Parser Generation

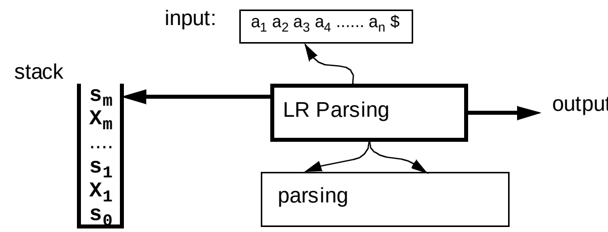
- ***Main Problem**: given a grammar **G**, how to build a **top-down parser** or a **bottom-up parser** for it ?*
- ***parser** : a program that, given a sentence, reconstructs a derivation for that sentence ---- if done sucessfully, it "recognize" the sentence*
- *all parsers read their input **left-to-right**, but construct parse tree differently.*
- ***bottom-up parsers ---** construct the tree from leaves to root*

  shift-reduce, LR, SLR, LALR, operator precedence
- ***top-down parsers ---** construct the tree from root to leaves*

  recursive descent, predictive parsing, LL(1)

Bottom-Up Parsing

- *Construct parse tree "bottom-up" --- from leaves to the root*
- *Bottom-up parsing always constructs **right-most derivation***
- *Important parsing algorithms: **shift-reduce**, **LR parsing***
- ***LR parser** components: input, stack (strings of grammar symbols and **states**), driver routine, parsing tables.*



LR Parsing

- *A sequence of new **state** symbols* $s_0, s_1, s_2, \ldots, s_m$ *----- each state sumarize the information contained in the stack below it.*
- *<u>Parsing configurations</u>: **(stack, remaining input)** written as*

  $(s_0 X_1 s_1 X_2 s_2 \ldots X_m s_m\ ,\ a_i a_{i+1} a_{i+2} \ldots a_n \$)$

  next "move" is determined by s_m and a_i
- *<u>Parsing tables</u>:* **`ACTION[s,a]`** *and* **`GOTO[s,X]`**

  Table A **`ACTION[s,a]` --- s : *state*, a : *terminal***

  its entries **(1) shift s_k** **(2) reduce *A* -> ?**
  (3) accept **(4) error**

  Table G **`GOTO[s,X]` --- s : *state*, X : *non-terminal***
  *its entries are **states***

Constructing LR Parser

How to construct the parsing table `ACTION` and `GOTO` ?

- ***basic idea**: first construct DFA to recognize handles, then use DFA to construct the parsing tables ! different parsing table yield different LR parsers **SLR(1)**, **LR(1)**, or **LALR(1)***
- ***augmented grammar** for context-free grammar **G** = **G**(T,N,P,S) is defined as **G' = G'**(T, N ? { S'}, P ? { S' -> S}, S') ------ adding non-terminal S' and the production S' -> S, and S' is the new start symbol. When S' -> S is reduced, parser accepts.*
- ***LR(0) item** for productions of a context-free grammar G ----- is a production with **dot** at some position in the r.h.s.*

  For *A -> XYZ* , its items are *A -> .XYZ* *A -> X.YZ*
  A -> XY.Z *A -> XYZ.*

  For *A* -> ? , its items are just *A -> .*

LR(0) items and LR(0) DFA

- *Informally, item* `A -> X.YZ` *means a string derivable from X has been seen, and one from YZ is expected.* ***LR(0) items*** *are used as state names for LR(0) DFA or LR(0) NFA that recognizes* ***viable prefixes.***
- ***Viable prefixes*** *of a CFG are prefixes of right-sentential forms with no symbols to right of the* ***handle****; we can always add terminals on right to form a right-sentential form.*
- ***Two way to construct the LR(0) DFA:***

  1. first construct LR(0) NFA and then convert it to a DFA !

  2. construct the LR(0) DFA directly !

- ***From LR(0) DFA to the Parsing Table*** *-------- transition table for the DFA is the* **GOTO** *table; the states of DFA are states of the parser.*

Example: LR(0) Items

CFG Grammar:

```
E -> E + T | T
T -> T * F | F
F -> ( E ) | id
```

Augmented Grammar:

```
E' -> E
E  -> E + T | T
T  -> T * F | F
F  -> ( E ) | id
```

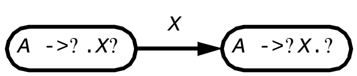
LR(0) terms:

E' -> . E	T -> . T * F	F -> (E .)
E' -> E .	T -> T . * F	F -> (E) .
E -> . E + T	T -> T * . F	F -> . id
E -> E . + T	T -> T * F .	F -> id .
E -> E + . T	T -> . F	
E -> E + T .	T -> F .	
E -> . T	F -> . (E)	
E -> T .	F -> (. E)	

From LR(0) NFA to LR(0) DFA

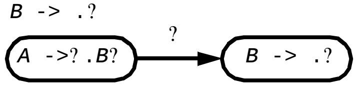
- *Construct* ***LR(0) NFA*** *with all LR(0) items of G as states, connect states by moving the* ***dot****;* ***final states*** *are those with dots at the end.*

  1. for each item `A -> ?.X ?`



  2. for each pair `A -> ?.B ?,  B -> .?`

  (expect to see a string derivable from ?)



- *Convert NFA to DFA using* ***subset construction algorithm.***
- *The states of the resulting* ***LR(0) DFA*** *---* $\mathbf{C = \{I_1, I_2, ..., I_n\}}$ *are called* ***canonical LR(0) collection*** *for grammar G'*
- ***Disadvantage****: the NFA is often huge, and converting from NFA to DFA is tedious and time-consuming.*

Building LR(0) DFA Directly

- *Instead of building DFA from NFA,* ***we can build the LR(0) DFA directly****.*
- *Given a set of LR(0) items* **I** *,* **CLOSURE(I)** *is defined as*

```
repeat
  for each item A -> ?.B? in I and
      each production B -> ?
            add B -> .? to I, if it's not in I
until I does not change
```

- **GOTO(I,X)** *is defined as*

  CLOSURE(*all items* `A -> ?X.?` *for each* `A -> ?.X?` *in* **I**)

- ***Canonical LR(0) collection*** *is computed by the following procedure:*

```
I0 = CLOSURE({S' -> .S}) and C = {I0}
repeat
  for each I?? C and grammar symbol X
    T = GOTO(I,X); if T ?? and T ? C then C = C ??{ T };
until C does not change
```

Resulting **`LR(0) DFA`*****:*** **`C`** ***is the set of states;*** **`GOTO`** ***is the transition table***

Constructing SLR(1) Parsing Table

- *From the **LR(0) DFA**, we can construct the parsing table ----- **SLR(1) parsing table.** The parser based on SLR(1) parsing table is called **SLR(1) parser**. The **SLR(1) grammars** are those whose SLR(1) parsing table does **not** contain any conflicts.*

- ***Algorithm --- use*** **`C = {I0,...,In}, GOTO, FOLLOW:`**

  1. **If** A -> ?.a? **is in I_i and GOTO(I_i,a) = I_j where** a **is a terminal, set ACTION[**i,a**] to "shift j".**
  2. **If** A -> ?. **is in I_i, set ACTION[**i,a**] to "reduce** A **->** ?**" for all terminal** a **in FOLLOW(**A**).**
  3. **If S' -> S. is in I_i, set ACTION[$_i$,$] to "accept"**
  4. **If GOTO(I_i,A) = I_j, set GOTO[i,A] = j**
  5. **set all other entries to "error"**
  6. **set initial state to be I_i with** S' -> .S

Limitation of SLR(1) Parser

- *Unfortunately, many **unambiguous** grammars are not SLR(1) gammars*

```
S -> L = R | R          L  means "l-value"
L -> *R | id            R  means "r-value"
R -> L                  *  means "contents of"
```

Canonical LR(0) collection ---

```
I0 : S' -> .S        I3:  S -> R.         I6: S -> L=.R
     S -> .L=R                                R -> .L
     S -> .R         I4:  L -> *.R            L -> .*R
     L -> .*R             R -> .L             L -> .id
     L -> .id             L -> .*R
     R -> .L              L -> .id        I7: L -> *R.

I1 : S' -> S.        I5:  L -> id.        I8: R -> L.

I2 : S -> L.=R                            I9: S -> L=R.
     R -> L.           FOLLOW(R) = {=,...}
```

state 2 has a shift/reduce conflict on **"="** *: shift 6 or reduce* `R -`

LR(1) Parsing

- *Conflict arises because **LR(0) states** do not encode enough left context --- in the previous example, reduction* `R -> L` *is wrong upon input* **`=`** *because "*`R = ...`*" **never** appears in right-sentential form.*

- ***Solution**: split LR(0) states by adding terminals to states, for example,* `[ A -> ?. , a]` *results in reduction only if next symbol is* `a`*.*

- ***An LR(1) term** is in the form of* `[ A -> ?.? , a ]` *where* `A -> ??` *is a production and* `a` *is a terminal or* **`$`**

- *To build **LR(1) parsing table** --- we first build **LR(1) DFA** --- then construct the parsing table using the same SLR(1) algorithm except*

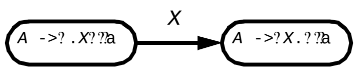
  2. only if `[A -> ?. , a]` *is in* **I_i** *, then set* **`ACTION[`**`i,a`**`]`** *to "reduce* `A-> ?`*"*

- *To way to build **LR(1) DFA** ---- from NFA -> DFA or build DFA directly*

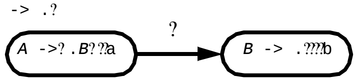
Building LR(1) DFA

- *Construct **LR(1) NFA** with all LR(1) items of G as states, connect states by moving the **dot**; then convert the NFA to DFA.*

*1. **for each item** [A -> ? .X ? ,a]*



*2. **for each pair** [A -> ? .B? , a] B -> .?*
***and** b **in** FIRST(??a).*



- *Construct the LR(1) DFA directly (see the Dragon book)*
- *Given a set of LR(1) items* **I** *,* **CLOSURE(I)** *is now defined as*

```
repeat
  for each item [A -> ?.B? , a] in I and
      each production B -> ?? and each terminal b in FIRST(?a)
              add [B -> .??? a] to I, if it's not in I
  until I does not change
```


Constructing LR(1) Parser

- ***Canonical LR(1) collection** is computed by the following procedure:*

```
I0 = CLOSURE([S' -> .S , $]) and C = {I0}
repeat
  for each I?? C and grammar symbol X
    T = GOTO(I,X); if T ? ?  and T ? C then C = C ? { T };
until C does not change
```

Resulting** LR(1) DFA**:** C **is the set of states;** GOTO **is the transition table

- *From the **LR(1) DFA**, we can construct the parsing table ----- **LR(1) parsing table.** The parser based on LR(1) parsing table is called **LR(1) parser**. The **LR(1) grammars** are those whose LR(1) parsing table does **not** contain any conflicts (no duplicate entries).*
- ***Example:***

```
S' -> S
S -> C C
C -> c C | d
```


LALR(1) Parsing

- ***Bad News:** LR(1) parsing tables are too big; for PASCAL, SLR tables has about 100 states, LR table has about 1000 states.*
- ***LALR** (LookAhead-LR) parsing tables have same number of states as SLR, but use lookahead for reductions. The **LALR(1) DFA** can be constructed from the **LR(1) DFA.***
- ***LALR(1) states** can be constructed from LR(1) states by merging states with same **core**, or same LR(0) items, and **union** their lookahead sets.*

```
Merging  I8: C -> cC., c/d          I9: C -> cC., $
into a new state     I89:  C -> cC., c/d/$

Merging  I3: C -> c.C, c/d          I6: C -> c.C, $
             C -> .cC, c/d              C -> .cC, $
             C -> .d, c/d               C -> .d, $
into a new state     I36:  C -> c.C, c/d/$
                           C -> .cC, c/d/$
                           C -> .d, c/d/$I
```


LALR(1) Parsing (cont'd)

- *From the **LALR(1) DFA**, we can construct the parsing table ----- **LALR(1) parsing table.** The parser based on LALR(1) parsing table is called **LALR(1) parser**. The **LALR(1) grammars** are those whose LALR(1) parsing table does **not** contain any conflicts (no duplicate entries).*
- *LALR(1) DFA and LALR(1) parsing table can be constructed without creating LR(1) DFA --- see Dragon book for detailed algorithm.*
- ***LALR parser** makes same number of moves as LR parser on **correct input.***
- ***On incorrect input,** LALR parser may make erroneous reductions, but will signal "error" before shifting input, i.e., merging states makes reduce determination "less accurate", but has no effect on shift actions.*

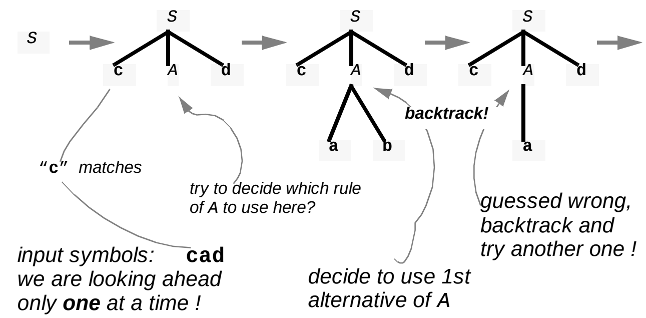
Summary: LR Parser

- *Relation of three LR parsers:* ***LR(1) > LALR(1) > SLR(1)***
- *Most programming language constructs are **LALR(1)**. The **LR(1)** is unnecessary in practice, but the **SLR(1)** is not enough.*
- *YACC is an LALR(1) Parser Generator.*
- *When parsing ambiguious grammars using LR parsers, the parsing table will contain multiple entries. We can specify the **precedence** and **associativity** for terminals and productions to resolve the conflicts. YACC uses this trick.*
- ***Other Issues** in parser implementation: 1. compact representation of parsing table 2. error recovery and diagnosis.*

Top-Down Parsing

- ***Starting from the start symbol** and "guessing" which production to use next step. It often uses **next input token** to guide "guessing".*

example: *S* -> **c** *A* **d**
A -> **ab** | **a**



Top-Down Parsing (cont'd)

- *Typical implementation is to write a **recursive procedure** for each **non-terminal** (according to the r.h.s. of each grammar rule)*

Grammar:

```
E  -> T E'

E' -> + T E'
    | ?

T  -> F T'

T' -> * F T'
    | ?

F  -> id
    | ( E )
```

`advance` *sets* `c` *to next input token*
`err` *reports error message*

```
fun e() = (t(); eprime())

and eprime() = if (c = "+")
  then (advance(); t(); eprime())

and t() = (f(); tprime())

and tprime() = if (c = "*")
  then (advance(); f(); tprime())

and f() =
  (if (c = id) then advance()
   else if (c = "(") then
     (advance(); e();
      if (c=")") then advance() else err())
     else err()
```


Recursive Descent Parsing

- *The previously referred top-down parsing method is often called **recursive descent parsing** !*
- ***Main challenges:***

1. **back-tracking** is messy, difficult and inefficient
   (<u>solution</u>: use input "lookahead" to help make the right choice)
2. **more alternatives** --- even if we use one lookahead input char, there are still > 1 rules to choose --- *A* -> **ab** | **a**
   (**solution**: rewrite the grammar by **left-factoring**)
3. **left-recursion** might cause infinite loop
   what is the procedure for *E* -> *E* **+** *E* ?
   (**solution**: rewrite the grammar by **eliminating left-recursions**)
4. **error handling ---** errors detected "far away" from actual source.

Algorithm: Recursive Descent

- ***Parsing Algorithm (using 1-symbol lookahead in the input)***

  1. Given a set of grammar rules for a non-terminal ***A***

     A `-> ?1 | ?2 | ... | ?n`

     we choose proper alternative by looking at first symbol it derives ---- the next input symbol decides which ?$_i$ we use

  2. for `A -> ?`, it is taken when none of the others are selected

- ***Algorithm****: constructing a recursive descent parser for grammar* ***G***

  1. transform grammer ***G*** *to* ***G'*** *by removing left-recursions and do the left-factoring.*

  2. write a (recursive) procedure for each non-terminal in ***G'***

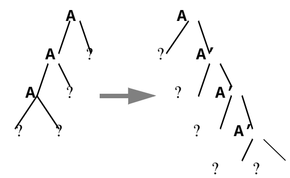
Left Recursion Elimination

- *Elimination of* ***Left Recursion*** *(useful for top-down parsing only)*

  replace productions of the form `A -> A ? | ?`

  with `A -> ??A'`
  `A' -> ? A' | ?`

  (yields different parse trees but same language)



```
example:
  E -> E + T | T
  T -> T * F | F
  F -> ( E ) | id
become

  E  -> T E'
  E' -> + T E' | ?
  T  -> F T'
  T' -> * F T' | ?
  F  -> ( E ) | id
```

Important: read Appel pp 51 - 53 for details

Left Factoring

- *Some grammars are unsuitable for recursive descent, even if there is no left recursion*

  *"****dangling-else****"*
  ```
  stmt -> if expr then stmt
        | if expr then stmt else stmt
        | ......
  ```

  input symbol **`if`** *does not uniquely determine alternative.*

- ***Left Factoring*** *--- factor out the common prefixes (****see AHU pp 178****)*

  change the production `A -> x y | x z`

  to `A -> x A'`
  `A' -> y | z`

  thus
  ```
  stmt -> if expr then stmt S'
    S' -> else stmt | ?
  ```


Predictive Parsing

- ***Predictive parsing*** *is just* ***table-driven*** *recursive descent; it contains:*

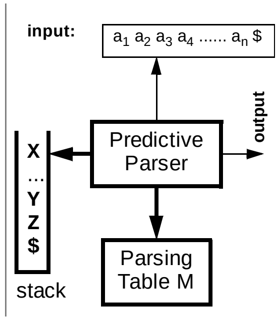
  A **parsing stack** --- contains terminals and non-terminals

  A **parsing table** : a 2-dimensional table **`M[X,a]`** where **`X`** is non-terminal, **`a`** is terminal, and table entries are *grammar productions* or *error indicators* .

algorithm `$` ***is end-of-file,*** *S* ***is start symbol***

```
push($); push(S);

while top <> $ do (
   a <- the input char
   if top is a terminal or $ then
       (if top == a then
              pop(); advance()
        else err())
   else if M[top,a] is X->Y1Y2...Yk then
             (pop();
              push(Yk); ...; push(Y1))
        else err()
)
```



Constructing Predictive Parser

- *The key is to build the parse table* **M[A,a]**

```
for each production A -> ? do
  for each a?? ?FIRST(?) do
        add A -> ? to M[A,a]
  if ? ? FIRST(?) then
        for each b?? ?FOLLOW(A) do
            add A -> ? to M[A,b]

rest of M is error
```

- **FIRST**(?) *is a set of terminals (plus ?) that* ***begin*** *strings derived from* ?, *where* ? *is any string of non-terminals and terminals.*
- **FOLLOW**(*A*) *is a set of terminals that can* ***follow*** *A in a sentential form, where A is any non-terminal*

C S 4 2 1 C O M P I L E R S A N D I N T E R P R E T E R S

First & Follow

- *To compute* **FIRST(X)** *for any grammar symbol* **X** *:*

```
FIRST(X) = {X},           if X is a terminal;
FIRST(X) = FIRST(X)?? ?{a}, if X -> a?;
FIRST(X) = FIRST(X)?? ?{?}, if X -> ? ; and
FIRST(X) = FIRST(X)?? ?FIRST(Y1Y2...Yk),
                             if X -> Y1Y2...Yk .
```

repeat until nothing new is added to any **FIRST**

- **FIRST**($Y_1Y_2...Y_k$) = **FIRST**(Y_1)**-{**?**}**
  - ? **FIRST**(Y_2)**-{**?**}** *if* ??? ?**FIRST**(Y_1)
  - ? **FIRST**(Y_3)**-{**?**}** *if* ??? ?**FIRST**(Y_1Y_2)
  - ....
  - ? **FIRST**(Y_k)**-{**?**}** *if* ??? ?**FIRST**($Y_1...Y_{k-1}$)
  - ? **{**?**}** *if all* **FIRST**(Y_i)$_{(i=1,...,k)}$ *contain* ?

C S 4 2 1 C O M P I L E R S A N D I N T E R P R E T E R S

First & Follow (cont'd)

- *To compute* **FOLLOW(X)** *for any non-terminal* **X** *:*

```
FOLLOW(S) = FOLLOW(S) ? ?{$},      if S is start symbol;

FOLLOW(B) = FOLLOW(B)?? ?(FIRST(?) - {?}),
                        if A -> ? ?B?? and ?????

FOLLOW(B) = FOLLOW(B)?? ?FOLLOW(A)
        if A -> ? ?B  or  ?A -> ? ?B?? ?and ??? ?FIRST(?)
```

- ***Example:***

	reason
FOLLOW(E) = {**$**},	E *is start symbol*
= {**$)**},	F -> **(** E **)**
FOLLOW(E')= **FOLLOW**(E)	E -> T E'
= {**$)**},	

(Read Appel pp 47 - 53 for detailed examples)

C S 4 2 1 C O M P I L E R S A N D I N T E R P R E T E R S

Summary: LL(1) Grammars

- *A grammar is* ***LL(1)*** *if parsing table* **M[A,a]** *has no duplicate entries, which is equivalent to specifying that for each production*

  A -> $?_1$ | $?_2$ | ... | $?_n$

  1. All **FIRST**($?_i$) *are disjoint.*

  2. At most one $?_i$ *can derive* ? *; in that case,* **FOLLOW**(***A***) *must be disjoint from* **FIRST**($?_1$)?? ?**FIRST**($?_2$)?? ??????? ?**FIRST**($?_n$)?

- *Left-recursion and ambiguity grammar lead to* ***multiple entries*** *in the parsing table. (try the* ***dangling-else*** *example)*
- *The* ***main difficulty*** *in using (top-down)* ***predicative parsing*** *is in rewriting a grammar into an LL(1) grammar. There is no general rule on how to resolve* ***multiple entries*** *in the parsing table.*