Lecture 12

CIS 341: COMPILERS

Announcements

- **Homework 4:** Building A Frontend
- **Goal:**
  - Work with lexer & parser
  - Compile a C-like source language to LLVM.
- **Available:** soon (tommorow?)
- **Due:** Wednesday, March 28th

- **MIDTERM EXAM**
  - Thursday, March 1st in class
  - Coverage: interpreters / program transformers / x86 / calling conventions / IRs / LLVM / Lexing / Parsing
  - See examples on the web pages

LR GRAMMARS

Shift/Reduce Parsing

$S \longmapsto S + E \mid E$
$E \longmapsto \text{number} \mid (S)$

- Parser state:
  - Stack of terminals and nonterminals.
  - Unconsumed input is a string of terminals
  - Current derivation step is stack + input
- Parsing is a sequence of *shift* and *reduce* operations:
- Shift: move look-ahead token to the stack
- Reduce: Replace symbols γ at top of stack with nonterminal X such that $X \longmapsto \gamma$ is a production. (pop γ, push X)

Stack	Input	Action
	(1 + 2 + (3 + 4)) + 5	shift (
(	1 + 2 + (3 + 4)) + 5	shift 1
(1	+ 2 + (3 + 4)) + 5	reduce: $E \longmapsto$ number
(E	+ 2 + (3 + 4)) + 5	reduce: $S \longmapsto E$
(S	+ 2 + (3 + 4)) + 5	shift +
(S +	2 + (3 + 4)) + 5	shift 2
(S + 2	+ (3 + 4)) + 5	reduce: $E \longmapsto$ number

Simple LR parsing with no look ahead.

LR(0) GRAMMARS

LR Parser States

- Goal: know what set of reductions are legal at any given point.
- Idea: Summarize all possible stack prefixes α as a finite parser state.
  - Parser state is computed by a DFA that reads the stack σ.
  - Accept states of the DFA correspond to unique reductions that apply.

- Example: LR(0) parsing
  - **L**eft-to-right scanning, **R**ight-most derivation, **zero** look-ahead tokens
  - Too weak to handle many language grammars (e.g. the "sum" grammar)
  - But, helpful for understanding how the shift-reduce parser works.

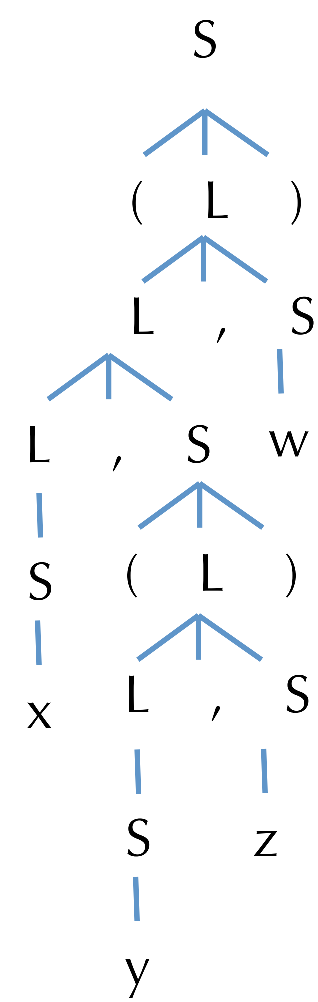
Example LR(0) Grammar: Tuples

- Example grammar for non-empty tuples and identifiers:

$$S \mapsto (\ L\ )\ \mid\ \mathrm{id}$$
$$L \mapsto S\ \mid\ L\ ,\ S$$

- Example strings:
  - x
  - (x,y)
  - ((((x))))
  - (x, (y, z), w)
  - (x, (y, (z, w)))

Parse tree for:
(x, (y, z), w)



Shift/Reduce Parsing

$S \mapsto (L) \mid id$
$L \mapsto S \mid L , S$

- Parser state:
  - Stack of terminals and nonterminals.
  - Unconsumed input is a string of terminals
  - Current derivation step is stack + input
- Parsing is a sequence of *shift* and *reduce* operations:
- Shift: move look-ahead token to the stack: e.g.

Stack	Input	Action
	(x, (y, z), w)	shift (
(	x, (y, z), w)	shift x

- Reduce: Replace symbols γ at top of stack with nonterminal X such that $X \mapsto \gamma$ is a production. (pop γ, push X): e.g.

Stack	Input	Action
(x	, (y, z), w)	reduce $S \mapsto id$
(S	, (y, z), w)	reduce $L \mapsto S$

Example Run

$S \longmapsto (\ L\ )\ \mid\ id$
$L \longmapsto S\ \mid\ L\ ,\ S$

Stack	Input	Action
	(x, (y, z), w)	shift (
(	x, (y, z), w)	shift x
(x	, (y, z), w)	reduce S ⟼ id
(S	, (y, z), w)	reduce L ⟼ S
(L	, (y, z), w)	shift ,
(L,	(y, z), w)	shift (
(L, (	y, z), w)	shift y
(L, (y	, z), w)	reduce S ⟼ id
(L, (S	, z), w)	reduce L ⟼ S
(L, (L	, z), w)	shift ,
(L, (L,	z), w)	shift z
(L, (L, z	), w)	reduce S ⟼ id
(L, (L, S	), w)	reduce L ⟼ L, S
(L, (L	), w)	shift)
(L, (L)	, w)	reduce S ⟼ (L)
(L, S	, w)	reduce L ⟼ L, S
(L	, w)	shift ,

Action Selection Problem

- Given a stack σ and a look-ahead symbol b, should the parser:
  - Shift b onto the stack (new stack is σb)
  - Reduce a production $X \longmapsto \gamma$, assuming that $\sigma = \alpha\gamma$ (new stack is αX)?

- Sometimes the parser can reduce but shouldn't
  - For example, $X \longmapsto \varepsilon$ can *always* be reduced
- Sometimes the stack can be reduced in different ways

- Main idea: decide what to do based on a *prefix* α of the stack plus the look-ahead symbol.
  - The prefix α is different for different possible reductions since in productions $X \longmapsto \gamma$ and $Y \longmapsto \beta$, γ and β might have different lengths.

- Main goal: know what set of reductions are legal at any point.
  - How do we keep track?

LR(0) States

- An LR(0) *state* is a *set* of *items* keeping track of progress on possible upcoming reductions.
- An LR(0) *item* is a production from the language with an extra separator "." somewhere in the right-hand-side

$$S \mapsto (L) \mid \mathrm{id}$$
$$L \mapsto S \mid L , S$$

- Example items: $S \mapsto .(L)$ or $S \mapsto (. L)$ or $L \mapsto S.$
- Intuition:
  - Stuff before the '.' is already on the stack (beginnings of possible γ's to be reduced)
  - Stuff after the '.' is what might be seen next
  - The prefixes α are represented by the state itself

Constructing the DFA: Start state & Closure

$S' \longmapsto S\$$
$S \longmapsto (\ L\ )\ |\ id$
$L \longmapsto S\ |\ L\ ,\ S$

- First step: Add a new production $S' \longmapsto S\$$ to the grammar
- Start state of the DFA = empty stack, so it contains the item:
  $S' \longmapsto .S\$$
- Closure of a state:
  - Adds items for all productions whose LHS nonterminal occurs in an item in the state just after the '.'
  - The added items have the '.' located at the beginning (no symbols for those items have been added to the stack yet)
  - Note that newly added items may cause yet more items to be added to the state… keep iterating until a *fixed point* is reached.
- Example: $\text{CLOSURE}(\{S' \longmapsto .S\$\}) = \{S' \longmapsto .S\$,\ S \longmapsto .(L),\ S \longmapsto .id\}$

- Resulting "closed state" contains the set of all possible productions that might be reduced next.

Example: Constructing the DFA

$S' \longmapsto .S\$$

$S' \longmapsto S\$$
$S \longmapsto (\ L\ ) \mid \text{id}$
$L \longmapsto S \mid L\ ,\ S$

- First, we construct a state with the initial item $S' \longmapsto .S\$$

Example: Constructing the DFA

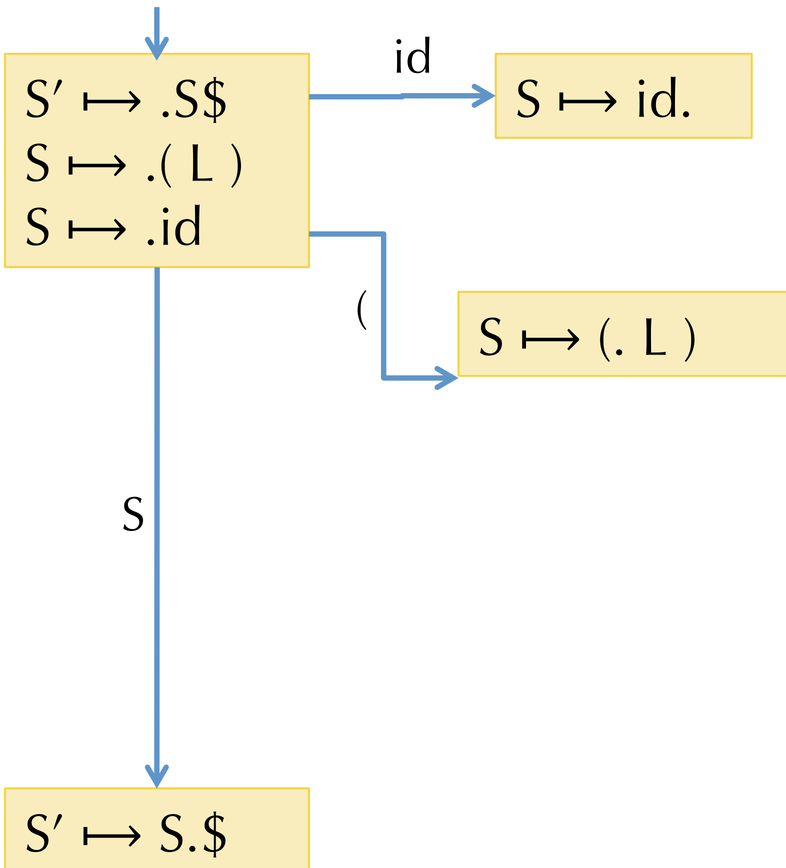
$S' \longmapsto .S\$$
$S \longmapsto .(\ L\ )$
$S \longmapsto .id$

$S' \longmapsto S\$$
$S \longmapsto (\ L\ )\ \mid\ id$
$L \longmapsto S\ \mid\ L\ ,\ S$

- Next, we take the closure of that state:
  CLOSURE({$S' \longmapsto .S\$$}) = {$S' \longmapsto .S\$$, $S \longmapsto .(\ L\ )$, $S \longmapsto .id$}

- In the set of items, the nonterminal S appears after the '.'
- So we add items for each S production in the grammar

Example: Constructing the DFA

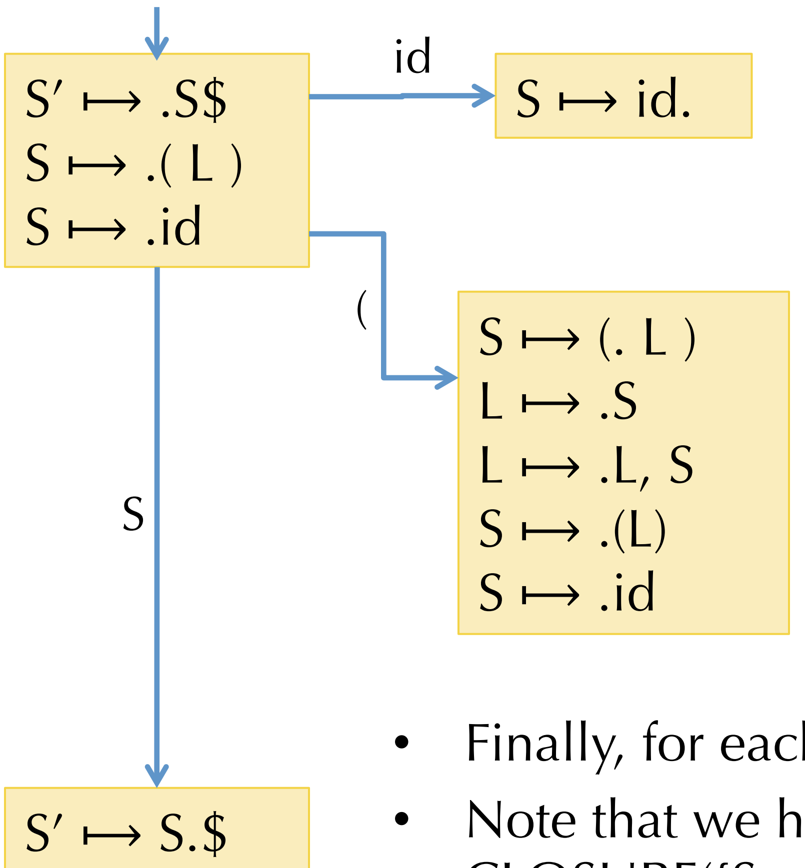


$S' \longmapsto S\$$
$S \longmapsto (\ L\ )\ \mid\ id$
$L \longmapsto S\ \mid\ L\ ,\ S$

- Next we add the transitions:
- First, we see what terminals and nonterminals can appear after the '.' in the source state.
  - Outgoing edges have those label.
- The target state (initially) includes all items from the source state that have the edge-label symbol after the '.', but we advance the '.' (to simulate shifting the item onto the stack)

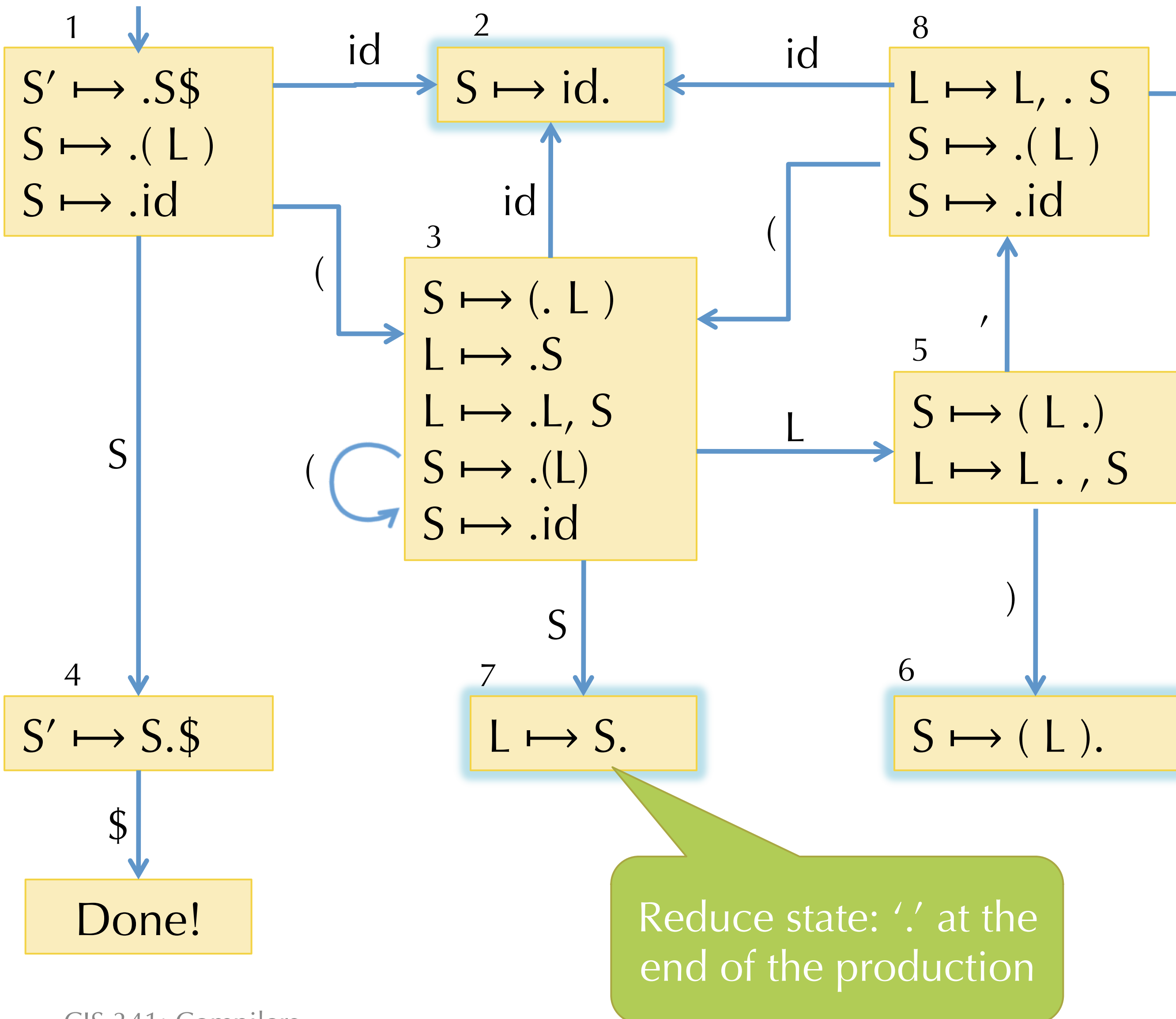
Example: Constructing the DFA

$S' \longmapsto S\$$
$S \longmapsto (\ L\ )\ \mid\ id$
$L \longmapsto S\ \mid\ L\ ,\ S$



- Finally, for each new state, we take the closure.
- Note that we have to perform two iterations to compute CLOSURE({$S \longmapsto (\ .\ L\ )$})
  - First iteration adds $L \longmapsto .S$ and $L \longmapsto .L,\ S$
  - Second iteration adds $S \longmapsto .(L)$ and $S \longmapsto .id$

Full DFA for the Example



- Current state: run the DFA on the stack.
- If a reduce state is reached, reduce
- Otherwise, if the next token matches an outgoing edge, shift.
- If no such transition, it is a parse error.

Using the DFA

- Run the parser stack through the DFA.
- The resulting state tells us which productions might be reduced next.
  - If not in a reduce state, then shift the next symbol and transition according to DFA.
  - If in a reduce state, $X \longmapsto \gamma$ with stack $\alpha\gamma$, pop γ and push X.

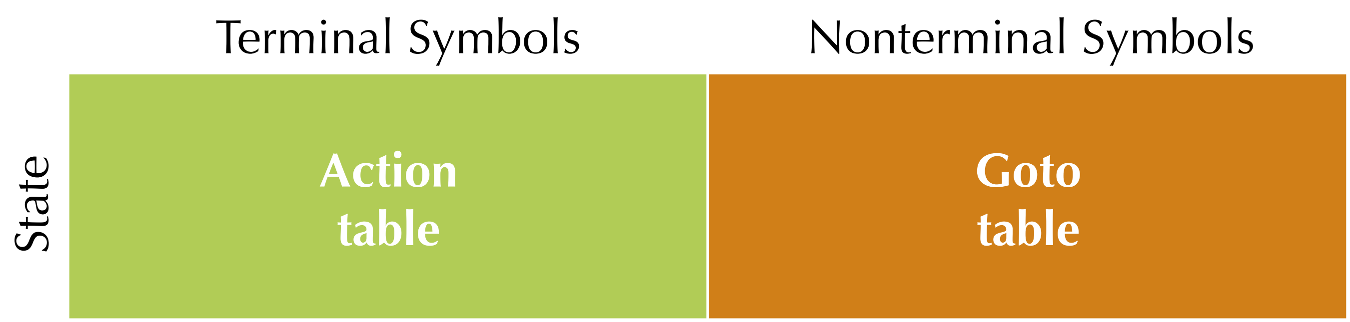
- Optimization: No need to re-run the DFA from beginning every step
  - Store the state with each symbol on the stack: e.g. ${}_1(_3(_3L_5)_6$
  - On a reduction $X \longmapsto \gamma$, pop stack to reveal the state too:
    e.g. From stack ${}_1(_3(_3L_5)_6$ reduce $S \longmapsto (\ L\ )$ to reach stack ${}_1(_3$
  - Next, push the reduction symbol: e.g. to reach stack ${}_1(_3S$
  - Then take just one step in the DFA to find next state: ${}_1(_3S_7$

Implementing the Parsing Table

Represent the DFA as a table of shape:

state * (terminals + nonterminals)

- Entries for the "action table" specify two kinds of actions:
  - Shift and goto state n
  - Reduce using reduction $X \longmapsto \gamma$
    - First pop γ off the stack to reveal the state
    - Look up X in the "goto table" and goto that state



Example Parse Table

	(	)	id	,	$	S	L
1	s3		s2			g4	
2	$S \mapsto id$	$S \mapsto id$	$S \mapsto id$	$S \mapsto id$	$S \mapsto id$		
3	s3		s2			g7	g5
4					DONE		
5		s6		s8			
6	$S \mapsto (L)$	$S \mapsto (L)$	$S \mapsto (L)$	$S \mapsto (L)$	$S \mapsto (L)$		
7	$L \mapsto S$	$L \mapsto S$	$L \mapsto S$	$L \mapsto S$	$L \mapsto S$		
8	s3		s2			g9	
9	$L \mapsto L,S$	$L \mapsto L,S$	$L \mapsto L,S$	$L \mapsto L,S$	$L \mapsto L,S$		

sx = shift and goto state x
gx = goto state x

Example

- Parse the token stream: (x, (y, z), w)$

Stack	Stream	Action (according to table)
ε_1	(x, (y, z), w)$	s3
$\varepsilon_1(_3$	x, (y, z), w)$	s2
$\varepsilon_1(_3x_2$	, (y, z), w)$	Reduce: $S \longmapsto id$
$\varepsilon_1(_3S$	, (y, z), w)$	g7 (from state 3 follow S)
$\varepsilon_1(_3S_7$	, (y, z), w)$	Reduce: $L \longmapsto S$
$\varepsilon_1(_3L$	, (y, z), w)$	g5 (from state 3 follow L)
$\varepsilon_1(_3L_5$	, (y, z), w)$	s8
$\varepsilon_1(_3L_5,_8$	(y, z), w)$	s3
$\varepsilon_1(_3L_5,_8(_3$	y, z), w)$	s2

LR(0) Limitations

- An LR(0) machine only works if states with reduce actions have a *single* reduce action.
  - In such states, the machine *always* reduces (ignoring lookahead)
- With more complex grammars, the DFA construction will yield states with shift/reduce and reduce/reduce conflicts:

OK	shift/reduce	reduce/reduce
$S \longmapsto (L).$	$S \longmapsto (L).$ $L \longmapsto .L , S$	$S \longmapsto L ,S.$ $S \longmapsto ,S.$

- Such conflicts can often be resolved by using a look-ahead symbol: LR(1)

Examples

- Consider the left associative and right associative "sum" grammars:

left	right
$S \mapsto S + E \mid E$ $E \mapsto \text{number} \mid (S)$	$S \mapsto E + S \mid E$ $E \mapsto \text{number} \mid (S)$

- One is LR(0) the other isn't… which is which and why?
- What kind of conflict do you get? Shift/reduce or Reduce/reduce?

- Ambiguities in associativity/precedence usually lead to shift/reduce conflicts.

LR(1) Parsing

- Algorithm is similar to LR(0) DFA construction:
  - LR(1) state = set of LR(1) items
  - An LR(1) item is an LR(0) item + a set of look-ahead symbols:

    $A \longmapsto \alpha.\beta \ , \ \mathcal{L}$

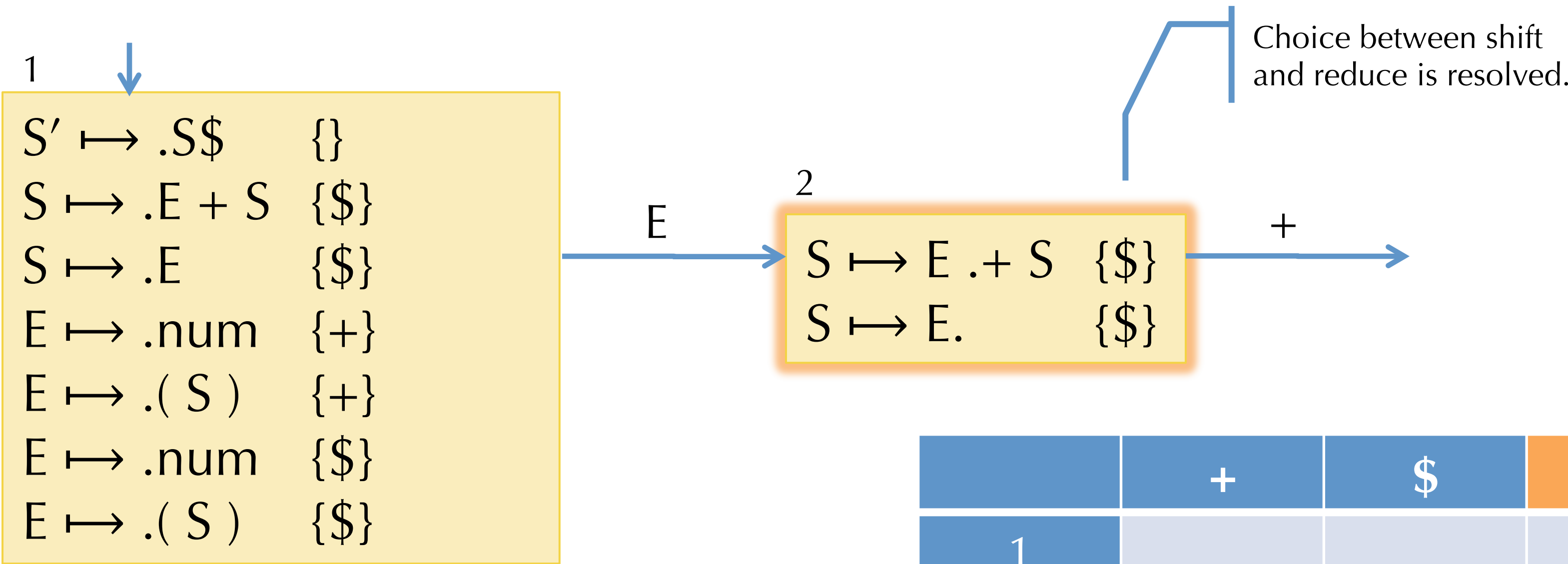
- LR(1) closure is a little more complex:
- Form the set of items just as for LR(0) algorithm.
- Whenever a new item $C \longmapsto .\gamma$ is added because $A \longmapsto \beta.C\delta \ , \ \mathcal{L}$ is already in the set, we need to compute its look-ahead set $\mathcal{M}$:
  1. The look-ahead set $\mathcal{M}$ includes FIRST(δ)
     (the set of terminals that may start strings derived from δ)
  2. If δ is or can derive ε (i.e. it is nullable), then the look-ahead $\mathcal{M}$ also contains $\mathcal{L}$

Example Closure

$S' \longmapsto S\$$
$S \longmapsto E + S \mid E$
$E \longmapsto \text{number} \mid (S)$

- Start item: $S' \longmapsto .S\$ \quad , \quad \{\}$
- Since S is to the right of a '.', add:
  $S \longmapsto .E + S \quad , \quad \{\$\}$ Note: $\{\$\}$ is FIRST($\$$)
  $S \longmapsto .E \quad , \quad \{\$\}$
- Need to keep closing, since E appears to the right of a '.' in '.E + S':
  $E \longmapsto .\text{number} \quad , \quad \{+\}$ Note: + added for reason 1
  $E \longmapsto .(S) \quad , \quad \{+\}$ FIRST(+ S) = {+}
- Because E also appears to the right of '.' in '.E' we get:
  $E \longmapsto .\text{number} \quad , \quad \{\$\}$ Note: \$ added for reason 2
  $E \longmapsto .(S) \quad , \quad \{\$\}$ δ is ε
- All items are distinct, so we're done

Using the DFA



	+	$	E
1			g2
2	s3	S ⟼ E	

Fragment of the Action & Goto tables

- The behavior is determined if:
  - There is no overlap among the look-ahead sets for each reduce item, and
  - None of the look-ahead symbols appear to the right of a ‘.’

LR variants

- LR(1) gives maximal power out of a 1 look-ahead symbol parsing table
  - DFA + stack is a push-down automaton (recall 262)
- In practice, LR(1) tables are big.
  - Modern implementations (e.g. menhir) directly generate code

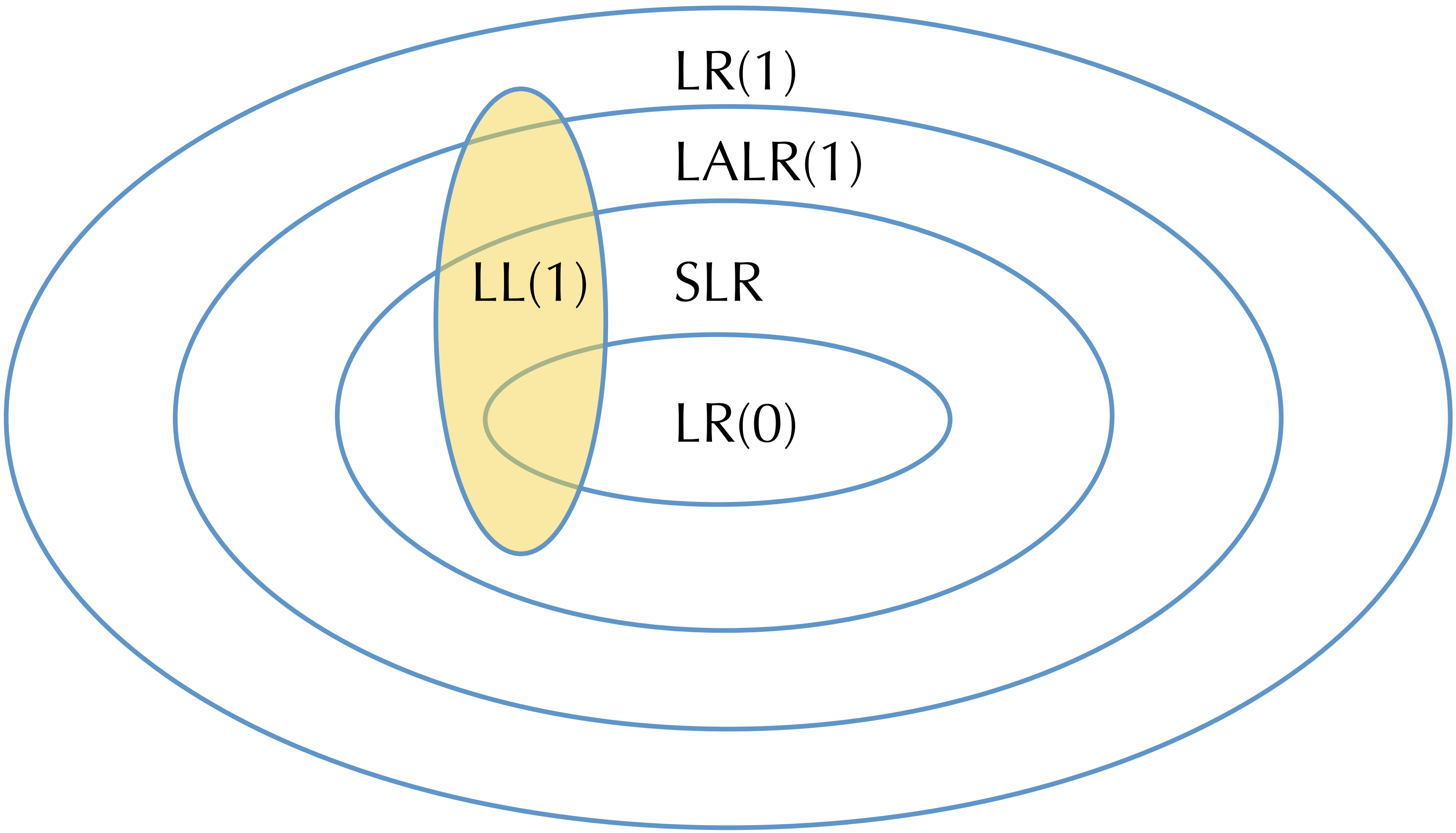
- LALR(1) = "Look-ahead LR"
  - Merge any two LR(1) states whose items are identical except for the look-ahead sets:

$S' \longmapsto .S\$$	{}
$S \longmapsto .E + S$	{\$}
$S \longmapsto .E$	{\$}
$E \longmapsto .num$	{+}
$E \longmapsto .(S)$	{+}
$E \longmapsto .num$	{\$}
$E \longmapsto .(S)$	{\$}

$S' \longmapsto .S\$$	{}
$S \longmapsto .E + S$	{\$}
$S \longmapsto .E$	{\$}
$E \longmapsto .num$	{+,\$}
$E \longmapsto .(S)$	{+,\$}

  - Such merging can lead to nondeterminism (e.g. reduce/reduce conflicts), but
  - Results in a much smaller parse table and works well in practice
  - This is the usual technology for automatic parser generators: yacc, ocamlyacc
- GLR = "Generalized LR" parsing
  - Efficiently compute the set of *all* parses for a given input
  - Later passes should disambiguate based on other context

Classification of Grammars



Debugging parser conflicts.
Disambiguating grammars.

MENHIR IN PRACTICE

Practical Issues

- Dealing with source file location information
  - In the lexer and parser
  - In the abstract syntax
  - See range.ml, ast.ml
- Lexing comments / strings

Menhir output

- You can get verbose ocamlyacc debugging information by doing:
  - `menhir --explain …`
  - or, if using ocamlbuild:
    `ocamlbuild –use-menhir -yaccflag -–explain …`

- The result is a <basename>.conflicts file that contains a description of the error
  - The parser items of each state use the '.' just as described above

- The flag --dump generates a full description of the automaton

- Example: see start-parser.mly

Precedence and Associativity Declarations

- Parser generators, like menhir often support precedence and associativity declarations.
  - Hints to the parser about how to resolve conflicts.
  - See: good-parser.mly

- Pros:
  - Avoids having to manually resolve those ambiguities by manually introducing extra nonterminals (as seen in parser.mly)
  - Easier to maintain the grammar

- Cons:
  - Can't as easily re-use the same terminal (if associativity differs)
  - Introduces another level of debugging

- Limits:
  - Not always easy to disambiguate the grammar based on just precedence and associativity.

Example Ambiguity in Real Languages

- Consider this grammar:
  $S \mapsto$ `if (E) S`
  $S \mapsto$ `if (E)` S `else` S
  $S \mapsto X = E$
  $E \mapsto \ldots$

- Is this grammar OK?

- Consider how to parse:

  `if` (E_1) `if` (E_2) S_1
  `else` S_2

- This is known as the "dangling else" problem.
- What should the "right" answer be?

- How do we change the grammar?

How to Disambiguate if-then-else

- Want to rule out:

$$\texttt{if (}E_1\texttt{)}\ \{\ \texttt{if (}E_2\texttt{)}\ S_1\ \}\ \texttt{else}\ S_2$$

- Observation: An un-matched '`if`' should not appear as the '`then`' clause of a containing '`if`'.

$S \mapsto M \mid U$ // M = "matched", U = "unmatched"
$U \mapsto$ `if (`E`)` S // Unmatched 'if'
$U \mapsto$ `if (`E`)` M `else` U // Nested if is matched
$M \mapsto$ `if (`E`)` M `else` M // Matched 'if'
$M \mapsto X = E$ // Other statements

- See: else-resolved-parser.mly

Alternative: Use { }

- Ambiguity arises because the 'then' branch is not well bracketed:

  `if (`E_1`) { if (`E_2`) { `S_1` } } else `S_2 // unambiguous
  `if (`E_1`) { if (`E_2`) { `S_1` } else `S_2` }` // unambiguous

- So: could just require brackets
  - But requiring them for the else clause too leads to ugly code for chained if-statements:

```
if (c1) {
  …
} else {
  if (c2) {

  } else {
    if (c3) {

    } else {

    }
  }
}
```

So, compromise? Allow unbracketed else block only if the body is 'if':

```
if (c1) {

} else if (c2) {

} else if (c3) {

} else {

}
```

Benefits:

- Less ambiguous
- Easy to parse
- Enforces good style