Agenda

- Top-Down Parsing
- Predictive Parsers
- LL(k) Grammars
- Recursive Descent
- Grammar Hacking
  - Left recursion removal
  - Factoring
Basic Parsing Strategies (1)

- **Bottom-up**
  - Build up tree from leaves
  - Shift next input or reduce a handle
  - Accept when all input read and reduced to start symbol of the grammar
- LR(k) and subsets (SLR(k), LALR(k), ...)

remaining input
Basic Parsing Strategies (2)

- **Top-Down**
  - Begin at root with start symbol of grammar
  - Repeatedly pick a non-terminal and expand
  - Success when expanded tree matches input
  - LL(k)
Top-Down Parsing

- Situation: have completed part of a derivation
  \[ S \Rightarrow^{*} wA_\alpha \Rightarrow^{*} wxy \]
- Basic Step: Pick some production
  \[ A ::= \beta_1 \beta_2 \ldots \beta_n \]
  that will properly expand \( A \) to match the input
  - Want this to be deterministic
Predictive Parsing

- If we are located at some non-terminal $A$, and there are two or more possible productions
  
  $\begin{align*}
  A &::= \alpha \\
  A &::= \beta
  \end{align*}$

  we want to make the correct choice by looking at just the next input symbol

- If we can do this, we can build a *predictive parser* that can perform a top-down parse without backtracking
Example

- Programming language grammars are often suitable for predictive parsing

Typical example

\[
stmt ::= id = exp ; | return exp ; \\
| if ( exp ) stmt | while ( exp ) stmt
\]

If the first part of the unparsed input begins with the tokens

\[\text{IF LPAREN ID(x) ...}\]

we should expand \textit{stmt} to an if-statement
LL(k) Property

- A grammar has the LL(1) property if, for all non-terminals $A$, if productions $A ::= \alpha$ and $A ::= \beta$ both appear in the grammar, then it is the case that $\text{FIRST}(\alpha) \cap \text{FIRST}(\beta) = \emptyset$

- If a grammar has the LL(1) property, we can build a predictive parser for it that uses 1-symbol lookahead
LL(k) Parsers

- An LL(k) parser
  - Scans the input left to right
  - Constructs a leftmost derivation
  - Looking ahead at most $k$ symbols
- 1-symbol lookahead is enough for many practical programming language grammars
  - LL($k$) for $k > 1$ is rare in practice
Table-Driven LL(k) Parsers

- As with LR(k), a table-driven parser can be constructed from the grammar.

Example

1. \( S ::= ( S ) S \)
2. \( S ::= [ S ] S \)
3. \( S ::= \varepsilon \)

Table

|   | ( | ) | [ | ] | $ |
|---|----|----|----|----|
| S | 1  | 3  | 2  | 3  | 3  |
LL vs LR (1)

- Table-driven parsers for both LL and LR can be automatically generated by tools.
- LL(1) has to make a decision based on a single non-terminal and the next input symbol.
- LR(1) can base the decision on the entire left context (i.e., contents of the stack) as well as the next input symbol.
LL vs LR (2)

- LR(1) is more powerful than LL(1)
  - Includes a larger set of languages
- (editorial opinion) If you’re going to use a tool-generated parser, might as well use LR
  - But there are some very good LL parser tools out there (ANTLR, JavaCC, ...) that might win for non-LL vs LR reasons
Recursive-Descent Parsers

- An advantage of top-down parsing is that it is easy to implement by hand.
- Key idea: write a function (procedure, method) corresponding to each non-terminal in the grammar.
- Each of these functions is responsible for matching its non-terminal with the next part of the input.
Example: Statements

Grammar

\[ stmt ::= id = exp; | return exp; | if ( exp ) stmt | while ( exp ) stmt \]

Method for this grammar rule

```cpp
// parse stmt ::= id=exp; | ...
void stmt() {
    switch(nextToken) {
        RETURN: returnStmt(); break;
        IF: ifStmt(); break;
        WHILE: whileStmt(); break;
        ID: assignStmt(); break;
    }
}
```
Example (cont)

// parse while (exp) stmt
void whileStmt() {
    // skip "while ("
    getNextToken();
    getNextToken();

    // parse condition
    exp();

    // skip ")"
    getNextToken();

    // parse stmt
    stmt();
}

// parse return exp ;
void returnStmt() {
    // skip "return"
    getNextToken();

    // parse expression
    exp();

    // skip ";"
    getNextToken();
}
Invariant for Functions

- The parser functions need to agree on where they are in the input
- Useful invariant: When a parser function is called, the current token (next unprocessed piece of the input) is the token that begins the expanded non-terminal being parsed
  - Corollary: when a parser function is done, it must have completely consumed input correspond to that non-terminal
Possible Problems

- Two common problems for recursive-descent (and LL(1)) parsers
  - Left recursion (e.g., $E ::= E + T | ...$)
  - Common prefixes on the right hand side of productions
Left Recursion Problem

- Grammar rule
  \[ expr ::= expr + term \]
  \[ \text{or} \]
  \[ term \]

- Code
  ```
  // parse expr ::= ...
  void expr() {
    expr();
    if (current token is PLUS) {
      getNextToken();
      term();
    }
  }
  ```

- And the bug is????
Left Recursion Problem

- If we code up a left-recursive rule as-is, we get an infinite recursion.
- Non-solution: replace with a right-recursive rule

\[
expr ::= \underbrace{term} + \underbrace{expr} \mid term
\]

- Why isn't this the right thing to do?
Left Recursion Solution

- Rewrite using right recursion and a new non-terminal
- Original:  
  \[ expr ::= expr + term \mid term \]
- New
  \[ expr ::= term exprtail \]
  \[ exprtail ::= + term exprtail \mid \varepsilon \]

- Properties
  - No infinite recursion if coded up directly
  - Maintains left associatively (required)
Another Way to Look at This

- Observe that
  \[ expr ::= expr + term \mid term \]
generates the sequence
  \[ \ldots ((term + term) + term) + \ldots ) + term \]

- We can sugar the original rule to show this
  \[ expr ::= term \{ + term \}^* \]

- This leads directly to parser code
  - Just be sure to do the correct thing to handle associativity as the terms are parsed
Code for Expressions (1)

```c
// parse
// expr ::= term { + term }*
void expr() {
  term();
  while (next symbol is PLUS) {
    getNextToken();
    term()
  }
}

// parse
// term ::= factor { * factor }*
void term() {
  factor();
  while (next symbol is TIMES) {
    getNextToken();
    factor()
  }
}
```
Code for Expressions (2)

// parse
// factor ::= int | id | ( expr )
void factor()
{
    switch(nextToken)
    {
        case INT:
            process int constant;
            getNextToken();
            break;
        case ID:
            process identifier;
            getNextToken();
            break;
        case LPAREN:
            getNextToken();
            expr();
            getNextToken();
            break;
        ...
    }
}
What About Indirect Left Recursion?

- A grammar might have a derivation that leads to a left recursion
  \[ A \Rightarrow \beta_1 \Rightarrow^* \beta_n \Rightarrow A \gamma \]
- There are systematic ways to factor such grammars
  - See any compiler or formal language book
Left Factoring

- If two rules for a non-terminal have right hand sides that begin with the same symbol, we can’t predict which one to use.
- Solution: Factor the common prefix into a separate production.
Left Factoring Example

- Original grammar
  
  \[ stmt ::= \text{if } ( expr ) \text{ stmt} \]
  
  \[ \quad | \text{if } ( expr ) \text{ stmt else stmt} \]

- Factored grammar
  
  \[ stmt ::= \text{if } ( expr ) \text{ stmt ifTail} \]
  
  \[ \text{ifTail ::= else stmt} \ | \ \epsilon \]
 Parsing if Statements

But it’s easiest to just code up the “else matches closest if” rule directly

```c
// parse
//   if (expr) stmt [ else stmt ]
void ifStmt() {
    getNextToken();
    getNextToken();
    expr();
    getNextToken();
    stmt();
    if (next symbol is ELSE) {
        getNextToken();
        stmt();
    }
}
```
Another Lookahead Problem

- In languages like FORTRAN, parentheses are used for array subscripts.
- A FORTRAN grammar includes something like
  \[
  \text{factor ::= id ( subscripts ) | id ( arguments ) | ...}
  \]
- When the parser sees \( \text{id (} \), how can it decide whether this begins an array element reference or a function call?
Two Ways to Handle \textit{id ( ? )}

- Use the type of \textit{id} to decide
  - Requires declare-before-use restriction if we want to parse in 1 pass
- Use a covering grammar
  \[
  \text{factor ::= id( commaSeparatedList ) | ...}
  \]
  and fix later when more information is available
Top-Down Parsing Concluded

- Works with a smaller set of grammars than bottom-up, but can be done for most sensible programming language constructs.
- If you need to write a quick-n-dirty parser, recursive descent is often the method of choice.
Parsing Concluded

- That’s it!
- On to the rest of the compiler
- Coming attractions
  - Intermediate representations (ASTs etc.)
  - Semantic analysis (including type checking)
  - Symbol tables
  - & more...