CMSC330

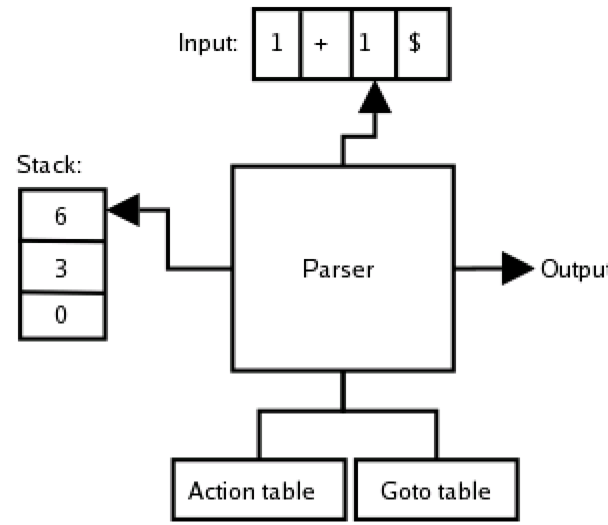
Parsing

Last time

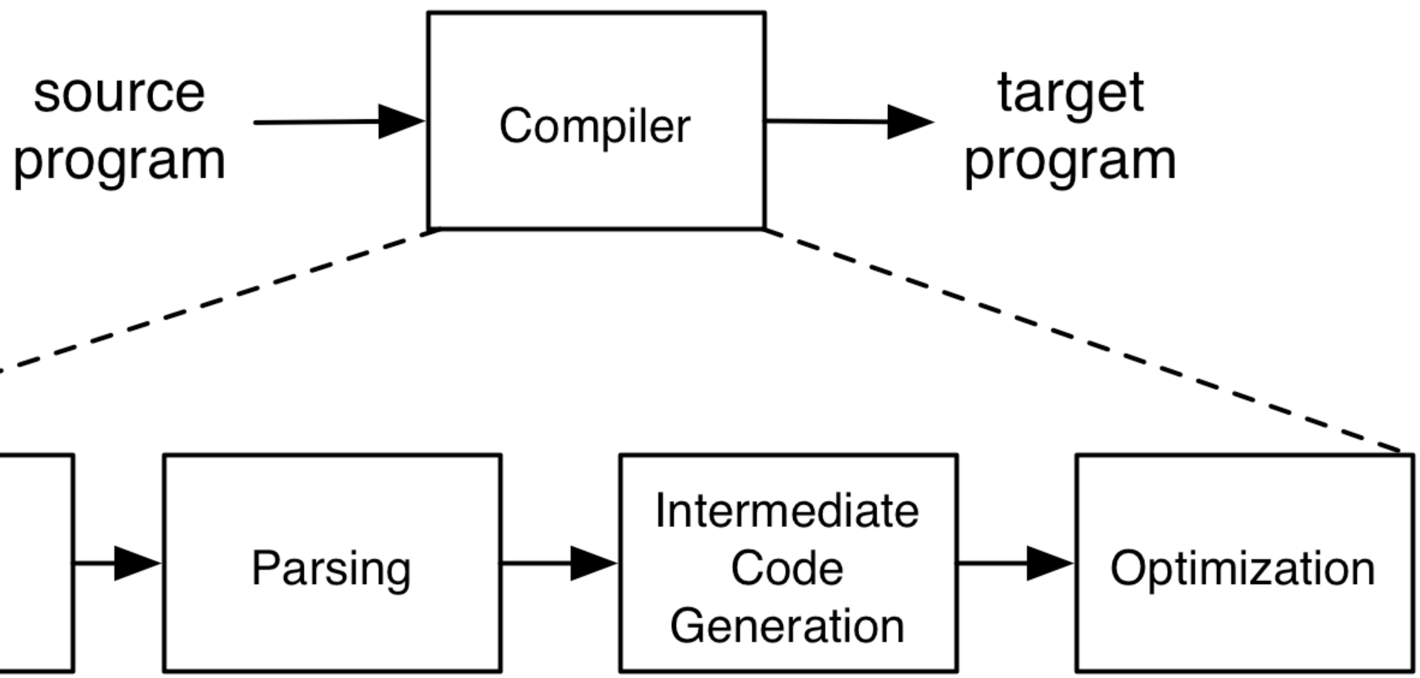
- Context Free Grammars
  - Definitions
  - Derivations
  - Parse trees
  - Ambiguity
  - Binding and precedence

This lecture

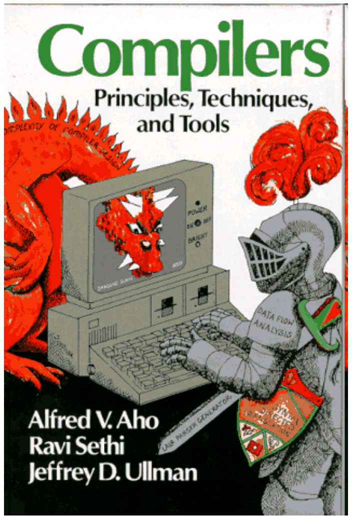
- Parsing
  - Recursive descent
  - FIRST sets
- Rewriting grammars
  - Left factoring
  - Eliminating left recursion
- Abstract syntax trees (ASTs)



Steps of compilation



Parsing



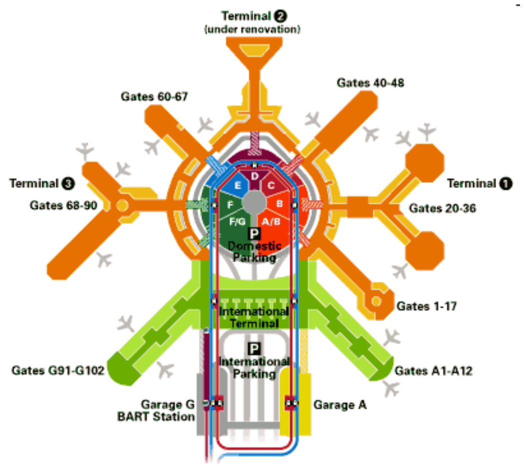
- Many efficient techniques for parsing
  - i.e., turning strings into parse trees
  - Examples
    - LL(k), SLR(k), LR(k), LALR(k)…
    - Take CMSC 430 for more details
- One simple technique: recursive descent parsing
  - This is a "top-down" parsing algorithm

Recursive Descent Parsing

- Goal
  - Determine if we can produce the string to be parsed from the grammar's start symbol
- Approach
  - Recursively replace nonterminal with RHS of production
- At each step, we'll keep track of two facts
  - What tree node are we trying to match?
  - What is the lookahead (next token of the input string)?
    - Helps guide selection of production used to replace nonterminal

Recursive Descent Parsing (cont.)

- At each step, 3 possible cases
  - If we're trying to match a terminal
    - If the lookahead is that token, then succeed, advance the lookahead, and continue
  - If we're trying to match a nonterminal
    - Pick which production to apply based on the lookahead
  - Otherwise fail with a parsing error



Parsing example

$E \rightarrow id = n \mid \{ L \}$

$L \rightarrow E ; L \mid \varepsilon$

– Here n is an integer and id is an identifier

- One input might be
  - { x = 3; { y = 4; }; }
  - This would get turned into a list of tokens

    { x = 3 ; { y = 4 ; } ; }
  - And we want to turn it into a parse tree

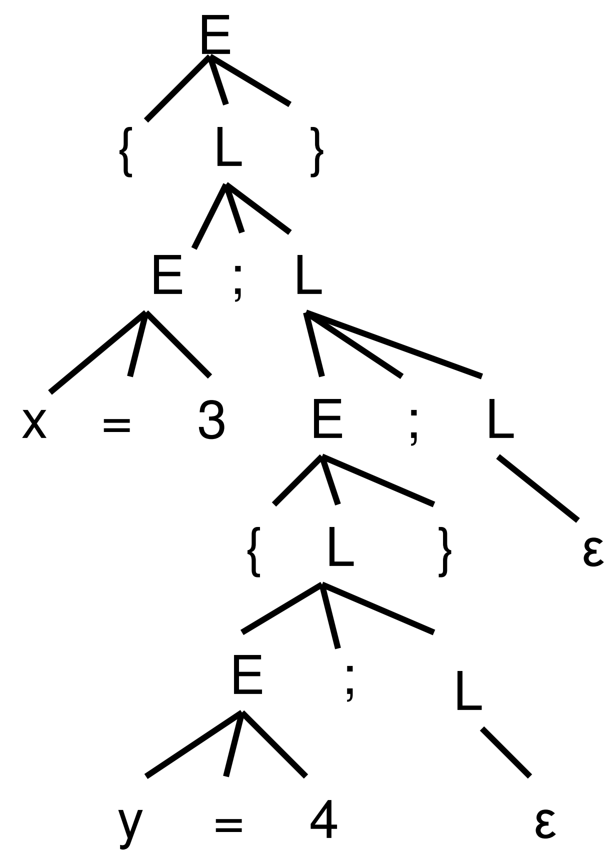
Parsing example (cont.)

$E \rightarrow \text{id} = \text{n} \mid \{\ L\ \}$

$L \rightarrow E\ ;\ L \mid \varepsilon$

{ x = 3 ; { y = 4 ; } ; }

lookahead



Recursive descent parsing

- Key step
  - Choosing which production should be selected
- Two approaches
  - Backtracking
    - Choose some production
    - If fails, try different production
    - Parse fails if all choices fail
  - Predictive parsing
    - Analyze grammar to find FIRST sets for productions
    - Compare with lookahead to decide which production to select
    - Parse fails if lookahead does not match FIRST

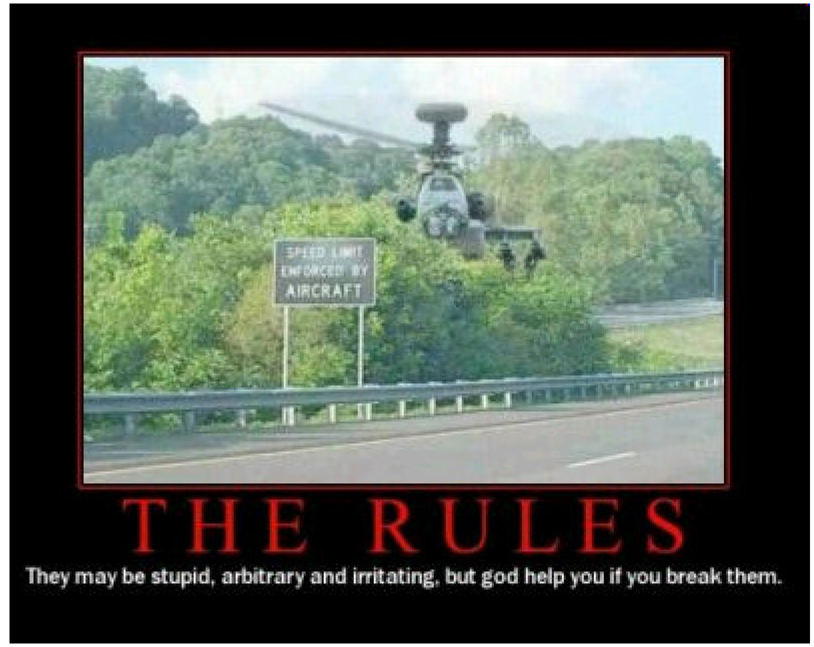
First Sets

- Motivating example
  - The lookahead is x
  - Given grammar S → xyz | abc
    - Select S → xyz since 1st terminal in RHS matches x
  - Given grammar S → A | B   A → x | y   B → z
    - Select S → A, since A can derive string beginning with x
- In general
  - Choose a production that can derive a sentential form beginning with the lookahead
  - Need to know what terminal may be first in any sentential form derived from a nonterminal / production

First sets

- Definition
  - First(γ), for any terminal or nonterminal γ, is the set of initial terminals of all strings that γ may expand to
  - We'll use this to decide what production to apply
- Examples
  - Given grammar $S \rightarrow xyz \mid abc$
    - First(xyz) = { x }, First(abc) = { a }
    - First(S) = First(xyz) U First(abc) = { x, a }
  - Given grammar $S \rightarrow A \mid B \quad A \rightarrow x \mid y \quad B \rightarrow z$
    - First(x) = { x }, First(y) = { y }, First(A) = { x, y }
    - First(z) = { z }, First(B) = { z }
    - First(S) = { x, y, z }

Calculating First(γ)



- For a terminal a
  - $\text{First}(a) = \{ a \}$
- For a nonterminal N
  - If $N \rightarrow \varepsilon$, then add ε to $\text{First}(N)$
  - If $N \rightarrow \alpha_1\ \alpha_2 \ldots \alpha_n$, then (note the α_i are all the symbols (terminal and non-terminal) on the right side of one single production):
    - Add $\text{First}(\alpha_1\alpha_2 \ldots \alpha_n)$ to $\text{First}(N)$, where $\text{First}(\alpha_1\ \alpha_2 \ldots \alpha_n)$ is defined as
      - $\text{First}(\alpha_1)$ if $\varepsilon \notin \text{First}(\alpha_1)$
      - Otherwise $(\text{First}(\alpha_1) - \varepsilon) \cup \text{First}(\alpha_2 \ldots \alpha_n)$
    - If $\varepsilon \in \text{First}(\alpha_i)$ for all i, $1 \le i \le k$, then add ε to $\text{First}(N)$

First() examples

$E \rightarrow id = n \mid \{ L \}$
$L \rightarrow E \; ; \; L \mid \varepsilon$

First(id) = { id }
First("=") = { "=" }
First(n) = { n }
First("{")= { "{" }
First("}")= { "}" }
First(";")= { ";" }
First(E) = { id, "{" }
First(L) = { id, "{", ε }

$E \rightarrow id = n \mid \{ L \} \mid \varepsilon$
$L \rightarrow E \; ; \; L$

First(id) = { id }
First("=") = { "=" }
First(n) = { n }
First("{")= { "{" }
First("}")= { "}" }
First(";")= { ";" }
First(E) = { id, "{", ε }
First(L) = { id, "{", ";" }

Recursive Descent Parser Implementation

- For terminals, create function **`match(a)`**
  - If lookahead is a it consumes the lookahead by advancing the lookahead to the next token, and returns
  - Otherwise fails with a parse error if lookahead is not a
  - In algorithm descriptions, consider **`parse_a`**, **`parse_term(a)`** to be aliases for **`match(a)`**
- For each nonterminal N, create a function **`parse_N`**
  - Called when we're trying to parse a part of the input which corresponds to (or can be derived from) N
  - **`parse_S`** for the start symbol S begins the parse

Parser Implementation (cont.)

- The body of **`parse_N`** for a nonterminal N does the following
  - Let $N \rightarrow \beta_1 \mid \ldots \mid \beta_k$ be the productions of N
    - Here β_i is the entire right side of a production- a sequence of terminals and nonterminals
  - Pick the production $N \rightarrow \beta_i$ such that the lookahead is in $\mathrm{First}(\beta_i)$
    - It must be that $\mathrm{First}(\beta_i) \cap \mathrm{First}(\beta_j) = \varnothing$ for $i \neq j$
    - If there is no such production, but $N \rightarrow \varepsilon$ then return
    - Otherwise fail with a parse error
  - Suppose $\beta_i = \alpha_1\ \alpha_2 \ldots \alpha_n$. Then call

    `parse_`α_1**`()`** ; ... ; **`parse_`**α_n**`()`**

    to match the expected right-hand side, and return

Parser Implementation (cont.)

- Parse is built on procedure calls
- Procedures may be (mutually) recursive

Recursive Descent Parser

- Given grammar S → xyz | abc
  - First(xyz) = { x }, First(abc) = { a }
- Parser

```
parse_S( ) {
    if (lookahead == "x") {
      match("x"); match("y"); match("z");// S → xyz
    }
    else if (lookahead == "a") {
      match("a"); match("b"); match("c");// S → abc
    }
    else error( );
}
```

Recursive Descent Parser

- Given grammar $S \rightarrow A \mid B \quad A \rightarrow x \mid y \quad B \rightarrow z$
  - First(A) = { x, y }, First(B) = { z }
- Parser

```
parse_S( ) {
    if ((lookahead == "x") || (lookahead == "y"))
      parse_A( );       // S → A
    else if (lookahead == "z")
      parse_B( );       // S → B
    else error( );
}
```

Example

$E \to id = n \mid \{ L \}$

$L \to E ; L \mid \varepsilon$

First(E) = { id, "{" }

```
parse_E( ) {
    if (lookahead == "id") {
      match("id");
      match("=");   // E → id = n
      match("n");
    }
    else if (lookahead == "{") {
      match("{");
      parse_L( );   // E → { L }
      match("}");
    }
    else error( );
}
```

```
parse_L( ) {
    if ((lookahead == "id")
      ||
      (lookahead == "{")) {
      parse_E( );
      match(";");// L → E ; L
      parse_L( );
    }
    else ;
      // L → ε
}
```

Things to notice

- If you draw the execution trace of the parser
  - You get the parse tree
- Examples
  - Grammar

    $S \rightarrow xyz$

    $S \rightarrow abc$
  - String "xyz"

    parse_S( )

    match("x")

    match("y")

    match("z")

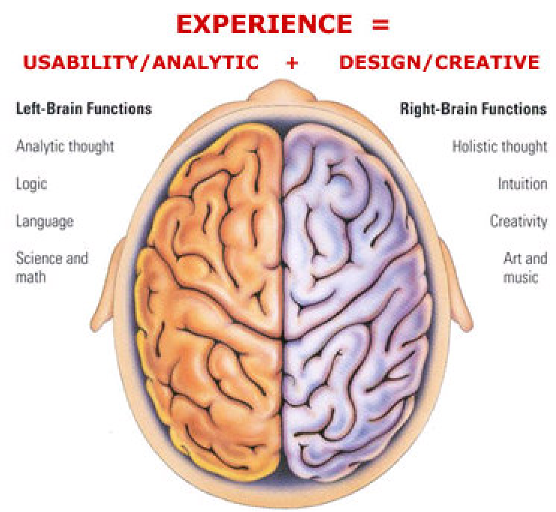
Things to Notice (cont.)

- This is a predictive parser
  - Because the lookahead determines exactly which production to use
- This parsing strategy may fail on some grammars
  - Possible infinite recursion
  - Production First sets overlap
  - Production First sets contain ε

- Does not mean grammar is not usable
  - Just means this parsing method not powerful enough
  - May be able to change grammar

Left factoring

- Consider parsing the grammar $E \rightarrow ab \mid ac$
  - First(ab) = a
  - First(ac) = a
  - Parser cannot choose between RHS based on lookahead!
- Parser fails whenever $A \rightarrow \alpha_1 \mid \alpha_2$ and
  - $First(\alpha_1) \cap First(\alpha_2)$!= ε or $\emptyset$
- Solution
  - Rewrite grammar using left factoring



Left Factoring algorithm

- Given grammar
  - $A \rightarrow x\alpha_1 \mid x\alpha_2 \mid \ldots \mid x\alpha_n \mid \beta$
- Rewrite grammar as
  - $A \rightarrow xL \mid \beta$
  - $L \rightarrow \alpha_1 \mid \alpha_2 \mid \ldots \mid \alpha_n$
- Repeat as necessary
- Examples
  - $S \rightarrow ab \mid ac$ ⇨ $S \rightarrow aL$ $L \rightarrow b \mid c$
  - $S \rightarrow abcA \mid abB \mid a$ ⇨ $S \rightarrow aL$ $L \rightarrow bcA \mid bB \mid \varepsilon$
  - $L \rightarrow bcA \mid bB \mid \varepsilon$ ⇨ $L \rightarrow bL' \mid \varepsilon$ $L' \rightarrow cA \mid B$

Left Recursion

- Consider grammar $S \rightarrow Sa \mid \varepsilon$
  - First(Sa) = a, so we're ok as far as which production
  - Try writing parser

```
parse_S( ) {
    if (lookahead == "a") {
      parse_S( );
      match("a"); // S → Sa
    }
    else { }
}
```

  - Body of `parse_S( )` has an infinite loop
    - `if (lookahead = "a") then parse_S( )`
  - Infinite loop occurs in grammar with left recursion

Right recursion

- Consider grammar $S \rightarrow aS \mid \varepsilon$
  - Again, First(aS) = a
  - Try writing parser

```
parse_S( ) {
    if (lookahead == "a") {
      match("a");
      parse_S( ); // S → aS
    }
    else { }
}
```

  - Will parse_S( ) infinite loop?
    - Invoking match( ) will advance lookahead, eventually stop
  - Top down parsers handles grammar w/ right recursion

Algorithm to eliminate left recursion

- Given grammar
  - $A \rightarrow A\alpha_1 \mid A\alpha_2 \mid \ldots \mid A\alpha_n \mid \beta$
    - Why must β exist?
- Rewrite grammar as
  - $A \rightarrow \beta L$
  - $L \rightarrow \alpha_1 L \mid \alpha_2 L \mid \ldots \mid \alpha_n L \mid \varepsilon$
- Replaces left recursion with right recursion
- Repeat as necessary

Eliminating Left Recursion (cont.)

- Examples
  - $S \rightarrow Sa \mid \varepsilon$ ⇨ $S \rightarrow L \quad L \rightarrow aL \mid \varepsilon$
  - $S \rightarrow Sa \mid Sb \mid c$ ⇨ $S \rightarrow cL \quad L \rightarrow aL \mid bL \mid \varepsilon$

- May need more powerful algorithms to eliminate mutual recursion leading to left recursion
  - $S \rightarrow Aa \mid b$

    $A \rightarrow Sb$

Expr Grammar for Top-Down Parsing

$E \rightarrow T\ E'$

$E' \rightarrow \varepsilon \mid +\ E$

$T \rightarrow P\ \ T'$

$T' \rightarrow \varepsilon \mid *\ T$

$P \rightarrow n\ \mid\ (\ E\ )$

– Notice we can always decide what production to choose with only one symbol of lookahead

Tradeoffs with Other Approaches

- Recursive descent parsers are easy to write
  - The formal definition is a little clunky, but if you follow the code then it’s almost what you might have done if you weren't told about grammars formally
  - They're unable to handle certain kinds of grammars
- Recursive descent is good for a simple parser
  - Though tools can be fast if you’re familiar with them
- Can implement top-down predictive parsing as a table-driven parser
  - By maintaining an explicit stack to track progress

Tradeoffs with Other Approaches

- More powerful techniques need tool support
  – Can take time to learn tools
- Main alternative is bottom-up, shift-reduce parser
  – Replaces RHS of production with LHS (nonterminal)
  – Example grammar
    - $S \rightarrow aA$, $A \rightarrow Bc$, $B \rightarrow b$
  – Example parse
    - $abc \rightarrow aBc \rightarrow aA \rightarrow S$
    - Derivation happens in reverse
  – Something to look forward to in CMSC 430

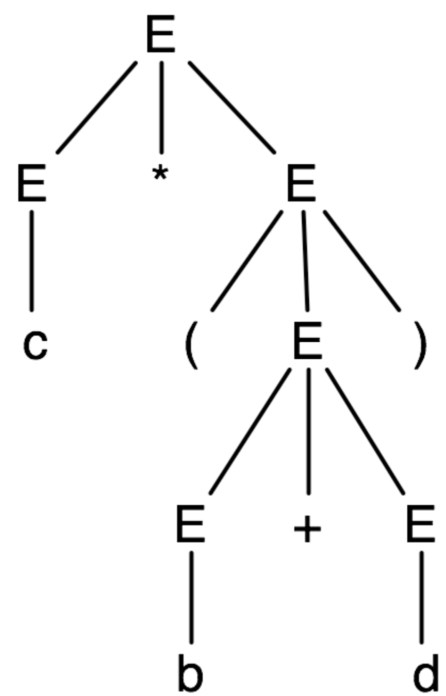
What's Wrong With Parse Trees?

- Parse trees contain too much information
  - Example
    - Parentheses
    - Extra nonterminals for precedence
  - This extra stuff is needed for parsing

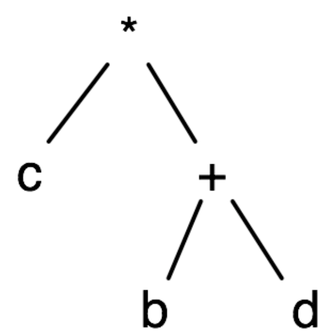
- But when we want to reason about languages
  - Extra information gets in the way (too much detail)

Abstract Syntax Trees (ASTs)

- An abstract syntax tree is a more compact, abstract representation of a parse tree, with only the essential parts



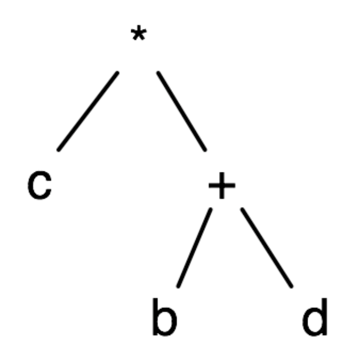
parse tree



AST

Abstract Syntax Trees (cont.)

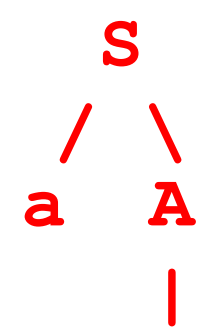
- Intuitively, ASTs correspond to the data structure you'd use to represent strings in the language
  - Note that grammars describe trees
  - So do OCaml datatypes (which we'll see later)
  - $E \rightarrow a \mid b \mid c \mid E+E \mid E-E \mid E*E \mid (E)$



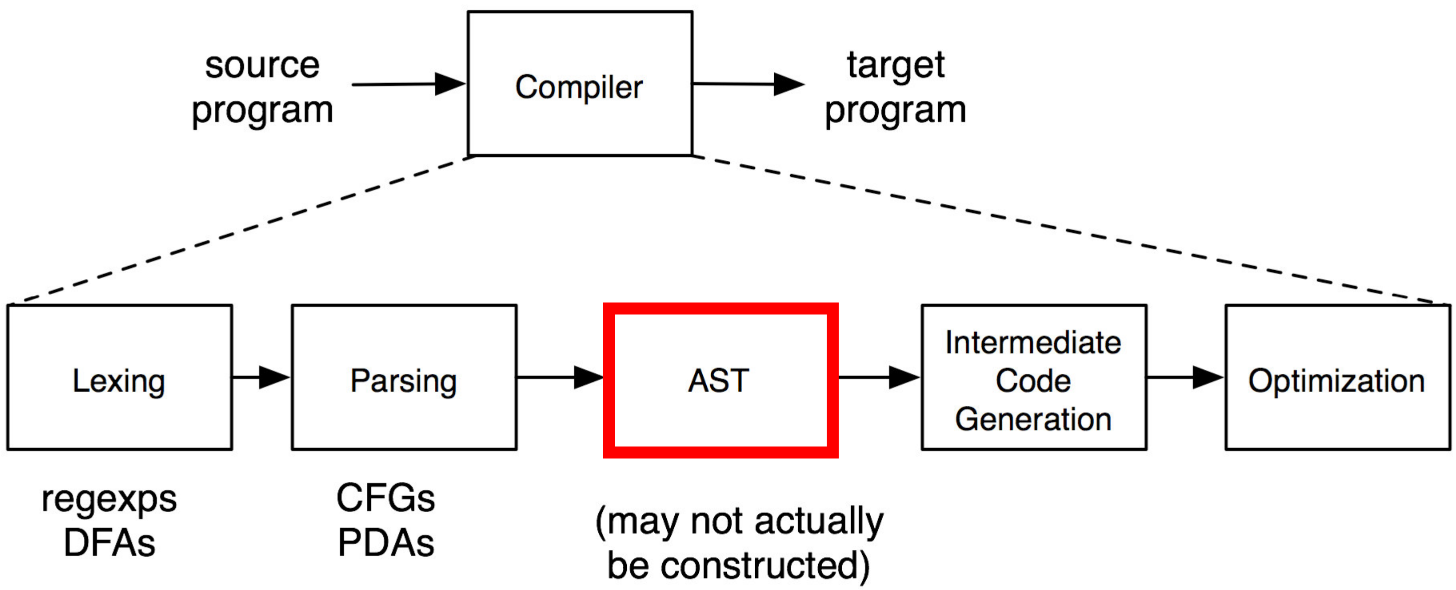
Producing an AST

- To produce an AST, we can modify the parse() functions to construct the AST along the way
  - match(a) returns an AST node (leaf) for a
  - Parse_A returns an AST node for A
    - AST nodes for RHS of production become children of LHS node
- Example
  - $S \rightarrow aA$

```
Node parse_S( ) {
    Node n1, n2;
    if (lookahead == “a”) {
      n1 = match(“a”);
      n2 = parse_A( );
      return new Node(n1,n2);
    }
}
```



The Compilation Process



Summary

- Learned a little about parsing
  - Recursive descent parser
  - Predictive parsing using FIRST sets
- Rewriting grammars for predicative parsing
  - Left factoring
  - Eliminating left recursion
- Abstract syntax trees (ASTs)

Next time

- Push Down automata
- Project 3 due Thursday