CSE401: Parsing

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Slides by Chambers, Eggers, Notkin, Ruzzo, Snyder and others

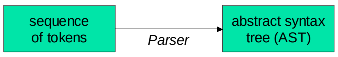
Objectives: parsing lectures

Understand:

- Theory and practice of parsing
- Underlying language theory (CFGs, ...)
- Top-down parsing (and be able to do it)
- Bottom-up parsing (time permitting)

- Today's focus: grammars and ambiguity

Parsing



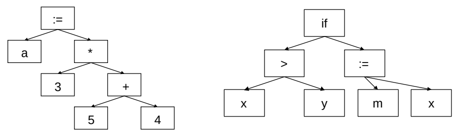
- Abstract Syntax Tree (AST)
  - Captures hierarchical structure of the program
  - Is the primary representation of the program used by the rest of the compiler
    - It gets augmented and annotated, but the basic structure of the AST is used throughout

Parsing: two jobs

- Is the program syntactically correct?

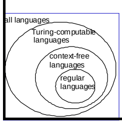
```
a := 3 * (5 + 4);     if x > y then m := x;
a := 3 * / 4;         if x < y else m := x;
```

- If so, build the corresponding AST



Context-free grammars (CFGs)

- For lexing, we used regular expressions as the underlying notation
- For parsing, we use context-free grammars in much the same way
  - Regular expressions are not powerful enough
    - Intuitively, can't express balance/nesting ($a^n b^n$, parens)
  - More general grammars are more powerful than we need
    - Well, we could use more power, but instead we delay some checking to semantic analysis instead of doing all the analysis based on the (general, but slow) grammar



CFG terminology

- *Terminals*: alphabet, or set of legal tokens
- *Nonterminals*: represent abstract syntax units
- *Productions*: rules defining nonterminals in terms of a finite sequence of terminals and nonterminals
- *Start symbol*: root symbol defining the language

```
Program ::= Stmt
Stmt    ::= if Expr then Stmt else Stmt end
Stmt    ::= while Expr do Stmt end
```

EBNF description of PL/0

```
Program      ::= module Id ; Block Id .
Block        ::= DeclList begin StmtList end
DeclList     ::= { Decl ; }
Decl         ::= ConstDecl | ProcDecl | VarDecl
ConstDecl    ::= const ConstDeclItem {, ConstDeclItem }
ConstDeclItem ::= Id : Type = ConstExpr
ConstExpr    ::= Id | Integer
VarDecl      ::= var VarDeclItem { , VarDeclItem }
VarDeclItem ::= Id : Type
```

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EBNF description of PL/0

```
ProcDecl   ::=
  procedure Id ( [ FormalDecl {, FormalDecl} ] ) ;
                 Block Id
FormalDecl ::= Id : Type
Type       ::= int
StmtList   ::= { Stmt ; }
Stmt       ::= CallStmt | AssignStmt | OutStmt |
               IfStmt | WhileStmt
CallStmt   ::= Id ( [ Exprs ] )
AssignStmt ::= Lvalue := Expr
Lvalue     ::= Id
```

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EBNF description of PL/0

```
OutStmt   ::= output := Expr
IfStmt    ::= if Test then StmtList end
WhileStmt ::= while Test do StmtList end
Test      ::= odd Sum | Sum Relop Sum
Relop     ::= <= | <> | < | >= | > | =
Exprs     ::= Expr {, Expr }
Expr      ::= Sum
Sum       ::= Term { (+ | -) Term }
Term      ::= Factor { (* | /) Factor }
Factor    ::= - Factor | LValue | Integer |
              input | ( Expr )
```

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Exercise: produce a syntax tree for squares.0

```
module main;
  var x:int, squareret:int;
  procedure square(n:int);
  begin
    squareret := n * n;
  end square;
begin
  x := input;
  while x <> 0 do
    square(x);
    output := squareret;
    x := input;
  end;
end main.
```

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Derivations and parsing

- Derivation
  - A sequence of expansion steps,
  - Beginning with the start symbol,
  - Leading to a string of terminals
- Parsing: inverse of derivation
  - Given a target string of terminals,
  - Recover nonterminals/productions representing structure

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Parse trees

- We represent derivations and parses as parse trees
- Concrete syntax tree
  - Exact reflection of the grammar
- Abstract syntax tree
  - Simplified version, reflecting key structural information
  - E.g., omit superfluous punctuation & keywords

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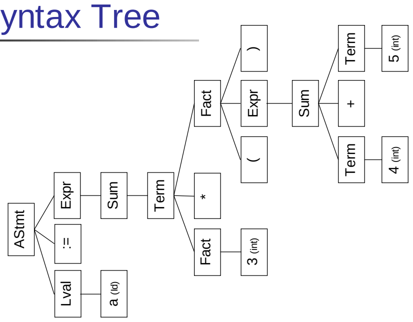
Concrete Syntax Tree

`a := 3 *(4+5)`



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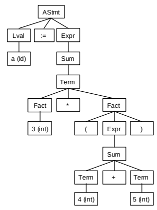
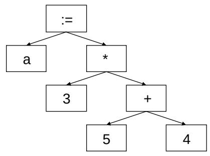
Abstract syntax trees

Concrete syntax tree

Abstract syntax tree

`a := 3 *(4+5)`





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Ex: An expression grammar

```
E  ::= E Op E | - E | ( E ) | int
Op ::= + | - | * | /
```

- Using this grammar, find parse trees for:
  - `3 * 5`
  - `3 + 4 * 5`

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Ambiguity

- Some grammars are *ambiguous*
  - Different parse trees with the same final string
  - (Some *languages* are ambiguous, with no possible non-ambiguous grammar; but we avoid them)
- The structure of the parse tree captures some of the meaning of a program
  - Ambiguity is bad since it implies multiple possible meanings for the same program
- Consider the example on the previous slide

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Another famous ambiguity: *dangling else*

```
Stmt  ::= … |
          if Expr then Stmt |
          if Expr then Stmt else Stmt
```

`if e1 then if e2 then s1 else s2`

- To which `then` does the `else` belong?
  - The compiler isn't going to be confused
  - However, if the compiler chooses a meaning different from what the programmer intended, it could get ugly
- Any ideas for overcoming this problem?

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Resolving ambiguity: #1

- Add a meta-rule
  - For instance, "`else` associates with the closest previous unmatched `if`"
- This works and keeps the original grammar intact
- But it's ad hoc and informal

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Resolving ambiguity: #2

- Rewrite the grammar to resolve it explicitly

```
Stmt         ::= MatchedStmt | UnmatchedStmt
MatchedStmt  ::= … |
                 if Expr then MatchedStmt
                           else MatchedStmt
UnmatchedStmt ::= if Expr then Stmt |
                  if Expr then MatchStmt
                           else UnmatchedStmt
```

- Formal, no additional meta-rules
- Somewhat more obscure grammar

Resolving ambiguity: #2 (cont.)

```
Stmt          ::= MatchedStmt | UnmatchedStmt
MatchedStmt   ::= … |
                  if Expr then MatchedStmt
                           else MatchedStmt
UnmatchedStmt ::= if Expr then Stmt |
                  if Expr then MatchStmt
                           else UnmatchedStmt
```

if e1 **then** **if** e2 **then** s1 **else** s2

Resolving ambiguity: #3

- Redesign the *programming language* to remove the ambiguity

```
Stmt   ::= if Expr then Stmt end |
           if Expr then Stmt else Stmt end
```

- Formal, clear, elegant
- Allows `StmtList` in `then` and `else` branch, without adding `begin/end`
- Extra `end` required for every `if` statement

What about that expression grammar?

How to resolve its ambiguity?

- Option #1: add meta-rules for precedence and associativity
- Option #2: modify the grammar to explicitly resolve the ambiguity
- Option #3: redefine the language

Option #1: add meta-rules

- Add meta-rules for precedence and associativity

E ::= E+E | E-E | E*E | E/E | E^E | (E) | -E | …

  - **+,-** < ***,/** < unary **-** < **^** etc.
  - **+,-,*,/** left-associative; **^** right associative
- Simple, intuitive
- But not all parsers can support this
  - yacc does

Option #2: new BNF

```
E ::= E+T|T
T ::= T*F|F
F ::= id |(E)
```

- Create a nonterminal for each precedence level
- `Expr` is the lowest precedence nonterminal
  - Each nonterminal can be rewritten with higher precedence operator
  - Highest precedence operator includes atomic expressions
- At each precedence level use
  - Left recursion for left-associative operators
  - Right recursion for right-associative operators
  - No recursion for non-associative operators

Option #2: example

```
E ::= E+T|T
T ::= T*F|F
F ::= id |(E)
```

w + x + y * z

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Option #3: New language

- Require parens
  - E.g., in APL all exprs evaluated left-to-right unless parenthesized
- Forbid parens
  - E.g.: RPN calculators

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Designing a grammar:
on what basis?

- Accuracy
- Readability, clarity
- Unambiguity
- Limitations of CFGs
- Similarity to desired AST structure
- Ability to be parsed by a particular parsing algorithm
  - Top-down parser => LL(k) grammar
  - Bottom-up parser => LR(k) grammar

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Parsing algorithms

- Given input (sequence of tokens) and grammar, how do we find an AST that represents the structure of the input with respect to that grammar?
- Two basic kinds of algorithms
  - Top-down: expand from grammar's start symbol until a legal program is produced
  - Bottom-up: create sub-trees that are merged into larger sub-trees, finally leading to the start symbol

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Top-down parsing

- Build AST from top (start symbol) to leaves (terminals)
  - Represents a leftmost derivation (e.g., always expand leftmost non-terminal)
- Basic issue: when replacing a non-terminal with a right-hand side (rhs), which rhs should you use?
- Basic solution: Look at next input tokens

```
Stmt   ::= Call | Assign | If
Call   ::= Id
Assign::= Id := Expr
If     ::= if Test then
             Stmts end
If     ::= if Test then
             Stmts else
             Stmts end
```

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Predictive parser

- A top-down parser that can select the correct rhs looking at the next *k* tokens (*lookahead*)
- Efficient
  - No backtracking is needed
  - Linear time to parse
- Implementation
  - Table-driven: pushdown automaton (PDA) — like table-driven FSA plus stack for recursive FSA calls
  - Recursive-descent parser [used in PL/0]
    - Each non-terminal parsed by a procedure
    - Call other procedures to parse sub-non-terminals, recursively

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LL(k), LR(k), …?

- These parsers have generally snazzy names
- The simpler ones look like the ones in the title of this slide
  - The first L means "process tokens left to right"
  - The second letter means "produce a (**R**ight / **L**eft)most derivation"
    - Leftmost => top-down
    - Rightmost => bottom-up
  - The k means "k tokens of lookahead"
- We won't discuss LALR(k), SLR, and lots more parsing algorithms

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LL(k) grammars

- It's easy to construct a predictive parser if a grammar is LL(k)
  - **L**eft-to-right scan on input, **L**eftmost derivation, **k** tokens of lookahead
- Restrictions include
  - Unambiguous
  - No common prefixes of length ≥ k
  - No left recursion
  - … (more details later)…
- Collectively, the restrictions guarantee that, given k input tokens, one can always select the correct rhs to expand

Common prefix

```
S ::= if Test then
        Stmts end |
      if Test then
        Stmts else
        Stmts end |
        …
```

Left recursion

```
E ::= E op E | …
```

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Eliminating common prefixes

- *Left factor* them, creating a new non-terminal for the common prefix and/or different suffixes
- Before
  - ```
    If  ::= if Test then Stmts end |
            if Test then Stmts else Stmts end
    ```
- After
  - ```
    If     ::= if Test then Stmts IfCont
    IfCont ::= end | else Stmts end
    ```
- Grammar is a bit uglier
- Easy to do manually in a recursive-descent parser

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Eliminating left recursion:

- Before

```
E ::= E + T | T
T ::= T * F | F
F ::= id | ( E ) | …
```

- After

```
E     ::= T ECont
ECont ::= + T ECont | ε
T     ::= F TCont
TCont ::= * F TCont | ε
F     ::= id | ( E ) | …
```

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Just add sugar

```
E ::= T { + T }
T ::= F { * F }
F ::= id | ( E ) | …
```

- Sugared form is still pretty readable
- Easy to implement in hand-written recursive descent parser
- Concrete syntax tree is not as close to abstract syntax tree

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LL(1) Parsing Theory

Goal: Formal, rigorous description of those grammars for which "I can figure out how to do a top-down parse by looking ahead just one token", plus corresponding algorithms.

Notation:

T = Set of Terminals (Tokens)

N = Set of Nonterminals

$ = End-of-file character (T-like, but not in N ∪ T)

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Table-driven predictive parser

- Automatically compute PREDICT table from grammar
- PREDICT(nonterminal,input-symbol)
  - Ł action, e.g. which rhs or error

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Example 1

```
Stmt  ::= 1 if expr then Stmt else Stmt |
          2 while Expr do Stmt |
          3 begin Stmts end
Stmts ::= 4 Stmt ; Stmts | 5 ε
Expr  ::= 6 id
```

	if	then	else	while	do	begin	end	id	;	$
Stmt	1			2		3				
Stmts	4			4		4	5			
Expr								6		

empty = error

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LL(1) Parsing Algorithm

```
push S$                              /* S is start symbol */
while Stack not empty
    X := pop(Stack)
    a := peek at next token          /* assume EOF = $ */
    if X is terminal or $
        If  X==a, read token a else abort;
    else look at PREDICT(X, a) /* X is nonterminal */
        Empty       : abort
        rule X → α : push α
If not at end of input, abort
```

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Constructing PREDICT: overview

- Compute FIRST set for each rhs
  - All tokens that can appear first in a derivation from that rhs
- In case rhs can be empty, compute FOLLOW set for each non-terminal
  - All tokens that can appear right after that non-terminal in a derivation
- Constructions of FIRST and FOLLOW sets are interdependent
- PREDICT depends on both

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Example 1 (cont.)

	FIRST	FOLLOW
1 S ::= **if** E **then** S **else** S		
2 | **while** E **do** S		
3 | **begin** Ss **end**		
4 Ss ::= S ; Ss		
5 | ε		
6 E ::= **id**		

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FIRST(α) – 1st "token" from α

Definition: For any string α of terminals and non-terminals, FIRST(α) is the set of terminals that begin strings derived from α, together with ε, if α can derive ε. More precisely:

For any $\alpha \in (N \cup T)^*$,
$FIRST(\alpha) =$
$\{ a \in T \mid \alpha \Rightarrow^* a\beta \text{ for some } \beta \in (N \cup T)^* \} \cup$
$\{\varepsilon, \text{ if } \alpha \Rightarrow^* \varepsilon\}$

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Computing FIRST– 4 cases

1. FIRST(ε) = {ε}
2. For all a ∈ T, FIRST(a) = {a}
3. For all A ∈ N, repeat until no change

   If there is a rule A → ε, add(ε) to FIRST(A)

   For all rules A → $Y_1 \ldots Y_k$ add(FIRST(Y_1) - {ε})

   if ε ∈ FIRST(Y_1) then add(FIRST(Y_2) - {ε})

   if ε ∈ FIRST($Y_1 Y_2$) then add(FIRST(Y_3) - {ε})

   …

   if ε ∈ FIRST(Y_1 Y_2...Y_k) then add(ε)

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Computing FIRST (Cont.)

4. For all any string $Y_1 \ldots Y_k$ ∈ (N ∪ T)*, similar:

   add(FIRST(Y_1) - {ε})

   if ε ∈ FIRST(Y_1) then add(FIRST(Y_2) - {ε})

   if ε ∈ FIRST($Y_1 Y_2$) then add(FIRST(Y_3) - {ε})

   …

   if ε ∈ FIRST(Y_1 Y_2...Y_k) then add(ε)

[Note: defined for all strings; really only care about FIRST(right hand sides).]

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FOLLOW(B) – Next "token" after B

Definition: for any non-terminal B, FOLLOW(B) is the set of terminals that can appear immediately after B in some derivation from the start symbol, together with $, if B can be the end of such a derivation. ($ represents "end of input".) More precisely: For all B ∈N,

FOLLOW(B) = { a ∈ (T ∪ {$}) | S$ ⇒* α B a β for some α, β ∈ (N ∪ T ∪ {$})* }

(S is the Start symbol of the grammar.)

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Computing FOLLOW(B)

Add $ to FOLLOW(S)

Repeat until no change

For all rules A → αBβ [i.e. all rules with a B in r.h.s],

Add (FIRST(β) - {ε}) to FOLLOW(B)

If ε ∈ FIRST(β) [in particular, if β is empty] then

Add FOLLOW(A) to FOLLOW(B)

Assume for all A that S ⇒* αAβ for some α,β ∈ (N ∪ T)*, else A irrelevant

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PREDICT – Given lhs, which rhs?

For all rules A → α

For all a ∈ FIRST(α) - {ε}

Add(A → α) to PREDICT(A,a)

If ε ∈ FIRST(α) then

For all b ∈ FOLLOW(A)

Add(A → α) to PREDICT(A,b)

Defn: G is LL(1) iff every cell has ≤ 1 entry

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Properties of LL(1) Grammars

- Clearly, given a conflict-free PREDICT table (≤ 1 entry/cell), the parser will do *something* unique with every input
- Key fact is, if the table is built as above, that something is the *correct* thing
- I.e., the PREDICT table will reliably guide the LL(1) parsing algorithm so that it will
  - Find a derivation for every string in the language
  - Declare an error on every string *not* in the language

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Exercises (1st especially recommended)

- Easy: Pick some grammar with common prefixes, left recursion, and/or ambiguity.
  - Build PREDICT; it *will* have conflicts
- Harder: prove that *every* grammar with ≥1 of those properties will have PREDICT conflicts
- Harder: Find a grammar with none of those features that nevertheless gives conflicts.
  - I.e., absence of those features is necessary but not sufficient for a grammar to be LL(1).
- Harder, for theoryheads: if the table has conflicts, and the parser chooses among them nondeterministically, it will work correctly

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Example 2

Sugared

```
E  ::= T { + T }
T  ::= F { * F }
F  ::= - F | id | ( E )
```

Unsugared

```
E  ::= 1 T E′
E′ ::= 2 + T E′  | 3 ε
T  ::= 4 F T′
T′ ::= 5 * F T′  | 6 ε
F  ::= 7 - F     | 8 id | 9 ( E )
```

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Example 2 (cont.)

	FIRST	FOLLOW
1 E ::= T E′		
2 E′ ::= + T E′		
3 | ε		
4 T ::= F T′		
5 T′ ::= * F T′		
6 | ε		
7 F ::= - F		
8 | **id**		
9 | (E)		

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Example 2: PREDICT

	id	+	-	*	/	(	)	$
E								
E′								
T								
T′								
F								

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PREDICT and LL(1)

- The PREDICT table has at most one entry in each cell if and only if the grammar is LL(1)
  - ∴ there is only one choice (it's predictive) , making it fast to parse and easy to implement
- Multiple entries in a cell
  - Arise with left recursion, ambiguity, common prefixes, etc.
  - Can patch by hand, if you know what to do
  - Or use more powerful parser (LL(2), or LR(k), or…?)
  - Or change the grammar

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Recursive descent parsers

- Write procedure for each non-terminal
- Each procedure selects the correct right-hand side by peeking at the input tokens
- Then the r.h.s. is consumed
  - If it's a terminal symbol, verify it is next and then advance through the token stream
  - If it's a non-terminal, call corresponding procedure
- Build and return AST representing the r.h.s.

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Recursive descent example

```
Stmt  ::= 1 if expr then Stmt else Stmt |
          2 while Expr do Stmt |
          3 begin Stmts end
Stmts ::= 4 Stmt ; Stmts | 5 ε
Expr  ::= 6 id
```

```
ParseStmt() {
   switch (next token) {
     "begin": ParseStmts();read "end"; break;
     "while": ParseExpr(); read "do"; ParseStmt(); break;
     "if":    ParseExpr(); read "then"; ParseStmt();
              read "else"; ParseStmt(); break;
     default: abort;
   }
}
```


LL(1) and Recursive Descent

- If the grammar is LL(1), it's easy to build a recursive descent parser
  - One nonterminal/row à one procedure
  - Use 1 token lookahead to decide which rhs
  - Table-driven parser's stack à recursive call stack
- Recursive descent can handle some non-LL(1) features, too.

Example

LL(1) & recursive descent

	if	then	else	while	do	begin	end	id	;	$
Stmt	1			2		3				
Stmts	4			4		4	5			
Expr								6		

```
Stmt  ::= 1 if expr then Stmt else Stmt |
          2 while Expr do Stmt |
          3 begin Stmts end
Stmts ::= 4 Stmt ; Stmts | 5 ε
Expr  ::= 6 id
```

```
ParseStmt() {
   switch (next token) {
     "begin": ParseStmts();read "end"; break;
     "while": ParseExpr(); read "do"; ParseStmt(); break;
     "if":    ParseExpr(); read "then"; ParseStmt();
              read "else"; ParseStmt(); break;
     default: abort;
   }
}
```


Example

non-LL(1) & recursive descent

	if	then	else	while	do	begin	end	id	;	$
Stmt	1, 1'			2		3				
Stmts	4			4		4	5			
Expr								6		

```
Stmt  ::= 1  if expr then Stmt |
          1' if expr then Stmt else Stmt |
          2  while Expr do Stmt |
          3  begin Stmts end
Stmts ::= 4  Stmt ; Stmts | 5 ε
Expr  ::= 6  id
```

The dangling else ambiguity

& common prefixes

```
ParseStmt() {
  switch (next token) {
    "if":    ParseExpr(); read "then"; ParseStmt();
             if(next token == "else")
                {read "else"; ParseStmt();}
             break;
    "begin": ...
  }
}
```


It's demo time…

- Let's look at some of the PL/0 code to see how the recursive descent parsing works in practice

<stmt list> ::= { <stmt> ; }
<stmt> ::= <id stmt> | <out stmt> | <if stmt> | <while stmt>

Parser::ParseStmts()

```
StmtArray* Parser::ParseStmts() {
  StmtArray* stmts = new StmtArray; Stmt* stmt;
  for (;;) {
    Token t = scanner->Peek();
    switch (t->kind()) {
      case IDENT:   stmt = ParseIdentStmt();  break;
      case OUTPUT:  stmt = ParseOutputStmt(); break;
      case IF:      stmt = ParseIfStmt();     break;
      case WHILE:   stmt = ParseWhileStmt();  break;
      default:      return stmts; // no more stmts
    }
    stmts->add(stmt);
    scanner->Read(SEMICOLON);
  }
}
```

<if stmt> ::= if <test> then <stmt list> end

Parser::ParseIfStmt()

```
Stmt* Parser::ParseIfStmt() {
  scanner->Read(IF);
  Expr* test = ParseTest();
  scanner->Read(THEN);
  StmtArray* stmts = ParseStmts();
  scanner->Read(END);
  return new IfStmt(test, stmts);
}
```


<while stmt> ::= while <test> do <stmt list> end

Parser::ParseWhileStmt()

```
Stmt* Parser::ParseWhileStmt() {
  scanner->Read(WHILE);
  Expr* test = ParseTest();
  scanner->Read(DO);
  StmtArray* stmts = ParseStmts();
  scanner->Read(END);
  return new WhileStmt(test, stmts);
}
```


<id stmt> ::= <call stmt> | <assign stmt>
<call stmt> ::= IDENT "(" [<exprs>] ")"
<assign stmt>::= <lvalue> := <expr>
<lvalue> ::= IDENT

Parser:: ParseIdentStmt()

```
Stmt* Parser:: ParseIdentStmt() {
  Token* id = scanner->Read(IDENT);
  if (scanner->CondRead(LPAREN)){
      ExprArray* args;
      if (scanner->CondRead(RPAREN)){
          args = NULL;
      } else {
          args = ParseExprs();
          scanner->Read(RPAREN);
      }
      return new CallStmt(id->ident(), args);
  } else {
      LValue* lvalue = new VarRef(id->ident());
      scanner->Read(GETS);
      return new AssignStmt(lvalue, ParseExpr());
}}
```


<sum> ::= <term> { (+ | -) <term> }

Parser::ParseSum()

```
Expr* Parser::ParseSum() {

  Expr* expr = ParseTerm();
  for (;;) {
    Token* t = scanner->Peek();
    if (t->kind() == PLUS || t->kind() == MINUS) {
      scanner->Get();   // eat the token
      Expr* expr2 = ParseTerm();
      expr = new BinOp(t->kind(), expr, expr2);
    } else {
      return expr;
    }
  }
}
```


<term> ::= <factor> { (* | /) <factor> }

Parser::ParseTerm()

```
Expr* Parser::ParseTerm() {

  Expr* expr = ParseFactor();
  for (;;) {
    Token* t = scanner->Peek();
    if (t->kind() == MUL || t->kind() == DIVIDE) {
      scanner->Get();   // eat the token
      Expr* expr2 = ParseFactor();
      expr = new BinOp(t->kind(), expr, expr2);
    } else {
      return expr;
    }
  }
}
```


Yacc – A bottom-up-parser generator

- "yet another compiler-compiler"
- Input:
  - grammar, possibly augmented with action code
- Output:
  - C code to parse it and perform actions
- LALR(1) parser generator
  - practical bottom-up parser
  - more powerful than LL(1)
- modern updates of yacc
  - yacc++, bison, byacc, …

Yacc input grammar Example

```
assignstmt: IDENT GETS expr
            ;
ifstmt:     IF test THEN stmts END
            | IF test THEN stmts ELSE stmts END
            ;
expr:       term
            | expr '+' term
            | expr '-' term
            ;
factor:     '-' factor
            | IDENT
            | INTEGER
            | INPUT
            | '(' expr ')'
            ;
```

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Yacc with actions

```
assignstmt: IDENT GETS expr    { $$ = new AssignStmt($1, $3);}
        ;
ifstmt:   IF be THEN stmts END{ $$ = new IfStmt($2,$4,NULL);}
        | IF be THEN stmts
              ELSE stmts END{ $$ = new IfStmt($2,$4,$6);}
        ;
expr:   term                  { $$ = $1; }
        | expr '+' term       { $$ = new BinOp(PLUS,  $1, $3);}
        | expr '-' term       { $$ = new BinOp(MINUS, $1, $3);}
        ;
factor: '-' factor            { $$ = new UnOp(MINUS, $2); }
        | IDENT               { $$ = new VarRef($1); }
        | INTEGER             { $$ = new IntLiteral($1); }
        | INPUT               { $$ = new InputExpr; }
        | '(' expr ')'        { $$ = $2; }
        ;
```

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Parsing summary

- Discover/impose a useful (hierarchical) structure on flat token sequence
  - Represented by Abstract Syntax Tree
- Validity check syntax of input
  - Could build concrete syntax tree (but don't)
- Many methods available
  - Top-down: LL(1)/recursive descent common for simple, by-hand projects
  - Bottom-up: LR(1)/LALR(1)/SLR(1) common for more complex projects
    - parser generator (e.g., yacc) almost necessary

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Parsing summary – Technical details you should know

- Context-free grammars
  - Definitions
  - Manipulations (algorithmic)
    - Left factor common prefixes
    - Eliminating left recursion
  - Ambiguity & (semi-heuristic) fixes
    - meta-rules (code/ precedence tables)
    - rewrite grammar
    - change language
- Building a table-driven predictive parser
  - LL(1) grammar: definition & common obstacles
  - PREDICT(nonterminal, input symbol)
  - FIRST(RHS)
  - FOLLOW(nonterminal)
- Building a recursive descent parser
  - Including AST

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Objectives: today

- Ambiguity
- Issues in designing a grammar
- AST extensions for the 401 project
- Overview of parsing algorithms
- Motivation and details of top-down, predictive parsers
- Recursive descent parsing
- Today++: a walk through the PL/0 parser

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Objectives: today

- Recap and clarify PREDICT table
- Describe computation of FIRST and FOLLOW
  - And the relationship to PREDICT
- Recursive descent parsing
  - High-level issues and
  - (time-permitting) a walk through the PL/0 parser

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```
Program        ::= module Id ; Block Id .
Block          ::= DeclList begin StmtList end
DeclList       ::= { Decl ; }
Decl           ::= ConstDecl | ProcDecl | VarDecl
ConstDecl      ::= const ConstDeclItem {, ConstDeclItem
   }
ConstDeclItem ::= Id : Type = ConstExpr
ConstExpr      ::= Id | Integer
VarDecl        ::= var VarDeclItem { , VarDeclItem }
VarDeclItem    ::= Id : Type
ProcDecl       ::= procedure Id ( [ FormalDecl
                   {, FormalDecl} ] ) ; Block Id
FormalDecl ::= Id : Type
Type       ::= int
StmtList   ::= { Stmt ; }
Stmt       ::= CallStmt | AssignStmt | OutStmt |
               IfStmt | WhileStmt
CallStmt   ::= Id ( [ Exprs ] )
AssignStmt ::= Lvalue := Expr
Lvalue     ::= Id
OutStmt   ::= output := Expr
IfStmt    ::= if Test then StmtList end
WhileStmt ::= while Test do StmtList end
Test      ::= odd Sum | Sum Relop Sum
Relop     ::= <= | <> | < | >= | > | =
Exprs     ::= Expr {, Expr }
Expr      ::= Sum
Sum       ::= Term { (+ | -) Term }
Term      ::= Factor { (* | /) Factor }
Factor    ::= - Factor | LValue | Integer |
              input | ( Expr )
```

AST extensions in project

- Expressions
  - `true` and `false` constants
  - array index expression (an lvalue)
  - function call expression
  - `and` and `or` operators
  - tests are expressions
  - constant expressions
- Statements
  - `for`
  - `break`
  - `return`
  - `if` with `else`
- Declarations
  - procedures with result types
  - `var` parameters
- Types
  - `bool`
  - `array`


```
if id then
  begin end
else
  while id do
    begin end
  end
```

```
ø   Stmt
1.  if Expr then Stmt else Stmt end
6.  if id then Stmt else Stmt end
3.  if id then begin Stmts end
           else Stmt end
5.  if id then begin end
           else Stmt end
2.  if id then begin end
           else while Expr do Stmt end
6.  if id then begin end
           else while id do Stmt end
3.  if id then begin end
           else while id do
                  begin Stmts end end
5.  if id then begin end
           else while id do
                  begin end end
```

Production applied