Introduction to Compiler Construction

Parsing: Preliminaries

Outline

Parser

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- Make sure the program is syntactically valid, ie, conforms to the grammar describing the program's syntax
- Identify syntax errors and report them along with the line numbers they appear on
- Not stop on the first error, but report the error, recover from it, and look for additional errors
- Produce an intermediate representation (IR) of the parsed program that is suitable for semantic analysis

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In *j--*, the IR is in the form of an abstract syntax tree (AST)

Parser

Example: parsing the *j*-- program

</> HelloWorld.java

```java
// Writes the message "Hello, World" to standard output.

import java.lang.System;

public class HelloWorld {
    // Entry point.
    public static void main(String[] args) {
        System.out.println("Hello, World");
    }
}
```

results in the following AST

Parser

Parser

```
{
    "JCompilationUnit:3":
    {
        "source": "tests/HelloWorld.java", "imports": ["java.lang.System"],
        "JClassDeclaration:5":
        {
            "modifiers": ["public"],
            "name": "HelloWorld",
            "super": "java.lang.Object",
            "JMethodDeclaration:7":
            {
                "modifiers": ["public", "static"],
                "returnType": "void",
                "name": "main",
                "parameters": [["args", "String[]"]],
                "JBlock:7":
                {
                    "JStatementExpression:8":
                    {
                        "JMessageExpression:8":
                        {
                            "ambiguousPart": "System.out", "name": "println",
                            "Argument":
                            {
                                "JLiteralString:8":
                                {
                                    "type": "", "value": "Hello, World"
                                }
                            }
                        }
                    }
                }
            }
        }
    }
}
```

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The AST makes the syntax implicit in the program text, explicit

Context-free Grammars and Languages

Context-free Grammars and Languages

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Example: the rule

$$S ::= \texttt{if (}E\texttt{)}\ S$$

says that, if E is an expression and S is a statement, then

$$\texttt{if (}E\texttt{)}\ S$$

is also a statement

Context-free Grammars and Languages

Example: the rule

$$S ::= \texttt{if (}E\texttt{)}\ S \\ \quad \mid \texttt{if (}E\texttt{)}\ S\ \texttt{else}\ S$$

is shorthand for

$$S ::= \texttt{if (}E\texttt{)}\ S$$
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Square brackets indicate that a phrase is optional

Example: the two rules from above can be written as

$$S ::= \texttt{if (}E\texttt{)}\ S\ [\texttt{else}\ S]$$

Context-free Grammars and Languages

Curly braces denote the Kleene closure, indicating that the phrase may appear zero or more times

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Example: the rule

$$E ::= T \{ + \ T \}$$

says that an E may be written as T (for term) followed by zero or more occurrences of + followed by T, such as

$$T + T + T + T \ldots$$

Context-free Grammars and Languages

One may use the alternation sign | to denote a choice and parentheses for grouping

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Example: the rule

$$E ::= T \; \{(\texttt{+} \mid \texttt{-}) \; T\}$$

says that the additive operator may be either + or -, such as

$$T \; \texttt{+} \; T \; \texttt{-} \; T \; \texttt{+} \; T \; \ldots$$

Context-free Grammars and Languages

Example (BNF rules in *j--*):

```
compilationUnit ::= [ PACKAGE qualifiedIdentifier SEMI ]
                    { IMPORT  qualifiedIdentifier SEMI }
                    { typeDeclaration }
                    EOF

qualifiedIdentifier ::= IDENTIFIER { DOT IDENTIFIER }

typeDeclaration ::= modifiers classDeclaration

modifiers ::= { ABSTRACT | PRIVATE | PROTECTED | PUBLIC | STATIC }

classDeclaration ::= CLASS IDENTIFIER [ EXTENDS qualifiedIdentifier ] classBody

classBody ::= LCURLY { modifiers memberDecl } RCURLY
```

Context-free Grammars and Languages

Context-free Grammars and Languages

A context-free grammar is a tuple $G = (N, T, S, P)$, where

- N is a set non-terminals
- T is a set of terminals
- $S \in N$ is the start symbol
- P is a set of productions (aka rules)

Context-free Grammars and Languages

Context-free Grammars and Languages

Example: arithmetic expression grammar $A = (N, T, S, P)$, where

- $N = \{E, T, F\}$
- $T = \{\texttt{+}, \texttt{*}, \texttt{(}, \texttt{)}, \texttt{id}\}$
- $S = E$
- P is the following set of productions

$$
\begin{aligned}
E &::= E \texttt{ + } T \\
E &::= T \\
T &::= T \texttt{ * } F \\
T &::= F \\
F &::= \texttt{(}E\texttt{)} \\
F &::= \texttt{id}
\end{aligned}
$$

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- $S = E$
- P is the following set of productions

$$E ::= E \texttt{ + } T$$
$$E ::= T$$
$$T ::= T \texttt{ * } F$$
$$T ::= F$$
$$F ::= \texttt{(}E\texttt{)}$$
$$F ::= \texttt{id}$$

A grammar can be specified informally as a sequence of productions

Context-free Grammars and Languages

From the start symbol, using productions, we can generate infinitely many strings

Example (strings generated from the start symbol E in A):

$$
\begin{aligned}
E &\Rightarrow E + T \\
&\Rightarrow T + T \\
&\Rightarrow F + T \\
&\Rightarrow \texttt{id} + T \\
&\Rightarrow \texttt{id} + T * F \\
&\Rightarrow \texttt{id} + F * F \\
&\Rightarrow \texttt{id} + \texttt{id} * F \\
&\Rightarrow \texttt{id} + \texttt{id} * \texttt{id}
\end{aligned}
$$

Context-free Grammars and Languages

When one string can be re-written as another string, using zero or more production rules from the grammar, we say the first string derives ($\overset{*}{\Rightarrow}$) the second string

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Example (derivations using productions in A):

$$E \overset{*}{\Rightarrow} E \text{ (in zero steps)}$$
$$E \overset{*}{\Rightarrow} \texttt{id + } F \texttt{ * } F$$
$$T \texttt{ + } T \overset{*}{\Rightarrow} \texttt{id + id * id}$$

Context-free Grammars and Languages

The language $L(G)$ described by a grammar G consists of all the strings comprised of only terminal symbols, ie,
$L(G) = \{w | S \overset{*}{\Rightarrow} w \text{ and } w \in T*\}$

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Example (the language $L(A)$):

$$E \stackrel{*}{\Rightarrow} \texttt{id}$$
$$E \stackrel{*}{\Rightarrow} \texttt{id + id * id}$$
$$E \stackrel{*}{\Rightarrow} \texttt{(id + id) * id}$$

so, $L(A)$ includes each of

```
id
id + id * id
(id + id) * id
```

and infinitely more finite strings

Context-free Grammars and Languages

A left-most derivation is a derivation in which at each step, the next string is derived by applying a production for rewriting the left-most non-terminal

Example (left-most derivation using productions in A):

$$\begin{aligned} \underline{E} &\Rightarrow \underline{E} + T \\ &\Rightarrow \underline{T} + T \\ &\Rightarrow \underline{F} + T \\ &\Rightarrow \texttt{id} + \underline{T} \\ &\Rightarrow \texttt{id} + \underline{T} * F \\ &\Rightarrow \texttt{id} + \underline{F} * F \\ &\Rightarrow \texttt{id} + \texttt{id} * \underline{F} \\ &\Rightarrow \texttt{id} + \texttt{id} * \texttt{id} \end{aligned}$$

Context-free Grammars and Languages

A right-most derivation is a derivation in which at each step, the next string is derived by applying a production for rewriting the right-most non-terminal

Example (right-most derivation using productions in A):

$$
\begin{aligned}
\underline{E} &\Rightarrow E + \underline{T} \\
&\Rightarrow E + T * \underline{F} \\
&\Rightarrow E + \underline{T} * \texttt{id} \\
&\Rightarrow E + \underline{F} * \texttt{id} \\
&\Rightarrow \underline{E} + \texttt{id} * \texttt{id} \\
&\Rightarrow \underline{T} + \texttt{id} * \texttt{id} \\
&\Rightarrow \underline{F} + \texttt{id} * \texttt{id} \\
&\Rightarrow \texttt{id} + \texttt{id} * \texttt{id}
\end{aligned}
$$

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A sentence is any string of only terminal symbols that can be derived from the start symbol

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Example (sentential forms and sentences derived using the start symbol E in A):

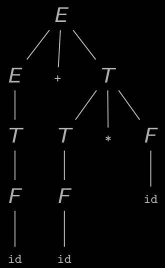
E
$E + T$
$E + T * F$
...
F `+ id * id`
`id + id * id`

are all sentential forms and `id + id * id` is a sentence

Context-free Grammars and Languages

A parse tree illustrates the derivation (and structure) of a sentence (at the leaves) from a start symbol (at the root)

Example (parse tree for `id + id * id` in $L(A)$):



Ambiguous Grammars and Languages

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Given a grammar G, if there exists a sentence $s \in L(G)$ for which there are more than one left- (or right-) most derivations or parse trees, we say the sentence s is ambiguous

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Given a grammar G, if there exists a sentence $s \in L(G)$ for which there are more than one left- (or right-) most derivations or parse trees, we say the sentence s is ambiguous

If a grammar G derives at least one ambiguous sentence, we say the grammar G is ambiguous; if there is no such sentence, we say the grammar is unambiguous

Ambiguous Grammars and Languages

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Example (ambiguous arithmetic expression grammar A_{amb}):

$$E ::= E \texttt{+} E \mid E \texttt{*} E \mid \texttt{(}E\texttt{)} \mid \texttt{id}$$

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Example (ambiguous arithmetic expression grammar A_{amb}):

$$E ::= E \texttt{ + } E \mid E \texttt{ * } E \mid \texttt{(}E\texttt{)} \mid \texttt{id}$$

One left-most derivation and corresponding parse tree for the sentence $\texttt{id + id * id}$:

$$\begin{aligned}
\underline{E} &\Rightarrow \underline{E} \texttt{ + } E \\
&\Rightarrow \texttt{id + } \underline{E} \\
&\Rightarrow \texttt{id + } \underline{E} \texttt{ * } E \\
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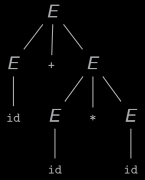

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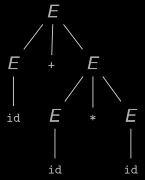

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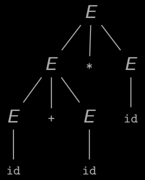

Ambiguous Grammars and Languages

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Example (dangling-else problem):

$$
\begin{aligned}
S &::= \texttt{if (}E\texttt{)}\ S \\
  &\mid \texttt{if (}E\texttt{)}\ S\ \texttt{else}\ S \\
  &\mid \texttt{s} \\
E &::= \texttt{e}
\end{aligned}
$$

Ambiguous Grammars and Languages

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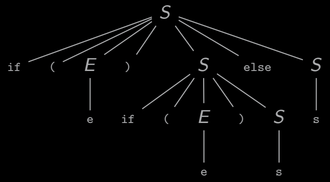
\mid\;& \texttt{if (}E\texttt{)}\ S\ \texttt{else}\ S \\
\mid\;& \texttt{s} \\
E \;::=\;& \texttt{e}
\end{aligned}
$$

Two left-most derivations and corresponding parse trees for the sentence `if (e) if (e) s else s`

$$
\begin{aligned}
\underline{S} &\Rightarrow \texttt{if (}\underline{E}\texttt{)}\ S\ \texttt{else}\ S \\
&\Rightarrow \texttt{if (e)}\ \underline{S}\ \texttt{else}\ S \\
&\Rightarrow \texttt{if (e) if (}\underline{E}\texttt{)}\ S\ \texttt{else}\ S \\
&\Rightarrow \texttt{if (e) if (e)}\ \underline{S}\ \texttt{else}\ S \\
&\Rightarrow \texttt{if (e) if (e) s else}\ \underline{S} \\
&\Rightarrow \texttt{if (e) if (e) s else s}
\end{aligned}
$$



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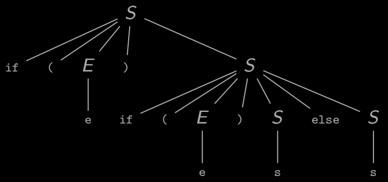

Ambiguous Grammars and Languages

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Resolution of the dangling-else problem:

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Ambiguous Grammars and Languages

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\end{aligned}
$$

But programmers have become accustomed to (and fond of) the ambiguous conditional

Compiler writers handle the rule as a special case in the parser such that an `else` is grouped along with the closest preceding `if`

Ambiguous Grammars and Languages

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j-- has another ambiguity, which is the problem of parsing the expression `x.y.z.w` (eg, `java.lang.Math.PI`)

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`x` might refer to an object with a field `y`, referring to another object with a field `z`, referring to the field `w`

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The parser represents `x.y.z` in the AST as an `AmbiguousName` node, which gets reclassified during semantic analysis