CS 412
Introduction to Compilers

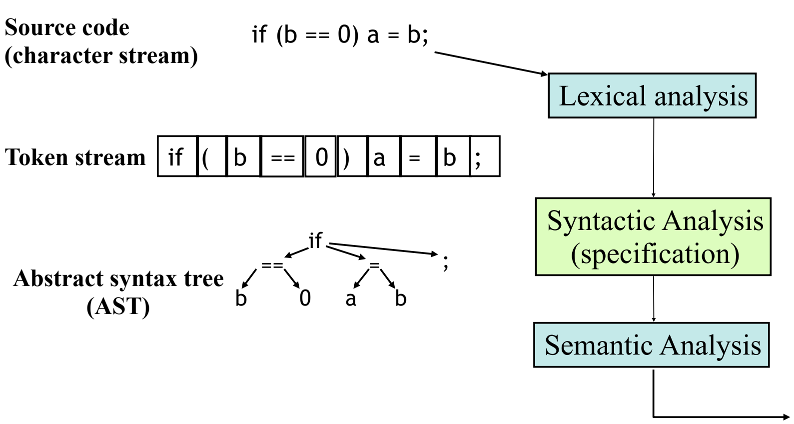
Andrew Myers
Cornell University

Lecture 4: Syntactic Analysis
31 Jan 01

Outline

- Context-Free Grammars (CFGs)
- Derivations
- Parse trees and abstract syntax
- Ambiguous grammars

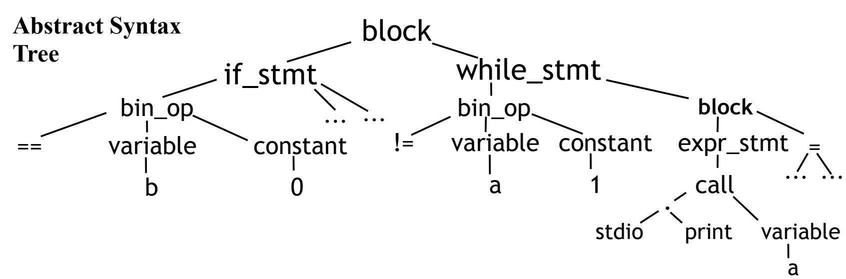
Where we are



What is Syntactic Analysis?

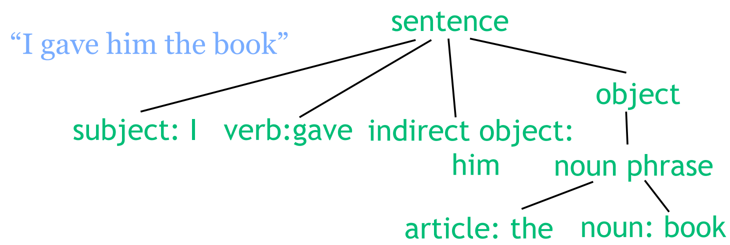
Source code (token stream)

```
{
    if (b == (0)) a = b;
    while (a != 1) {
        stdio.print(a);
        a = a - 1;
    }
}
```



Parsing

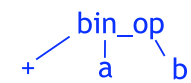
- Parsing: recognizing whether a program (or sentence) is grammatically well-formed & identifying the function of each component.



Overview of Syntactic Analysis

- Input: stream of tokens
- Output: abstract syntax tree

- Implementation:
  - Parse token stream to traverse concrete syntax (**parse tree**)
  - During traversal, build abstract syntax tree
  - Abstract syntax tree removes extra syntax $a + b \approx (a) + (b) \approx ((a)+((b)))$



What Parsing doesn't do

- Doesn't check many things: type agreement, variables declared, variables initialized, etc.

```
int x = true;
int y;
z = f(y);
```

- Deferred until semantic analysis

Specifying Language Syntax

- First problem: how to describe language syntax precisely and conveniently
- Last time: can describe tokens using regular expressions
- Regular expressions easy to implement, efficient (by converting to DFA)
- Why not use regular expressions (on tokens) to specify programming language syntax?

Limits of REs

- Programming languages are not regular -- cannot be described by regular exprs
- Consider: language of all strings that contain balanced parentheses (easier than PLs)

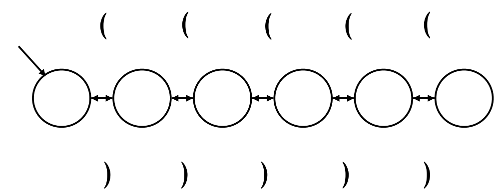
  ()   (())   ()()()   (())()((()()))

  ((   )(())   (()()

- Problem: need to keep track of number of parentheses seen so far: unbounded counting

Need more power!

- RE = DFA
- DFA has only finite number of states; cannot perform unbounded counting



maximum depth: 5 parens

Context-Free Grammars

- A specification of the balanced-parenthesis language:

  $S \rightarrow (S) S$

  $S \rightarrow \varepsilon$

- The definition is recursive
- A **context-free grammar**
  - More expressive than regular expressions
  - $S = (S)\,\varepsilon = ((S)\,S)\,\varepsilon = ((\varepsilon)\,\varepsilon)\,\varepsilon = (())$

If a grammar accepts a string, there is a *derivation* of that string using the productions of the grammar

Definition of CFG

- Terminals
  - Token or ε
- Non-terminals
  - Syntactic variables
- Start symbol
  - A special nonterminal is designated (S)
- Productions
  - Specify how non-terminals may be expanded to form strings
  - LHS: single non-terminal, RHS: string of terminals or non-terminals
- Vertical bar is shorthand for multiple prod'ns

$S \rightarrow (S) S$

$S \rightarrow \varepsilon$

RE is subset of CFG

Regular Expression defn of real numbers:

digit → [**0-9**]
posint → *digit*+
int → -? *posint*
real → *int* . (ε | *posint*)

- RE symbolic names are only *shorthand:* no recursion, so all symbols can be fully expanded:

real → -? [**0-9**]+ . (ε | ([**0-9**]+))

Sum grammar

$S \rightarrow E + S \mid E$

$E \rightarrow$ **number** | (S)

e.g. (1 + 2 + (3+4))+5

$S \rightarrow E + S$
$S \rightarrow E$
$E \rightarrow$ number
$E \rightarrow (S)$

4 productions
2 non-terminals (S, E)
4 terminals: (,), +, number
start symbol S

Derivation Example

$S \rightarrow E + S \mid E$

$E \rightarrow$ number | (S)

Derive (1+2+ (3+4))+5:

S → ***E*** + S → (***S***) + S → (***E*** + S)+ S
→ (1 + ***S***)+S → (1 + ***E*** + S)+S
→ (1 + 2 + ***S***)+S → (1 + 2 + ***E***)+S
→ (1 + 2 + (***S***))+S→ (1 + 2 + (***E*** + S))+S
→ (1 + 2 + (3 + ***S***))+S
→ (1 + 2 + (3 + ***E***))+S
→ (1 + 2+ (3+4))+***S***
→ (1 + 2+ (3+4))+***E***
→ (1 + 2+ (3+4))+5

replacement string

non-terminal being expanded

Constructing a derivation

- Start from start symbol (*S*)
- Productions are used to derive a sequence of tokens from the start symbol
- For arbitrary strings α, β and γ and a production A → β A single step of derivation is

$$\alpha A \gamma \Rightarrow \alpha \beta \gamma$$

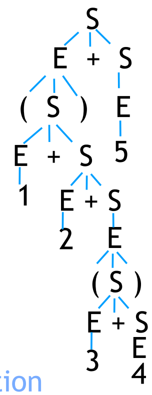
– *i.e.*, substitute β for an occurrence of A

(**S** + E) + E → (**E + S** + E)+E

(A = S, β = E + S)

Derivation ⇒ Parse Tree

Parse Tree



- Tree representation of the derivation
- Leaves of tree are terminals; in-order traversal yields string
- Internal nodes: non-terminals
- No information about order of derivation steps

(1+2+ (3+4))+5

$S \rightarrow E + S \mid E$

$E \rightarrow$ number | (S)

Derivation

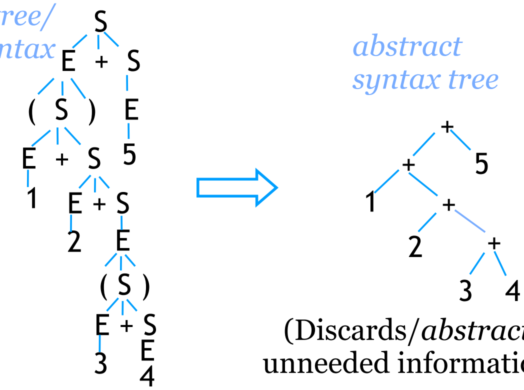
$\boldsymbol{S} \rightarrow \boldsymbol{E} + \mathrm{S} \rightarrow (\boldsymbol{S}) + \mathrm{S} \rightarrow (\boldsymbol{E} + \mathrm{S}) + \mathrm{S} \rightarrow (1 + \boldsymbol{S}) + \mathrm{S} \rightarrow (1 + \boldsymbol{E} + \mathrm{S}) + \mathrm{S} \rightarrow (1 + 2 + \boldsymbol{S}) + \mathrm{S} \rightarrow \ldots \rightarrow (1 + 2 + (\boldsymbol{S})) + \mathrm{S} \rightarrow (1 + 2 + (\boldsymbol{E} + \mathrm{S})) + \mathrm{S} \rightarrow \ldots \rightarrow (1 + 2 + (3 + \boldsymbol{E})) + \mathrm{S} \rightarrow \ldots \rightarrow (1 + 2 + (3+4)) + 5$

Parse Tree

- Also called "concrete syntax"

parse tree/ concrete syntax

abstract syntax tree



(Discards/*abstracts* unneeded information)

Derivation order

- Can choose to apply productions in any order; select any non-terminal A

  $\alpha A \gamma \Rightarrow \alpha \beta \gamma$
- Two standard orders: left- and right-most -- useful for different kinds of automatic parsing
- **Leftmost derivation**: In the string, find the left-most non-terminal and apply a production to it $E + S \rightarrow 1 + S$
- **Rightmost derivation**: find right-most non-terminal...etc. $E + S \rightarrow E + E + S$

Example

$S \rightarrow E + S \mid E$

$E \rightarrow$ number | (S)

- Left-most derivation

$\boldsymbol{S} \rightarrow \boldsymbol{E}+\mathrm{S} \rightarrow (\boldsymbol{S}) + \mathrm{S} \rightarrow (\boldsymbol{E} + \mathrm{S}) + \mathrm{S} \rightarrow (1 + \boldsymbol{S})+\mathrm{S} \rightarrow (1+\boldsymbol{E}+\mathrm{S})+\mathrm{S} \rightarrow (1+2+\boldsymbol{S})+\mathrm{S} \rightarrow (1+2+\boldsymbol{E})+\mathrm{S} \rightarrow (1+2+(\boldsymbol{S}))+\mathrm{S} \rightarrow (1+2+(\boldsymbol{E}+\mathrm{S}))+\mathrm{S} \rightarrow (1+2+(3+\boldsymbol{S}))+\mathrm{S} \rightarrow (1+2+(3+\boldsymbol{E}))+\mathrm{S} \rightarrow (1+2+(3+4))+\boldsymbol{S} \rightarrow (1+2+(3+4))+\boldsymbol{E} \rightarrow (1+2+(3+4))+5$

- Right-most derivation

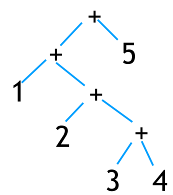
$\boldsymbol{S} \rightarrow \mathrm{E}+\boldsymbol{S} \rightarrow \mathrm{E}+\boldsymbol{E} \rightarrow \boldsymbol{E}+5 \rightarrow (\boldsymbol{S})+5 \rightarrow (\mathrm{E}+\boldsymbol{S})+5 \rightarrow (\mathrm{E}+\mathrm{E}+\boldsymbol{S})+5 \rightarrow (\mathrm{E}+\mathrm{E}+\boldsymbol{E})+5 \rightarrow (\mathrm{E}+\mathrm{E}+(\boldsymbol{S}))+5 \rightarrow (\mathrm{E}+\mathrm{E}+(\mathrm{E}+\boldsymbol{S}))+5 \rightarrow (\mathrm{E}+\mathrm{E}+(\mathrm{E}+\boldsymbol{E}))+5 \rightarrow (\mathrm{E}+\mathrm{E}+(\boldsymbol{E}+4))+5 \rightarrow (\mathrm{E}+\boldsymbol{E}+(3+4))+5 \rightarrow (\boldsymbol{E}+2+(3+4))+5 \rightarrow (1+2+(3+4))+5$

- Same parse tree: same productions chosen, diff. order

Ambiguous Grammars

- In example grammar, left-most and right-most derivations produced identical parse trees
- + operator associates to right in parse tree regardless of derivation order

(1+2+(3+4))+5 ⇒



An Ambiguous Grammar

- + associates to right because of ***right-recursive*** production $S \rightarrow E + S$
- Consider another grammar:

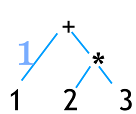
$$S \rightarrow S + S \;\;|\;\; S * S \;\;|\;\; \text{number}$$

- Different derivations produce different parse trees: ambiguous grammar

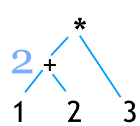
Differing Parse Trees

$S \rightarrow S + S \;|\; S * S \;|\; \text{number}$

- Consider expression $1 + 2 * 3$
- Derivation 1: $\boldsymbol{S} \rightarrow \boldsymbol{S} + S \rightarrow 1 + \boldsymbol{S} \rightarrow 1 + \boldsymbol{S} * S \rightarrow 1 + 2 * \boldsymbol{S} \rightarrow 1 + 2 * 3$
- Derivation 2: $\boldsymbol{S} \rightarrow S * \boldsymbol{S} \rightarrow \boldsymbol{S} * 3 \rightarrow S + \boldsymbol{S} * 3 \rightarrow \boldsymbol{S} + 2 * 3 \rightarrow 1 + 2 * 3$

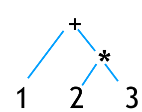


≠

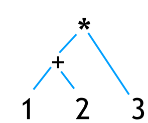


Impact of Ambiguity

- Different parse trees correspond to different evaluations!
- Meaning of program not defined



= 7

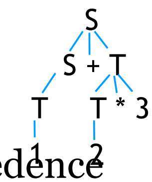


= 9

Eliminating Ambiguity

- Often can eliminate ambiguity by adding non-terminals & allowing recursion only on right or left

$$S \rightarrow S + T \mid T$$
$$T \rightarrow T * \textbf{num} \mid \textbf{num}$$



- T non-terminal enforces precedence
- Left-recursion : left-associativity

Limits of CFGs

- Syntactic analysis can't catch all "syntactic" errors
- Example: C++

```
HashTable<Key,Value> x;
```

- Need to know whether `HashTable` is the name of a type to understand syntax! Problem: "<", "," are overloaded
- Iota:

```
f(4)[1][2] = 0;
```

- Difficult to write grammar for LHS of assign – may be easier to allow all exprs, check later

CFGs

- Context-free grammars allow concise specification of programming languages
- CFG specifies how to convert token stream to parse tree (if unambiguous!)
- Read Appel 3.1, 3.2

Next time: implementing a top-down parser (leftmost derivation)