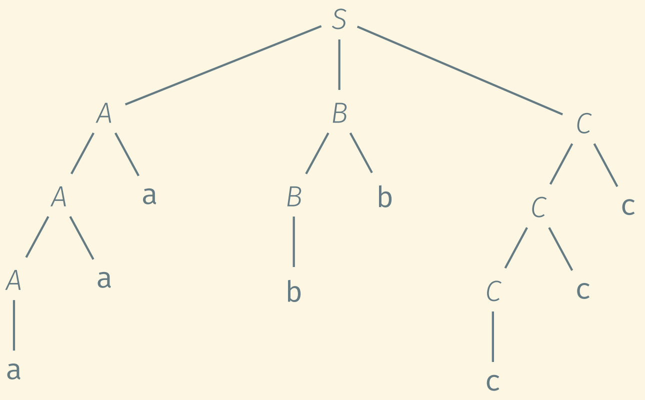

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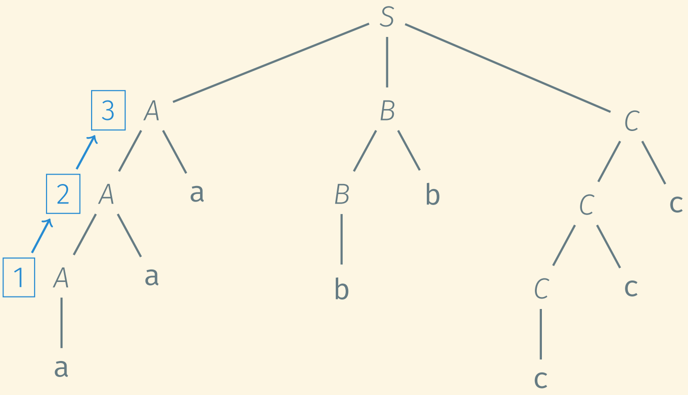

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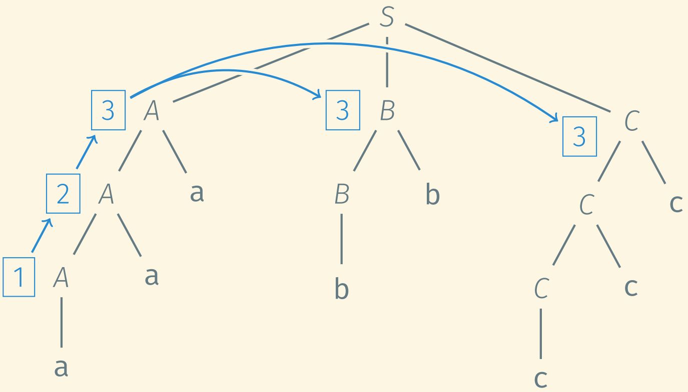

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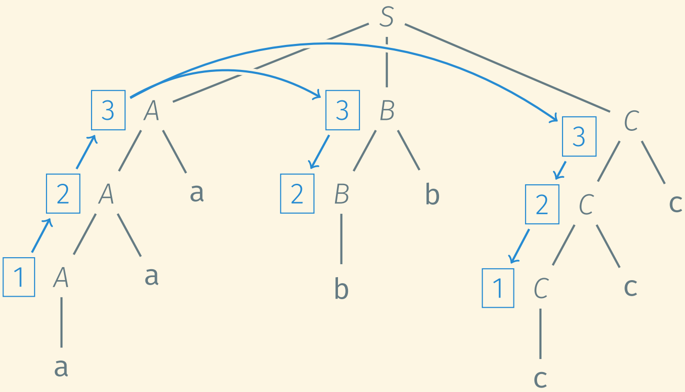

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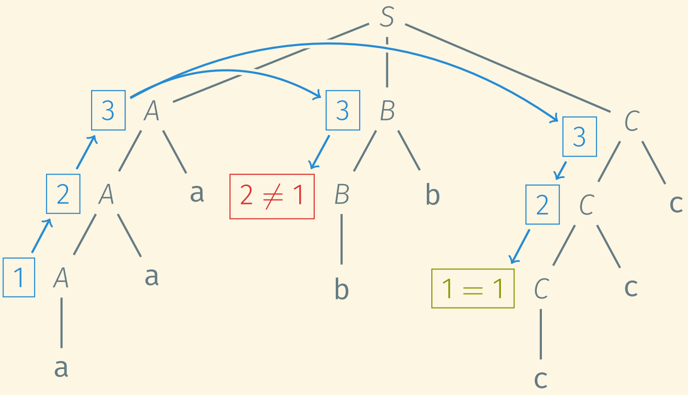

Annotation or decoration of the parse tree:

- Process of evaluating attributes

ATTRIBUTE FLOW

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Synthesized attributes:

- Attributes of LHS of each production are computed from attributes of symbols on the RHS of the production.
- Attributes flow bottom-up in the parse tree.

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- Attributes of LHS of each production are computed from attributes of symbols on the RHS of the production.
- Attributes flow bottom-up in the parse tree.

Inherited attributes:

- Attributes for symbols in the RHS of each production are computed from attributes of symbols to their left in the production.
- Attributes flow top-down in the parse tree.

S-attributed grammar

- All attributes are synthesized.
- Attributes flow bottom-up.

S-ATTRIBUTED AND L-ATTRIBUTED GRAMMARS

S-attributed grammar

- All attributes are synthesized.
- Attributes flow bottom-up.

L-attributed grammar

For each production $X \to Y_1 Y_2 \ldots Y_k$,

- $X.syn$ depends on $X.inh$ and all attributes of $Y_1, Y_2, \ldots, Y_k$.
- For all $1 \leq i \leq k$, $Y_i.inh$ depends on $X.inh$ and all attributes of $Y_1, Y_2, \ldots, Y_{i-1}$.

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S-attributed grammars are a special case of L-attributed grammars.

LL(1) PARSING, LEFT-ASSOCIATIVITY, AND L-ATTRIBUTED GRAMMARS (1)

A simple grammar for arithmetic expressions using addition and subtraction:

$E \rightarrow T$

$E \rightarrow EAT$

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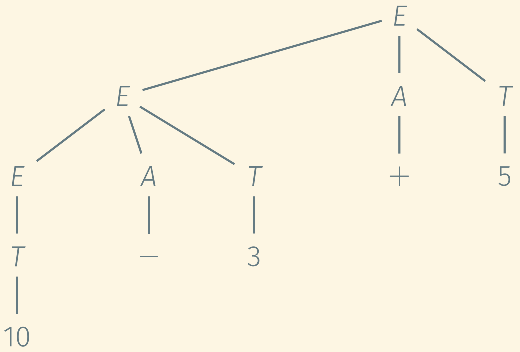
$10 - 3 + 5$



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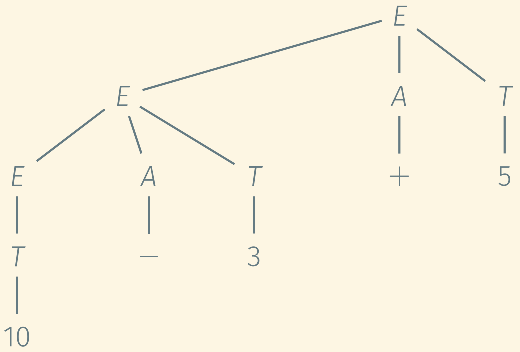
$10 - 3 + 5 \neq 10 - (3 + 5) = 2$



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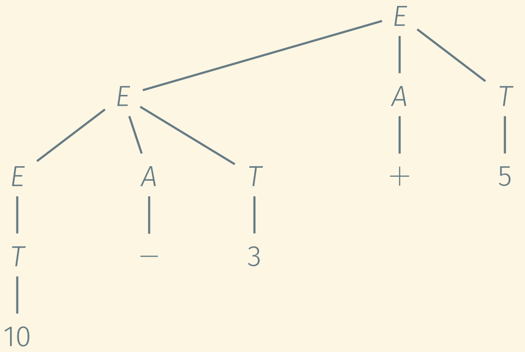

This grammar captures left-associativity.

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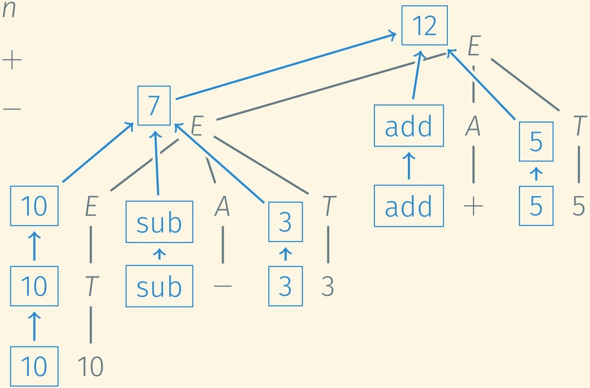

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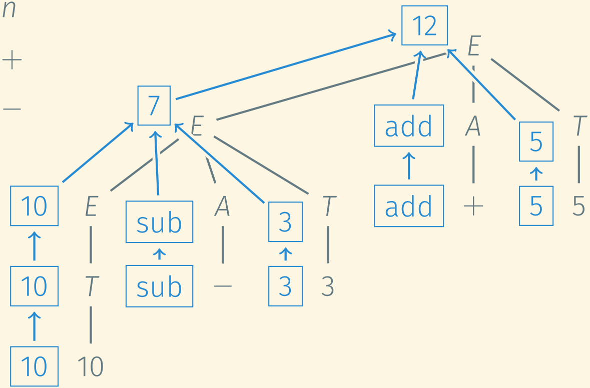

Rule R	PREDICT(R)
$E \to T$	$\{n\}$
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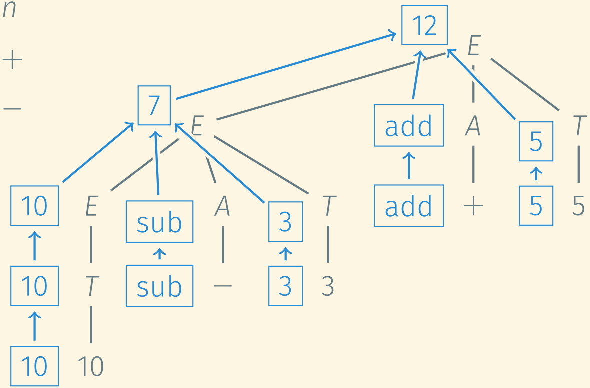

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This grammar captures left-associativity. It is not LL(1)!

An LL(1) grammar for the same language:

	PREDICT
$E \rightarrow TE'\$$	$\{n\}$
$E' \rightarrow \epsilon$	$\{\$\}$
$E' \rightarrow ATE'$	$\{+, -\}$
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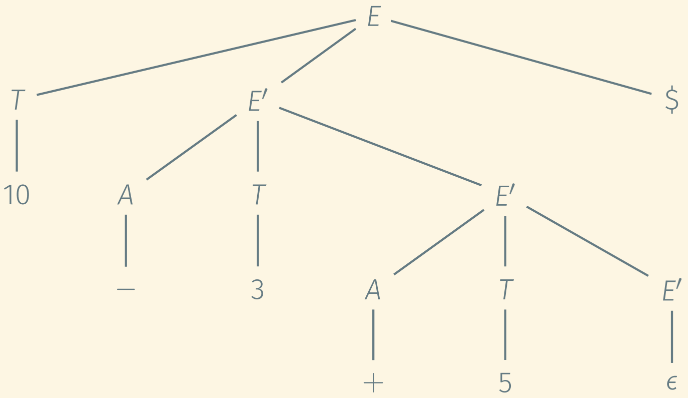

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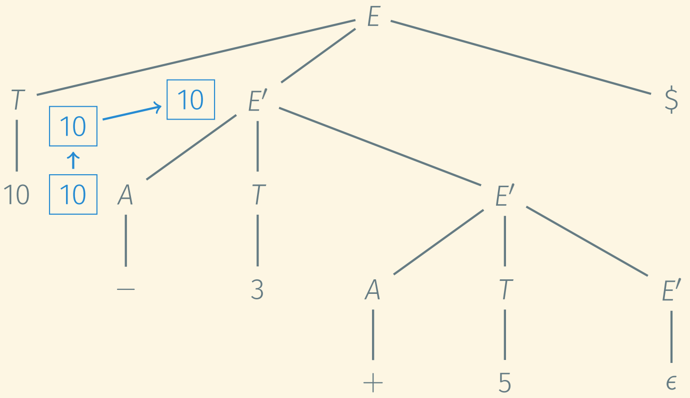

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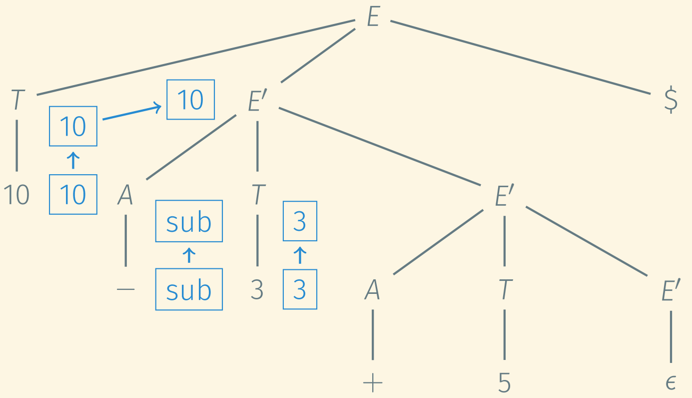

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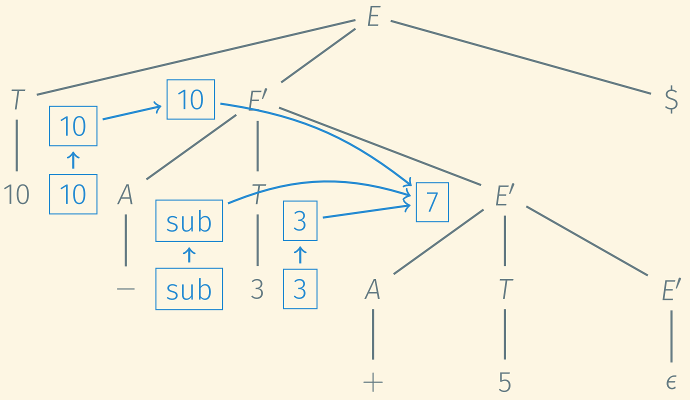

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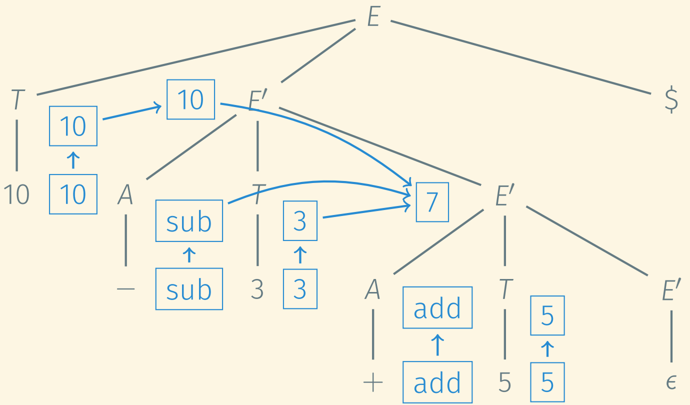

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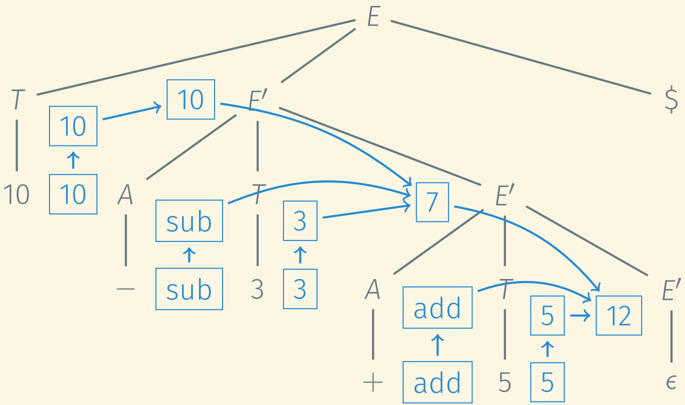

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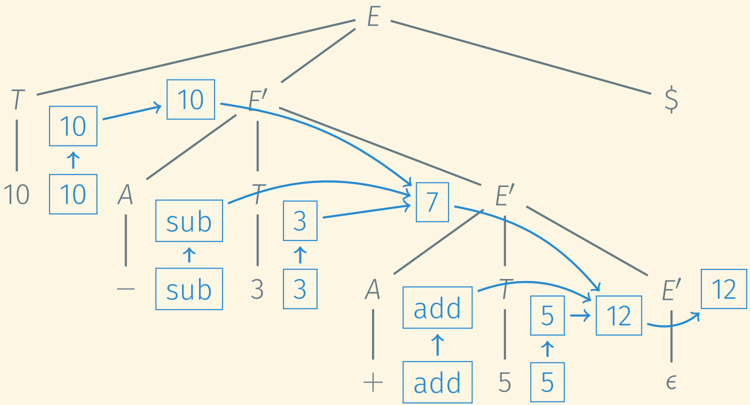

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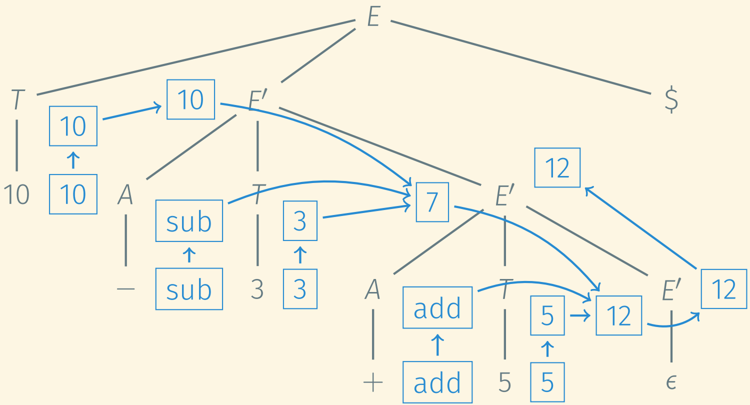

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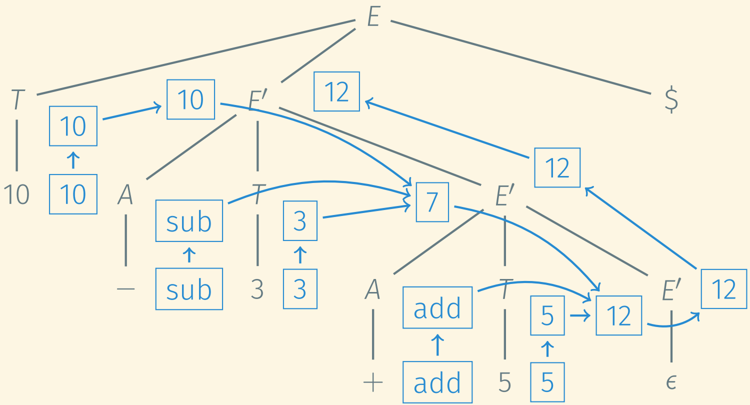
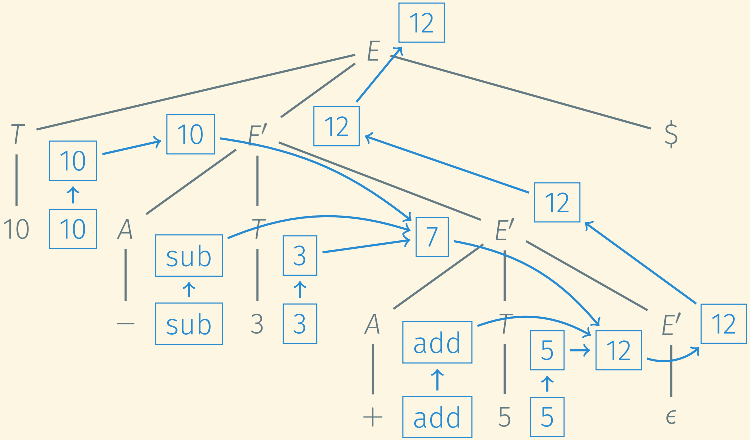


An LL(1) grammar for the same language:

	PREDICT
$E \rightarrow TE'\$$	$\{n\}$
$E' \rightarrow \epsilon$	$\{\$\}$
$E' \rightarrow ATE'$	$\{+, -\}$
$T \rightarrow n$	$\{n\}$
$A \rightarrow +$	$\{+\}$
$A \rightarrow -$	$\{-\}$



An LL(1) grammar for the same language:

$$
\begin{array}{ll}
E \to TE'\$ & \{E'.in = T.val; E.val = E'.val\} \\
E' \to \epsilon & \{E'.val = E'.in\} \\
E'_1 \to ATE'_2 & \{E'_2.in = A.fun(E'_1.in, T.val); E'_1.val = E'_2.val\} \\
T \to n & \{T.val = n.val\} \\
A \to + & \{T.fun = \text{add}\} \\
A \to - & \{T.fun = \text{sub}\}
\end{array}
$$

ROAD MAP

- Syntax, semantics, and semantic analysis
- Attribute grammars
- Action routines
- Abstract syntax trees

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ACTION ROUTINES

Action routines are instructions for ad-hoc translation interleaved with parsing.

Parser generators (e.g., `bison` or `yacc`) allow programmers to specify action routines in the grammar.

Action routines can appear anywhere in a rule (as long as the grammar is LL(1)).

ACTION ROUTINES: EXAMPLE

Example:

$$E' \rightarrow AT \; \{\$3.in = \$1.fun(\$0.in, \$2.val)\} \; E' \; \{\$0.val = \$3.val\}$$

Example:

$$E' \rightarrow AT\ \{\$3.in = \$1.fun(\$0.in, \$2.val)\}\ E'\ \{\$0.val = \$3.val\}$$

Corresponding parse function in recursive descent parser:

```
def parseEE(node0):
  node1 = ParseTreeNode()
  node2 = ParseTreeNode()
  node3 = ParseTreeNode()
  parseA(node1)
  parseT(node2)
  node3.op = node1.fun(node0.in, node2.val)
  parseEE(node3)
  node0.val = node3.val
```

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Problem with parse trees:

- They represent the full derivation of the program using grammar rules.
- Some grammar variables are there only to aid in parsing (e.g., to eliminate left-recursion or common prefixes).
- Code generator is easier to implement if the output of the parser is as compact as possible.

Abstract syntax tree (AST)

A compressed parse tree that represents the program structure rather than the parsing process.

ABSTRACT SYNTAX TREE: EXAMPLE (1)

$$
\begin{aligned}
Fun &\rightarrow \textbf{fun}\ id\ Stmts\ \textbf{.} \\
Stmts &\rightarrow \epsilon \\
Stmts &\rightarrow Stmt\ Stmts \\
Stmt &\rightarrow \ldots
\end{aligned}
$$

ABSTRACT SYNTAX TREE: EXAMPLE (1)

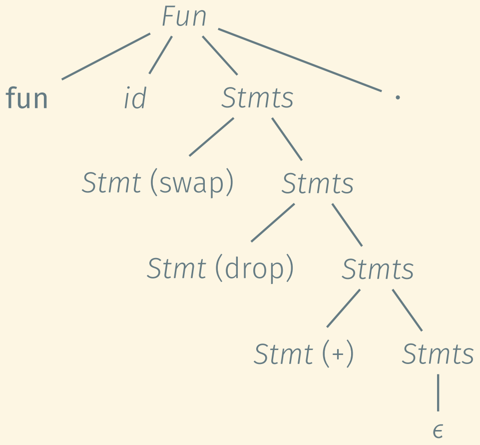
$$
\begin{aligned}
\mathit{Fun} &\rightarrow \textbf{fun}\ \mathit{id}\ \mathit{Stmts}\ \texttt{.} \\
\mathit{Stmts} &\rightarrow \epsilon \\
\mathit{Stmts} &\rightarrow \mathit{Stmt}\ \mathit{Stmts} \\
\mathit{Stmt} &\rightarrow \ldots
\end{aligned}
$$

```
fun foo
  swap drop +
.
```

ABSTRACT SYNTAX TREE: EXAMPLE (1)

$$
\begin{aligned}
\mathit{Fun} &\rightarrow \textbf{fun}\ \mathit{id}\ \mathit{Stmts}\ \texttt{.} \\
\mathit{Stmts} &\rightarrow \epsilon \\
\mathit{Stmts} &\rightarrow \mathit{Stmt}\ \mathit{Stmts} \\
\mathit{Stmt} &\rightarrow \ldots
\end{aligned}
$$

```
fun foo
  swap drop +
.
```



ABSTRACT SYNTAX TREE: EXAMPLE (1)

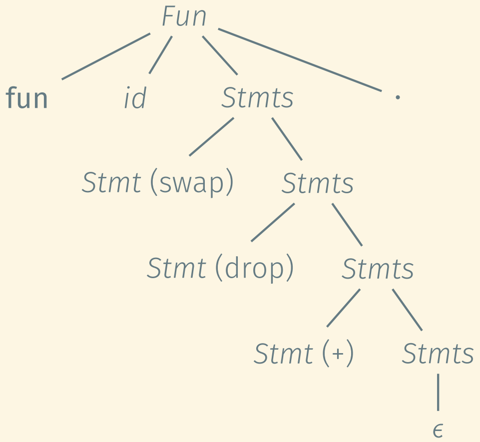
$$Fun \to \textbf{fun}\ id\ Stmts\ \texttt{.}$$

$$Stmts \to \epsilon$$

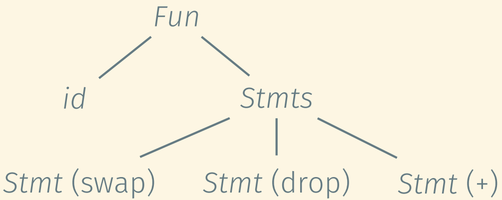
$$Stmts \to Stmt\ Stmts$$

$$Stmt \to \ldots$$

```
fun foo
  swap drop +
.
```



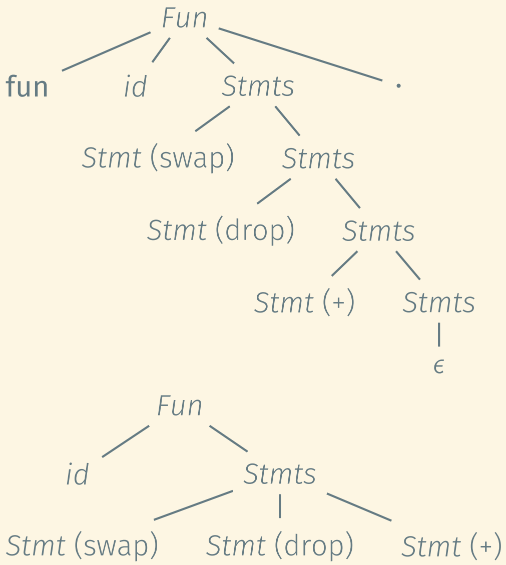
AST:



ABSTRACT SYNTAX TREE: EXAMPLE (2)

```
def parseFun(node0):
  node1 = ParseTreeNode()
  node2 = ParseTreeNode()
  matchFunKW()
  parseId(node1)
  parseStatements(node2)
  matchEndKW()

def parseStatements(node0):
  if next token is .:
    node0.statements = []
  else:
    node1 = ParseTreeNode()
    node2 = ParseTreeNode()
    parseStatement(node1)
    parseStatement(node2)
    node0.statements = \
      [node1.statement] + \
      node2.statements
```



SUMMARY

- Semantic analysis augments the parsing process to represent the meaning of the program.
- The output is often an annotated abstract syntax tree (AST).
- Attribute grammars and action routines are used to construct the AST.