CSE P 501 – Compilers

Parsing & Context-Free Grammars

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Administrivia

- Project partner signup: please find a partner and fill out the signup form by noon tomorrow if not done yet (only one form per group, please)
  - Who's still looking for a partner?
  - Watch for spam from CSE GitLab as repos are set up (save and ignore for now)
- Written HW2 out tonight or tomorrow, due Monday
- HW1 solution posted this weekend
- First part of project – scanner – out later this week, due in two weeks
  - Programming is fairly simple; this is the infrastructure shakedown cruise. More about this next week.

Deadlines & office hours

- From the discussion board: what should we do about assignment deadlines and office hours?
    - Deadlines: early in the week to finish off old stuff before class and next assignment, or later in the week to catch office hours on Tuesdays?
    - We could add virtual or maybe in-person office hours on Sunday. Useful? Not? How does it affect deadline issues?

Communications

Yikes! With luck we've sorted out most of the discussion group issues. Let's see if we can channel things like this:

- Google discussion group – general traffic about the class. Staff will monitor and post as needed regularly, but everyone should join in.
- Email to csep501-staff[at]cs for things not appropriate for posting.
- Class mailing list for announcement from staff only.
- There are lots of other things that generate email to instructor/staff when clicked – if we can minimize that it would help. Thanks.

Agenda for Today

- Parsing overview
- Context free grammars
- Ambiguous grammars
- Reading: Cooper & Torczon 3.1-3.2
  - Dragon book is also particularly strong on grammars and languages

Syntactic Analysis / Parsing

- Goal: Convert token stream to an abstract syntax tree
- Abstract syntax tree (AST):
  - Captures the structural features of the program
  - Primary data structure for next phases of compilation
- Plan
  - Study how context-free grammars specify syntax
  - Study algorithms for parsing and building ASTs

Context-free Grammars

- The syntax of most programming languages can be specified by a context-free grammar (CGF)
- Compromise between
  - REs: can't nest or specify recursive structure
  - General grammars: too powerful, undecidable
- Context-free grammars are a sweet spot
  - Powerful enough to describe nesting, recursion
  - Easy to parse; restrictions on general CFGs improve speed
- Not perfect
  - Cannot capture semantics, like "must declare every variable" or "must be `int`" – requires later semantic pass
  - Can be ambiguous (something we'll deal with)

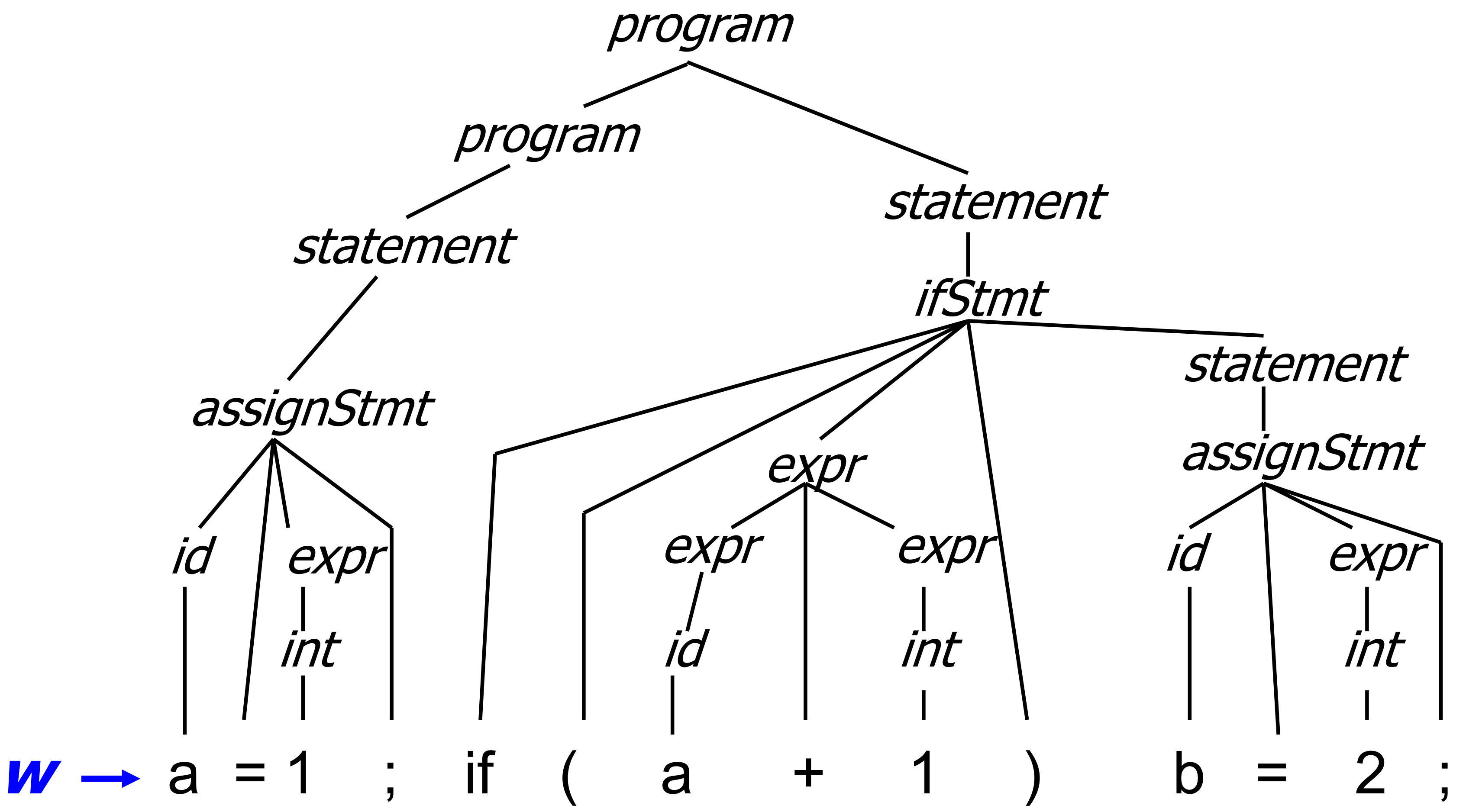
Derivations and Parse Trees

- Derivation: a sequence of expansion steps, beginning with a start symbol and leading to a sequence of terminals
- Parsing: inverse of derivation
  - Given a sequence of terminals (aka tokens) recover (discover) the nonterminals and structure, i.e., the parse tree (concrete syntax)

Old Example

G

program ::= *statement* | *program statement*
statement ::= *assignStmt* | *ifStmt*
assignStmt ::= *id* = *expr* ;
ifStmt ::= if (*expr*) *statement*
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



Parsing

- 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 the parser will correspond to a traversal

“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*.
  - (i.e., 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), recursive-descent
- 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 (AST) (common)
  - Construct linear, lower-level representation (often produced in later phases of production compilers by traversing initial AST)
  - Generate target code on the fly (done in 1-pass compilers; not common in production compilers)
    - Can’t generate great code in one pass, – but useful if you need a quick ‘n dirty working compiler

Context-Free Grammars

- Formally, a *grammar G* is a tuple <*N*,Σ,*P*,*S*> where
  - *N* is a finite set of *non-terminal* symbols
  - Σ is a finite set of *terminal* symbols (alphabet)
  - *P* is a finite set of *productions*
    - A subset of $N \times (N \cup \Sigma)^*$
  - *S* is 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

w, x, y, z elements of Σ^*

A, B, C elements of N

X, Y, Z elements of $N \cup \Sigma$

α, β, γ elements of $(N \cup \Sigma)^*$

$A \rightarrow \alpha$ or $A ::= \alpha$ if $\langle A, \alpha \rangle \in P$

Derivation Relations (1)

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

Derivation Relations (2)

- $w\ A\ \gamma \Rightarrow_{lm} w\ \beta\ \gamma$ 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*(A) = { w | A =>* w }
- If *S* is the start symbol of grammar *G*, define *L*(*G*) = *L*(*S*)
  - Nonterminal on left of first rule is taken to be the start symbol if one is not specified explicitly

Reduced Grammars

- Grammar *G* is ***reduced*** iff for every production $A ::= \alpha$ 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
  - There are algorithms for pruning useless productions from grammars – see a formal language or compiler book for details

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, i.e., ambiguity is a property of grammars, not languages
- We need unambiguous grammars for parsing

Example: Ambiguous Grammar for Arithmetic Expressions

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

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

- Exercise: 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 (cont)

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

Example (cont)

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 associatively
- Traditional 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
  - Use left- or right-recursion for left- or right-associative operators (non-associative operators are not recursive)

Classic Expression Grammar

(first used in ALGOL 60)

expr ::= *expr* + *term* | *expr* – *term* | *term*

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

factor ::= *int* | (*expr*)

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

Check:
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

Check:
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

- Note interaction between left- vs right-recursive rules and resulting associativity

Check:
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

  stmt ::= if (*expr*) *stmt*

  | if (*expr*) *stmt* else *stmt*

  (This is the "dangling else" problem found in many, many grammars for languages beginning with Algol 60)

  – Exercise: show that this is ambiguous
    - How?

stmt ::= if (*expr*) *stmt*
| if (*expr*) *stmt* else *stmt*

One Derivation

if (*expr*) if (*expr*) *stmt* else *stmt*

stmt ::= if (*expr*) *stmt*
| if (*expr*) *stmt* else *stmt*

Another Derivation

if (*expr*) if (*expr*) *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
- or, Change the language
  - But it’d better be ok to do this – you need to “own” the language or get permission from owner
- or, Use some ad-hoc rule in the parser
  - “else matches closest unpaired if”

Resolving Ambiguity with Grammar (1)

Stmt ::= MatchedStmt | UnmatchedStmt

MatchedStmt ::= ... |

if (Expr) MatchedStmt **else** MatchedStmt

UnmatchedStmt ::= ... |

if (Expr) Stmt |

if (Expr) MatchedStmt **else** UnmatchedStmt

– formal, no additional rules beyond syntax

– can be more obscure than original grammar

Check

Stmt ::= MatchedStmt | UnmatchedStmt
MatchedStmt ::= ... |
    if (Expr) MatchedStmt **else** MatchedStmt
UnmatchedStmt ::= **if** (Expr) Stmt |
    if (Expr) MatchedStmt **else** UnmatchedStmt

if (*expr*) if (*expr*) *stmt* else *stmt*

Resolving Ambiguity with Grammar (2)

- If you can (re-)design the language, just avoid the problem entirely

Stmt ::= ... |
    if Expr **then** Stmt **end** |
    if Expr **then** Stmt **else** Stmt **end**

  - formal, clear, elegant
  - allows sequence of Stmts in then and else branches, no { , } needed
  - extra end required for every if

    (But maybe this is a good idea anyway?)

Parser Tools and Operators

- Most parser tools can cope with ambiguous grammars
  - Makes life simpler if used with discipline
- Usually can specify precedence & associativity
  - Allows simpler, ambiguous grammar with fewer nonterminals as basis for parser – let the tool handle the details (but only when it makes sense)
    - (i.e., expr ::= expr+expr | expr*expr | … with assoc. & precedence declarations can be the best solution)
- Take advantage of this to simplify the grammar when using parser-generator tools

Parser Tools and Ambiguous Grammars

- Possible rules for resolving other problems:
  - Earlier productions in the grammar preferred to later ones (danger here if parser input changed)
  - Longest match used if there is a choice (good solution for dangling if)
- Parser tools normally allow for this
  - But be sure that what the tool does is really what you want
    - And that it's part of the tool spec, so that v2 won't do something different (that you *don't* want!)

Coming Attractions

- Next topic: LR parsing
  - Continue reading ch. 3