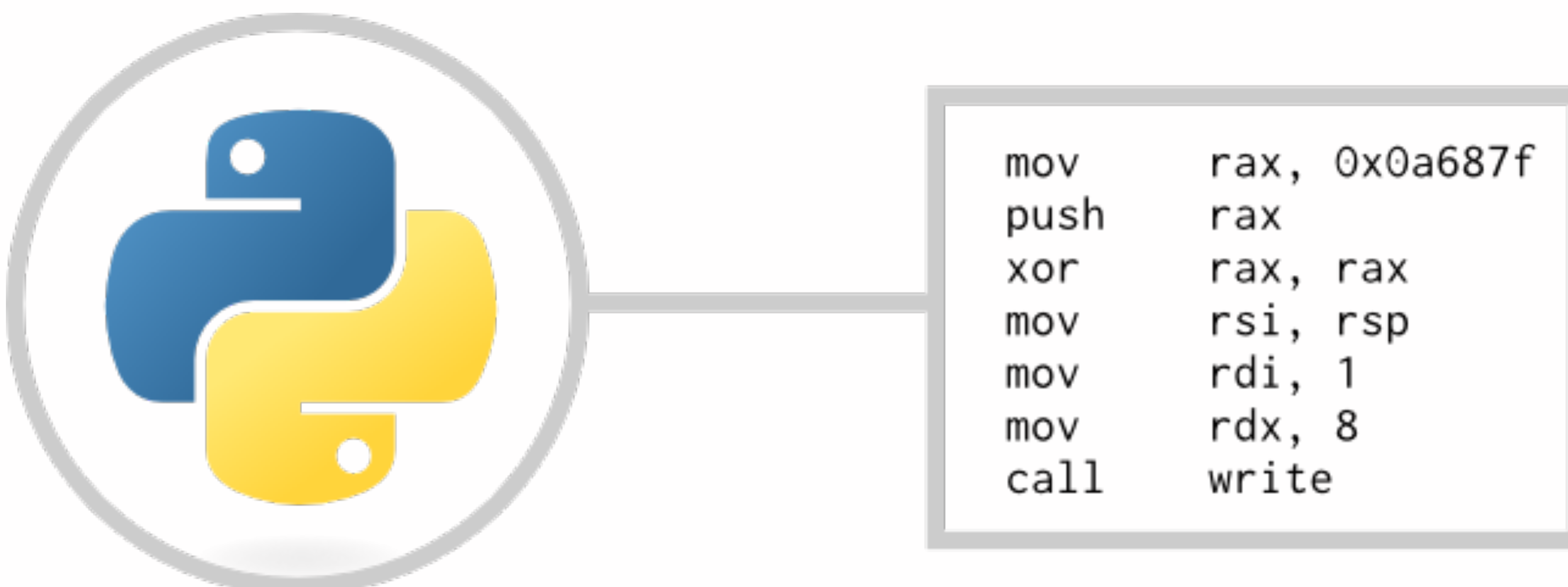
CS 480

Translators (Compilers)

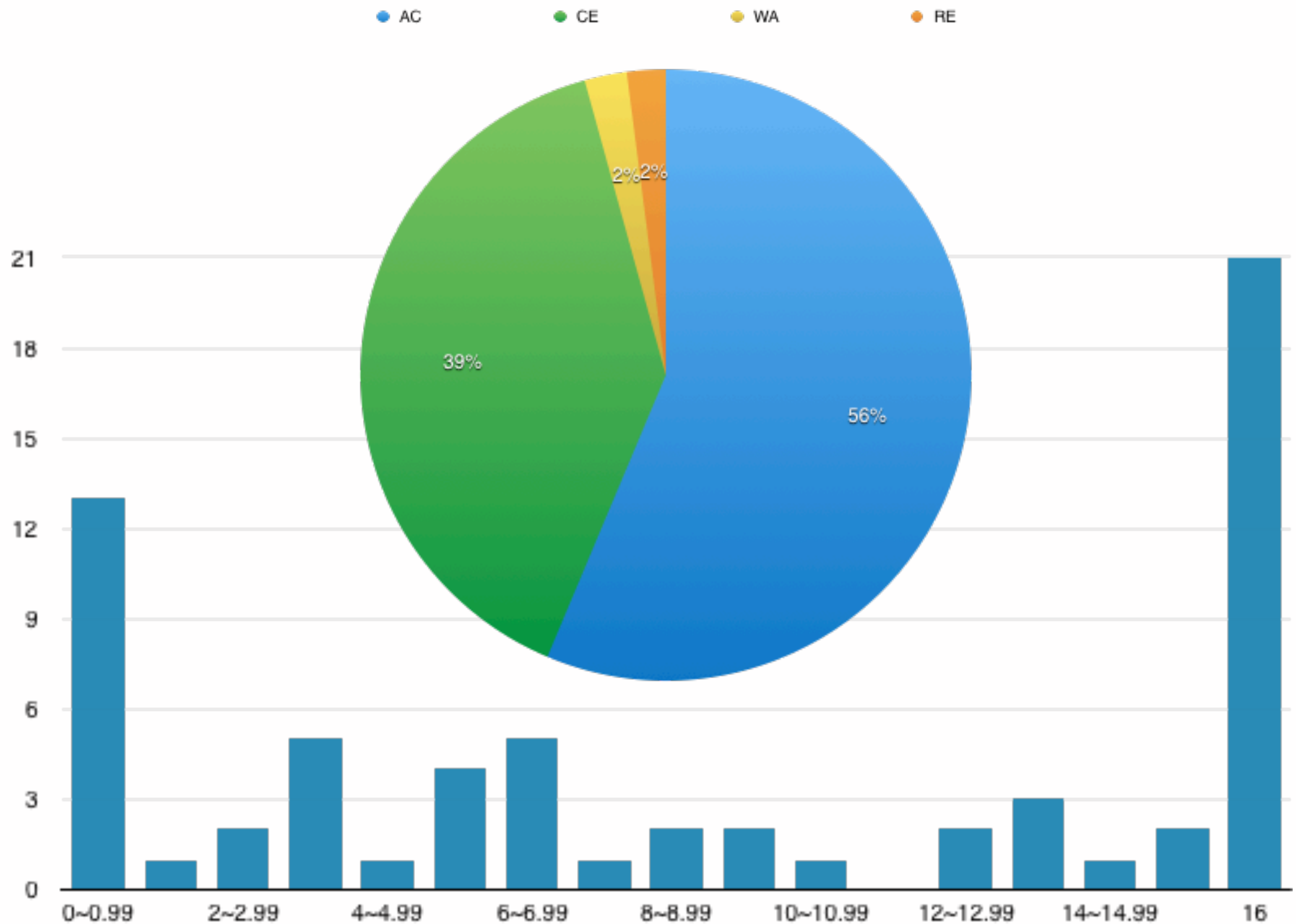


weeks 4: yacc, LR parsing

Instructor: Liang Huang

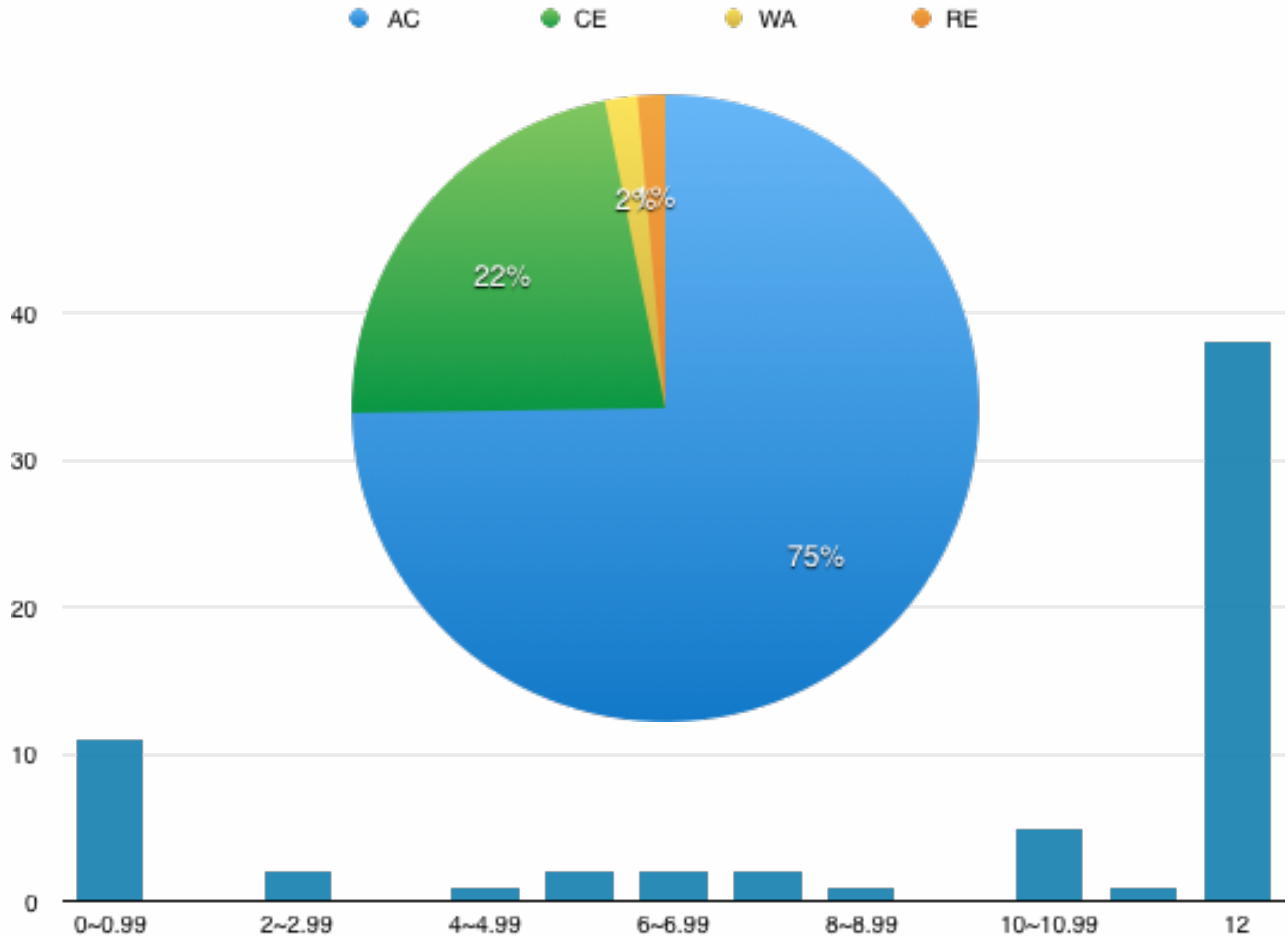
(some slides courtesy of David Beazley and Zhendong Su)

HW3 Distribution (coding part)



number of cases passed

ONLY on HW1 cases (60% of grade)



HW1 cases passed

ply.yacc preliminaries

- ply.yacc is a module for creating a parser
- Assumes you have defined a BNF grammar

```
assign : NAME EQUALS expr
expr   : expr PLUS term
       | expr MINUS term
       | term
term   : term TIMES factor
       | term DIVIDE factor
       | factor
factor : NUMBER
```

```
compare with (ambiguity):

expr : expr PLUS expr
     | expr TIMES expr
     | NUMBER
```

ply.yacc example

```
import ply.yacc as yacc
import mylexer              # Import lexer information
tokens = mylexer.tokens     # Need token list

def p_assign(p):
    '''assign : NAME EQUALS expr'''

def p_expr(p):
    '''expr : expr PLUS term
            | expr MINUS term
            | term'''
def p_term(p):
    '''term : term TIMES factor
            | term DIVIDE factor
            | factor'''
def p_factor(p):
    '''factor : NUMBER'''

yacc.yacc()              # Build the parser
```

ply.yacc example

```
import ply.yacc as yacc
import mylexer
tokens = mylexer.tokens

def p_assign(p):
    '''assign : NAME EQUALS expr'''

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    '''term : term TIMES factor
            | term DIVIDE factor
            | factor'''
def p_factor(p):
    '''factor : NUMBER'''

yacc.yacc()                # Build the parser
```

token information imported from lexer

ply.yacc example

```
import ply.yacc as yacc
import mylexer               # Import lexer information
tokens = mylexer.tokens      # Need token list

def p_assign(p):
    '''assign : NAME EQUALS expr'''

def p_expr(p):
    '''expr : expr PLUS term
            | expr MINUS term
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def p_term(p):
    '''term : term TIMES factor
            | term DIVIDE factor
            | factor'''
def p_factor(p):
    '''factor : NUMBER'''

yacc.yacc()                  # Build the parser
```

grammar rules encoded as functions with names p_*rulename*

Note: Name doesn't matter as long as it starts with p_

ply.yacc example

```
import ply.yacc as yacc
import mylexer               # Import lexer information
tokens = mylexer.tokens      # Need token list

def p_assign(p):
    '''assign : NAME EQUALS expr'''

def p_expr(p):
    '''expr : expr PLUS term
            | expr MINUS term
            | term'''
def p_term(p):
    '''term : term TIMES factor
            | term DIVIDE factor
            | factor'''
def p_factor(p):
    '''factor : NUMBER'''

yacc.yacc()                 # Build the parser
```

docstrings contain grammar rules from BNF

ply.yacc example

```
import ply.yacc as yacc
import mylexer               # Import lexer information
tokens = mylexer.tokens      # Need token list

def p_assign(p):
    '''assign : NAME EQUALS expr'''

def p_expr(p):
    '''expr : expr PLUS term
            | expr MINUS term
            | term'''
def p_term(p):
    '''term : term TIMES factor
            | term DIVIDE factor
            | factor'''
def p_factor(p):
    '''factor : NUMBER'''

yacc.yacc()
```

Builds the parser using introspection

ply.yacc parsing

- yacc.parse() function

```
yacc.yacc()      # Build the parser
...
data = "x = 3*4+5*6"
yacc.parse(data)   # Parse some text
```

- This feeds data into lexer
- Parses the text and invokes grammar rules

A peek inside

- PLY uses LR-parsing. LALR(1)
- AKA: Shift-reduce parsing
- Widely used parsing technique
- Table driven

Bottom-Up Parsing

- Bottom-up parsing is more general than top-down parsing
  - And just as efficient
  - Builds on ideas in top-down parsing
  - Preferred method in practice

- Also called LR parsing
  - L means that tokens are read left to right
  - R means that it constructs a rightmost derivation

An Introductory Example

- LR parsers
  - Don't need left-factored grammars, and
  - Can handle left-recursive grammars
- Consider the following grammar

$$E \rightarrow E + (E) \mid int$$

  - Why is this not LL(1)?
- Consider the string: int + (int) + (int)

The Idea

- LR parsing *reduces* a string to the start symbol by inverting productions:

str $\leftarrow$ input string of terminals

repeat

- Identify β in str such that $A \rightarrow \beta$ is a production (i.e., str = $\alpha\ \beta\ \gamma$)
- Replace β by A in str (i.e., str becomes $\alpha\ A\ \gamma$)

until str = S

A Bottom-up Parse in Detail (1)

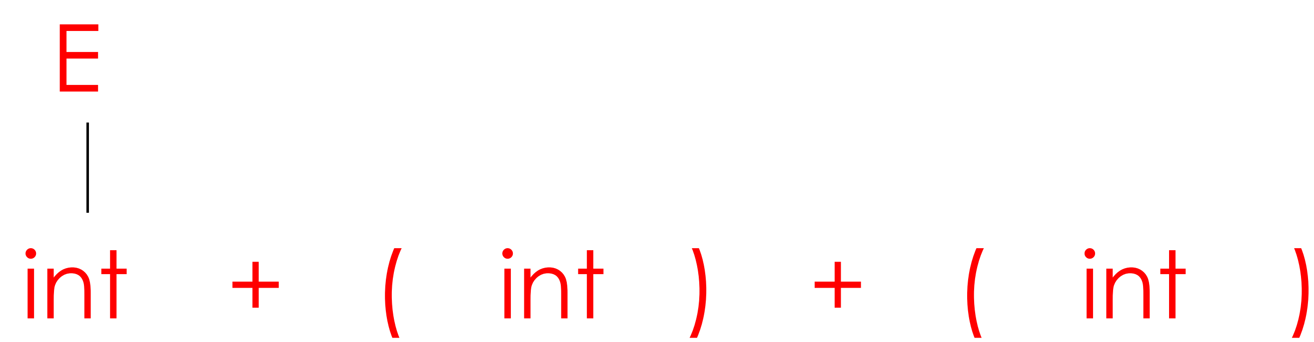
int + (int) + (int)

int + (int) + (int)

E → E + (E) | int

A Bottom-up Parse in Detail (2)

int + (int) + (int)
E + (int) + (int)

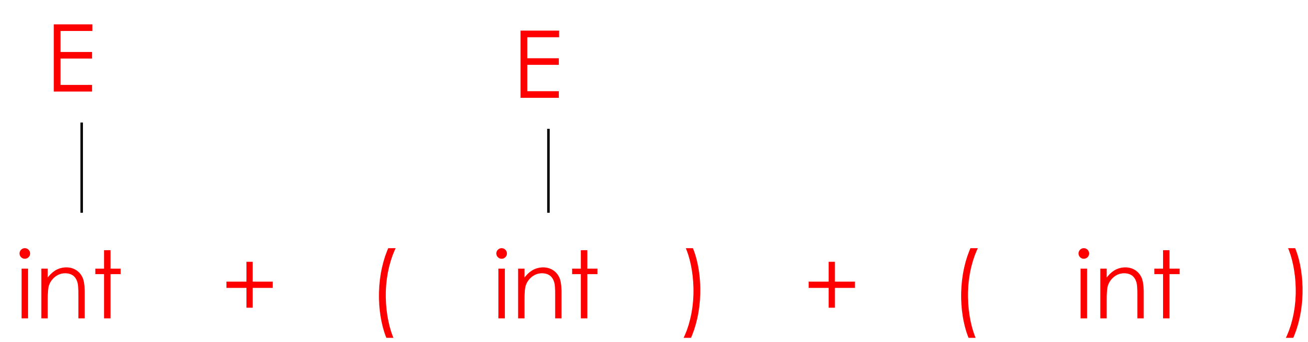


A Bottom-up Parse in Detail (3)

int + (int) + (int)

E + (int) + (int)

E + (E) + (int)



$E \rightarrow E + (E) \mid int$

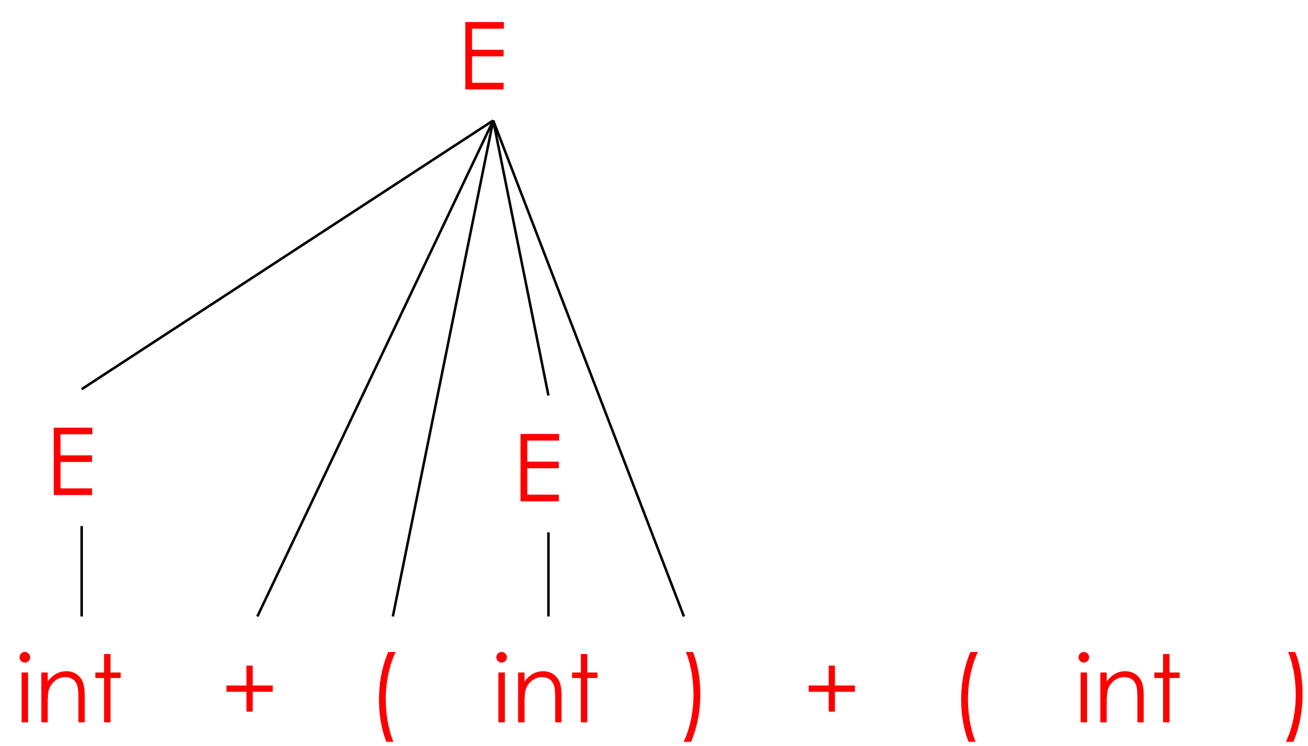
A Bottom-up Parse in Detail (4)

int + (int) + (int)

E + (int) + (int)

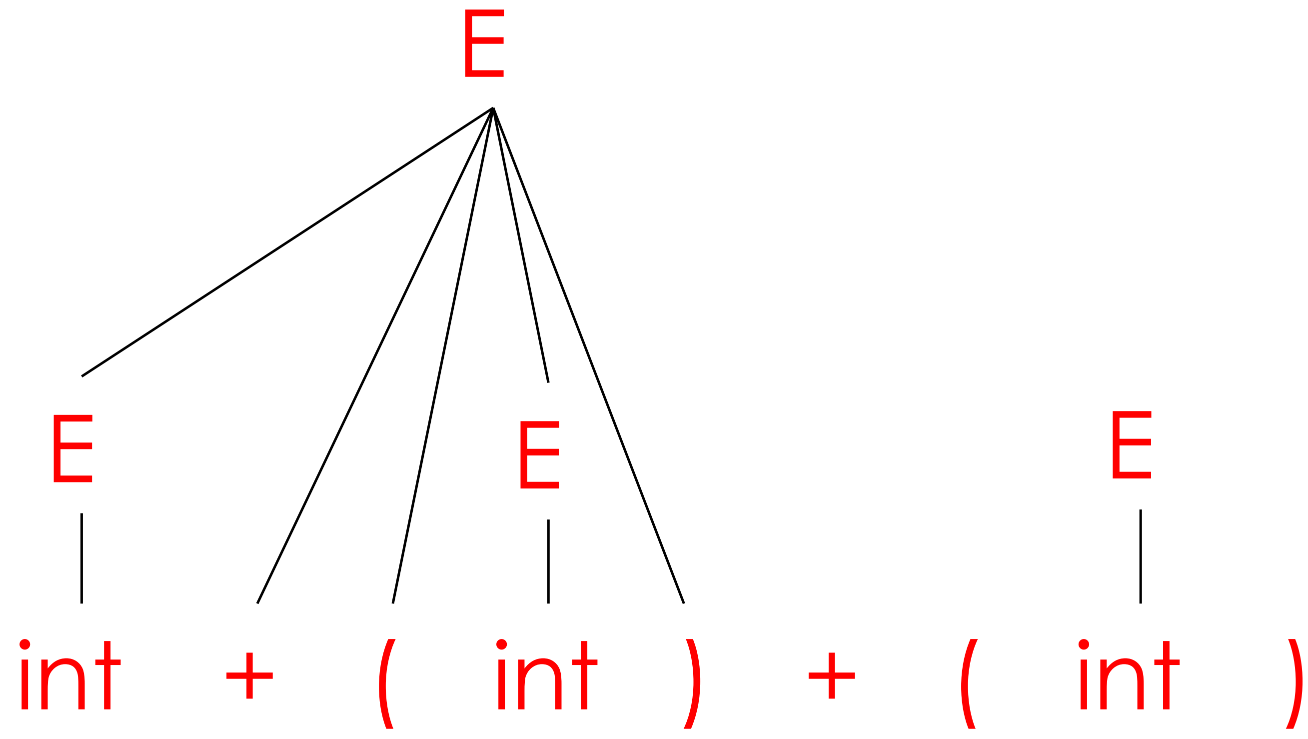
E + (E) + (int)

E + (int)



A Bottom-up Parse in Detail (5)

int + (int) + (int)
E + (int) + (int)
E + (E) + (int)
E + (int)
E + (E)

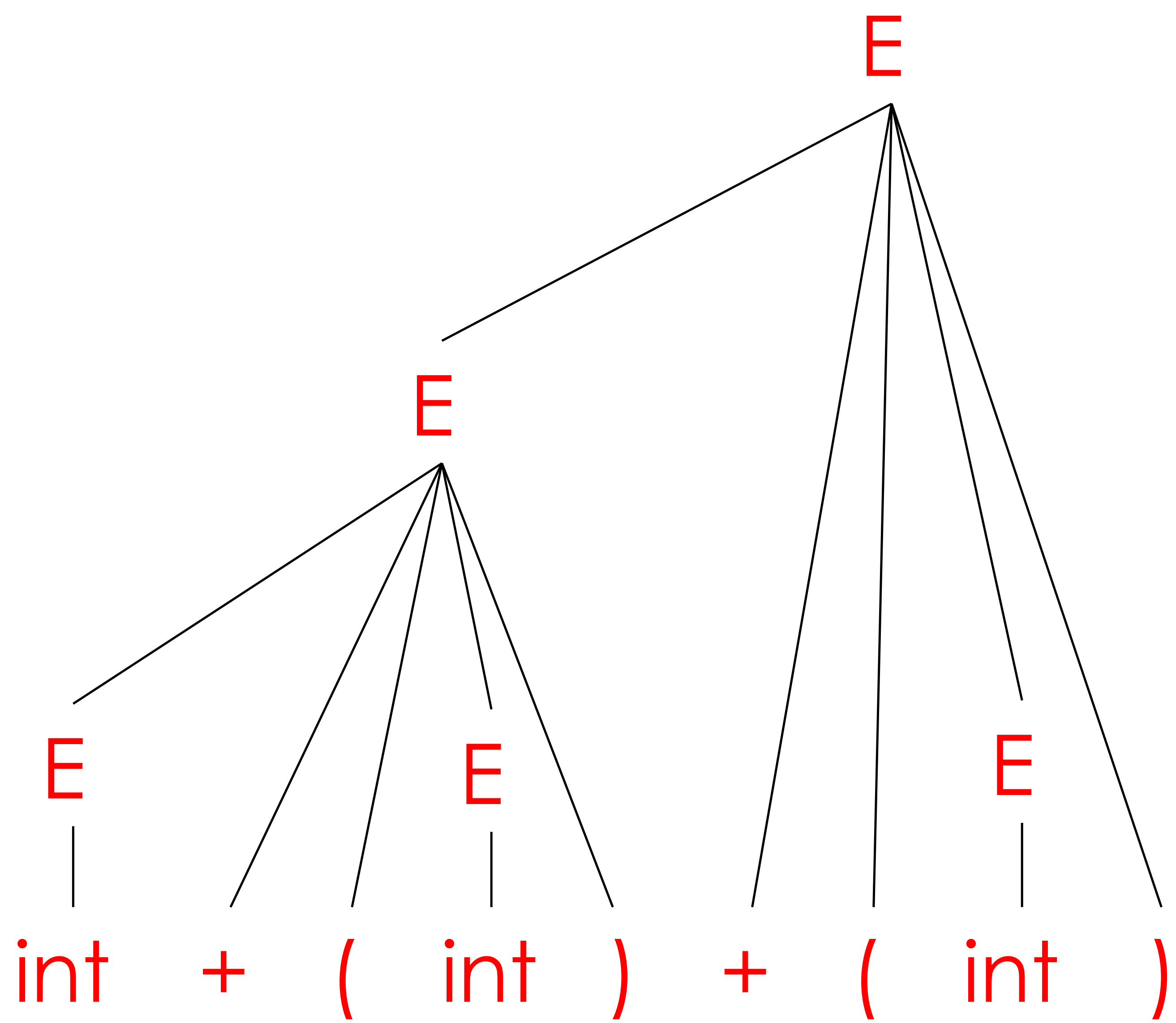


A Bottom-up Parse in Detail (6)

int + (int) + (int)
E + (int) + (int)
E + (E) + (int)
E + (int)
E + (E)
E

A rightmost derivation in reverse

(always rewrite the rightmost nonterminal in each step)



Important Fact #1

Important Fact #1 about bottom-up parsing:

An LR parser traces a rightmost derivation in reverse

Where Do Reductions Happen

Important Fact #1 has an interesting consequence:

- Let $\alpha\beta\gamma$ be a step of a bottom-up parse
- Assume the next reduction is by $A \rightarrow \beta$
- Then γ is a string of terminals !

Why? Because $\alpha A\gamma \rightarrow \alpha\beta\gamma$ is a step in a right-most derivation

Notation

- Idea: Split the string into two substrings
  - Right substring (a string of terminals) is as yet unexamined by parser
  - Left substring has terminals and non-terminals

- The dividing point is marked by a ▶
  - The ▶ is not part of the string

- Initially, all input is unexamined: ▶$x_1 x_2 \ldots x_n$

Shift-Reduce Parsing

- Bottom-up parsing uses only two kinds of actions:

Shift

Reduce

Shift

Shift: Move ▶ one place to the right

- Shifts a terminal to the left string

$$E + (\blacktriangleright\ int\ ) \Rightarrow E + (int\ \blacktriangleright\ )$$

Reduce

Reduce: Apply a production in reverse at the right end of the left string

- If $E \rightarrow E + (E)$ is a production, then

$$E + (\underline{E + (E)} \blacktriangleright) \Rightarrow E + (\underline{E} \blacktriangleright)$$

Shift-Reduce Example

- ▸ int + (int) + (int)$ shift

int + (int) + (int)

↑

Shift-Reduce Example

▶ int + (int) + (int)\$ shift

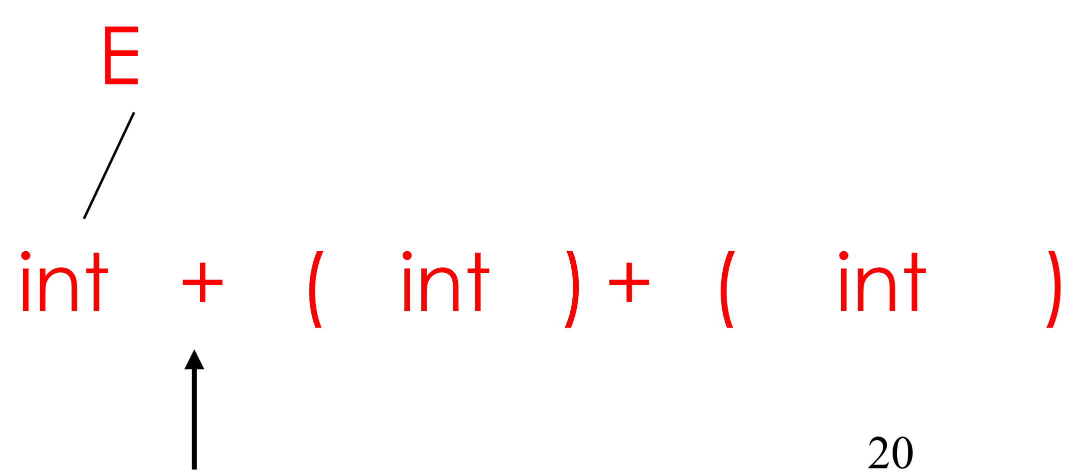
int ▶ + (int) + (int)\$ red. $E \rightarrow int$

int + (int) + (int)

↑

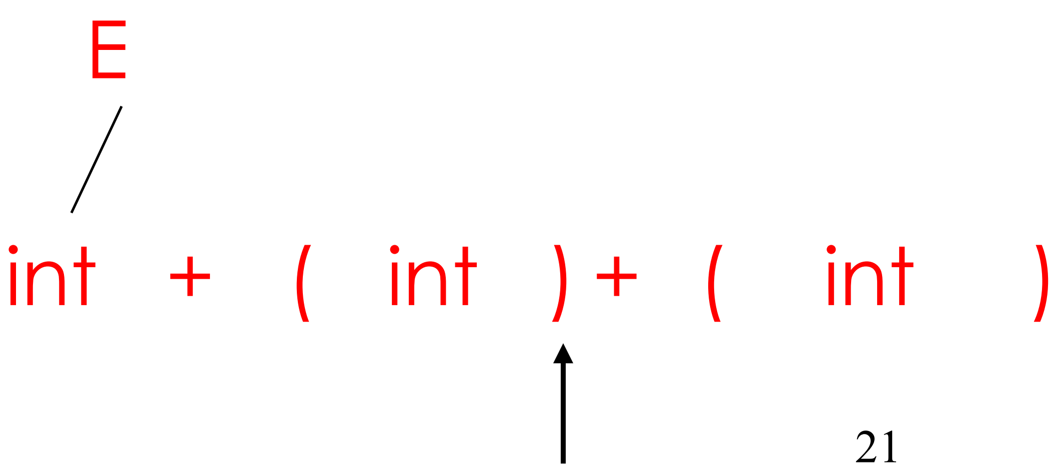
Shift-Reduce Example

▶ int + (int) + (int)$	shift
int ▶ + (int) + (int)$	red. E $\rightarrow$ int
E ▶ + (int) + (int)$	shift 3 times



Shift-Reduce Example

▶ int + (int) + (int)$	shift
int ▶ + (int) + (int)$	red. $E \rightarrow$ int
E ▶ + (int) + (int)$	shift 3 times
E + (int ▶) + (int)$	red. $E \rightarrow$ int



Shift-Reduce Example

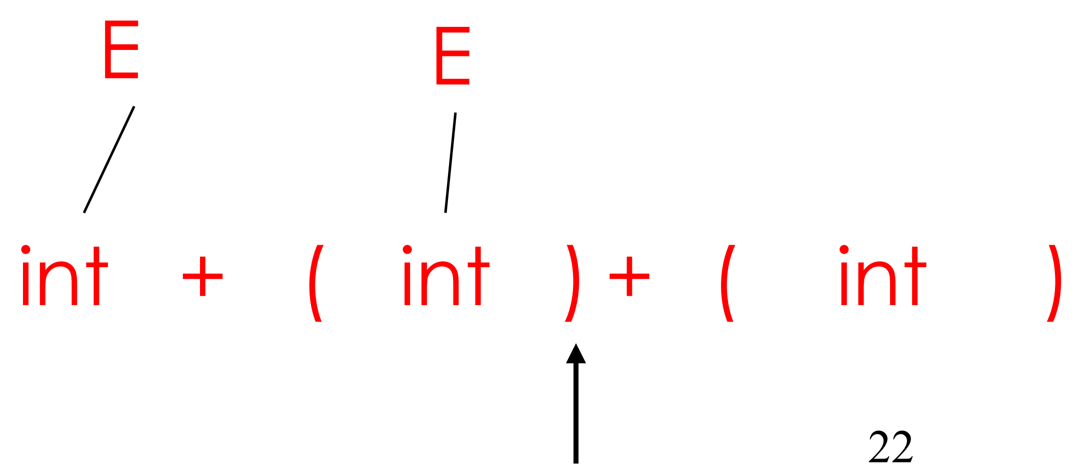
▶ int + (int) + (int)$ shift

int ▶ + (int) + (int)$ red. E → int

E ▶ + (int) + (int)$ shift 3 times

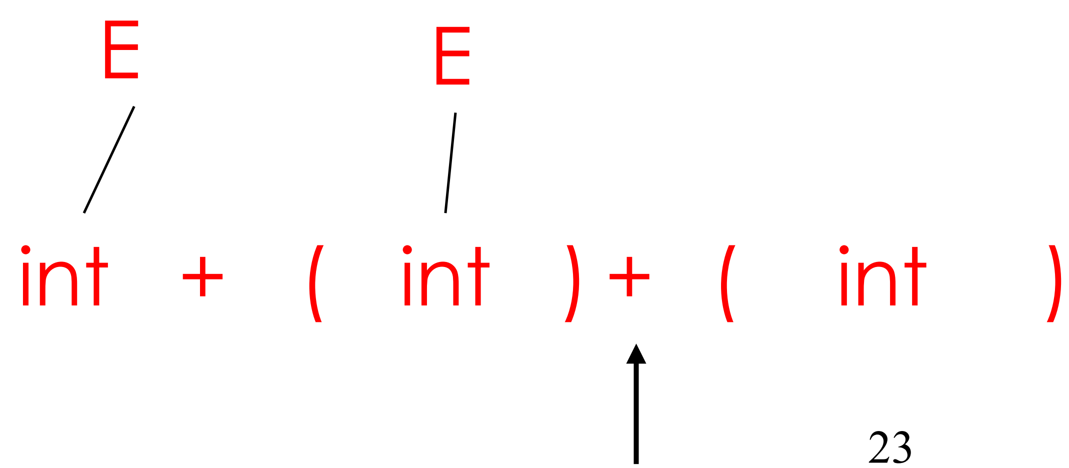
E + (int ▶) + (int)$ red. E → int

E + (E ▶) + (int)$ shift



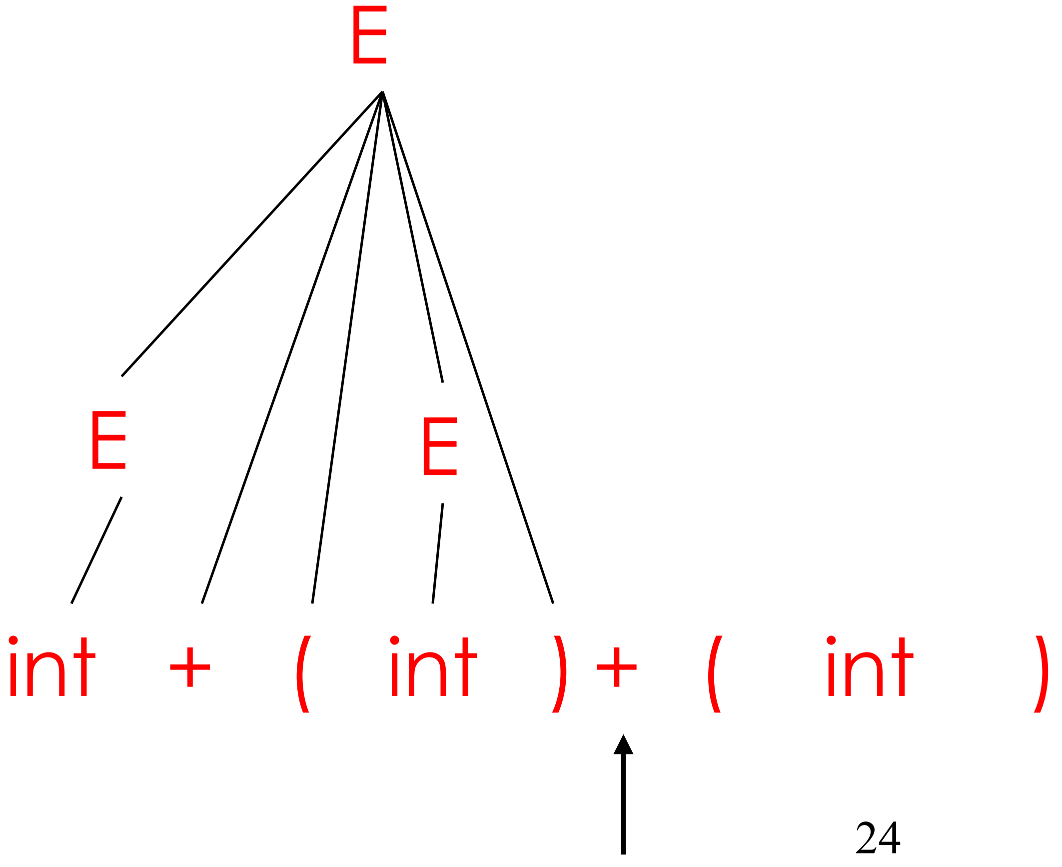
Shift-Reduce Example

▶ int + (int) + (int)$	shift
int ▶ + (int) + (int)$	red. E $\rightarrow$ int
E ▶ + (int) + (int)$	shift 3 times
E + (int ▶) + (int)$	red. E $\rightarrow$ int
E + (E ▶) + (int)$	shift
E + (E) ▶ + (int)$	red. E $\rightarrow$ E + (E)



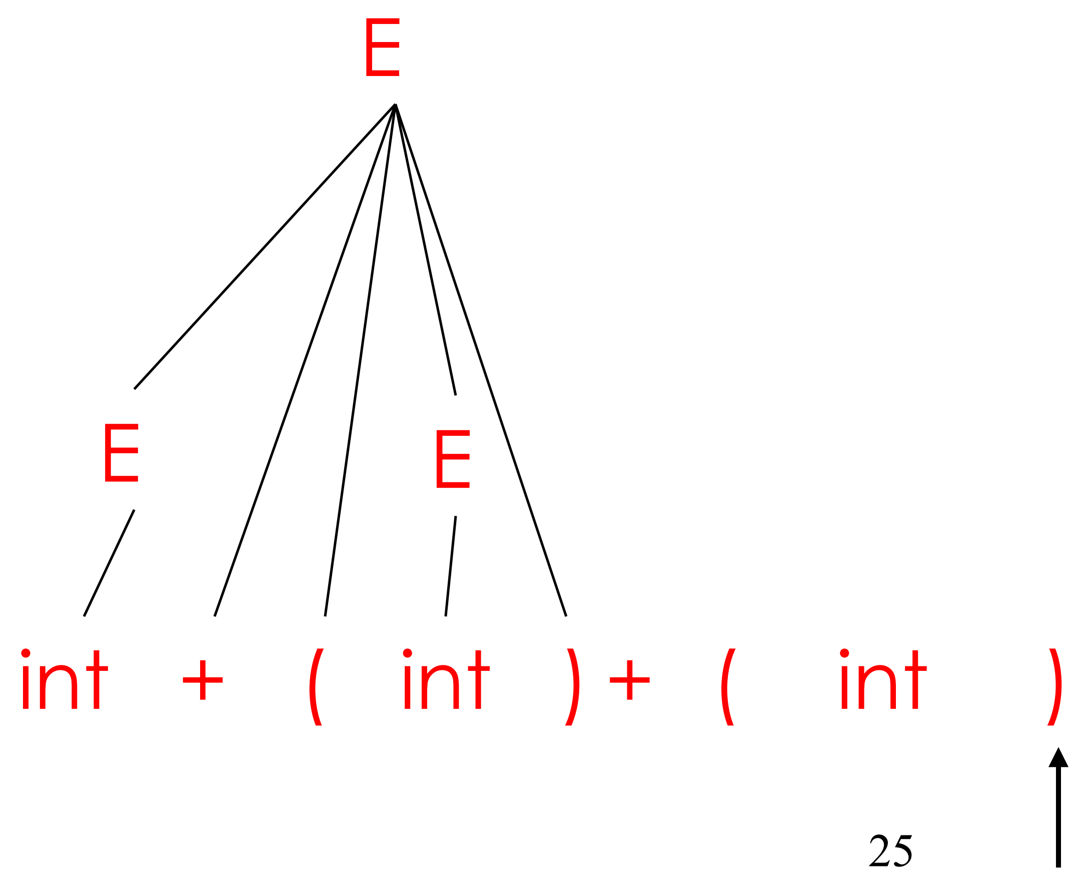
Shift-Reduce Example

▶ int + (int) + (int)$	shift
int ▶ + (int) + (int)$	red. E → int
E ▶ + (int) + (int)$	shift 3 times
E + (int ▶) + (int)$	red. E → int
E + (E ▶) + (int)$	shift
E + (E) ▶ + (int)$	red. E → E + (E)
E ▶ + (int)$	shift 3 times



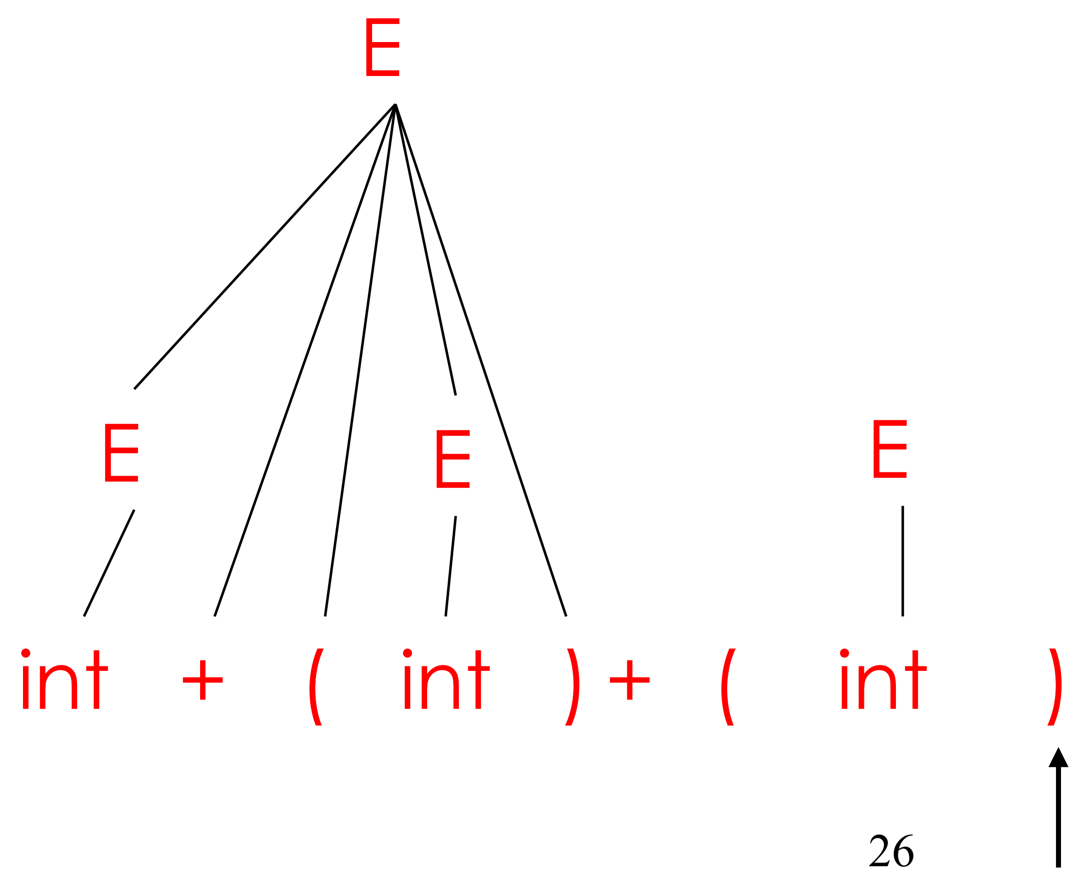
Shift-Reduce Example

▸ int + (int) + (int)$	shift
int ▸ + (int) + (int)$	red. E → int
E ▸ + (int) + (int)$	shift 3 times
E + (int ▸) + (int)$	red. E → int
E + (E ▸) + (int)$	shift
E + (E) ▸ + (int)$	red. E → E + (E)
E ▸ + (int)$	shift 3 times
E + (int ▸)$	red. E → int



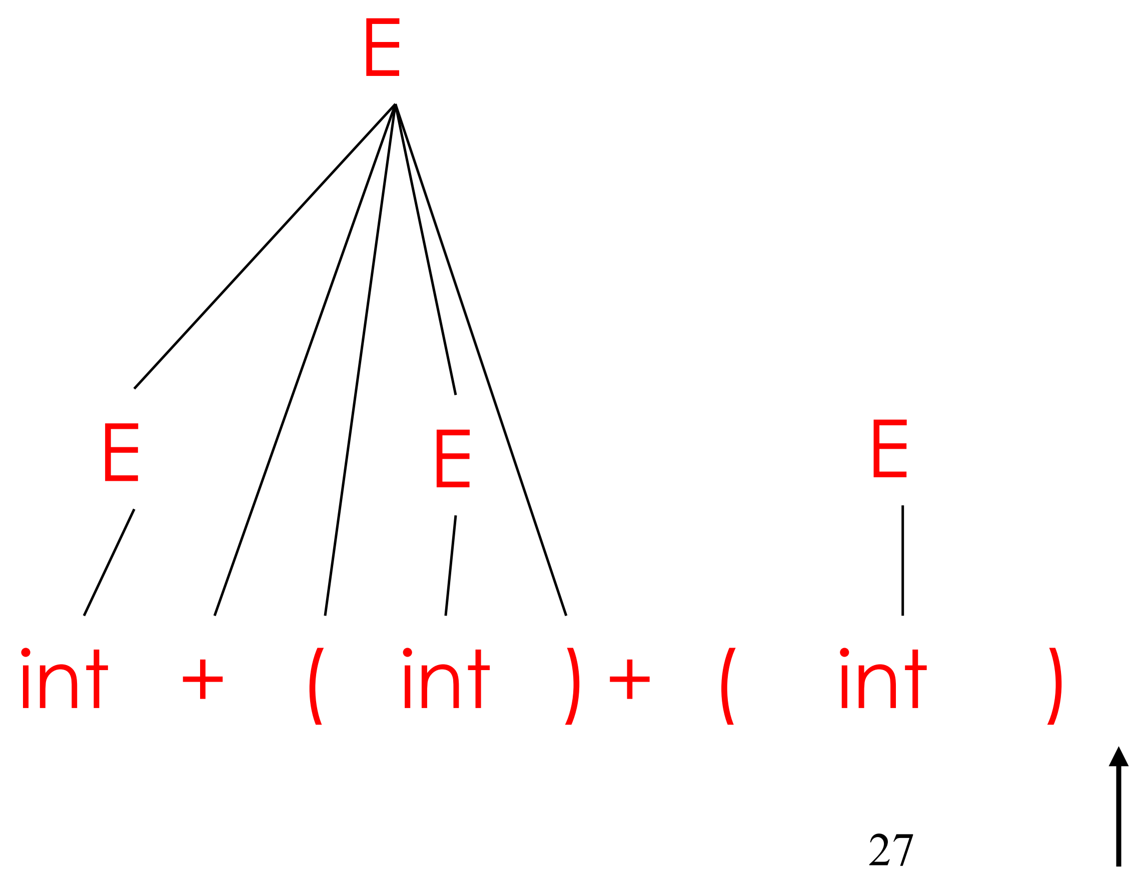
Shift-Reduce Example

▶ int + (int) + (int)$	shift
int ▶ + (int) + (int)$	red. E → int
E ▶ + (int) + (int)$	shift 3 times
E + (int ▶) + (int)$	red. E → int
E + (E ▶) + (int)$	shift
E + (E) ▶ + (int)$	red. E → E + (E)
E ▶ + (int)$	shift 3 times
E + (int ▶)$	red. E → int
E + (E ▶)$	shift



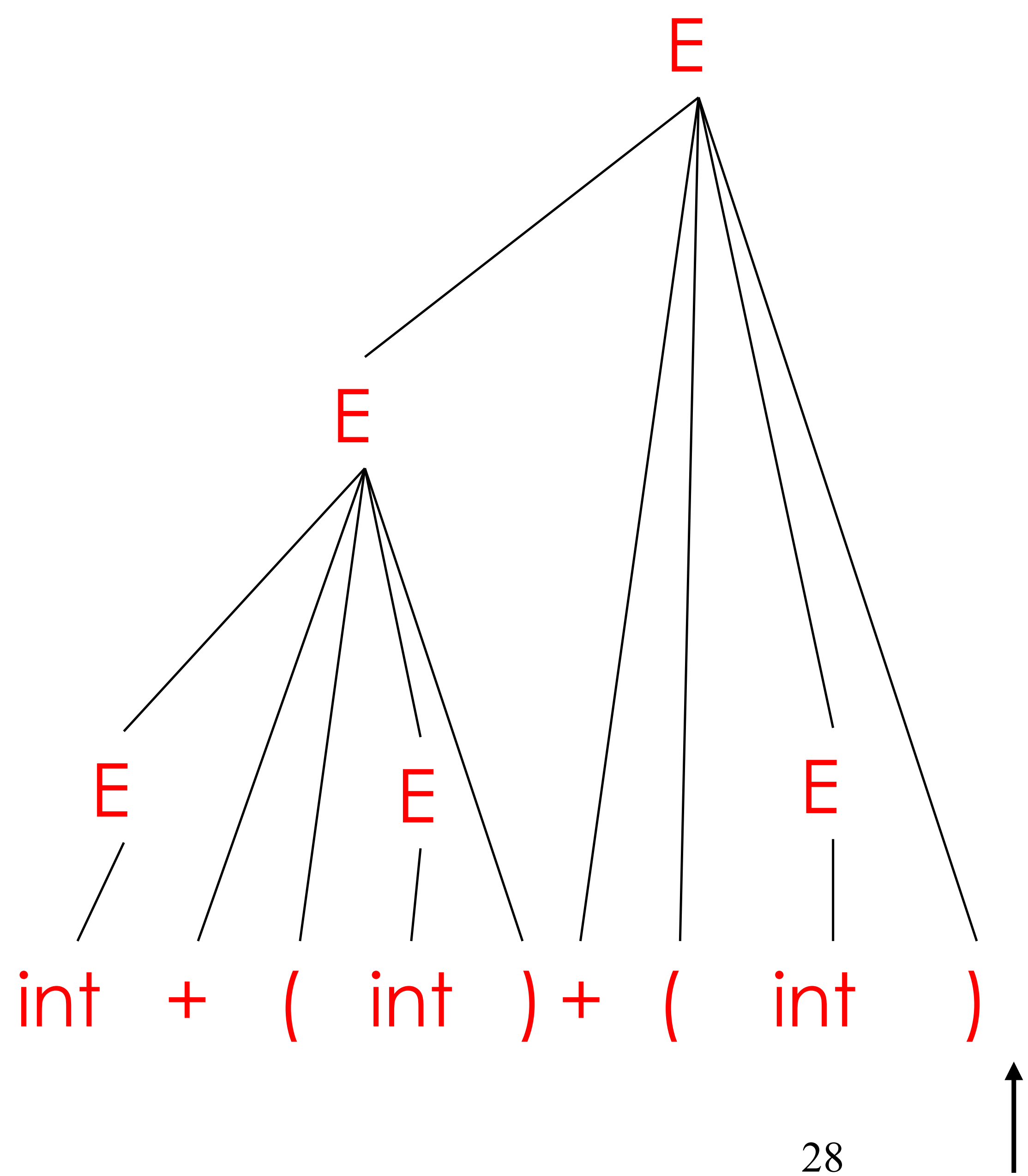
Shift-Reduce Example

▶ int + (int) + (int)$	shift
int ▶ + (int) + (int)$	red. E $\rightarrow$ int
E ▶ + (int) + (int)$	shift 3 times
E + (int ▶) + (int)$	red. E $\rightarrow$ int
E + (E ▶) + (int)$	shift
E + (E) ▶ + (int)$	red. E $\rightarrow$ E + (E)
E ▶ + (int)$	shift 3 times
E + (int ▶)$	red. E $\rightarrow$ int
E + (E ▶)$	shift
E + (E) ▶ $	red. E $\rightarrow$ E + (E)

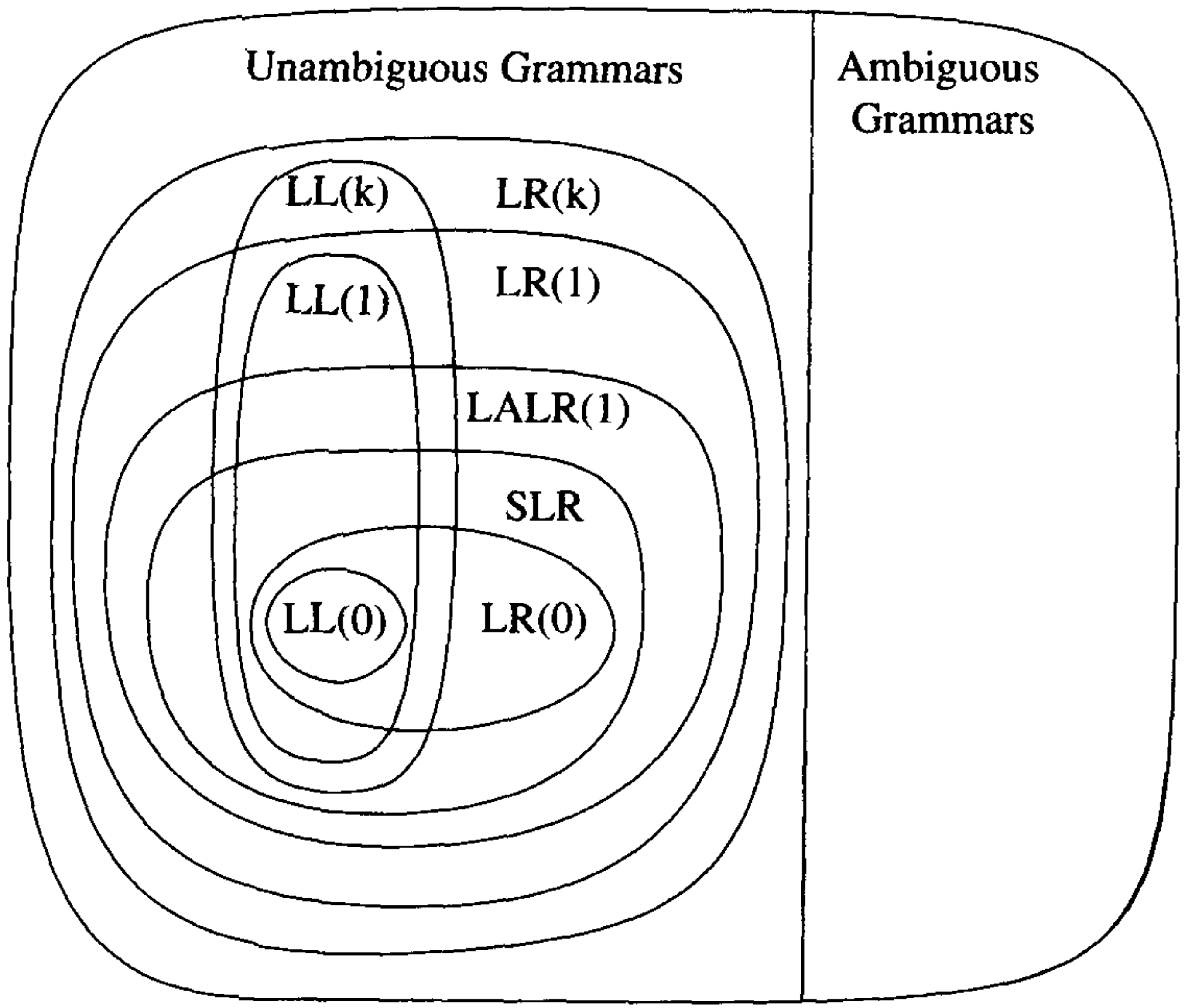


Shift-Reduce Example

▶ int + (int) + (int)$	shift
int ▶ + (int) + (int)$	red. E $\rightarrow$ int
E ▶ + (int) + (int)$	shift 3 times
E + (int ▶) + (int)$	red. E $\rightarrow$ int
E + (E ▶) + (int)$	shift
E + (E) ▶ + (int)$	red. E $\rightarrow$ E + (E)
E ▶ + (int)$	shift 3 times
E + (int ▶)$	red. E $\rightarrow$ int
E + (E ▶)$	shift
E + (E) ▶ $	red. E $\rightarrow$ E + (E)
E ▶ $	accept



A Hierarchy of Grammar Classes



From Andrew Appel, "Modern Compiler Implementation in Java"

Shift/Reduce Conflicts

- If a DFA state contains both

  $[X \to \alpha \bullet a\beta,\ b]$ and $[Y \to \gamma \bullet,\ a]$

- Then on input "a" we could either
  - Shift into state $[X \to \alpha a \bullet \beta,\ b]$, or
  - Reduce with $Y \to \gamma$

- This is called a <u>shift-reduce conflict</u>

Shift/Reduce Conflicts

- Typically due to ambiguities in the grammar
- Classic example: the dangling else

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

- Will have DFA state containing

  [$S \rightarrow$ if E then S•, else]

  [$S \rightarrow$ if E then S• else S, x]

- If else follows then we can shift or reduce
- Default (bison, CUP, etc.) is to shift
  - Default behavior is as needed in this case

The Stack

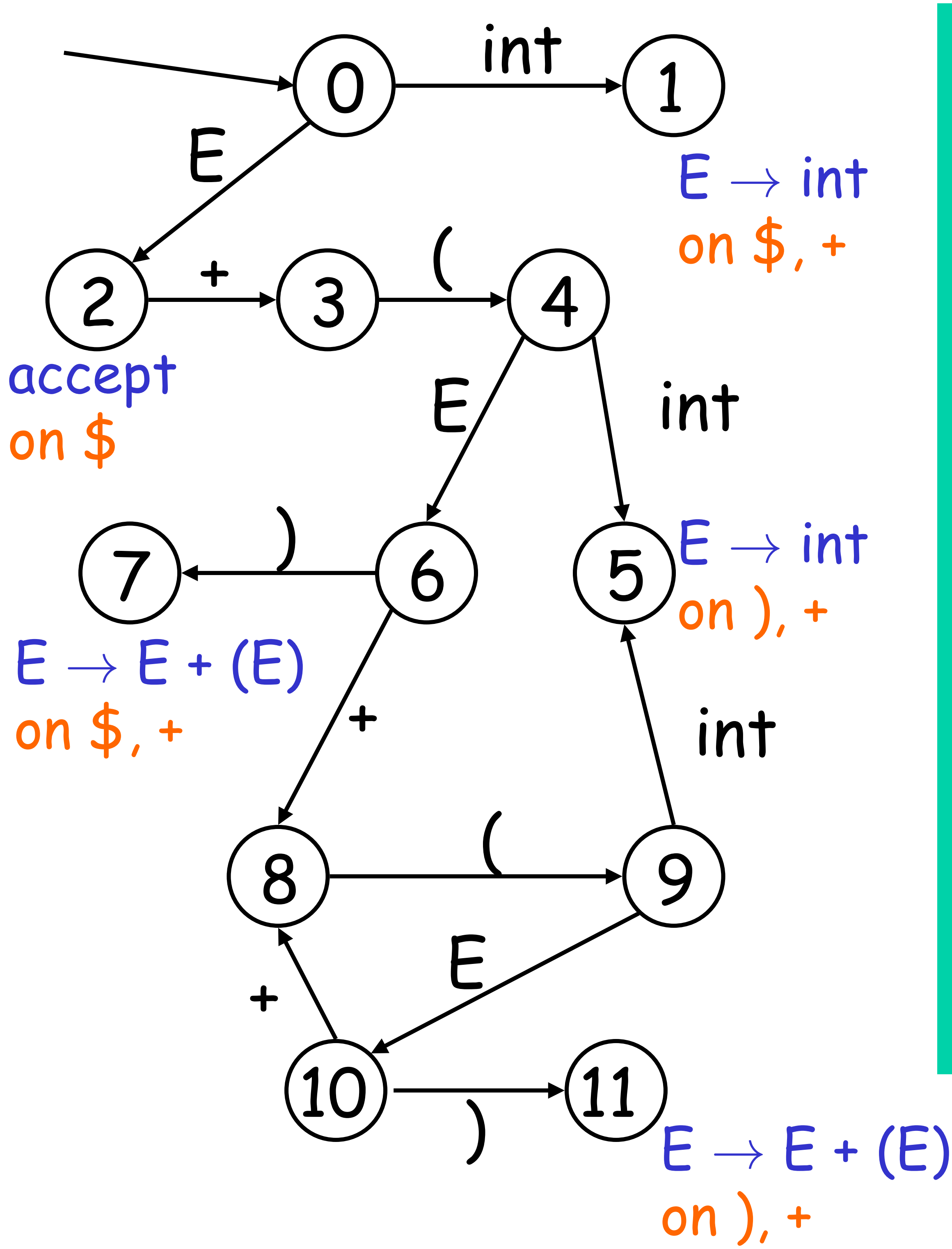
- Left string can be implemented as a stack
  - Top of the stack is the ▸
- Shift pushes a terminal on the stack
- Reduce
  - Pops 0 or more symbols off the stack: production rhs
  - Pushes a non-terminal on the stack: production lhs

Key Issue: When to Shift or Reduce?

- Decide based on the left string (the stack)
- Idea: use a finite automaton (DFA) to decide when to shift or reduce
  - The DFA input is the stack
  - The language consists of terminals and non-terminals

- We run the DFA on the stack and examine the resulting state X and the token tok after ▸
  - If X has a transition labeled tok then shift
  - If X is labeled with "$A \rightarrow \beta$ on tok" then reduce

LR(1) Parsing: An Example



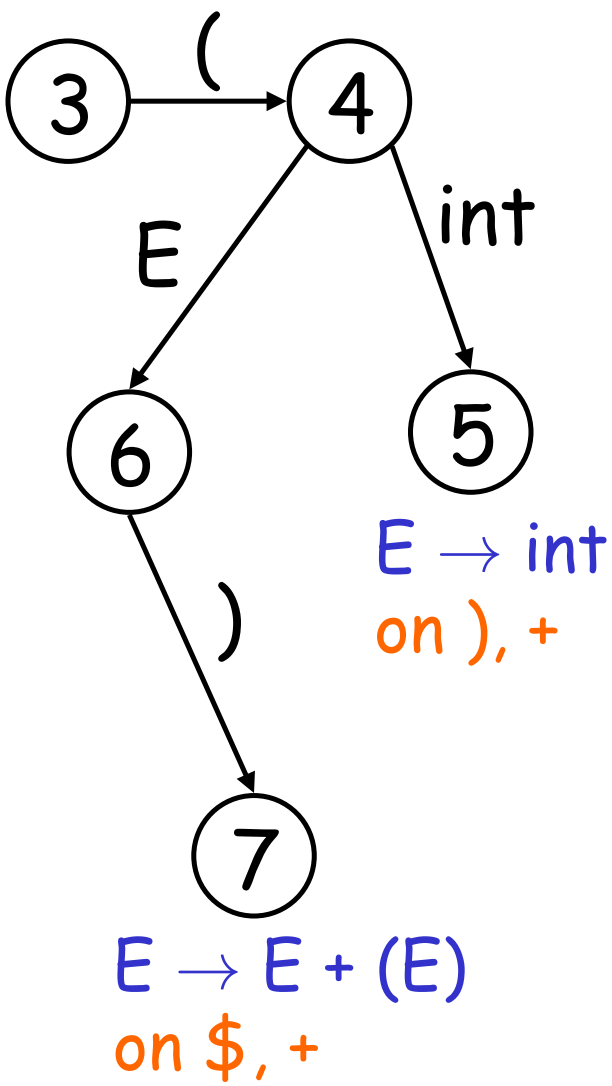
▶ int + (int) + (int)$	shift
int ▶ + (int) + (int)$	E → int
E ▶ + (int) + (int)$	shift(x3)
E + (int ▶) + (int)$	E → int
E + (E ▶) + (int)$	shift
E + (E) ▶ + (int)$	E → E+(E)
E ▶ + (int)$	shift (x3)
E + (int ▶)$	E → int
E + (E ▶)$	shift
E + (E) ▶ $	E → E+(E)
E ▶ $	accept

Representing the DFA

- Parsers represent the DFA as a 2D table
  - Recall table-driven lexical analysis
- Lines correspond to DFA states
- Columns correspond to terminals and non-terminals
- Typically columns are split into:
  - Those for terminals: action table
  - Those for non-terminals: goto table

Representing the DFA. Example

The table for a fragment of our DFA



	int	+	(	)	$	E
…						
3			s4			
4	s5					g6
5		$r_{E \to \text{int}}$		$r_{E \to \text{int}}$		
6	s8		s7			
7		$r_{E \to E+(E)}$			$r_{E \to E+(E)}$	
…						

The LR Parsing Algorithm

- After a shift or reduce action we rerun the DFA on the entire stack
  - This is wasteful, since most of the work is repeated
- Remember for each stack element to which state it brings the DFA
- LR parser maintains a stack

$$\langle \text{sym}_1, \text{state}_1 \rangle \ldots \langle \text{sym}_n, \text{state}_n \rangle$$

state_k is the final state of the DFA on $\text{sym}_1 \ldots \text{sym}_k$

The LR Parsing Algorithm

	int	+	(	)	$	E
…						
3			s4			
4	s5					g6
5		$r_{E \to int}$		$r_{E \to int}$		
6	s8		s7			
7		$r_{E \to E+(E)}$			$r_{E \to E+(E)}$	
…						

Let I = w$ be initial input

Let j = 0

Let DFA state 0 be the start state

Let stack = ⟨ dummy, 0 ⟩

repeat

case action[top_state(stack), I[j]] of

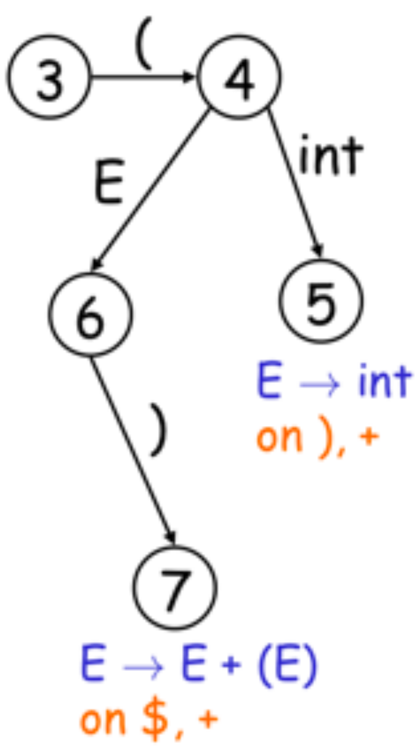
shift k: push ⟨ I[j++], k ⟩

reduce X → α:

- pop $|\alpha|$ pairs off the stack
- push ⟨X, Goto[top_state(stack), X]⟩

accept: halt normally

error: halt and report error



LR Parsing Notes

- Can be used to parse more grammars than LL
- Most programming languages grammars are LR
- Can be described as a simple table
- There are tools for building the table
- How is the table constructed?

Recap …

- A bottom-up parser rewrites the input string to the start symbol
- The state of the parser is described as

$$\alpha \blacktriangleright \gamma$$

  - α is a stack of terminals and non-terminals
  - γ is the string of terminals not yet examined

- Initially: $\blacktriangleright x_1 x_2 \ldots x_n$

The Shift and Reduce Actions

- Recall the CFG: $E \rightarrow \text{int} \mid E + (E)$
- A bottom-up parser uses two kinds of actions
  - Shift pushes a terminal from input on the stack

    $E + (\blacktriangleright \text{int}) \Rightarrow E + (\text{int} \blacktriangleright)$

  - Reduce pops 0 or more symbols off of the stack (production rhs) and pushes a non-terminal on the stack (production lhs)

    $E + (\underline{E + (E)} \blacktriangleright) \Rightarrow E + (\underline{E} \blacktriangleright)$

Key Issue: When to Shift or Reduce?

- Idea: use a finite automaton (DFA) to decide when to shift or reduce
  - The input is the stack
  - The language consists of terminals and non-terminals
- We run the DFA on the stack and we examine the resulting state X and the token tok after ▶
  - If X has a transition labeled tok then shift
  - If X is labeled with "$A \to \beta$ on tok" then reduce

Key Issue: How is the DFA Constructed?

- The stack describes the context of the parse
  - What non-terminal we are looking for
  - What production rhs we are looking for
  - What we have seen so far from the rhs
- Each DFA state describes several such contexts
  - E.g., when we are looking for non-terminal E, we might be looking either for an int or an E + (E) rhs

LR(1) Items

- An LR(1) item is a pair

$$X \to \alpha \bullet \beta, a$$

  - $X \to \alpha\beta$ is a production
  - a is a terminal (the lookahead terminal)
  - LR(1) means 1 lookahead terminal

- $[X \to \alpha \bullet \beta, a]$ describes a context of the parser
  - We are trying to find an X followed by an a, and
  - We have α already on top of the stack
  - Thus we need to see next a prefix derived from βa

Note

- The symbol ▶ was used before to separate the stack from the rest of input
  - α ▶ γ, where α is the stack and γ is the remaining string of terminals
- In LR(1) items • is used to mark a prefix of a production rhs:

$$X \rightarrow \alpha \bullet \beta, a$$

  - Here β might contain non-terminals as well
- In both case the stack is on the left

Convention

- We add to our grammar a fresh new start symbol S and a production $S \to E$
  - Where E is the old start symbol

- The initial parsing context contains:

$$S \to \bullet E, \$$$

  - Trying to find an S as a string derived from $E\$$
  - The stack is empty

LR(1) Items (Cont.)

- In context containing

  $$E \rightarrow E + \bullet (E), +$$

  - If (follows then we can perform a shift to context containing

    $$E \rightarrow E + (\bullet E), +$$

- In a context containing

  $$E \rightarrow E + (E) \bullet, +$$

  - We can perform a reduction with $E \rightarrow E + (E)$
  - But only if a + follows

LR(1) Items (Cont.)

- Consider a context with the item

$$E \rightarrow E + (\bullet E), +$$

- We expect next a string derived from E) +
- There are two productions for E

$$E \rightarrow \text{int} \quad \text{and} \quad E \rightarrow E + (E)$$

- We describe this by <u>extending</u> the context with two more items:

$$E \rightarrow \bullet \text{int},)$$

$$E \rightarrow \bullet E + (E),)$$

The Closure Operation

- The operation of extending the context with items is called the closure operation

Closure(Items) =
  repeat
    for each $[X \to \alpha \bullet Y\beta, a]$ in Items
      for each production $Y \to \gamma$
        for each $b \in First(\beta a)$
          add $[Y \to \bullet\gamma, b]$ to Items
  until Items is unchanged

Constructing the Parsing DFA (1)

- Construct the start context: Closure({$S \rightarrow \bullet E, \$$})

$$S \rightarrow \bullet E, \$$$
$$E \rightarrow \bullet E+(E), \$$$
$$E \rightarrow \bullet int, \$$$
$$E \rightarrow \bullet E+(E), +$$
$$E \rightarrow \bullet int, +$$

- We abbreviate as

$$S \rightarrow \bullet E, \$$$
$$E \rightarrow \bullet E+(E), \$/+$$
$$E \rightarrow \bullet int, \$/+$$

Constructing the Parsing DFA (2)

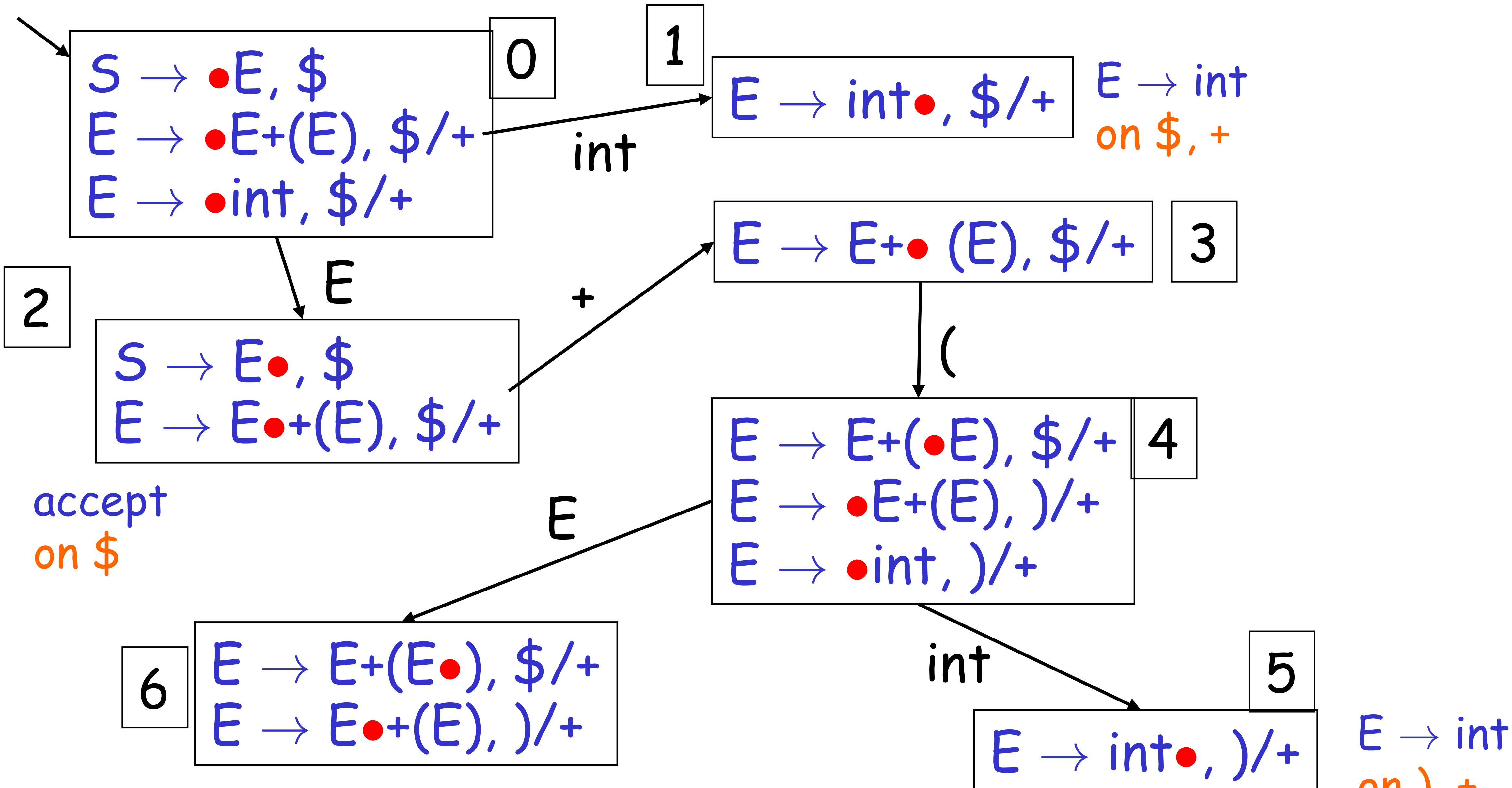
- A DFA state is a <u>**closed**</u> set of LR(1) items
  - This means that we performed Closure
- The start state contains $[S \to \bullet E, \$]$
- A state that contains $[X \to \alpha\bullet, b]$ is labeled with "reduce with $X \to \alpha$ on b"
- And now the transitions …

The DFA Transitions

- A state "State" that contains $[X \to \alpha \bullet y\beta, b]$ has a transition labeled y to a state that contains the items "Transition(State, y)"
  - y can be a terminal or a non-terminal

```
Transition(State, y)
  Items ← ∅
  for each [X → α•yβ, b] ∈ State
      add [X → αy•β, b] to Items
  return Closure(Items)
```

Constructing the Parsing DFA: An Example



and so on…

LR Parsing Tables. Notes

- Parsing tables (i.e. the DFA) can be constructed automatically for a CFG
- But we still need to understand the construction to work with parser generators
  - E.g., they report errors in terms of sets of items
- What kind of errors can we expect?

Shift/Reduce Conflicts

- If a DFA state contains both

  $[X \to \alpha \bullet a\beta, b]$ and $[Y \to \gamma \bullet, a]$

- Then on input "a" we could either
  - Shift into state $[X \to \alpha a \bullet \beta, b]$, or
  - Reduce with $Y \to \gamma$

- This is called a shift-reduce conflict

Shift/Reduce Conflicts

- Typically due to ambiguities in the grammar
- Classic example: the dangling else

  S → if E then S | if E then S else S | OTHER

- Will have DFA state containing

  [S → if E then S•, else]

  [S → if E then S• else S, x]

- If else follows then we can shift or reduce
- Default (bison, CUP, etc.) is to shift
  - Default behavior is as needed in this case

More Shift/Reduce Conflicts

- Consider the ambiguous grammar

$$E \rightarrow E + E \mid E * E \mid int$$

- We will have the states containing

$[E \rightarrow E * \bullet E, +]$ $\quad$ $[E \rightarrow E * E \bullet, +]$

$[E \rightarrow \bullet E + E, +]$ $\Rightarrow^{E}$ $[E \rightarrow E \bullet + E, +]$

… $\quad$ …

- Again we have a shift/reduce on input +
  - We need to reduce (* binds more tightly than +)
  - Recall solution: declare the precedence of * and +

More Shift/Reduce Conflicts

- In bison declare precedence and associativity:

```
%left +
%left *
```

- Precedence of a rule = that of its last terminal
  - See bison manual for ways to override this default
    - Context-dependent precedence (Section 5.4, pp 70)
- Resolve shift/reduce conflict with a <u>shift</u> if:
  - no precedence declared for either rule or terminal
  - input terminal has higher precedence than the rule
  - the precedences are the same and right associative

Using Precedence to Solve S/R Conflicts

- Back to our example:

  [E → E * • E, +]   [E → E * E•, +]

  [E → • E + E, +] $\Rightarrow^{E}$ [E → E • + E, +]

  …   …

- Will choose reduce because precedence of rule E → E * E is higher than of terminal +

Using Precedence to Solve S/R Conflicts

- Same grammar as before

  $E \rightarrow E + E \mid E * E \mid int$

- We will also have the states

  $[E \rightarrow E + \bullet E, +] \qquad [E \rightarrow E + E\bullet, +]$

  $[E \rightarrow \bullet E + E, +] \quad \Rightarrow^{E} \quad [E \rightarrow E \bullet + E, +]$

  … …

- Now we also have a shift/reduce on input +
  - We choose reduce because $E \rightarrow E + E$ and + have the same precedence and + is left-associative

Using Precedence to Solve S/R Conflicts

- Back to our dangling else example

  [S → if E then S•, else]

  [S → if E then S• else S, x]

- Can eliminate conflict by declaring else with higher precedence than then
  - Or just rely on the default shift action
- But this starts to look like "hacking the parser"
- Best to avoid overuse of precedence declarations or you'll end with unexpected parse trees

Reduce/Reduce Conflicts

- If a DFA state contains both

  $[X \to \alpha\bullet, a]$ and $[Y \to \beta\bullet, a]$

  - Then on input "a" we don't know which production to reduce

- This is called a reduce/reduce conflict

Reduce/Reduce Conflicts

- Usually due to gross ambiguity in the grammar
- Example: a sequence of identifiers

$$S \rightarrow \varepsilon \ | \ id \ | \ id\ S$$

- There are two parse trees for the string id

$$S \rightarrow id$$

$$S \rightarrow id\ S \rightarrow id$$

- How does this confuse the parser?

More on Reduce/Reduce Conflicts

- Consider the states

$[S' \to \bullet\, S,\ \$]$		$[S \to id\, \bullet,\ \$]$
$[S \to \bullet,\ \$]$		$[S \to id\, \bullet\, S,\ \$]$
$[S \to \bullet\, id,\ \$]$	$\Rightarrow^{id}$	$[S \to \bullet,\ \$]$
$[S \to \bullet\, id\ S,\ \$]$		$[S \to \bullet\, id,\ \$]$
		$[S \to \bullet\, id\ S,\ \$]$

- Reduce/reduce conflict on input $

$$S' \to S \to id$$

$$S' \to S \to id\ S \to id$$

- Better rewrite the grammar: $S \to \varepsilon \mid id\ S$

Using Parser Generators

- Parser generators construct the parsing DFA given a CFG
  - Use precedence declarations and default conventions to resolve conflicts
  - The parser algorithm is the same for all grammars (and is provided as a library function)
- But most parser generators do not construct the DFA as described before
  - Because the LR(1) parsing DFA has 1000s of states even for a simple language

LR(1) Parsing Tables are Big

- But many states are similar, e.g.

1			5	
$E \rightarrow$ int•, \$/+	$E \rightarrow$ int on \$, +	and	$E \rightarrow$ int•,)/+	$E \rightarrow$ int on), +

- Idea: merge the DFA states whose items differ only in the lookahead tokens
  - We say that such states have the same core
- We obtain

1'	
$E \rightarrow$ int•, \$/+/)	$E \rightarrow$ int on \$, +,)

The Core of a Set of LR Items

- Definition: The <u>core</u> of a set of LR items is the set of first components
  - Without the lookahead terminals

- Example: the core of

$$\{ [X \to \alpha \bullet \beta, b], [Y \to \gamma \bullet \delta, d] \}$$

is

$$\{X \to \alpha \bullet \beta, \; Y \to \gamma \bullet \delta\}$$

LALR States

- Consider for example the LR(1) states

$$\{[X \rightarrow \alpha\bullet, a], [Y \rightarrow \beta\bullet, c]\}$$

$$\{[X \rightarrow \alpha\bullet, b], [Y \rightarrow \beta\bullet, d]\}$$

- They have the same core and can be merged
- And the merged state contains:

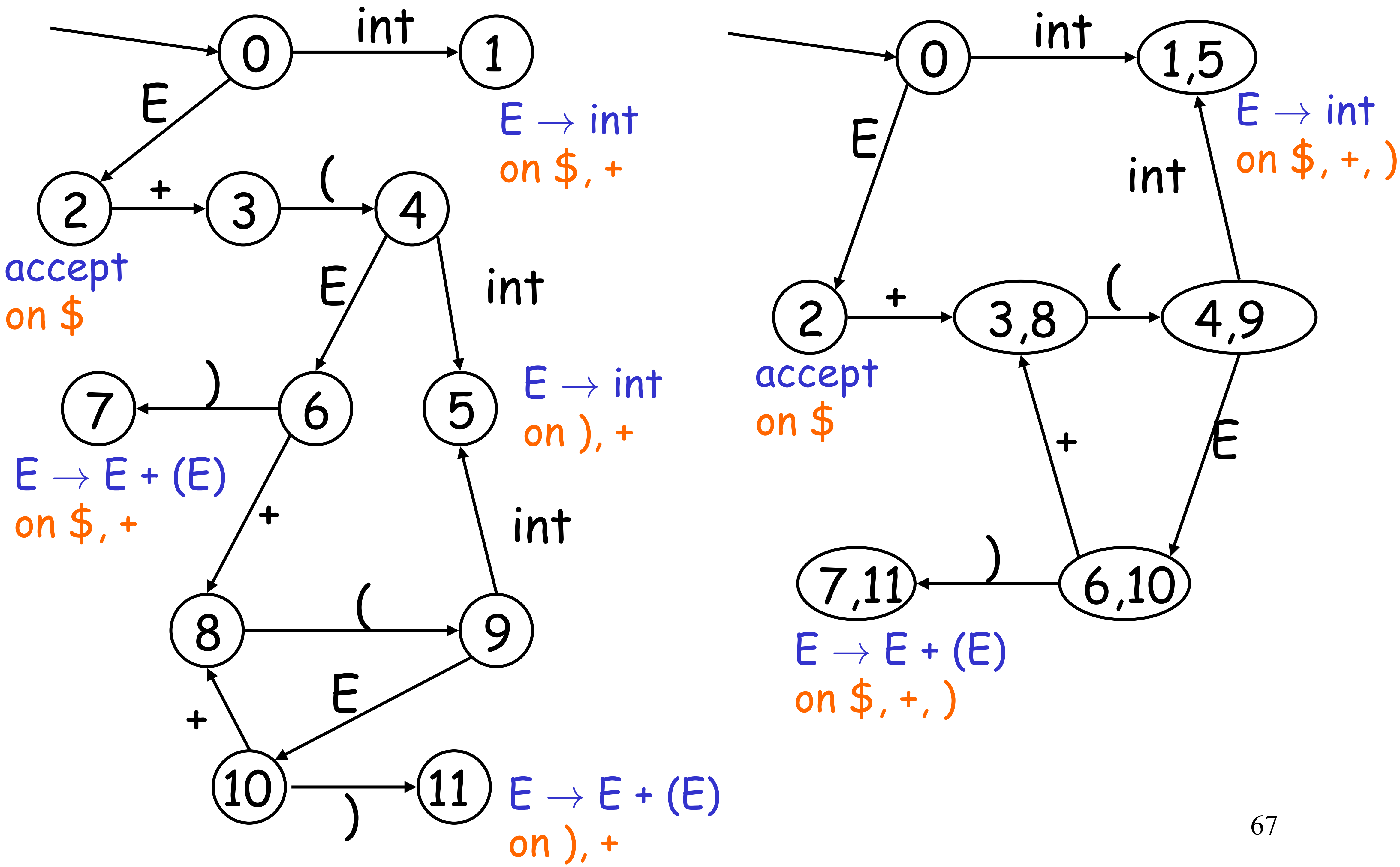
$$\{[X \rightarrow \alpha\bullet, a/b], [Y \rightarrow \beta\bullet, c/d]\}$$

- These are called LALR(1) states
  - Stands for LookAhead LR
  - Typically 10 times fewer LALR(1) states than LR(1)

A LALR(1) DFA

- Repeat until all states have distinct core
  - Choose two distinct states with same core
  - Merge the states by creating a new one with the union of all the items
  - Point edges from predecessors to new state
  - New state points to all the previous successors

Conversion LR(1) to LALR(1). Example.



The LALR Parser Can Have Conflicts

- Consider for example the LR(1) states

  $\{[X \to \alpha\bullet, a], [Y \to \beta\bullet, b]\}$

  $\{[X \to \alpha\bullet, b], [Y \to \beta\bullet, a]\}$

- And the merged LALR(1) state

  $\{[X \to \alpha\bullet, a/b], [Y \to \beta\bullet, a/b]\}$

- Has a new reduce-reduce conflict
- In practice such cases are rare

- However, no new shift/reduce conflicts. Why?

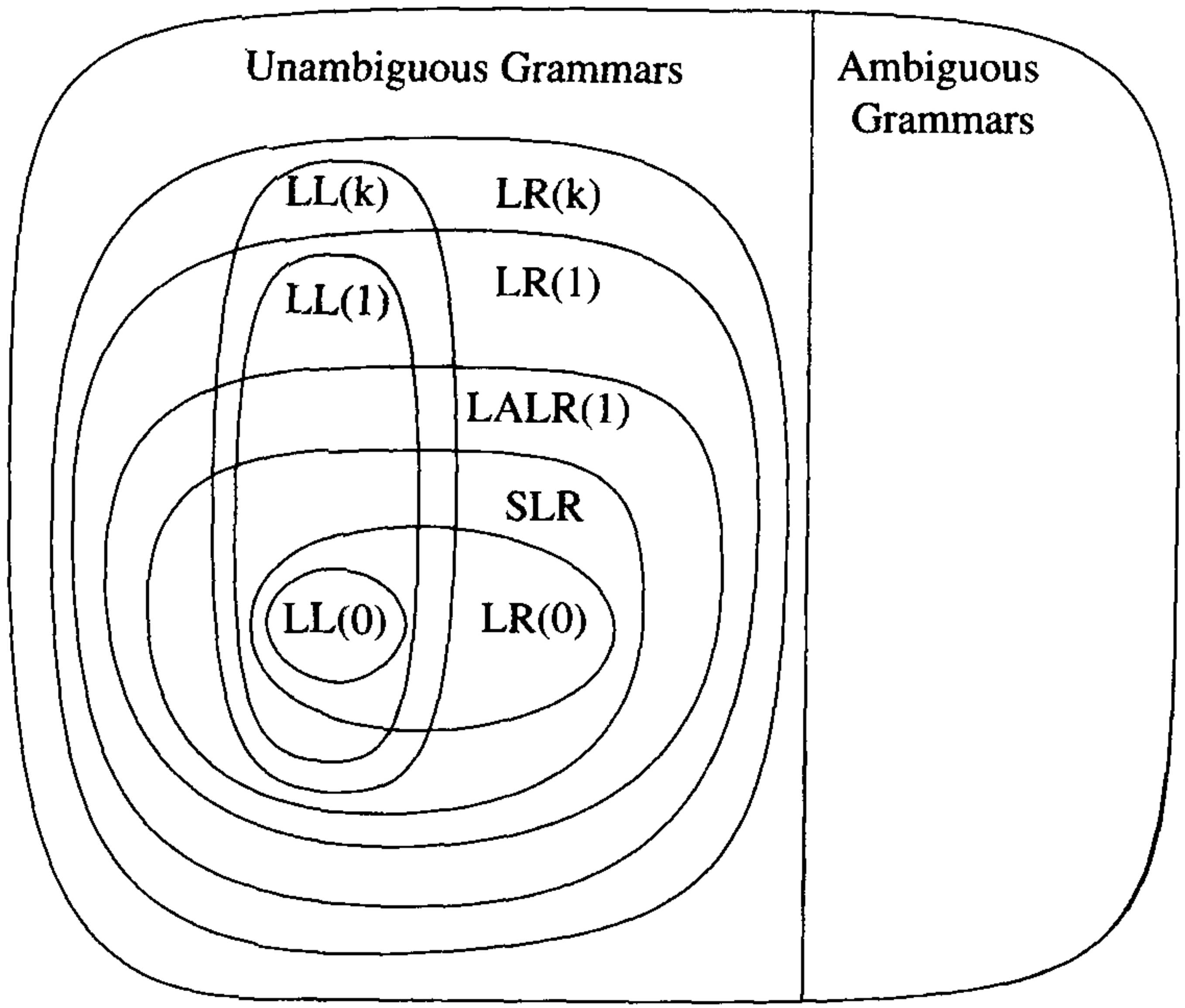
LALR vs. LR Parsing

- LALR languages are not natural
  - They are an efficiency hack on LR languages

- Any reasonable programming language has a LALR(1) grammar

- LALR(1) has become a standard for programming languages and for parser generators

A Hierarchy of Grammar Classes



From Andrew Appel, "Modern Compiler Implementation in Java"

Notes on Parsing

- Parsing
  - A solid foundation: context-free grammars
  - A simple parser: LL(1)
  - A more powerful parser: LR(1)
  - An efficiency hack: LALR(1)
  - LALR(1) parser generators
  - Didn't discuss another variant: SLR(1)

- Now we move on to semantic analysis

General Idea

- Input tokens are shifted onto a parsing stack

Stack		Input
	←	`X = 3 * 4 + 5`
`NAME`	←	`= 3 * 4 + 5`
`NAME =`	←	`3 * 4 + 5`
`NAME = NUM`		`* 4 + 5`

- This continues until a complete grammar rule appears on the top of the stack

General Idea

- If rules are found, a "reduction" occurs

Stack		Input
	←	X = 3 * 4 + 5
NAME	←	= 3 * 4 + 5
NAME =	←	3 * 4 + 5
NAME = **NUM**		* 4 + 5
↓ reduce	←	`factor : NUM`
NAME = **factor**		

- RHS of grammar rule replaced with LHS

Rule Functions

- During reduction, rule functions are invoked

```
def p_factor(p):
    'factor : NUMBER'
```

- Parameter p contains grammar symbol values

```
def p_factor(p):
    'factor : NUMBER'
        ↑         ↑
      p[0]      p[1]
```

Using an LR Parser

- Rule functions generally process values on right hand side of grammar rule
- Result is then stored in left hand side
- Results propagate up through the grammar
- Bottom-up parsing

Example: Calculator

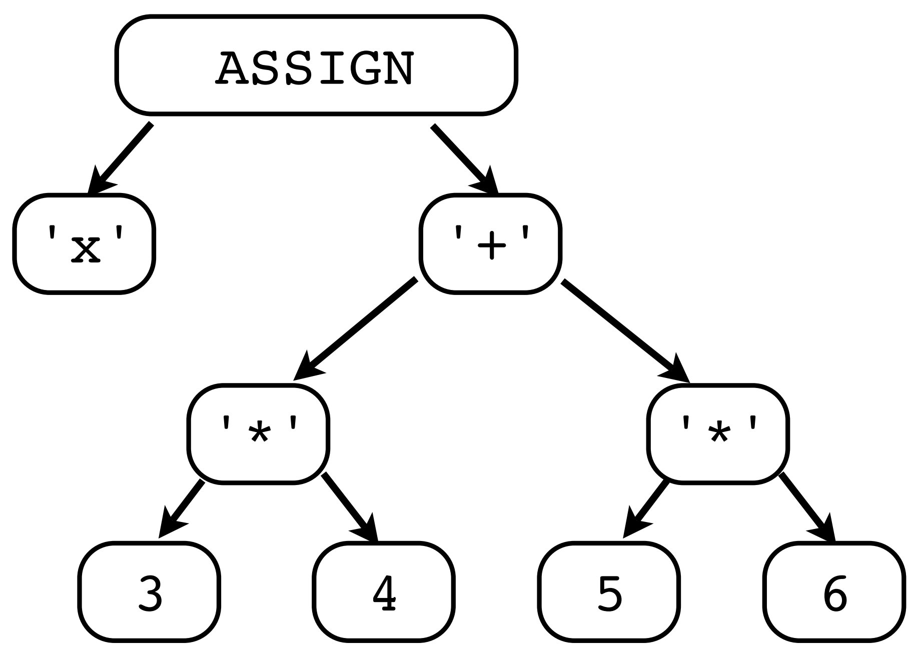
```
def p_assign(p):
    '''assign : NAME EQUALS expr'''
    vars[p[1]] = p[3]

def p_expr_plus(p):
    '''expr : expr PLUS term'''
    p[0] = p[1] + p[3]

def p_term_mul(p):
    '''term : term TIMES factor'''
    p[0] = p[1] * p[3]

def p_term_factor(p):
    '''term : factor'''
    p[0] = p[1]

def p_factor(p):
    '''factor : NUMBER'''
    p[0] = p[1]
```

Example: Parse Tree

```
def p_assign(p):
    ‘’’assign : NAME EQUALS expr’’’
    p[0] = (‘ASSIGN’,p[1],p[3])

def p_expr_plus(p):
    ‘’’expr : expr PLUS term’’’
    p[0] = (‘+’,p[1],p[3])

def p_term_mul(p):
    ‘’’term : term TIMES factor’’’
    p[0] = (‘*’,p[1],p[3])

def p_term_factor(p):
    '''term : factor'''
    p[0] = p[1]

def p_factor(p):
    ‘’’factor : NUMBER’’’
    p[0] = (‘NUM’,p[1])
```

Example: Parse Tree

```
>>> t = yacc.parse("x = 3*4 + 5*6")
>>> t
('ASSIGN','x',('+',
                  ('*',('NUM',3),('NUM',4)),
                  ('*',('NUM',5),('NUM',6))
               )
)
>>>
```



Why use PLY?

- There are many Python parsing tools
- Some use more powerful parsing algorithms
- Isn't parsing a "solved" problem anyways?

PLY is Informative

- Compiler writing is hard
- Tools should not make it even harder
- PLY provides extensive diagnostics
- Major emphasis on error reporting
- Provides the same information as yacc

PLY Diagnostics

- PLY produces the same diagnostics as yacc
- Yacc

```
% yacc grammar.y
4 shift/reduce conflicts
2 reduce/reduce conflicts
```

- PLY

```
% python mycompiler.py
yacc: Generating LALR parsing table...
4 shift/reduce conflicts
2 reduce/reduce conflicts
```

- PLY also produces the same debugging output

Debugging Output

```
Grammar

Rule 1     statement -> NAME = expression
Rule 2     statement -> expression
Rule 3     expression -> expression + expression
Rule 4     expression -> expression - expression
Rule 5     expression -> expression * expression
Rule 6     expression -> expression / expression
Rule 7     expression -> NUMBER

Terminals, with rules where they appear

*                    : 5
+                    : 3
-                    : 4
/                    : 6
=                    : 1
NAME                 : 1
NUMBER               : 7
error                :

Nonterminals, with rules where they appear

expression           : 1 2 3 3 4 4 5 5 6 6
statement            : 0

Parsing method: LALR

state 0

    (0) S' -> . statement
    (1) statement -> . NAME = expression
    (2) statement -> . expression
    (3) expression -> . expression + expression
    (4) expression -> . expression - expression
    (5) expression -> . expression * expression
    (6) expression -> . expression / expression
    (7) expression -> . NUMBER

    NAME            shift and go to state 1
    NUMBER          shift and go to state 2


    expression                     shift and go to state 4
    statement                      shift and go to state 3

state 1

    (1) statement -> NAME . = expression

    =               shift and go to state 5
```

```
state 10

    (1) statement -> NAME = expression .
    (3) expression -> expression . + expression
    (4) expression -> expression . - expression
    (5) expression -> expression . * expression
    (6) expression -> expression . / expression

    $end            reduce using rule 1 (statement -> NAME = expression .)
    +               shift and go to state 7
    -               shift and go to state 6
    *               shift and go to state 8
    /               shift and go to state 9


state 11

    (4) expression -> expression - expression .
    (3) expression -> expression . + expression
    (4) expression -> expression . - expression
    (5) expression -> expression . * expression
    (6) expression -> expression . / expression

  ! shift/reduce conflict for + resolved as shift.
  ! shift/reduce conflict for - resolved as shift.
  ! shift/reduce conflict for * resolved as shift.
  ! shift/reduce conflict for / resolved as shift.
    $end            reduce using rule 4 (expression -> expression - expression .)
    +               shift and go to state 7
    -               shift and go to state 6
    *               shift and go to state 8
    /               shift and go to state 9

  ! +               [ reduce using rule 4 (expression -> expression - expression .) ]
  ! -               [ reduce using rule 4 (expression -> expression - expression .) ]
  ! *               [ reduce using rule 4 (expression -> expression - expression .) ]
  ! /               [ reduce using rule 4 (expression -> expression - expression .) ]
```

Debugging Output

```
...
state 11

    (4) expression -> expression - expression .
    (3) expression -> expression . + expression
    (4) expression -> expression . - expression
    (5) expression -> expression . * expression
    (6) expression -> expression . / expression

  ! shift/reduce conflict for + resolved as shift.
  ! shift/reduce conflict for - resolved as shift.
  ! shift/reduce conflict for * resolved as shift.
  ! shift/reduce conflict for / resolved as shift.
    $end            reduce using rule 4 (expression -> expression - expression .)
    +               shift and go to state 7
    -               shift and go to state 6
    *               shift and go to state 8
    /               shift and go to state 9

  ! +               [ reduce using rule 4 (expression -> expression - expression .) ]
  ! -               [ reduce using rule 4 (expression -> expression - expression .) ]
  ! *               [ reduce using rule 4 (expression -> expression - expression .) ]
  ! /               [ reduce using rule 4 (expression -> expression - expression .) ]
...
```

```
    =               shift and go to state 5
```

PLY Validation

- PLY validates all token/grammar specs
- Duplicate rules
- Malformed regexs and grammars
- Missing rules and tokens
- Unused tokens and rules
- Improper function declarations
- Infinite recursion

Error Example

```
import ply.lex as lex
tokens = [ ‘NAME’,’NUMBER’,’PLUS’,’MINUS’,’TIMES’,
           ’DIVIDE’, EQUALS’ ]
t_ignore = ‘ \t’
t_PLUS   = r’\+’
t_MINUS  = r’-’
t_TIMES  = r’\*’
t_DIVIDE = r’/’
t_EQUALS = r’=’
t_NAME   = r’[a-zA-
t_MINUS  = r'-'
t_POWER  = r'\^'

def t_NUMBER():
    r’\d+’
    t.value = int(t.value)
    return t

lex.lex()          # Build the lexer
```

```
example.py:12: Rule t_MINUS redefined.
               Previously defined on line 6
```

Error Example

```
import ply.lex as lex
tokens = [ 'NAME','NUMBER','PLUS','MINUS','TIMES',
           'DIVIDE', EQUALS' ]
t_ignore = ' \t'
t_PLUS   = r'\+'
t_MINUS  = r'-'
t_TIMES  = r'\*'
t_DIVIDE = r'/'
t_EQUALS = r'='
t_NAME   = r'[a-zA-Z_][a-zA-Z0-9_]*'
t_MINUS  = r'-'
t_POWER  = r'\^'

def t_NUMBER():
    r'\d+'
    t.value = int(t.value)
    return t

lex.lex()           # Build the lexer
```

lex: Rule 't_POWER' defined for an unspecified token POWER

Error Example

```
import ply.lex as lex
tokens = [ 'NAME','NUMBER','PLUS','MINUS','TIMES',
           'DIVIDE', EQUALS' ]
t_ignore = ' \t'
t_PLUS   = r'\+'
t_MINUS  = r'-'
t_TIMES  = r'\*'
t_DIVIDE = r'/'
t_EQUALS = r'='
t_NAME   = r'[a-zA-Z_][a-zA-Z0-9_]*'
t_MINUS  = r'-'
t_POWER  = r'\^'

def t_NUMBER():
    r'\d+'
    t.value = int(t.value)
    return t

lex.lex()         # Build the lexer
```

```
example.py:15: Rule 't_NUMBER' requires
an argument.
```

PLY is Yacc

- PLY supports all of the major features of Unix lex/yacc
- Syntax error handling and synchronization
- Precedence specifiers
- Character literals
- Start conditions
- Inherited attributes

Precedence Specifiers

- Yacc

```
%left PLUS MINUS
%left TIMES DIVIDE
%nonassoc UMINUS
...
expr : MINUS expr %prec UMINUS {
    $$ = -$1;
}
```

- PLY

```
precedence = (
   ('left','PLUS','MINUS'),
   ('left','TIMES','DIVIDE'),
   ('nonassoc','UMINUS'),
)
def p_expr_uminus(p):
   'expr : MINUS expr %prec UMINUS'
   p[0] = -p[1]
```

Character Literals

- Yacc

```
expr : expr '+' expr { $$ = $1 + $3; }
     | expr '-' expr { $$ = $1 - $3; }
     | expr '*' expr { $$ = $1 * $3; }
     | expr '/' expr { $$ = $1 / $3; }
     ;
```

- PLY

```
def p_expr(p):
    '''expr : expr '+' expr
            | expr '-' expr
            | expr '*' expr
            | expr '/' expr'''
    ...
```

Error Productions

- Yacc

```
funcall_err : ID LPAREN error RPAREN {
                printf("Syntax error in arguments\n");
         }
         ;
```

- PLY

```
def p_funcall_err(p):
    '''ID LPAREN error RPAREN'''
    print "Syntax error in arguments\n"
```

PLY is Simple

- Two pure-Python modules. That's it.
- Not part of a "parser framework"
- Use doesn't involve exotic design patterns
- Doesn't rely upon C extension modules
- Doesn't rely on third party tools

PLY is Fast

- For a parser written entirely in Python
- Underlying parser is table driven
- Parsing tables are saved and only regenerated if the grammar changes
- Considerable work went into optimization from the start (developed on 200Mhz PC)

PLY Performance

- Parse file with 1000 random expressions (805KB) and build an abstract syntax tree
  - PLY-2.3 : 2.95 sec, 10.2 MB (Python)
  - DParser : 0.71 sec, 72 MB (Python/C)
  - BisonGen : 0.25 sec, 13 MB (Python/C)
  - Bison : 0.063 sec, 7.9 MB (C)
- 12x slower than BisonGen (mostly C)
- 47x slower than pure C
- System: MacPro 2.66Ghz Xeon, Python-2.5

Class Example

```
import ply.yacc as yacc

class MyParser:
    def p_assign(self,p):
        '''assign : NAME EQUALS expr'''
    def p_expr(self,p):
        '''expr : expr PLUS term
                | expr MINUS term
                | term'''
    def p_term(self,p):
        '''term : term TIMES factor
                | term DIVIDE factor
                | factor'''
    def p_factor(self,p):
        '''factor : NUMBER'''
    def build(self):
        self.parser = yacc.yacc(object=self)
```

Limitations

- LALR(1) parsing
- Not easy to work with very complex grammars (e.g., C++ parsing)
- Retains all of yacc's black magic
- Not as powerful as more general parsing algorithms (ANTLR, SPARK, etc.)
- Tradeoff : Speed vs. Generality