Grammar

CSE 413, Autumn 2002

Programming Languages

http://www.cs.washington.edu/education/courses/413/02au/

Recall: Programming Language Specs

- Syntax of every significant programming language is specified by a formal grammar
  - » BNF or some variation there on
- As language engineering has developed, formal methods have improved for defining useful grammars and tools for processing them

Productions

- The rules of a grammar are called *productions*
- Rules contain
  - » Nonterminal symbols: grammar variables (*program, statement, id,* etc.)
  - » Terminal symbols: concrete syntax that appears in programs: a, b, c, 0, 1, if, (, …
- Meaning of

  nonterminal ::= <sequence of terminals and nonterminals>

  In a derivation, an instance of *nonterminal* can be replaced by the sequence of terminals and nonterminals on the right of the production
- Often, there are two or more productions for a single nonterminal – can use either at different times

Grammar for D, a little language

program ::= *function-def* | *program function-def*

function-def ::= **`int`** *id* **( )** { *statements* }

| **`int`** *id* **(** *parameters* **)** { *statements* }

| **`int`** *id* **( )** { *declarations statements* }

| **`int`** *id* **(** *parameters* **)** { *declarations statements* }

parameters ::= *parameter* | *parameters* **,** *parameter*

parameter ::= **`int`** *id*

declarations ::= *declaration* | *declarations declaration*

declaration ::= **`int`** *id* **;**

statements ::= *statement* | *statements statement*

statement ::= *id* **=** *exp* **;** | **`return`** *exp* **;** | { *statements* }

| **`if`** **(** *bool-exp* **)** *statement* | **`if`** **(** *bool-exp* **)** *statement* **`else`** *statement*

| **`while`** **(** *bool-exp* **)** *statement*

bool-exp ::= *rel-exp* | **!** (*rel-exp*)

rel-exp ::= *exp* **==** *exp* | *exp* **>** *exp*

exp ::= *term* | *exp* **+** *term* | *exp* **-** *term*

term ::= *factor* | *term* ***** *factor*

factor ::= *id* | *int* | **(** *exp* **)** | *id* **( )** | *id* **(** *exps* **)**

exps ::= *exp* | *exps* **,** *exp*

Grammar for Java, a big language

- The Java™ Language Specification, *Second Edition*
  - » *Entire document*
    - *500+ pages*
    - *Grammar productions with explanatory text*
  - » *Chapter 18, Syntax*
    - *8 pages of grammar productions, presented in "BNF-style"*

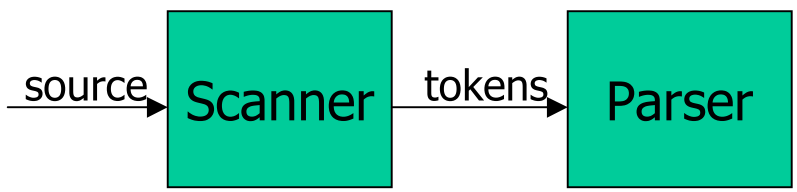
Parsing

- Parsing: reconstruct the derivation (syntactic structure) of a program
- In principle, a single recognizer could work directly from the concrete, character-by-character grammar
  - » In practice this is never done

Parsing & Scanning

- In real compilers the recognizer is split into two phases
  - » Scanner: translate input characters to tokens

    Also, report lexical errors like illegal characters and illegal symbols
  - » Parser: read token stream and reconstruct the derivation



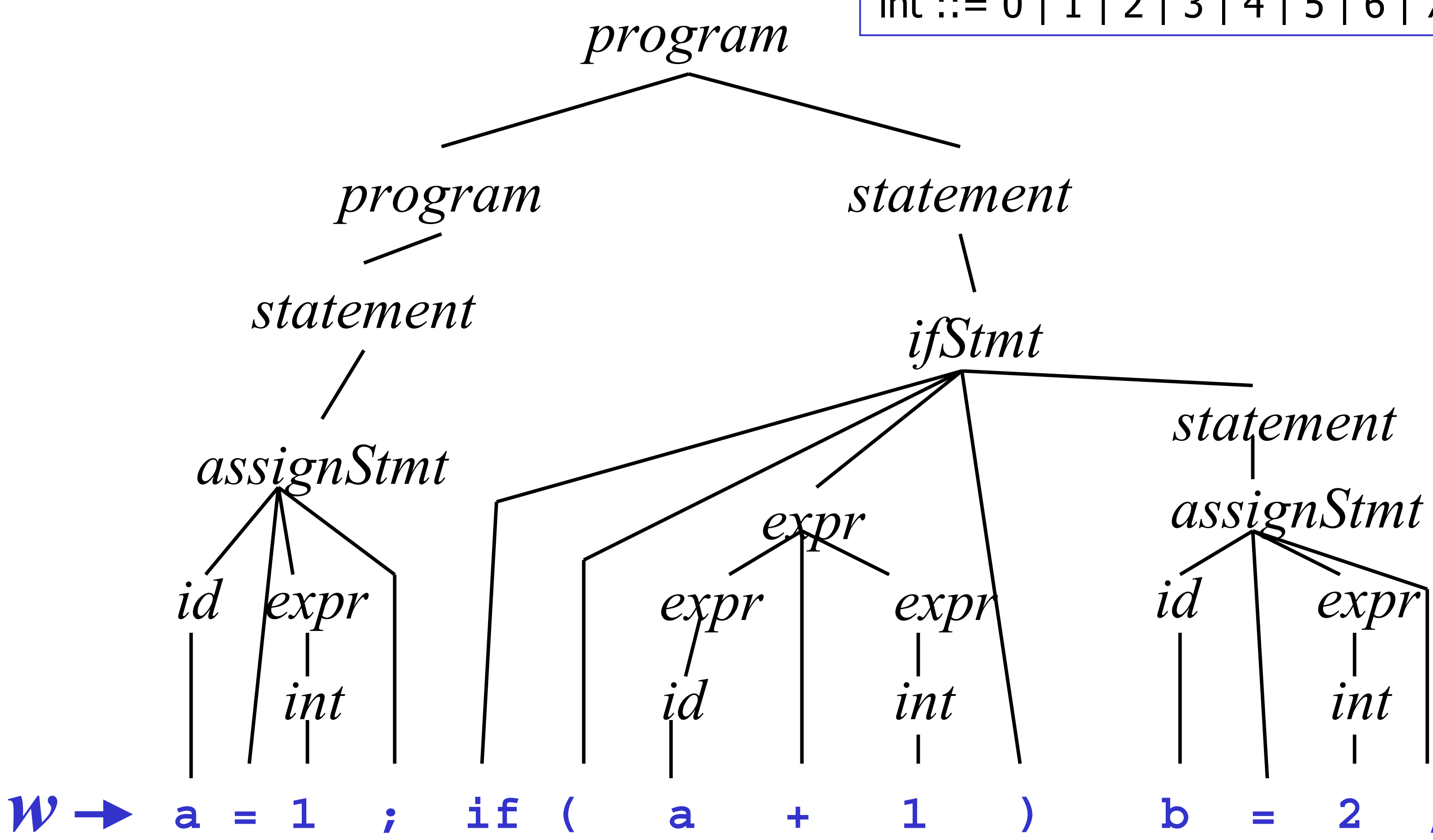
Parsing

- The syntax of most programming languages can be specified by a *context-free grammar* (CFG)
- Parsing
  - » Given a grammar G and a sentence w in $L(G)$, traverse the derivation (parse tree) for w in some *standard order* and do *something useful* at each node
  - » The tree might not be produced explicitly, but the control flow of a parser corresponds to a traversal

Parse Tree Example

G

program ::= *statement* | *program statement*
statement ::= *assignStmt* | *ifStmt*
assignStmt ::= *id* = *expr* ;
ifStmt ::= if (*expr*) *stmt*
expr ::= *id* | *int* | *expr* + *expr*
Id ::= a | b | c | i | j | k | n | x | y | z
int ::= 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9



“Standard Order”

- For practical reasons we want the parser to be *deterministic* (no backtracking), and we want to examine the source program from *left to right.*
  - » parse the program in linear time in the order it appears in the source file

Common Orderings

- Top-down
  - » Start with the root
  - » Traverse the parse tree depth-first, left-to-right (leftmost derivation)
  - » LL(k)
- Bottom-up
  - » Start at leaves and build up to the root
    - Effectively a rightmost derivation in reverse
  - » LR(k) and subsets (LALR(k), SLR(k), etc.)

“Something Useful”

- At each point (node) in the traversal, perform some *semantic action*
  - » Construct nodes of full parse tree (rare)
  - » Construct abstract syntax tree (common)
  - » Construct linear, lower-level representation (more common in later parts of a modern compiler)
  - » Generate target code on the fly (1-pass compiler; not common in production compilers – can’t generate very good code in one pass)

Context-Free Grammars

- Formally, a grammar G is a tuple $<N,\Sigma,P,S>$ where
  - » N a finite set of non-terminal symbols
  - » Σ a finite set of terminal symbols
  - » P a finite set of productions

    A subset of $N \times (N \cup \Sigma)^*$
  - » S the *start symbol,* a distinguished element of N

    If not specified otherwise, this is usually assumed to be the non-terminal on the left of the first production

Standard Notations

a, b, c	elements of Σ	*terminals*
w, x, y, z	elements of Σ^*	*strings of terminals*
A, B, C	elements of N	*non-terminals*
X, Y, Z	elements of $N \cup \Sigma$	*grammar symbols*
α, β, γ	elements of $(N \cup \Sigma)^*$	*strings of symbols*

$A \rightarrow \alpha$ or $A ::= \alpha$ if $<A, \alpha>$ in P

"non-terminal A can take the form α"

Derivation Relations

- $\alpha\ A\ \gamma \Rightarrow \alpha\ \beta\ \gamma$ iff $A ::= \beta$ in P
  - » "=>" is read "derives"
- A =>* w if there is a chain of productions starting with A that generates w
  - » transitive closure

Derivation Relations

- $w\ A\ \gamma \Rightarrow_{lm} w\ \beta\ \gamma$ iff $A ::= \beta$ in P
  - » derives leftmost
- $\alpha\ A\ w \Rightarrow_{rm} \alpha\ \beta\ w$ iff $A ::= \beta$ in P
  - » derives rightmost
- We will only be interested in leftmost and rightmost derivations – not random orderings

Languages

- For A in N, $L(\mathrm{A}) = \{ \mathrm{w} \mid \mathrm{A} \Rightarrow^* \mathrm{w} \}$
- If S is the start symbol of grammar G, define $L(G) = L(S)$
  » The language derived by G is the language derived by the start symbol S

Reduced Grammars

- Grammar *G* is *reduced* iff for every production A ::= α in *G* there is a derivation

$$S \Rightarrow^* x\,A\,z \Rightarrow x\,\alpha\,z \Rightarrow^* xyz$$

  » i.e., no production is useless

- Convention: we will use only reduced grammars

Ambiguity

- Grammar G is *unambiguous* iff every w in $L(G)$ has a unique leftmost (or rightmost) derivation
  - » Fact: unique leftmost or unique rightmost implies the other
- A grammar without this property is *ambiguous*
  - » Note that other grammars that generate the same language may be unambiguous
- We need unambiguous grammars for parsing

Ambiguous Grammar for Expressions

expr ::= *expr* + *expr* | *expr* - *expr*
| *expr* * *expr* | *expr* / *expr* | *int*

int ::= 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9

- Show that this is ambiguous
  - » How? Show two different leftmost or rightmost derivations for the same string
  - » Equivalently: show two different parse trees for the same string

Example Derivation

expr ::= *expr* + *expr* | *expr* - *expr*
| *expr* * *expr* | *expr* / *expr* | *int*
int ::= 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9

Give a leftmost derivation of 2+3*4 and show the parse tree

Another Derivation

expr ::= *expr* + *expr* | *expr* - *expr*
| *expr* * *expr* | *expr* / *expr* | *int*
int ::= 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9

Give a different leftmost derivation of 2+3*4 and show the parse tree

Another Example

expr ::= *expr* + *expr* | *expr* - *expr*
| *expr* * *expr* | *expr* / *expr* | *int*
int ::= 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9

Give two different derivations of 5+6+7

What's going on here?

- The grammar has no notion of precedence or associativity
- Solution
  - » Create a non-terminal for each level of precedence
  - » Isolate the corresponding part of the grammar
  - » Force the parser to recognize higher precedence subexpressions first

Classic Expression Grammar

$expr ::= expr + term \mid expr - term \mid term$

$term ::= term * factor \mid term \,/\, factor \mid factor$

$factor ::= int \mid (\ expr\ )$

$int ::= 0 \mid 1 \mid 2 \mid 3 \mid 4 \mid 5 \mid 6 \mid 7$

Derive 2 + 3 * 4

expr ::= *expr* + *term* | *expr* – *term* | *term*
term ::= *term* * *factor* | *term* / *factor* | *factor*
factor ::= *int* | (*expr*)
int ::= 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7

Derive 5 + 6 + 7

expr ::= *expr* + *term* | *expr* – *term* | *term*
term ::= *term* * *factor* | *term* / *factor* | *factor*
factor ::= *int* | (*expr*)
int ::= 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7

Derive 5 + (6 + 7)

expr ::= *expr* + *term* | *expr* – *term* | *term*
term ::= *term* * *factor* | *term* / *factor* | *factor*
factor ::= *int* | (*expr*)
int ::= 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7

Another Classic Example

- Grammar for conditional statements

  ifStmt ::= **if (** *cond* **)** *stmt*

  | **if (** *cond* **)** *stmt* **else** *stmt*

  » Exercise: show that this is ambiguous

  How?

One Derivation

ifStmt ::= if (*cond*) *stmt*
| if (*cond*) *stmt* else *stmt*

if (*cond*) if (*cond*) *stmt* else *stmt*

Another Derivation

ifStmt ::= if (*cond*) *stmt*
| if (*cond*) *stmt* else *stmt*

if (*cond*) if (*cond*) *stmt* else *stmt*

Solving **if** Ambiguity

- Fix the grammar to separate if statements with else clause and if statements with no else
  - » Done in Java reference grammar
  - » Adds lots of non-terminals
- Use some ad-hoc rule in parser
  - » "else matches closest unpaired if"