CSE 401 – Compilers

LR Parser Construction

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Agenda

- LR(0) state construction
- FIRST, FOLLOW, and nullable
- Variations: SLR, LR(1), LALR

LR State Machine

- Idea: Build a DFA that recognizes handles
  - Language generated by a CFG is generally not regular, but
  - Language of handles for a CFG is regular
    - So a DFA can be used to recognize handles
  - Parser reduces when DFA accepts

Prefixes, Handles, &c (review)

- If S is the start symbol of a grammar G,
  - If $S =>^* \alpha$ then α is a *sentential form* of G
  - γ is a *viable prefix* of G if there is some derivation $S =>^*_{rm} \alpha A w =>^*_{rm} \alpha\beta w$ and γ is a prefix of $\alpha\beta$.
  - The occurrence of β in $\alpha\beta w$ is a *handle* of $\alpha\beta w$
- An *item* is a marked production (a . at some position in the right hand side)
  - [*A* ::= . *X Y*] [*A* ::= *X* . *Y*] [*A* ::= *X Y* .]

Building the LR(0) States

- Example grammar

  $S' ::= S\,\$$

  $S ::= (\ L\ )$

  $S ::= \mathrm{x}$

  $L ::= S$

  $L ::= L\ ,\ S$

  - We add a production S' with the original start symbol followed by end of file ($)
  - Question: What language does this grammar generate?

0. $S' ::= S\$$
1. $S ::= (L)$
2. $S ::= x$
3. $L ::= S$
4. $L ::= L , S$

Start of LR Parse

- Initially
  - Stack is empty
  - Input is the right hand side of S', i.e., $S\$$
  - Initial configuration is $[S' ::= .\ S\$]$
  - But, since position is just before S, we are also just before anything that can be derived from S

0. $S' ::= S\,\$$
1. $S ::= (\ L\ )$
2. $S ::= \mathrm{x}$
3. $L ::= S$
4. $L ::= L\ ,\ S$

Initial state

$$S' ::= .\ S\,\$$$
$$S ::= .\ (\ L\ )$$
$$S ::= .\ \mathrm{x}$$

start

completion

- A state is just a set of items
  - Start: an initial set of items
  - Completion (or closure): additional productions whose left hand side appears to the right of the dot in some item already in the state

0. $S' ::= S\ \$$
1. $S ::= (\ L\ )$
2. $S ::= \mathrm{x}$
3. $L ::= S$
4. $L ::= L\ ,\ S$

Shift Actions (1)

$$\boxed{\begin{array}{l} S' ::= .\ S\ \$ \\ S ::= .\ (\ L\ ) \\ S ::= .\ \mathrm{x} \end{array}} \xrightarrow{\mathrm{x}} \boxed{S ::= \mathrm{x}\ .}$$

- To shift past the x, add a new state with the appropriate item(s)
  - In this case, a single item; the closure adds nothing
  - This state will lead to a reduction since no further shift is possible

Shift Actions (2)

0. $S' ::= S\,\$$
1. $S ::= (\ L\ )$
2. $S ::= \mathrm{x}$
3. $L ::= S$
4. $L ::= L\ ,\ S$

$$\boxed{\begin{array}{l} S' ::= .\ S\,\$ \\ S ::= .\ (\ L\ ) \\ S ::= .\ \mathrm{x} \end{array}} \xrightarrow{\ (\ } \boxed{\begin{array}{l} S ::= (\ .\ L\ ) \\ L ::= .\ L\ ,\ S \\ L ::= .\ S \\ S ::= .\ (\ L\ ) \\ S ::= .\ \mathrm{x} \end{array}}$$

- If we shift past the (, we are at the beginning of *L*
- the closure adds all productions that start with *L*, which requires adding all productions starting with *S*

Goto Actions

0. $S' ::= S\,\$$
1. $S ::= (\, L \,)$
2. $S ::= \mathrm{x}$
3. $L ::= S$
4. $L ::= L \,,\, S$

$$\boxed{\begin{array}{l} S' ::= .\ S\,\$ \\ S ::= .\ (\ L\ ) \\ S ::= .\ \mathrm{x} \end{array}} \xrightarrow{\ S\ } \boxed{S' ::= S\ .\ \$}$$

- Once we reduce *S*, we'll pop the rhs from the stack exposing the first state. Add a *goto* transition on *S* for this.

Basic Operations

- *Closure* (*S*)
  - Adds all items implied by items already in *S*
- *Goto* (*I*, *X*)
  - *I* is a set of items
  - *X* is a grammar symbol (terminal or non-terminal)
  - *Goto* moves the dot past the symbol *X* in all appropriate items in set *I*

Closure Algorithm

- *Closure* (S) =

  repeat

  for any item [A ::= α . $X\beta$] in S

  for all productions X ::= γ

  add [X ::= . γ] to S

  until S does not change

  return S

Goto Algorithm

- *Goto* (*I*, *X*) =

  set *new* to the empty set

  for each item [A ::= α . *X* β] in *I*

  add [A ::= α *X* . β] to *new*

  return *Closure* (*new*)

  - This may create a new state, or may return an existing one

LR(0) Construction

- First, augment the grammar with an extra start production $S' ::= S\,\$$
- Let T be the set of states
- Let E be the set of edges
- Initialize T to *Closure*($[S' ::= .\ S\,\$]$)
- Initialize E to empty

LR(0) Construction Algorithm

repeat
  for each state I in T
    for each item $[A ::= \alpha\ .\ X\ \beta]$ in I
      Let *new* be *Goto* (I, X)
      Add *new* to T if not present
      Add $I \xrightarrow{X}$ *new* to E if not present
until E and T do not change in this iteration

- Footnote: For symbol \$, we don't compute *goto* (I, \$); instead, we make this an *accept* action.

LR(0) Reduce Actions

- Algorithm:

  Initialize R to empty

  for each state I in T

  for each item $[A ::= \alpha\ .]$ in I

  add $(I, A ::= \alpha)$ to R

Building the Parse Tables (1)

- For each edge $I \xrightarrow{X} J$
  - if X is a terminal, put sj in column X, row I of the action table (shift to state j)
  - If X is a non-terminal, put gj in column X, row I of the goto table

Building the Parse Tables (2)

- For each state I containing an item $[S' ::= S\ .\ \$]$, put *accept* in column \$ of row I
- Finally, for any state containing $[A ::= \gamma\ .]$ put action r*n* in every column of row I in the table, where n is the production number

Example: States for

0. $S' ::= S \$$
1. $S ::= (L)$
2. $S ::= \mathrm{x}$
3. $L ::= S$
4. $L ::= L , S$

Example: Tables for

0. $S' ::= S\,\$$
1. $S ::= (\ L\ )$
2. $S ::= \mathrm{x}$
3. $L ::= S$
4. $L ::= L\ ,\ S$

Where Do We Stand?

- We have built the LR(0) state machine and parser tables
  - No lookahead yet
  - Different variations of LR parsers add lookahead information, but basic idea of states, closures, and edges remains the same

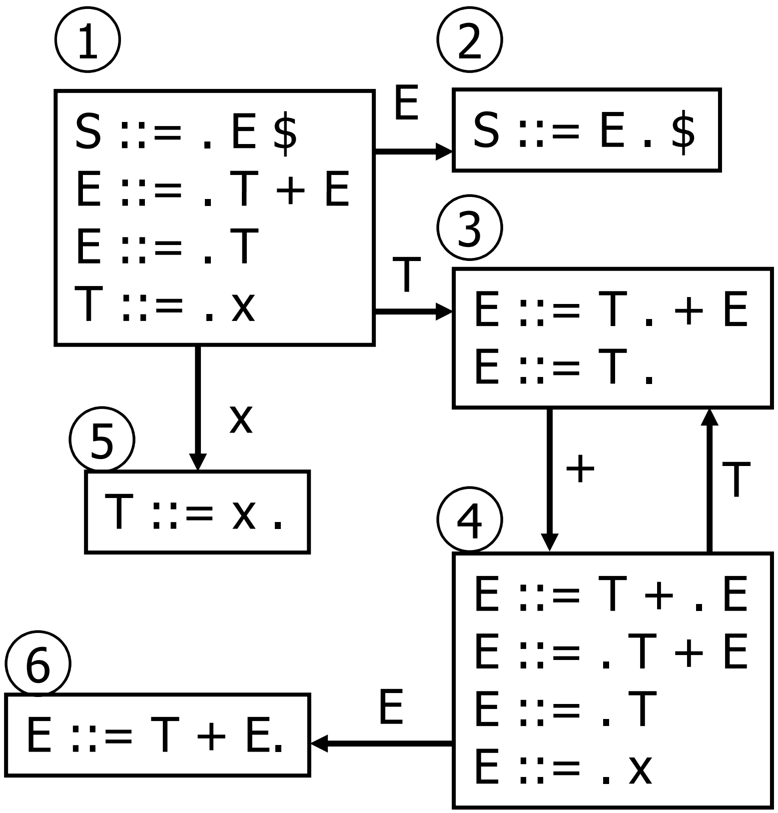
A Grammar that is not LR(0)

- Build the state machine and parse tables for a simple expression grammar

$$S ::= E\,\$$$
$$E ::= T + E$$
$$E ::= T$$
$$T ::= \mathrm{x}$$

LR(0) Parser for

0. *S* ::= *E* $
1. *E* ::= *T* + *E*
2. *E* ::= *T*
3. *T* ::= x



	x	+	$	E	T
1	s5			g2	G3
2			acc		
3	r2	s4,r2	r2		
4	s5			g6	G3
5	r3	r3	r3		
6	r1	r1	r1		

- State 3 is has two possible actions on +
  - shift 4, or reduce 2
- ∴ Grammar is not LR(0)

SLR Parsers

- Idea: Use information about what can follow a non-terminal to decide if we should perform a reduction
- Easiest form is SLR – Simple LR
- So we need to be able to compute FOLLOW(*A*) – the set of symbols that can follow *A* in any possible derivation
  - But to do this, we need to compute FIRST(γ) for strings γ that can follow *A*

Calculating FIRST(γ)

- Sounds easy… If $\gamma = X\,Y\,Z$, then FIRST(γ) is FIRST(X), right?
  - But what if we have the rule $X ::= \varepsilon$?
  - In that case, FIRST(γ) includes anything that can follow an X – i.e. FOLLOW(X)

FIRST, FOLLOW, and nullable

- nullable(X) is true if X can derive the empty string
- Given a string γ of terminals and non-terminals, FIRST(γ) is the set of terminals that can begin strings derived from γ.
- FOLLOW(X) is the set of terminals that can immediately follow X in some derivation
- All three of these are computed together

Computing FIRST, FOLLOW, and nullable (1)

- Initialization

  set FIRST and FOLLOW to be empty sets

  set nullable to false for all non-terminals

  set FIRST[a] to a for all terminal symbols a

Computing FIRST, FOLLOW, and nullable (2)

repeat
    for each production $X := Y_1\ Y_2 \ldots Y_k$
        if $Y_1 \ldots Y_k$ are all nullable (or if $k = 0$)
            set nullable[X] = true
        for each i from 1 to k and each j from i+1 to k
            if $Y_1 \ldots Y_{i-1}$ are all nullable (or if $i = 1$)
                    add FIRST[Y_i] to FIRST[X]
            if $Y_{i+1} \ldots Y_k$ are all nullable (or if $i = k$)
                    add FOLLOW[X] to FOLLOW[Y_i]
            if $Y_{i+1} \ldots Y_{j-1}$ are all nullable (or if i+1=j)
                    add FIRST[Y_j] to FOLLOW[Y_i]
Until FIRST, FOLLOW, and nullable do not change

Example

- Grammar

  $Z ::= \text{d}$

  $Z ::= X\ Y\ Z$

  $Y ::= \varepsilon$

  $Y ::= \text{c}$

  $X ::= Y$

  $X ::= \text{a}$

	nullable	FIRST	FOLLOW
X			
Y			
Z			

SLR Construction

- This is identical to LR(0) – states, etc., except for the calculation of reduce actions
- Algorithm:

  Initialize R to empty

  for each state I in T

  for each item [$A ::= \alpha$.] in I

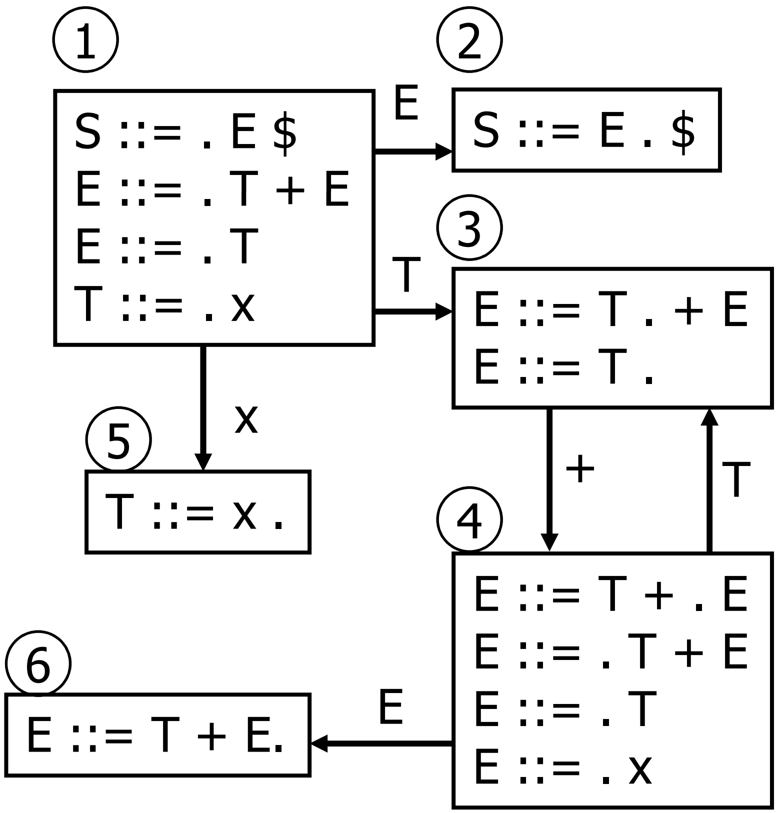
  for each terminal a in FOLLOW(A)

  add (I, a, $A ::= \alpha$) to R

  - i.e., reduce α to A in state I only on lookahead a

SLR Parser for

0. S ::= E $
1. E ::= T + E
2. E ::= T
3. T ::= x



	x	+	$	E	T
1	s5			g2	g3
2			acc		
3		s4	r2		
4	s5			g6	g3
5		r3	r3		
6			r1		

On To LR(1)

- Many practical grammars are SLR
- LR(1) is more powerful yet
- Similar construction, but notion of an item is more complex, incorporating lookahead information

LR(1) Items

- An LR(1) item [A ::= α . β, a] is
  - A grammar production (A ::= $\alpha\beta$)
  - A right hand side position (the dot)
  - A lookahead symbol (a)
- Idea: This item indicates that α is the top of the stack and the next input is derivable from βa.
- Full construction: see the book

LR(1) Tradeoffs

- LR(1)
  - Pro: extremely precise; largest set of grammars
  - Con: potentially very large parse tables with many states

LALR(1)

- Variation of LR(1), but merge any two states that differ only in lookahead
  - Example: these two would be merged

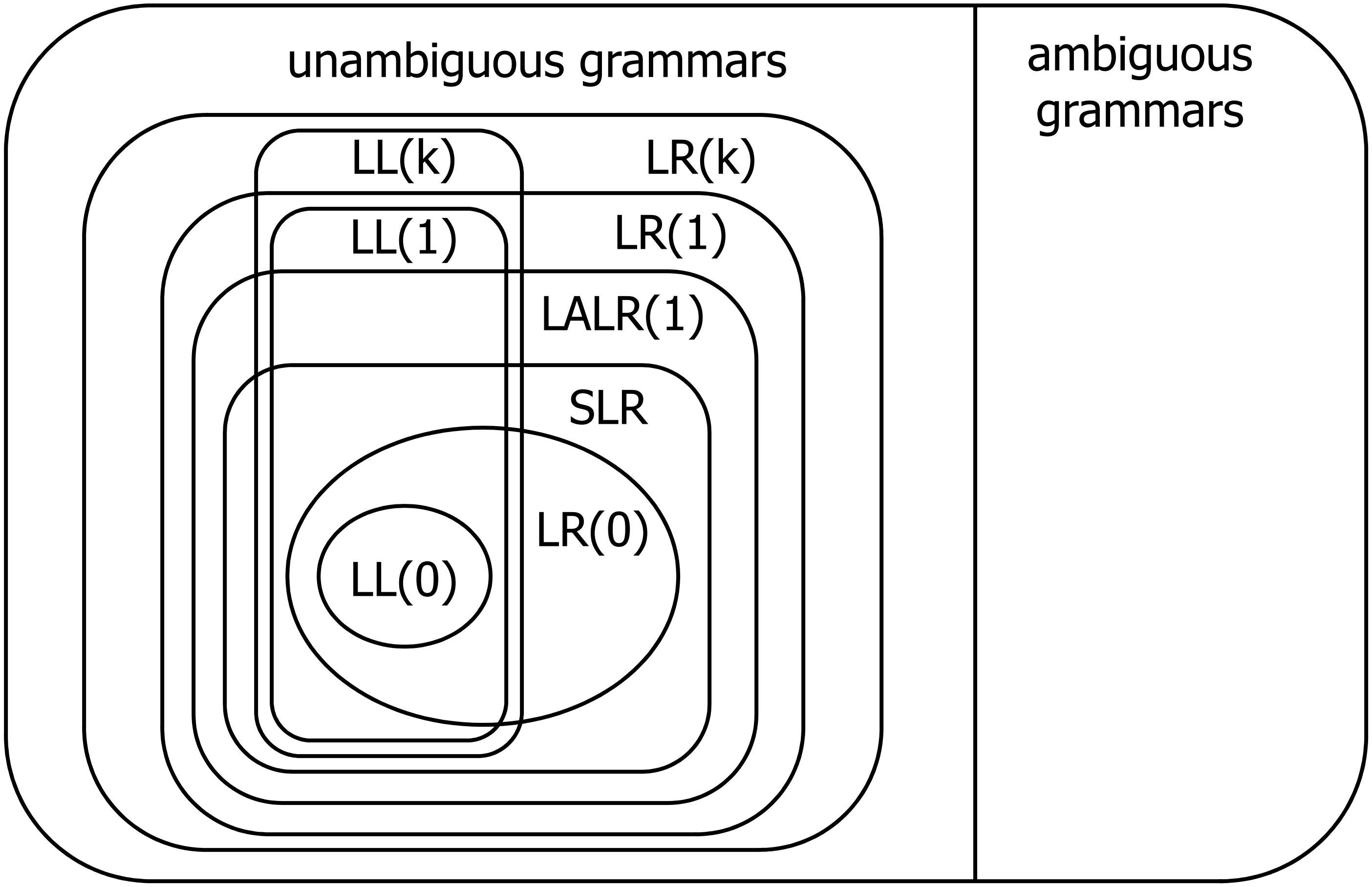
    [A ::= x . , a]

    [A ::= x . , b]

LALR(1) vs LR(1)

- LALR(1) tables can have many fewer states than LR(1)
- LALR(1) may have reduce conflicts where LR(1) would not (but in practice this doesn't happen often)

Language Heirarchies



Coming Attractions

- LL(k) Parsing – Top-Down
- Recursive Descent Parsers
  - What you can do if you need a parser in a hurry

- But first, the next part of the project: parsing and AST generation