Programming Language Syntax: Scanning and Parsing

Read: Scott, Chapter 2.2 and 2.3.1

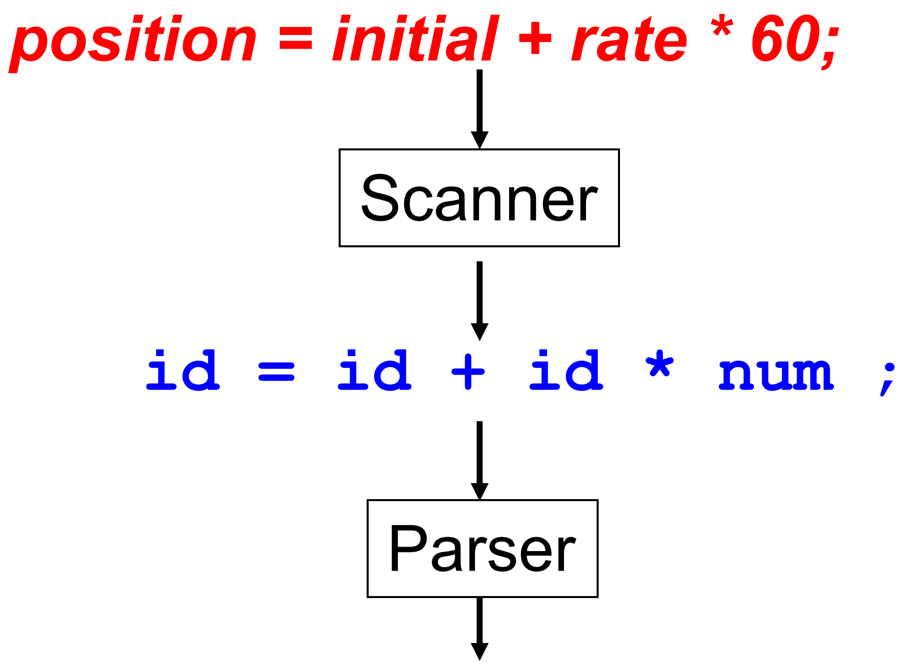
Lecture Outline

- Overview of scanning
- Overview of top-down and bottom-up parsing

- Top-down parsing
  - Recursive descent
  - LL(1) parsing tables

Scanning

- Scanner groups characters into tokens
- Scanner simplifies the job of the parser



- Scanner is essentially a Finite Automaton
  - Regular expressions specify the syntax of tokens
  - Scanner recognizes the tokens in the program

Question

- Why most programming languages disallow nested multi-line comments?

  - Comments are usually handled by the scanner, which essentially is a DFA. Handling multiline comments would require recognizing $(/*)^n(*/)^n$ which is beyond the power of a DFA.

Calculator Language

- Tokens

times $\rightarrow$ *****

plus $\rightarrow$ **+**

id $\rightarrow$ *letter* **(** *letter* | *digit* **)** *****

except for **read** and **write** which are keywords (keywords are tokens as well)

Ad-hoc (By hand) Scanner

skip any initial white space (space, tab, newline)

if current_char in { `+`, `*` }

  return corresponding single-character token (*plus* or *times*)

if current_char is a letter

  read any additional letters and digits

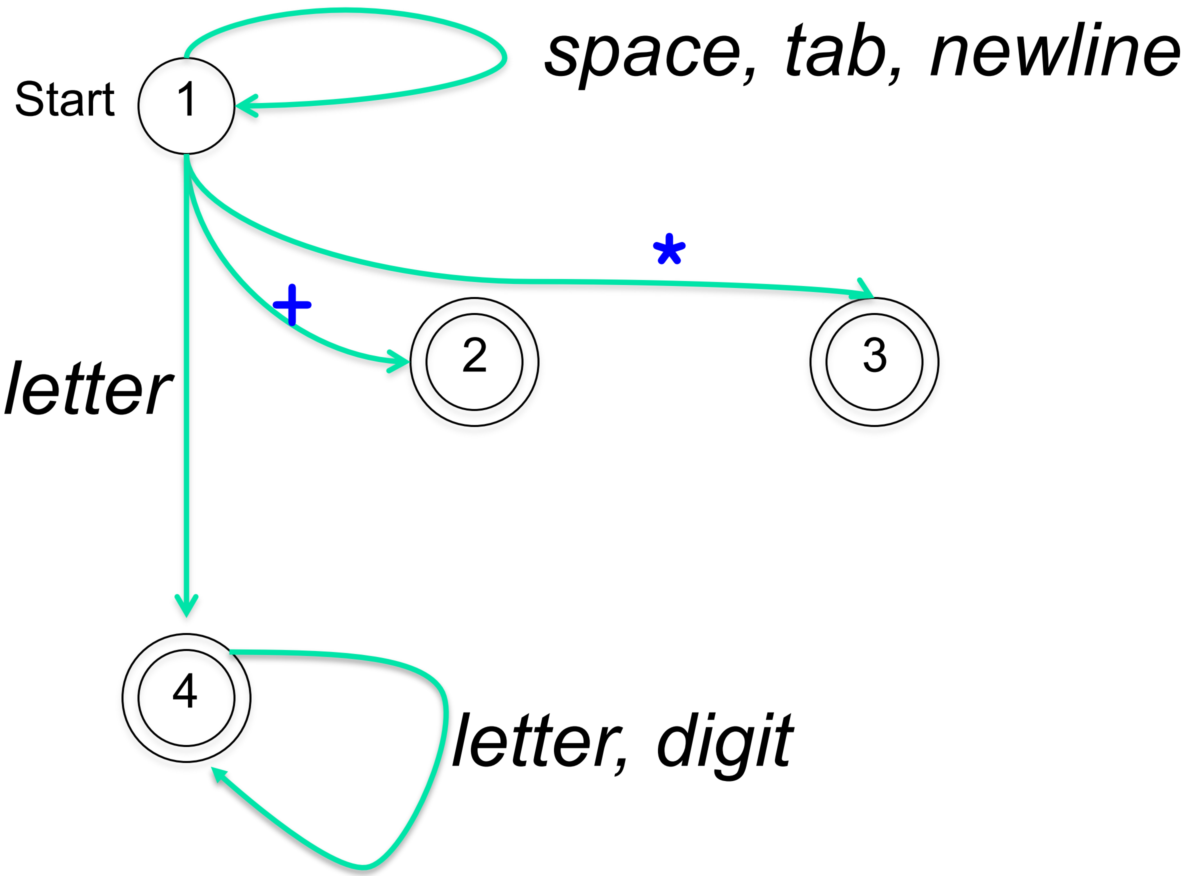
  check to see if the resulting string is **read** or **write**

  if so, then return the corresponding token

  else return `id`

else announce an ERROR

The Scanner as a DFA



Building a Scanner

- Scanners are (usually) automatically generated from regular expressions:

  Step 1: From a Regular Expression to an NFA

  Step 2: From an NFA to a DFA

  Step 3: Minimizing the DFA
- **lex/flex** utilities generate scanner code
- Scanner code explicitly captures the states and transitions of the DFA

Table-Driven Scanning

```
…
cur_state := 1
loop
    read cur_char
    case scan_tab[cur_char, cur_state].action of
        move:
          …
          cur_state = scan_tab[cur_char, cur_state].new_state
        recognize: // emits the token
          tok = token_tab[current_state]
          unread cur_char --- push back char
          exit loop
        error:
```

Table-Driven Scanning

	space,tab,newline	*	+	*digit*	*letter*	other	
1	5	2	3	-	4	-	
2	-	-	-	-	-	-	*plus*
3	-	-	-	-	-	-	*times*
4	-	-	-	4	4	-	*id*
5	5	-	-	-	-	-	*space*

Sketch of table: scan_tab and token_tab. See Scott for details.

Today's Lecture Outline

- Overview of scanning
- Overview of top-down and bottom-up parsing

- Top-down parsing
  - Recursive descent
  - LL(1) parsing tables

A Simple Calculator Language

asst_stmt → **`id`** **`=`** *expr* // *asst_stmt is the start symbol*
expr → *expr* **`+`** *expr* | *expr* **`*`** *expr* | **`id`**

Character stream: `position = initial + rate * time`

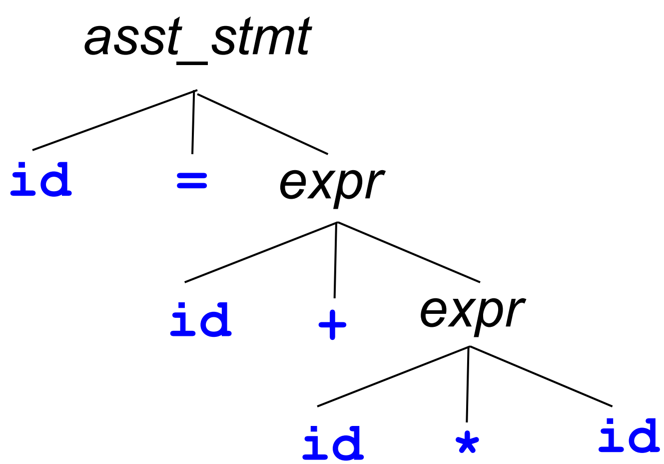
↓

Scanner

↓ ***Token stream:*** `id = id + id * id`

Parser

↓ ***Parse tree:***



(Parse tree simplified to fit on slide.)

A Simple Calculator Language

asst_stmt → `id` `=` *expr* // *asst_stmt is the start symbol*
expr → *expr* `+` *expr* | *expr* `*` *expr* | `id`

Character stream: `position + initial = rate * time`

Scanner

Token stream: `id + …`

Parser

Parse tree:

Token stream is ill-formed according to our grammar, parse tree construction fails, therefore Syntax error!

Most compiler errors occur in the parser.

Parsing

- For any CFG, one can build a parser that runs in $O(n^3)$
  - Well-known algorithms
- But $O(n^3)$ time is unacceptable for a parser in a compiler!

Parsing

- Objective: build a parse tree for an input string of tokens from a single scan of input
  - Only special subclasses of context-free grammars (LL and LR) can do this
- Two approaches
  - Top-down: builds parse tree from the root to the leaves
  - Bottom-up: builds parse tree from the leaves to the top
  - Both are easily automated

Grammar for Comma-separated Lists

list $\rightarrow$ **`id`** *list_tail* *// list is the start symbol*

list_tail $\rightarrow$ **`,`** **`id`** *list_tail* | **`;`**

Generates comma-separated lists of **`id`**'s.

E.g., **`id ;`** **`id, id, id ;`**

Example derivation:

list $\Rightarrow$ **`id`** *list_tail*

$\Rightarrow$ **`id , id`** *list_tail*

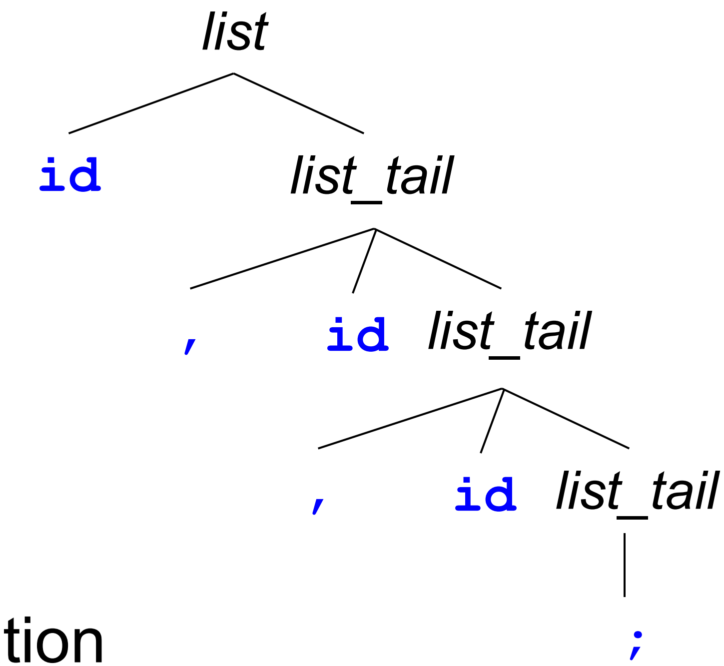
$\Rightarrow$ **`id , id ;`**

Top-down Parsing

list → **`id`** *list_tail*
list_tail → **`,`** **`id`** *list_tail* | **`;`**

- Terminals are seen in the order of appearance in the token stream

  `id , id , id ;`



- The parse tree is constructed
  - From the top to the leaves
  - Corresponds to a left-most derivation
- Look at left-most nonterminal in current sentential form, and lookahead terminal and "predict" which production to apply

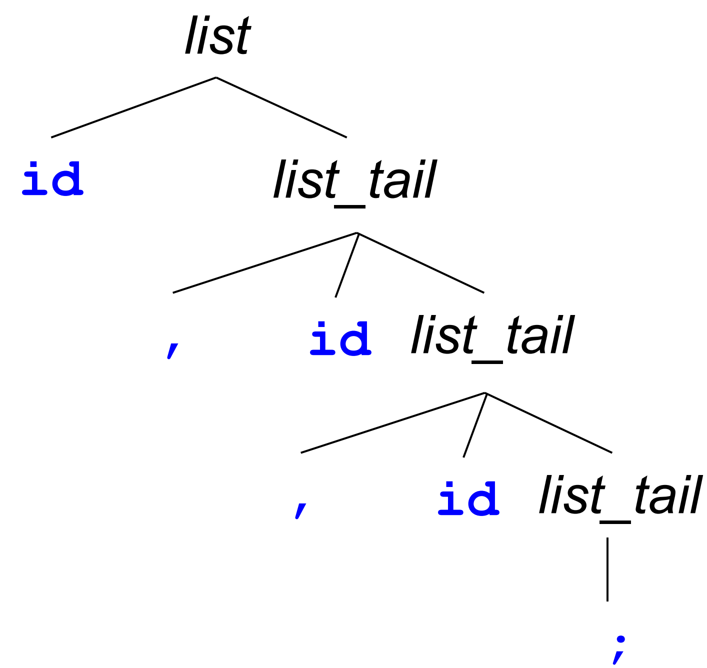
Bottom-up Parsing

list → `id` *list_tail*
list_tail → `,` `id` *list_tail* | `;`

- Terminals are seen in the order of appearance in the token stream

  `id , id , id ;`

- The parse tree is constructed
  - From the leaves to the top
  - A right-most derivation in reverse



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Top-down Predictive Parsing

- “Predicts” production to apply based on one or more lookahead token(s)
- Predictive parsers work with LL(k) grammars
  - First L stands for “left-to-right” scan of input
  - Second L stands for “left-most” derivation
    - Parse corresponds to left-most derivation
  - k stands for “need k tokens of lookahead to predict”
- We are interested in LL(1)

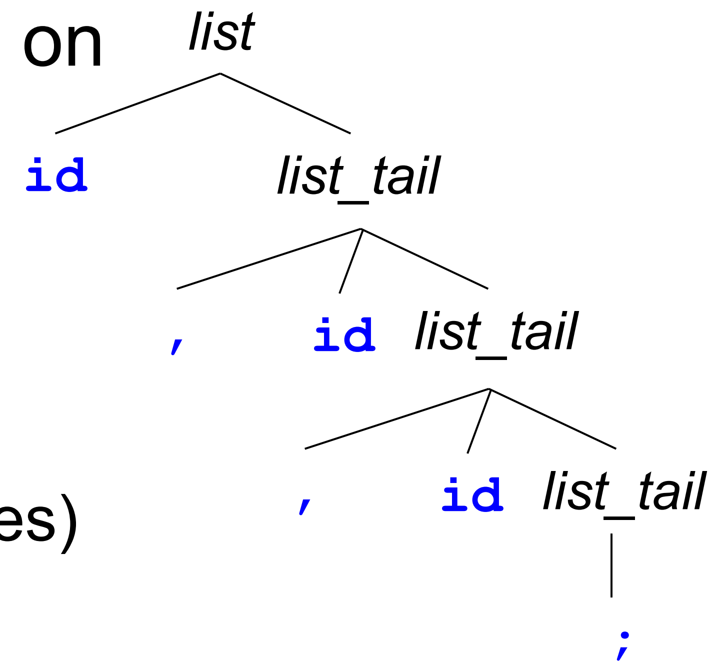
Question

$list \rightarrow$ **id** $list\_tail$

$list\_tail \rightarrow$ **,** **id** $list\_tail$ | **;**

- Can we always predict (i.e., for <u>any</u> input) what production to applies, based on one token of lookahead?

id , id , id ;

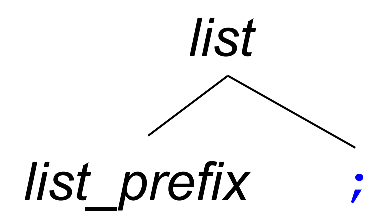


  - Yes, there is at most one choice (i.e., at most one production applies)
  - This grammar is an LL(1) grammar

Question

list → *list_prefix* **`;`**
list_prefix → *list_prefix* **`,`** **`id`** | **`id`**

- A new grammar
- What language does it generate?
  - Same, comma-separated lists
- Can we predict based on one token of lookahead?



?

```
id , id , id ;
```

Top-down Predictive Parsing

- Back to predictive parsing

- "Predicts" production to apply based on one or more lookahead token(s)
  - Parser always gets it right!
  - There is no need to backtrack, undo expansion, then try a different production

- Predictive parsers work with LL(k) grammars

Top-down Predictive Parsing

- Expression grammar:
  - Not LL(1)

$$
\begin{aligned}
expr &\rightarrow expr\ \mathtt{+}\ expr \\
&\quad\mid expr\ \mathtt{*}\ expr \\
&\quad\mid \mathtt{id}
\end{aligned}
$$

- Unambiguous version:
  - Still not LL(1). Why?

$$
\begin{aligned}
expr &\rightarrow expr\ \mathtt{+}\ term \mid term \\
term &\rightarrow term\ \mathtt{*}\ \mathtt{id} \mid \mathtt{id}
\end{aligned}
$$

- LL(1) version:

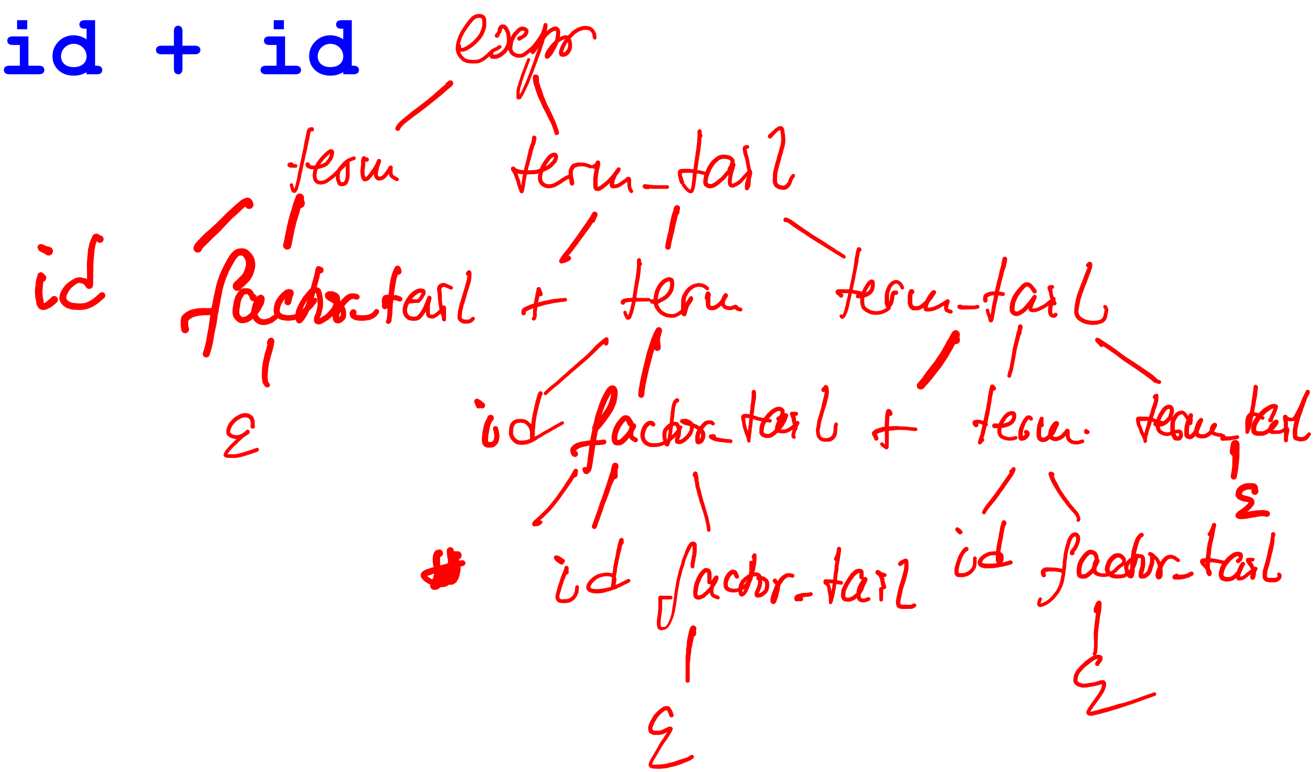
$$
\begin{aligned}
expr &\rightarrow term\ term\_tail \\
term\_tail &\rightarrow \mathtt{+}\ term\ \ term\_tail \mid \boldsymbol{\varepsilon} \\
term &\rightarrow \mathtt{id}\ factor\_tail \\
factor\_tail &\rightarrow \mathtt{*}\ \ \mathtt{id}\ \ factor\_tail \mid \boldsymbol{\varepsilon}
\end{aligned}
$$

Exercise

expr → *term term_tail*
term_tail → **+** *term term_tail* | **ε**
term → **id** *factor_tail*
factor_tail → ***** **id** *factor_tail* | **ε**

- Draw parse tree for expression

id + id * id + id



Recursive Descent

- Each nonterminal has a procedure
- The right-hand-sides (rhs) for the nonterminal form the body of its procedure

- lookahead()
  - Peeks at current token in input stream
- match(t)
  - if lookahead() == t then consume current token, else PARSE_ERROR

Recursive Descent

start → *expr* **$$**
expr → *term* *term_tail*
term → **id** *factor_tail*
term_tail → **+** *term* *term_tail* | **ε**
factor_tail → ***** **id** *factor_tail* | **ε**

```
start()
    case lookahead() of
        id:  expr(); match($$)          ($$ - end-of-input marker)
        otherwise PARSE_ERROR

expr()
    case lookahead() of
        id:  term(); term_tail()
        otherwise PARSE_ERROR

term_tail()
    case lookahead() of
        +:   match('+'); term(); term_tail()
        $$:  skip
        otherwise: PARSE_ERROR
```

Predicting production *term_tail* → **+** *term* *term_tail*

Predicting epsilon production *term_tail* → **ε**

Recursive Descent

start → *expr* **$$**
expr → *term term_tail*
term → **id** *factor_tail*
term_tail → **+** *term term_tail* | **ε**
factor_tail → ***** **id** *factor_tail* | **ε**

```
term()
    case lookahead() of
        id: match( 'id' ); factor_tail()
        otherwise: PARSE_ERROR

factor_tail()
    case lookahead() of
        *: match( '*' ); match( 'id' ); factor_tail();
        +,$$: skip
        otherwise PARSE_ERROR
```

Predicting production *factor_tail* → ***id** *factor_tail*

Predicting production *factor_tail* → **ε**

LL(1) Parsing Table

- But how does the parser "predict"?
  - E.g., how does the parser know to expand a *factor_tail* by *factor_tail* $\rightarrow$ **ε** on **+** and **$$**?
- It uses the LL(1) parsing table
  - One dimension is nonterminal to expand
  - Other dimension is lookahead token
    - We are interested in one token of lookahead
  - Entry "nonterminal on token" contains the production to apply or contains nothing

LL(1) Parsing Table

- One dimension is nonterminal to expand
- Other dimension is lookahead token

	`a`	
A	α	

- E.g., entry "nonterminal *A* on terminal **`a`**" contains production $A \rightarrow \alpha$

Meaning: when parser is at nonterminal *A* and lookahead token is **`a`**, then parser expands *A* by production $A \rightarrow \alpha$

LL(1) Parsing Table

start → *expr* `$$`

expr → *term term_tail*

term → `id` *factor_tail*

term_tail → `+` *term term_tail* | ε

factor_tail → `*` `id` *factor_tail* | ε

	`id`	`+`	`*`	`$$`
start	*expr* `$$`	-	-	-
expr	*term term_tail*	-	-	-
term_tail	-	`+` *term term_tail*	-	ε
term	`id` *factor_tail*	-	-	-
factor_tail	-	ε	`*` `id` *factor_tail*	ε

Question

- Fill in the LL(1) parsing table for the comma-separated list grammar

start → *list* **$$**
list → **id** *list_tail*
list_tail → **,** **id** *list_tail* | **;**

	id	**,**	**;**	**$$**
start	*list* **$$**	–	–	–
list	**id** *list_tail*	–	–	–
list_tail	–	**,** **id** *list_tail*	**;**	–

The End