Compilation

0368-3133

Lecture 3:

Syntax Analysis: Top-Down parsing

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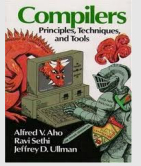
Recursive descent parsing

- Define a function for every nonterminal
- Every function work as follows
  - Find applicable production rule
  - Terminal function checks match with next input token
  - Nonterminal function calls (recursively) other functions
- If there are several applicable productions for a nonterminal, use lookahead

FIRST sets

- FIRST(X) = { t | X →* t β} ∪ {ℇ | X →* ℇ}
  - FIRST(X) = all terminals that α can appear as first in some derivation for X
    - + ℇ if can be derived from X

- Example:
  - FIRST(**LIT**) = { **true**, **false** }
  - FIRST(**(E OP E)**) = { **(** }
  - FIRST(**not E**) = { **not** }



p. 189

FOLLOW sets

- What do we do with nullable (ε) productions?
  - $A \rightarrow B\ C\ D \quad B \rightarrow \varepsilon\ C \rightarrow \varepsilon$
  - Use what comes afterwards to predict the right production
- For every production rule $A \rightarrow \alpha$
  - FOLLOW(A) = set of tokens that can immediately follow A
- Can predict the alternative A_k for a non-terminal N when the lookahead token is in the set
  - FIRST(A_k) $\rightarrow$ (if A_k is nullable then FOLLOW(N))

FOLLOW sets: Constraints

- $ ∈ FOLLOW(S)
- FIRST(β) – {ℰ} ⊆ FOLLOW(X)
  - For each A → α X β
- FOLLOW(A) ⊆ FOLLOW(X)
  - For each A → α X β and ℰ ∈ FIRST(β)

Example: FOLLOW sets

- E→ TX
- T→ (E) | int Y

X→+ E | ε

Y → * T | ε

Terminal	+	(	*	)	int
FOLLOW	int, (	int, (	int, (	+,), $	*,), +, $

Non. Term.	E	T	X	Y
FOLLOW	), $	+,), $	$,)	+,), $

Prediction Table

- $A \rightarrow \alpha$

- $T[A,t] = \alpha$ if $t \in FIRST(\alpha)$
- $T[A,t] = \alpha$ if $\varepsilon \in FIRST(\alpha)$ and $t \in FOLLOW(A)$
  - t can also be $

- T is not well defined → the grammar is not LL(1)

LL(k) grammars

- A grammar is in the class LL(K) when it can be derived via:
  - Top-down derivation
  - Scanning the input from left to right (L)
  - Producing the leftmost derivation (L)
  - With lookahead of k tokens (k)
- A language is said to be LL(k) when it has an LL(k) grammar

LL(1) grammars

- A grammar is in the class LL(1) iff
  - For every two productions $A \rightarrow \alpha$ and $A \rightarrow \beta$ we have
    - $FIRST(\alpha) \cap FIRST(\beta) = \{\}$ // including ε
    - If $\varepsilon \in FIRST(\alpha)$ then $FIRST(\beta) \cap FOLLOW(A) = \{\}$
    - If $\varepsilon \in FIRST(\beta)$ then $FIRST(\alpha) \cap FOLLOW(A) = \{\}$

Problem: Non LL Grammars

Problem 1: productions with common prefix

term → ID | indexed_elem
indexed_elem → ID [expr]

- The function for indexed_elem will never be tried…
  - What happens for input of the form **`ID[expr]`**

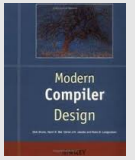
Problem 2: null productions

$S \rightarrow A\ a\ b$

$A \rightarrow a \mid \varepsilon$

```
S() {
  return  A()  ;  match(token('a'))  ;  match(token('b'))
}
A()  {
  match(token('a'))   ||   skip
}
```

- What happens for input "ab"?
- What happens if you flip order of alternatives and try "aab"?



Problem 3: left recursion

$E \rightarrow E$ - term | term

```
E() {
  return E()  ;  match(token('-'))   ;   term()
  ||
  term()
}
```

- What happens with this procedure?
- Recursive descent parsers cannot handle left-recursive grammars

What to do?

Problem: Non LL Grammars

$S \rightarrow A\ a\ b$

$A \rightarrow a \mid \varepsilon$

```
bool S() {
  return  A() && match(token('a')) && match(token('b'));
}

bool A()  {
 return  match(token('a')) || true;
}
```

- What happens for input "ab"?
- What happens if you flip order of alternatives and try "aab"?

Problem: Non LL Grammars

$S \rightarrow A\ a\ b$
$A \rightarrow a \mid \varepsilon$

- FIRST(S) = { a } FOLLOW(S) = { $ }
- FIRST(A) = { a, ε } FOLLOW(A) = { a }

- FIRST/FOLLOW conflict

Back to problem 1

term → ID | indexed_elem
indexed_elem → ID [expr]

- FIRST(term) = { ID }
- FIRST(indexed_elem) = { ID }

- FIRST/FIRST conflict

Solution: left factoring

- Rewrite the grammar to be in LL(1)

term → ID | indexed_elem
indexed_elem → ID [expr]

term → ID after_ID
After_ID → [expr] | ε

Intuition: just like factoring x*y + x*z into x*(y+z)

Left factoring – another example

$S \rightarrow$ if E then S else S
| if E then S
| T

$S \rightarrow$ if E then S S'
| T
$S' \rightarrow$ else S | ε

Back to problem 2

$S \rightarrow A\ a\ b$
$A \rightarrow a \mid \varepsilon$

- FIRST(S) = { a } FOLLOW(S) = { }
- FIRST(A) = { a , ε } FOLLOW(A) = { a }

- FIRST/FOLLOW conflict

Solution: substitution

$S \rightarrow A\ a\ b$
$A \rightarrow a \mid \varepsilon$

Substitute A in S

$S \rightarrow a\ a\ b \mid a\ b$

Left factoring

$S \rightarrow a\ after\_A$
$after\_A \rightarrow a\ b \mid b$

Back to problem 3

$E \rightarrow E$ - term | term

- Left recursion cannot be handled with a bounded lookahead

- What can we do?

Left recursion removal

$N \rightarrow N\alpha \mid \beta$

G_1

$N \rightarrow \beta N'$
$N' \rightarrow \alpha N' \mid \varepsilon$

G_2

Can be done algorithmically.
Problem: grammar becomes mangled beyond recognition

- $L(G_1) = \beta, \beta\alpha, \beta\alpha\alpha, \beta\alpha\alpha\alpha, \ldots$
- $L(G_2)$ = same

- For our 3rd example:

$E \rightarrow E$ - term | term

$E \rightarrow$ term TE | term
$TE \rightarrow$ - term TE | ε

LL(k) Parsers

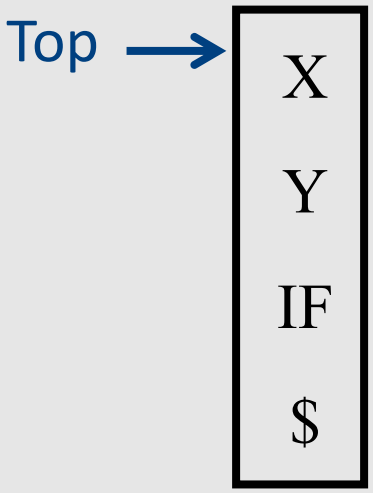
- Recursive Descent
  - Manual construction
  - Uses recursion

- Wanted
  - A parser that can be generated automatically
  - Does not use recursion

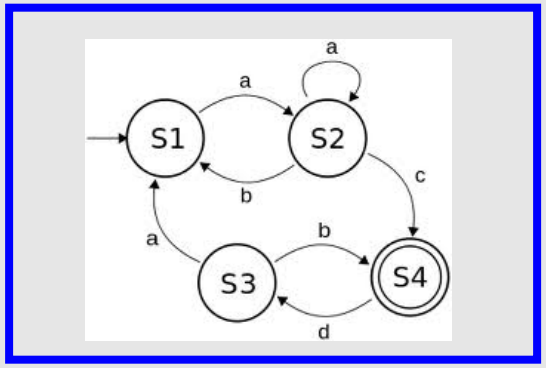
Pushdown Automata (PDA)

Intuition: PDA

- An ε-NFA with the additional power to manipulate **one** stack



stack



control (ε-NFA)

Intuition: PDA

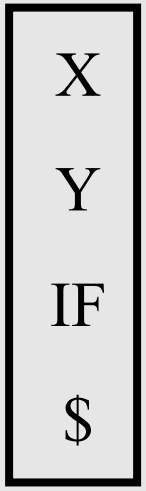
- Think of an ε-NFA with the additional power that it can manipulate a stack
- PDA moves are determined by:
  - The current state (of its "ε-NFA")
  - The current input symbol (or ε)
  - The current symbol on top of its stack

Intuition: PDA

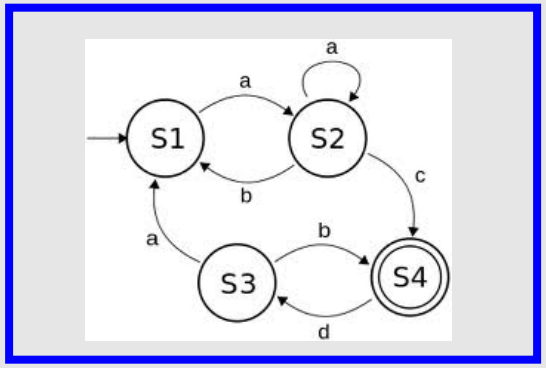
Current

input `if (oops) then stat:= blah else abort`

Top



stack



control (ε-NFA)

PDA Formalism

- PDA = (Q, Σ, Γ, δ, q_0, $, F):
  - Q: finite set of states
  - Σ: Input symbols alphabet
  - Γ: stack symbols alphabet
  - δ: transition function
  - q_0: start state
  - $: start symbol
  - F: set of final states

Tokens

Non terminals

LL(k) parsing via pushdown automata

- Pushdown automaton uses
  - Prediction stack
  - Input stream
  - Transition table
    - nonterminals x tokens -> production alternative
    - Entry indexed by nonterminal N and token t contains the alternative of N that must be predicated when current input starts with t

LL(k) parsing via pushdown automata

- Two possible moves
  - Prediction
    - When top of stack is nonterminal N, pop N, lookup table[N,t]. If table[N,t] is not empty, push table[N,t] on prediction stack, otherwise – syntax error
  - Match
    - When top of prediction stack is a terminal T, must be equal to next input token t. If (t == T), pop T and consume t. If (t ≠ T) syntax error
- Parsing terminates when prediction stack is empty
  - If input is empty at that point, success. Otherwise, syntax error

Example transition table

(1) E → LIT

(2) E → (E OP E)

(3) E → not E

(4) LIT → true

(5) LIT → false

(6) OP → and

(7) OP → or

(8) OP → xor

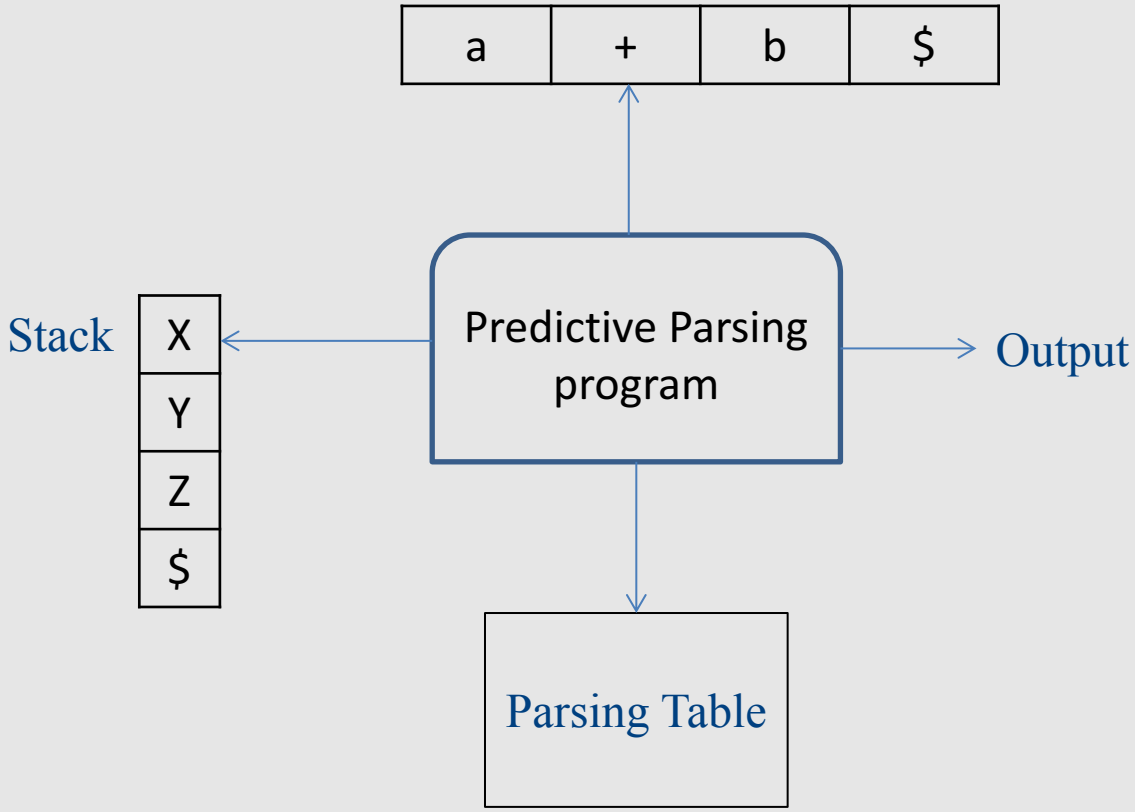
Which rule should be used

Input tokens

Nonterminals

	(	)	not	true	false	and	or	xor	$
E	2		3	1	1				
LIT				4	5				
OP						6	7	8	

Model of non-recursive predictive parser



Running parser example

aacbb$

$A \rightarrow aAb \mid c$

Input suffix	Stack content	Move
aacbb$	A$	predict(A,a) = A → aAb
aacbb$	aAb$	match(a,a)
acbb$	Ab$	predict(A,a) = A → aAb
acbb$	aAbb$	match(a,a)
cbb$	Abb$	predict(A,c) = A → c
cbb$	cbb$	match(c,c)
bb$	bb$	match(b,b)
b$	b$	match(b,b)
$	$	match($,$) – success

	a	b	c
A	A → aAb		A → c

Erorrs

Handling Syntax Errors

- Report and locate the error
- Diagnose the error
- Correct the error
- Recover from the error in order to discover more errors
  - without reporting too many “strange” errors

Error Diagnosis

- Line number
  - may be far from the actual error
- The current token
- The expected tokens
- Parser configuration

Error Recovery

- Becomes less important in interactive environments
- Example heuristics:
  - Search for a semi-column and ignore the statement
  - Try to “replace” tokens for common errors
  - Refrain from reporting 3 subsequent errors
- Globally optimal solutions
  - For every input w, find a valid program w’ with a “minimal-distance” from w

Illegal input example

abcbb$

A → aAb | c

Input suffix	Stack content	Move
abcbb$	A$	predict(A,a) = A → aAb
abcbb$	aAb$	match(a,a)
bcbb$	Ab$	predict(A,b) = ERROR

	a	b	c
A	A → aAb		A → c

Error handling in LL parsers

c$

S → a c | b S

Input suffix	Stack content	Move
c$	S$	predict(S,c) = ERROR

- Now what?
  - Predict b S anyway "missing token b inserted in line XXX"

	a	b	c
S	S → a c	S → b S	

Error handling in LL parsers

c$

S → a c | b S

Input suffix	Stack content	Move
bc$	S$	predict(b,c) = S → bS
bc$	bS$	match(b,b)
c$	S$	Looks familiar?

- Result: infinite loop

	a	b	c
S	S → a c	S → b S	

Error handling and recovery

- x = a * (p+q * (-b * (r-s);
  - Where should we report the error?
  - The valid prefix property

The Valid Prefix Property

- For every prefix tokens
  - $t_1, t_2, \ldots, t_i$ that the parser identifies as legal:
    - there exists tokens $t_{i+1}, t_{i+2}, \ldots, t_n$ such that $t_1, t_2, \ldots, t_n$ is a syntactically valid program

- If every token is considered as single character:
  - For every prefix word u that the parser identifies as legal there exists w such that u.w is a valid program

The Valid Prefix Property

- For every prefix tokens
  - $t_1, t_2, \ldots, t_i$ that the parser identifies as legal:
    - there exists tokens $t_{i+1}, t_{i+2}, \ldots, t_n$ such that $t_1, t_2, \ldots, t_n$ is a syntactically valid program

- If every token is considered as single character:
  - For every prefix word u that the parser identifies as legal there exists w such that u.w is a valid program

Recovery is tricky

- Heuristics for dropping tokens, skipping to semicolon, etc.

Building the Parse Tree

Adding semantic actions

- Can add an action to perform on each production rule
- Can build the parse tree
  - Every function returns an object of type Node
  - Every Node maintains a list of children
  - Function calls can add new children

Building the parse tree

```
Node E() {
  result = new Node();
  result.name = "E";
  if (current ∈ {TRUE, FALSE}) // E → LIT
    result.addChild(LIT());
  else if (current == LPAREN)  // E → ( E OP E )
    result.addChild(match(LPAREN));
    result.addChild(E());
    result.addChild(OP());
    result.addChild(E());
    result.addChild(match(RPAREN));
  else if (current == NOT)          // E → not E
    result.addChild(match(NOT));
    result.addChild(E());
  else error;
    return result;
}
```

Parser for Fully Parenthesized Expers

```
static int Parse_Expression(Expression **expr_p) {
  Expression *expr = *expr_p = new_expression() ;
  /* try to parse a digit */
  if (Token.class == DIGIT) {
        expr->type='D';  expr->value=Token.repr -'0';
        get_next_token();
        return 1;       }
/* try parse parenthesized expression */
if (Token.class == '(') {
      expr->type='P';   get_next_token();
      if (!Parse_Expression(&expr->left))  Error("missing expression");
      if (!Parse_Operator(&expr->oper))  Error("missing operator");
      if (Token.class != ')') Error("missing )");
      get_next_token();
      return 1; }
return 0;
}
```