CS345H: Programming Languages

Lecture 5: Introduction to Parsing

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Outline

- Limitations of Regular Languages
- Parser Overview
- Context-free Grammars (CFGs)
- Derivations
- Ambiguity

Regular Languages

- Last time, we saw that regular languages are very useful for partitioning input into tokens
- But regular languages are not expressive enough to turn a stream of tokens into structure
- For this, we need a more expressive formal language

Beyond Regular Languages

- Many languages are not regular
- Classic Example: Strings of balanced parenthesis:

$$\{(^i)^j \mid i \geq 0\}$$

- Question: Why is there no automata that can recognize this language?

What Can Regular Languages Express?

- Languages requiring counting modulo a fixed integer
- Intuition: A finite automaton that runs long enough must repeat states
- Finite automaton cannot remember the number of times it has visited a particular state

Side Note: Comments in L

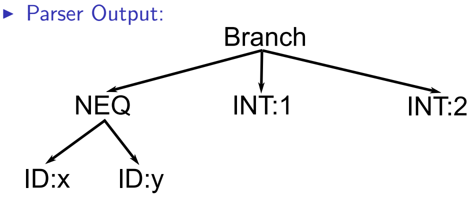
- Recall: Comments in L start with (*, end with *) and can be nested
- Also Recall: Comments are removed during lexing
- Question: Are comments in L a regular language?

The Functionality of the Parser

- Input: sequence of tokens from the lexer
- Output: parse tree of the program

Example

- Consider the following L expression:
  `if x<>y then 1 else 2`
- Parse Input: `TOKEN_IF TOKEN_ID("x") TOKEN_NEQ TOKEN_ID("y") TOKEN_THEN TOKEN_INT(1) TOKEN_ELSE TOKEN_INT(2)`
- Parser Output:



Parsing vs. Lexing

Phase	Input	Output
Lexer	String of characters	String of tokens
Parser	String of tokens	Parse tree

The Role of the Parser

- Not all strings of tokens are programs . . .
- Parser must distinguish between valid and invalid strings of tokens
- We need:
  - A language for describing valid strings of tokens
  - A method for recognizing if a string of tokens is in this language or not

Context-free Grammars (CFGs)

- Programming language constructs have recursive structure
- Example: An L expression is `expression + expression`, `if expression then expression else expression`, . . .
- Context free grammars are a natural notation for this recursive structure

CFGs in more detail

- A CFG consists of:
  - A set of terminals T
  - A set of non-terminals N
  - A start symbol S (non-terminal)
  - A set of productions

$$X \rightarrow Y_1 Y_2 \ldots Y_n$$

where $X \in N$ and $Y_i \in (T \cup N \cup \{\varepsilon\})$

Notational Conventions in this Class

- Non-terminals are always written upper-case
- Terminals are written lower-case
- The start symbol is the left-hand side of the first production

CFG Examples

- A fragment of L

```
EXPR → if EXPR then EXPR else EXPR
     |  EXPR + EXPR
     |  id
```


CFG Examples continued

- Simple arithmetic expressions:

```
EXPR → E * E
     |  E + E
     |  (E)
     |  id
```


The Language of a CFG

- Recall production rules: $X \to Y_1 \dots Y_n$
- Means that X can be replaced by $Y_1 \dots Y_N$
- More specifically:
  1. Begin with string consisting of the start symbol "S"
  2. Replace any non-terminal X in string with the right-hand side of some production
     $$X \to Y_1 \dots Y_n$$
  3. Repeat (2) until there are no non-terminals in the string

The Language of a CFG continued

- More formally, write
  $$X_1 \dots X_i \dots X_n \to X_1 \dots X_{i-1} Y_1 \dots Y_m X_{i+1} \dots X_n$$
  if there is a production
  $$X_i \to Y_1 \dots Y_m$$
- Abbreviation: Write $X_1 \dots X_n \to^* Y_1 \dots Y_m$ if $X_1 \dots X_n \to \dots \to Y_1 \dots Y_m$ in 0 or more steps

The Language of a CFG continued

- Now, let G be a context-free grammar with start symbol S. Then the language of G is:
  $$\{a_1 \dots a_n | S \to^* a_1 \dots a_n \text{ and every } a_i \text{ is a terminal}\}$$

Terminals

- Terminals are called "terminals" because there are no rules for replacing them
- Once generated, terminals are permanent
- Question: What should terminals be when parsing a programming language?
- Answer: Tokens

Examples

- $L(G)$ is the language of CFG G
- Strings of balanced parentheses:

$$\{(^i)^j | i \geq 0\}$$

- CFG:

$$S \rightarrow (S)$$
$$S \rightarrow \varepsilon$$

or equivalently

$$S \rightarrow (S) \mid \varepsilon$$

Examples

- Recall the earlier fragment of L:

```
EXPR → if EXPR then EXPR else EXPR
        |  EXPR + EXPR
        |  id
```

- Some strings in this language:
```
ID
IF ID THEN ID ELSE ID
ID + ID
IF ID THEN ID+ID ELSE ID
IF IF ID THEN ID ELSE IF THEN ID ELSE ID
...
```


Examples

- Recall simple arithmetic expressions:

```
EXPR → E * E
      |  E + E
      |  (E)
      |  id
```

- Some strings in this language:
```
id
(id)
(id)*id
id+id
id*id
id*(id) ...
```


Where are we?

- The idea of a CFG is a big step towards parsing tokens.
- But we don't just want to know if a string of tokens is in a language, we also need parse tree of input tokens
- Must also handle errors gracefully
- Need an implementation of CFGs (e.g., bison)

From Derivations to Parse Trees

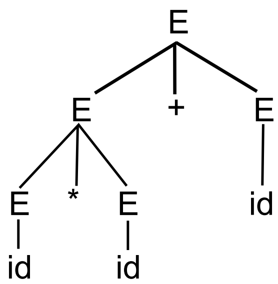
- A derivation is a sequence of productions

$$S \rightarrow \ldots \rightarrow \ldots \rightarrow \ldots$$

- A derivation can be drawn as a tree
  - Start symbol is the tree's root
  - For a production $X \rightarrow Y_1 \ldots Y_n$ add children $Y_1 \ldots Y_n$ to node X

Derivation Example

```
  E
→ E+E
→ E*E+E
→ id*E+E
→ id*id + E
→ id*id + id
```



Derivation in Detail

```
  E
→ E+E
→ E*E+E
→ id*E+E
→ id*id + E
→ id*id + id
```

Notes on Derivations

- A parse tree has terminals at the leaves and non-terminals at the interior nodes
- An in-order traversal of the leaves is the original input
- The parse tree shows the associativity of operations, the input token string does not
- Example: The parse tree from the last slide encodes that times has higher precedence than plus

Left-most and Right-most Derivations

- The example we looked at is a left-most derivation
- This means: At each step, we replace the left-most non-terminal
- There is also an equivalent notion of right-most derivation

Right-most Derivation in Detail

```
  E
→ E+E
→ E+id
→ E*E+id
→ E*id + id
→ id*id + id
```

Derivations and Parse Trees

- Observe that left-most and right-most derivations have the same parse tree
- The only difference is the order in which branches are added
- But when parsing tokens, we only care about the final parse tree, which may have many different derivations
- Left-most and right-most derivations are important in parser implementations

Ambiguity

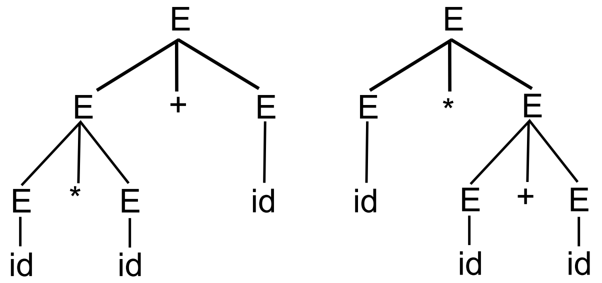
- Recall our example grammar:

```
EXPR → E * E
     | E + E
     | (E)
     | id
```

- Now, consider the string `id*id+id`

Ambiguity continued

- This string has two parse trees!



Ambiguity

- A grammar is ambiguous if it has more than one parse tree for some string
- Equivalently: There is more than one left-most or right-most derivation for some string
- Ambiguity is bad!
- Leaves meaning of programs ill-defined

Dealing with Ambiguity

- First method: Rewrite grammar unambiguously
- Question: How can we write simple arithmetic expressions unambiguously?
- Solution: Enforce precedence of times over plus by generating all pluses fist:

$$
\begin{array}{lcl}
S & \rightarrow & E + S \mid E \\
E & \rightarrow & \text{id} * E \mid \text{id} \mid (S) * E \mid (S)
\end{array}
$$

Ambiguity

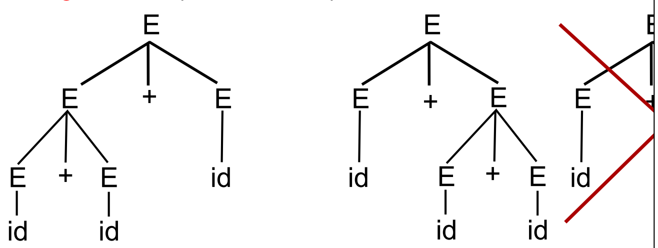
- However, converting grammars to unambiguous form can be very difficult
- It also often results in horrible, unintuitive grammars with many non-terminals
- It is also fundamentally impossible to transform an ambiguous grammar into a unambiguous grammar
- For this reason, tools such as `bison` include disambiguation mechanisms

Precedence and Associativity

- Instead of rewriting the grammar:
  - Use the more natural ambiguous grammar
  - Along with disambiguating declarations
- The parser tool `bison` allows you to declare precedence and associativity for this

Associativity Declarations

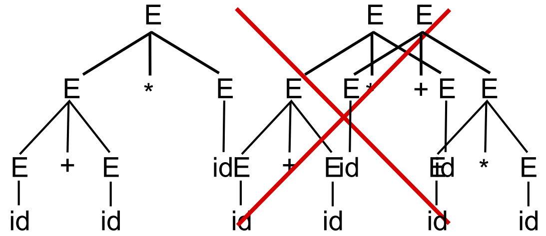
- Consider the grammar $E \rightarrow E + E \mid$ id
- Ambiguous: Two parse trees of input `id + id + id`



- Declare left associativity of plus as: `%left +`

Precedence Declarations

- Consider the grammar $E \rightarrow E + E \mid$ id and input `id + id * id`



- Precedence Declaration:
  `%left +`
  `%left *`

Conclusion

- We have seem how to specify programming language syntax with CFGs
- We built parse trees that express the high-level syntactic structure
- Parse trees of programs are known as abstract syntax trees
- We discussed ambiguity of CFGs