## CS345H: Programming Languages

## Lecture 6: Parsing Algorithms

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## Outline

- Extend CFGs to build parse trees
- We will build a parser that recognizes a CFG
- We will look at syntactic grammar restrictions that allows our algorithm to always succeed
- Error recovery



## Extending CFGs for program parsing

- CFGs describe the structure of a program.
- But we also need this structure in form of a tree, not just a yes/no answer
- Insight: We do not need all program structure, only the relevant part
- We call this an abstract syntax tree

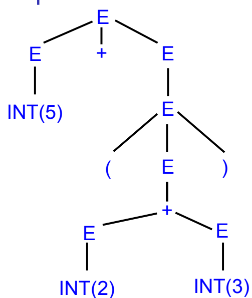


## ASTs

- Consider the grammar: $E \rightarrow \text{int} \mid (E) \mid E + E$
- And the string `5 + (2 + 3)`
- After lexical analysis as string of tokens: `INT(5) '+' '(' INT(2) '+' INT(3) ')'`
- During parsing, we built a parse tree:



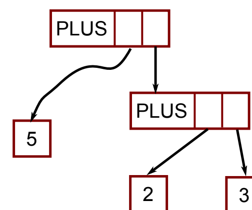
## Example of Parse Tree




- Captures the nesting structure
- But too much information!
- Example: We do not care about the parentheses



## Example of Abstract Syntax Tree




- Also captures the nesting structure
- But abstracts from the concrete syntax
- More compact and easier to use

## Semantic Actions to built the AST

- Each grammar symbol has one attribute
- For terminals (lexer tokens), the attribute is just the token
- Each production has a action computing its resulting attribute
- Written as: $X \rightarrow Y_1 \dots Y_n\{\text{action}\}$



## Semantic Actions: An Example

- Consider again the grammar: $E \rightarrow \text{int} \mid (E) \mid E + E$
- For each non-terminal on left-hand side, define its value in terms of symbols on right-hand side
- Recall: The value of each terminal is just its token
- Assume value of symbol $S$ is given by $S.val$
- Grammar annotated with actions to compute the AST:

$$
\begin{array}{lcl}
E & \rightarrow & \text{int}\ \{\texttt{E.val} = \texttt{int.val}\} \\
E & \rightarrow & E_1 + E_2\ \{\texttt{E.val} = \texttt{makeAstPlus}(\texttt{E}_1\texttt{.val}, \texttt{E}_2\texttt{.val})\} \\
E & \rightarrow & (E')\ \{\texttt{E.val} = \texttt{E}'\texttt{.val}\}
\end{array}
$$



## Semantic Actions to built the AST

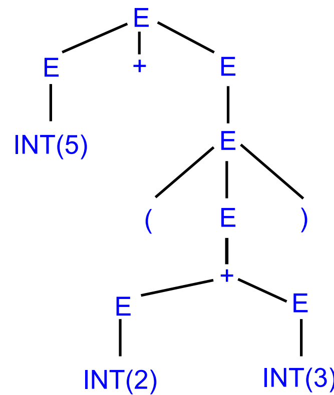
- You can think of semantic actions as defining a system of equations that describe the values of the let-hand sides in terms of values on the right-hand side
- Recall again

$$
\begin{array}{lcl}
E & \rightarrow & \text{int}\ \{\texttt{E.val} = \texttt{int.val}\} \\
E & \rightarrow & E_1 + E_2\ \{\texttt{E.val} = \texttt{makeAstPlus}(\texttt{E}_1\texttt{.val}, \texttt{E}_2\texttt{.val})\} \\
E & \rightarrow & (E')\ \{\texttt{E.val} = \texttt{E}'\texttt{.val}\}
\end{array}
$$

- Question: What order do we need to evaluate these equations to compute a solution?
- Answer: Bottom-up



## Semantic Actions: An Example cont.






## Semantic Actions

- We have seen how we can use semantic actions to build the AST
- Next: How to build the parser that will allow us to execute these semantic actions



## Parsing

- Consider the non-ambiguous grammar for simple arithmetic expressions:

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

- Assume token stream is ( $\texttt{INT}_5$ )
- Idea: Start with start symbol $S$ and try rules for $S$ in order, backtrack if we made the wrong choice

## Parsing

$$
\begin{array}{rcl}
S & \to & E \mid E + S \\
E & \to & \text{int} \mid \text{int} * E \mid (S)
\end{array}
$$

S

( INT5 )

( INT5 )

## Recursive Descent Parsing

- This parsing strategy is called recursive-descent parsing
- It is easy to automate this strategy: For this assume:
  - `TOKEN` is the type of tokens
  - `next` is global pointer to array of `TOKEN`'s



## Recursive Descent Parsing 1

- Define boolean functions that check token stream for match and advance the `next` pointer
  - Generic function for each terminal:
    `bool term(TOKEN tok) { return token == *next++;}`
  - For the n'th production of a non-terminal $S$, we will define
    `bool S_n() { ... }`
  - To try all productions of a non-terminal $S$, we will define
    `bool S() { ... }`



## Recursive Descent Parsing 2

- For production $S \to E$

```
bool S_1() { return E(); }
```

- For production $S \to E + S$

```
bool S_2() { return E() && term(PLUS) && S(); }
```

- For all production $S$ (with backtracking)

```
bool S() {
  TOKEN* save = next;
  if(S_1() == true) return true;
  next = save;
  return S_2(); }
```

- Or, equivalently written as

```
bool S() {
  return ((next = save, S_1())
    || ((next = save, S_2()) }
```



## Recursive Descent Parsing 3

- Now, the functions $E \to \text{int} \mid \text{int} * E \mid (S)$:

```
bool E_1() { return TERM(INT); }
bool E_2() { return TERM(INT) &&
  term(TIMES) && T(); }
bool E_3() { return TERM(LPAREN) && S() &&
  TERM(RPAREN) }
```

- For all productions in $E$, again with backtracking:

```
bool E() {
  TOKEN* save = next;
  return (next = save, E_1()) ||
  (next = save, E_2()) ||
  (next = save, E_3())
}
```



## Complete Parser

```
bool term(TOKEN tok) { return token == *next++;}

bool S_1() { return E(); }
bool S_2() { return E() && term(PLUS) && S(); }
bool S() { return ((next = save, S_1())
    || ((next = save, S_2()) }

bool E_1() { return TERM(INT); }
bool E_2() { return TERM(INT) &&
  term(TIMES) && T(); }
bool E_3() { return TERM(LPAREN) && S() &&
  TERM(RPAREN) }
bool E() {
  TOKEN* save = next;
  return (next = save, E_1()) ||
  (next = save, E_2()) ||
  (next = save, E_3())
}
```

## Recursive Descent Parsing 4

- To start this parser, initialize `next` to the first token and call `S()`
- This simulates the example parse and is easy to implement by hand



## Are we done?

- Consider a production of the form

$$S \rightarrow Sa$$

- We will generate the following functions using our scheme:

```
bool S_1() { return S() && term(a); }
bool S() { return S_1; }
```

- Here, `S()` goes into an infinite loop
- General Problem: If for some non-terminal S, it is possible to derive $S \rightarrow^* S\alpha$, recursive descent does not work
- Such grammars are called left-recursive



## Eliminating Left-Recursion

- Fortunately, it is always possible to eliminate left-recursion from grammars
- Example: Consider the grammar:

$$S \rightarrow S\alpha \mid \beta$$

- This grammar generates all strings starting with one $\beta$ and followed by one or more $\alpha$s
- Can rewrite using right-recursion:

$$\begin{array}{lcl} S & \rightarrow & \beta S' \\ S' & \rightarrow & \alpha S' \mid \varepsilon \end{array}$$



## Eliminating Left-Recursion cont.

- In general:

$$S \rightarrow S\alpha_1 \mid \ldots \mid S\alpha_n \mid \beta_1 \mid \ldots \mid \beta_m$$

- Insight: All strings derived from $S$ start with one of $\beta_1, \ldots, \beta_m$ and continue with several instances of $\alpha_1, \ldots, \alpha_n$
- Rewrite as:

$$\begin{array}{lcl} S & \rightarrow & \beta_1 S' \mid \ldots \mid \beta_m S' \\ S' & \rightarrow & \alpha_1 S' \mid \ldots \mid \alpha_n S' \mid \varepsilon \end{array}$$

- Easy to generalize this procedure slightly for non-direct left-recursion, such as

$$\begin{array}{lcl} S & \rightarrow & A\alpha \\ A & \rightarrow & S\beta \mid \varepsilon \end{array}$$



## Recursive Descent Parsing

- Result: Recursive Descent parsing can parse any non-ambiguous grammar
- Downside: Potentially expensive to backtrack
- Left-recursion must be eliminated for recursive descent parsing to work, but this can be done automatically
- In practice, you can often eliminate much backtracking by restricting the grammar



## Other Parsing Algorithms

- Researchers works for 20 years to develop efficient paring algorithms, known as LL(1), LR(1), etc
- All these algorithms avoid branching by some (bounded) token lookahead and only work on some grammars.
- However: With computers getting faster every year, recursive descent parsing is very popular
- Example: GCC and G++ both use a hand-written recursive descent parser
- However, you will use the parser-generator `bison` for your homework which has some restrictions on your grammar. Read the posted manual!

## Dealing with Errors

- Reality: Not every string of tokens can be parsed
- Example: `let let lambda x .  .`
- Option 1: Abort with an error message
- This is what you will do in PA2
- Often a reasonable choice
- Option 2: Try to continue parsing after some tokens to report more errors
- Often results in garbage error reports



## Dealing with Errors cont.

- Option 3: Try to find "nearby" program that parses
- Typically, try inserting and deleting tokens until program compiles
- Drawbacks:
  - Hard to implement
  - Can be very slow
  - "Nearby" program is often not intended program
- This used to be a big research area, but today nobody cares
- Question: Why is this the case?



## Real Example

- Cornell developed a programming language called CUPL that parsed every program
- If you feed to following to the CUPL compiler:
  "To be, or not to be, that is the question:
  Whether 'tis Nobler in the mind to suffer
  The Slings and Arrows of outrageous Fortune,
  Or to take Arms against a Sea of troubles,
  ... "
- `Unknown construct "To be", did you mean BEGIN?`
- `Unknown construct ", or", did you mean "VAR or" ?`
- ...
- Final output: `BEGIN END`