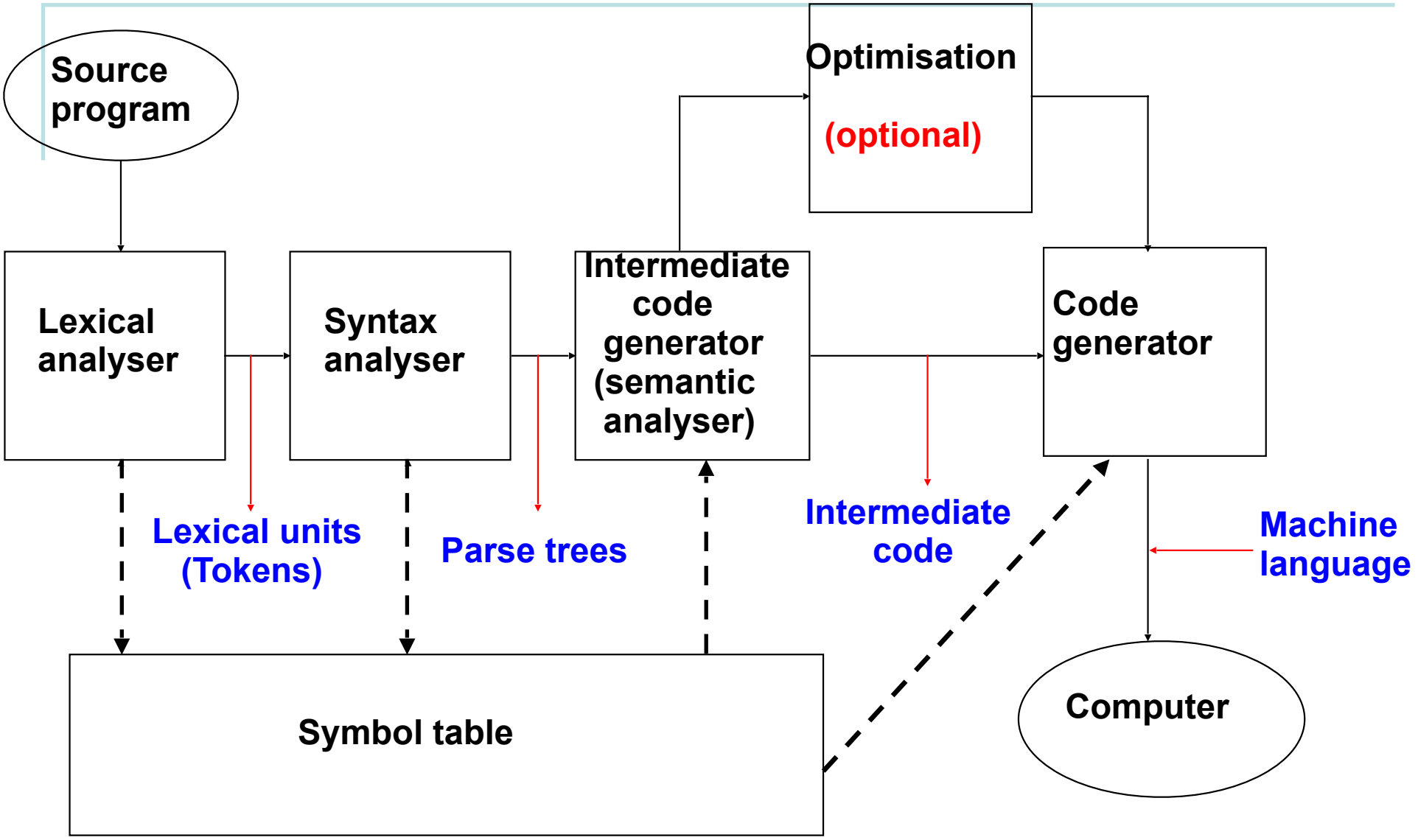
CC410: System Programming

Dr. Manal Helal – Spring 2015 – Lecture 14–Compilers 1

Chapter 5 - Compilers



Terminology

- Statement
  - Declaration, assignment containing expression
- Grammar
  - A set of rules specify the form of legal statements
- Syntax vs. Semantics
  - Example: assuming I, J, K: integer and X,Y: float
  - I:=J+K vs. X:= Y+I
- Compilation
  - Matching statements written by the programmer to structures defined by the grammar and generating the appropriate object code.

Basic Compiler

- Lexical analysis - scanner
  - Scanning the source statement, recognising and classifying the various tokens
- Syntactic analysis - parser
  - Recognising the statement as some language construct.
  - Construct a parser tree (syntax tree)
- Code generation – code generator
  - Generate assembly language codes that require an assembler
  - Generate machine codes (Object codes) directly

Scanner

SUM:=0;
SUMSQ:= 0;

PROGRAM
STATS
VAR
SUM,SUMSQ,I

FIGURE 5.1 Example of a Pascal program.

```
 1   PROGRAM STATS
 2   VAR
 3       SUM,SUMSQ,I,VALUE,MEAN,VARIANCE : INTEGER
 4   BEGIN
 5       SUM := 0;
 6       SUMSQ := 0;
 7       FOR I := 1 TO 100 DO
 8           BEGIN
 9           READ(VALUE);
10           SUM := SUM + VALUE;
11           SUMSQ := SUMSQ + VALUE * VALUE
12           END;
13       MEAN := SUM DIV 100;
14       VARIANCE := SUMSQ DIV 100 - MEAN * MEAN;
15       WRITE(MEAN,VARIANCE)
16   END.
```

READ (VALUE);

Grammar

- Grammar: a set of rules
  - Backus-Naur Form (BNF)
  - Ex: Figure 5.2

```
<read> ::= READ ( <id-list> )
<id-list>     ::= id | <id-list> , id
```

- Terminology
  - Define symbol ::=
  - Nonterminal symbols <>
  - Alternative symbols |
  - Terminal symbols

Simplified Pascal Grammar

```
1  <prog>          ::= PROGRAM <prog-name> VAR <dec-list> BEGIN <stmt-list> END.
2  <prog-name>     ::= id
3  <dec-list>      ::= <dec> | <dec-list> ; <dec>
4  <dec>           ::= <id-list> : <type>
5  <type>          ::= INTEGER
6  <id-list>       ::= id | <id-list> , id
7  <stmt-list>     ::= <stmt> | <stmt-list> ; <stmt>
8  <stmt>          ::= <assign> | <read> | <write> | <for>
9  <assign>        ::= id := <exp>
10 <exp>           ::= <term> | <exp> + <term> | <exp> - <term>
11 <term>          ::= <factor> | <term> * <factor> | <term> DIV <factor>
12 <factor>        ::= id | int | ( <exp> )
13 <read>          ::= READ ( <id-list> )
14 <write>         ::= WRITE ( <id-list> )
15 <for>           ::= FOR <index-exp> DO <body>
16 <index-exp>     ::= id := <exp> TO <exp>
17 <body>          ::= <stmt> | BEGIN <stmt-list> END
```

Figure 5.2 Simplified Pascal grammar.

Parser

- READ(VALUE)
- SUM := 0
- SUM := SUM + VALUE
- MEAN := SUM DIV 100

- <read> ::= READ (<id-list>)
- <id-list>::= id | <id-list>,id
- <assign>::= id := <exp>
- <exp> ::= <term> | <exp>+<term> | <exp>-<term>
- <term>::=<factor> | <term>*<factor> | <term> DIV <factor>
- <factor>::= id | int | (<exp>)

Syntax Tree

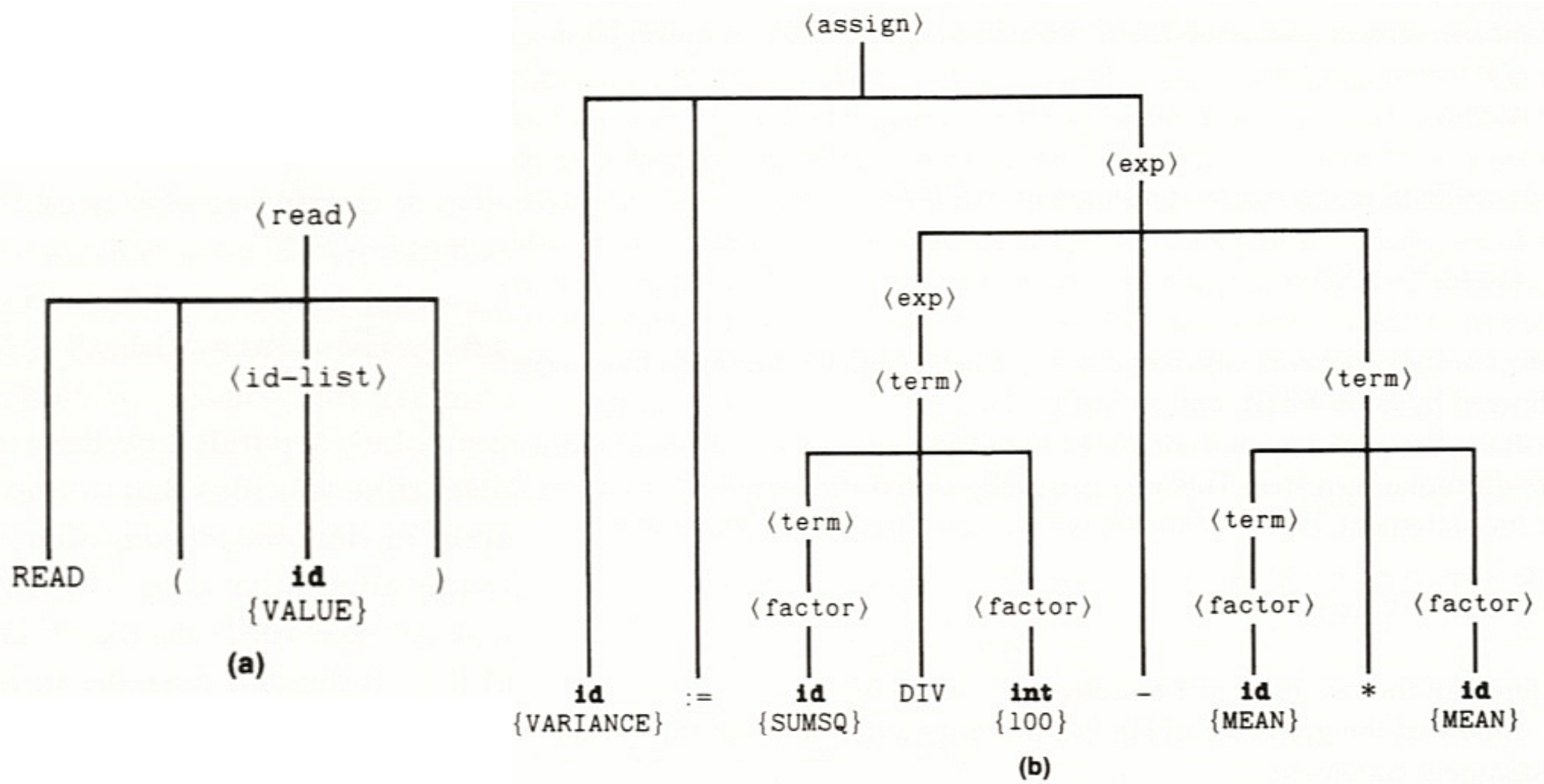
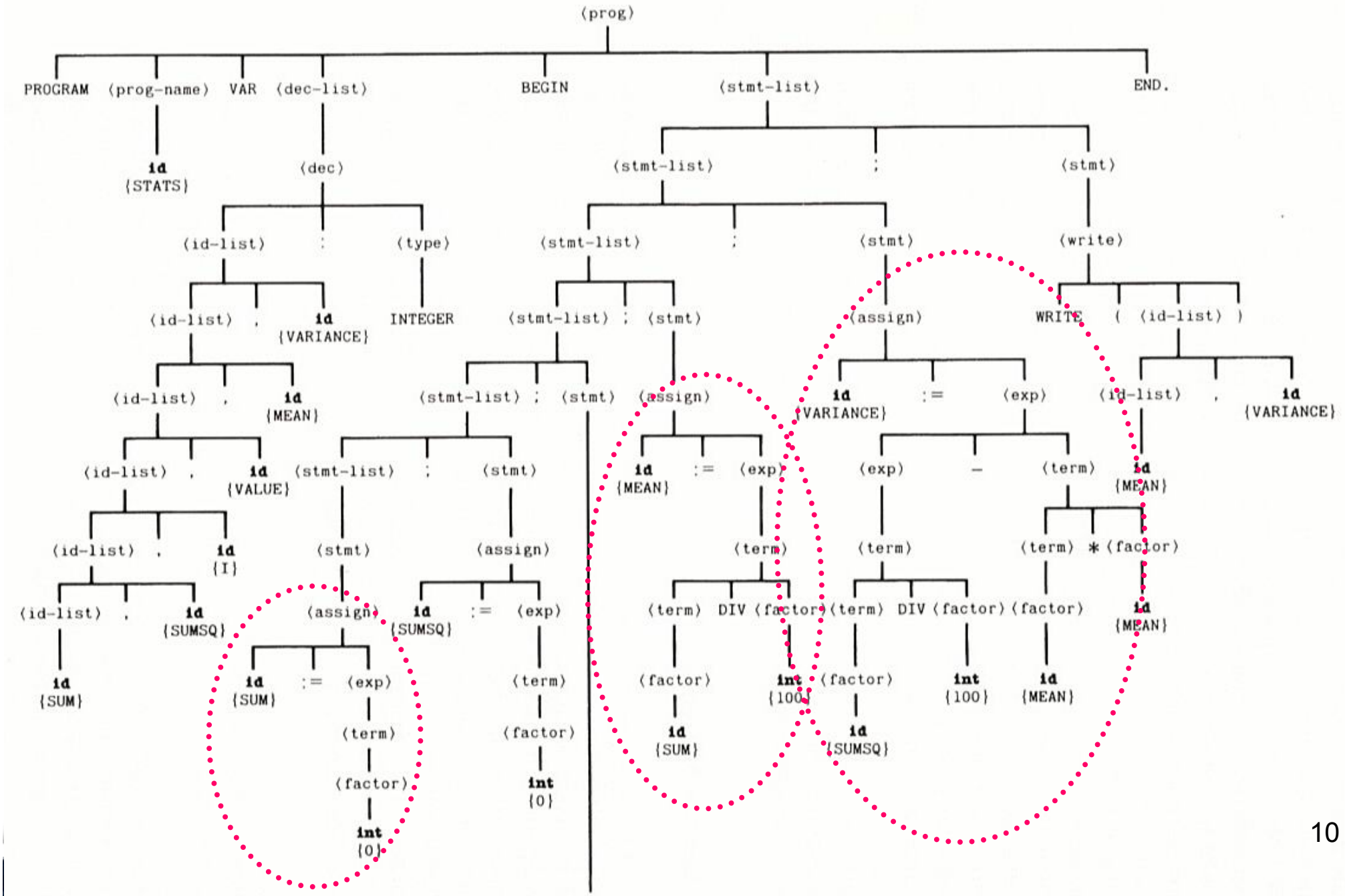


Figure 5.3 Parse trees for two statements from Fig. 5.1.

Syntax Tree for Program 5.1



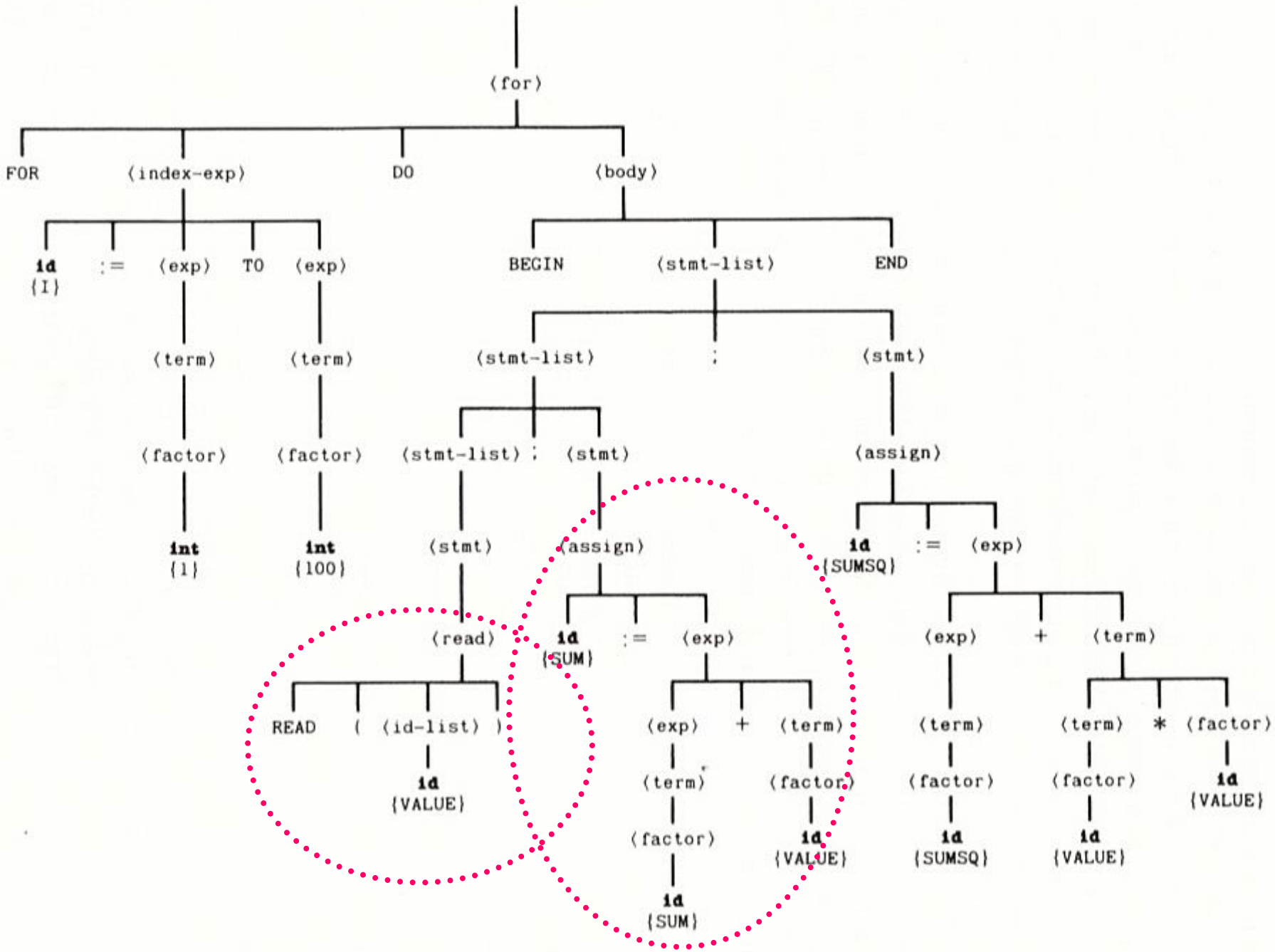


Figure 5.4 Parse tree for the program from Fig. 5.1.

Lexical Analysis

- Function
  - Scanning the program to be compiled and recognising the *tokens* that make up the source statements.

```
<ident>   ::=  <letter> | <ident> <letter> | <ident> <digit>
<letter>  ::=  A | B | C | D | ... | Z
<digit>   ::=  0 | 1 | 2 | 3 | ... | 9
```

- Tokens
  - Tokens can be keywords, operators, identifiers, integers, floating-point numbers, character strings, etc.
  - Each token is usually represented by some fixed-length code, such as an integer, rather than as a variable-length character string (see Figure 5.5)
  - Token type, Token specifier (value) (see Figure 5.6)

Scanner Output

- Token specifier
  - Identifier name, integer value, (type)
- Token coding scheme
  - Figure 5.5

Token	Code
PROGRAM	1
VAR	2
BEGIN	3
END	4
END.	5
INTEGER	6
FOR	7
READ	8
WRITE	9
TO	10
DO	11
;	12
:	13
,	14
:=	15
+	16
-	17
*	18
DIV	19
(	20
)	21
id	22
int	23

Line	Token type	Token specifier
1	1	
	22	^STATS
2	2	
3	22	^SUM
	14	
	22	^SUMSQ
	14	
	22	^I
	14	
	22	^VALUE
	14	
	22	^MEAN
	14	
	22	^VARIANCE
	13	
	6	
4	3	
5	22	^SUM
	15	
	23	#0
	12	
6	22	^SUMSQ
	15	
	23	#0
	12	
7	7	
	22	^I
	15	
	23	#1
	10	
	23	#100
	11	
8	3	
9	8	
	20	
	22	^VALUE
	21	
	12	

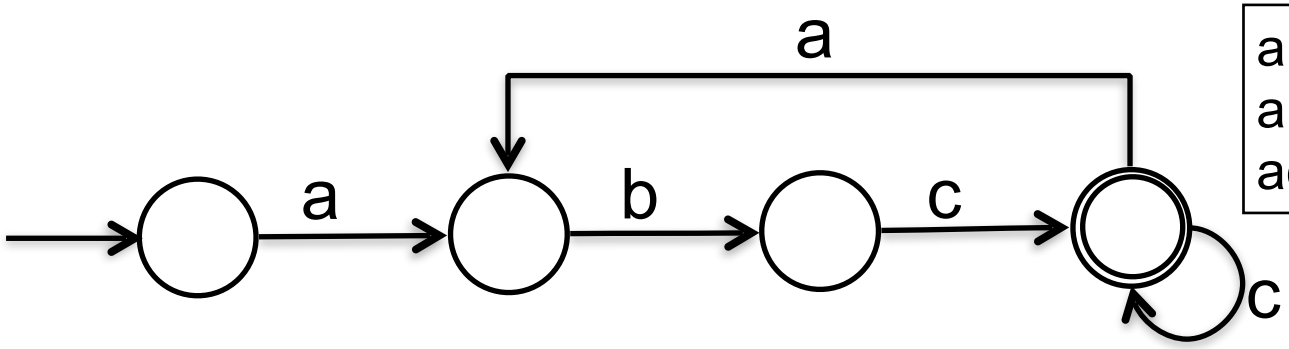
Line	Token type	Token specifier
10	22	^SUM
	15	
	22	^SUM
	16	
	22	^VALUE
	12	
11	22	^SUMSQ
	15	
	22	^SUMSQ
	16	
	22	^VALUE
	18	
	22	^VALUE
12	4	
	12	
13	22	^MEAN
	15	
	22	^SUM
	19	
	23	#100
	12	
14	22	^VARIANCE
	15	
	22	^SUMSQ
	19	
	23	#100
	17	
	22	^MEAN
	18	
	22	^MEAN
	12	
15	9	
	20	
	22	^MEAN
	14	
	22	^VARIANCE
	21	
16	5	

Figure 5.6 Lexical scan of the program from Fig. 5.1.

Can be entered directly into a symbol table and a pointer used in the output of the lexicon

Finite Automata (FA)

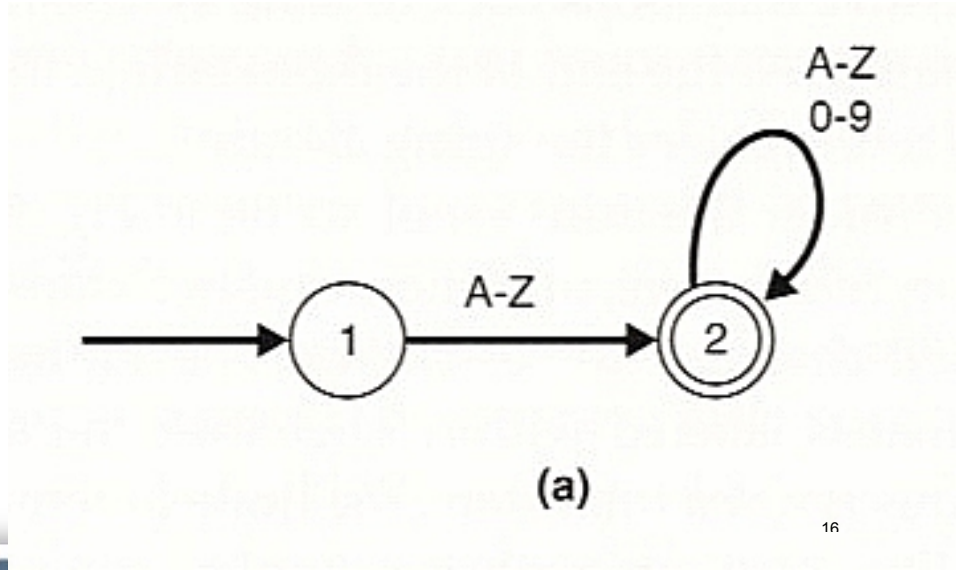
- Starting State
- Ending State(s)
- Transitions upon scanning a character
- The sequence of characters are recognised (accepted) by the FA if it moves it from a start state to an end state, otherwise, it is not recognised (rejected)



abc	recognised
abccabc	recognised
ac	not recognised

Token Recogniser

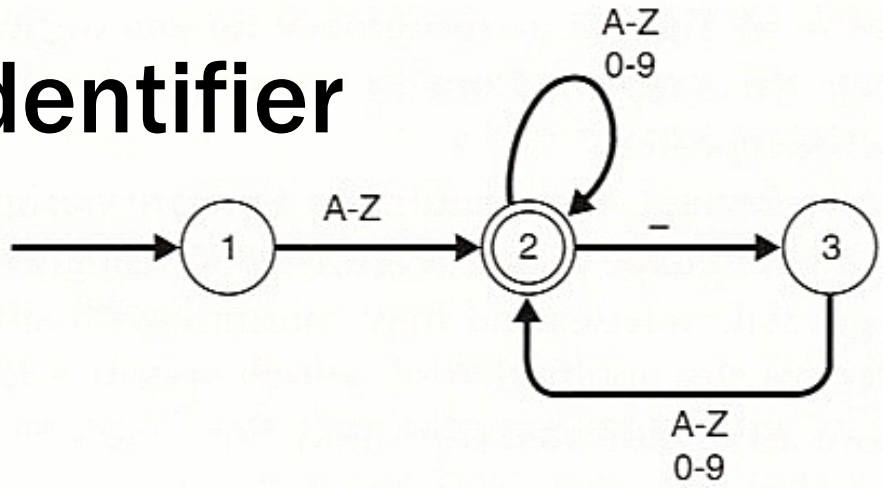
- By grammar
  - <ident> ::= <letter> | <ident> <letter> | <ident> <digit>
  - <letter>::= A | B | C | D | ... | Z
  - <digit> ::= 0 | 1 | 2 | 3 | ... | 9
- By scanner - modelling as finite automata
  - Figure 5.8 (a)



Recognising Identifier

```
get first Input_Character
if Input_Character in ['A'..'Z'] then
   begin
     while Input_Character in ['A'..'Z', '0'..'9']
       begin
          get next Input_Character
          if Input_Character = '_' then
               begin
                  get next Input_Character
                  Last_Char_Is_Underscore := true
               end  {if '_'}
          else
               Last_Char_Is_Underscore := false
       end  {while}
     if Last_Char_Is_Underscore then
       return (Token_Error)
     else
       return (Valid_Token)
   end  {if first in ['A'..'Z']}
else
    return (Token_Error)
```

(a)



(b)

Identifiers allowing underscore (_)

State	A-Z	0-9	_	
1	2			{starting state}
2	2	2	3	{final state}
3	2	2		

(b)

Figure 5.10 Token recognition using (a) algorithmic code and (b) tabular representation of finite automaton.

Recognising Integer

- Allowing leading zeroes
  - Figure 5.8 (c)
- Disallowing leading zeroes
  - Figure 5.8 (d)

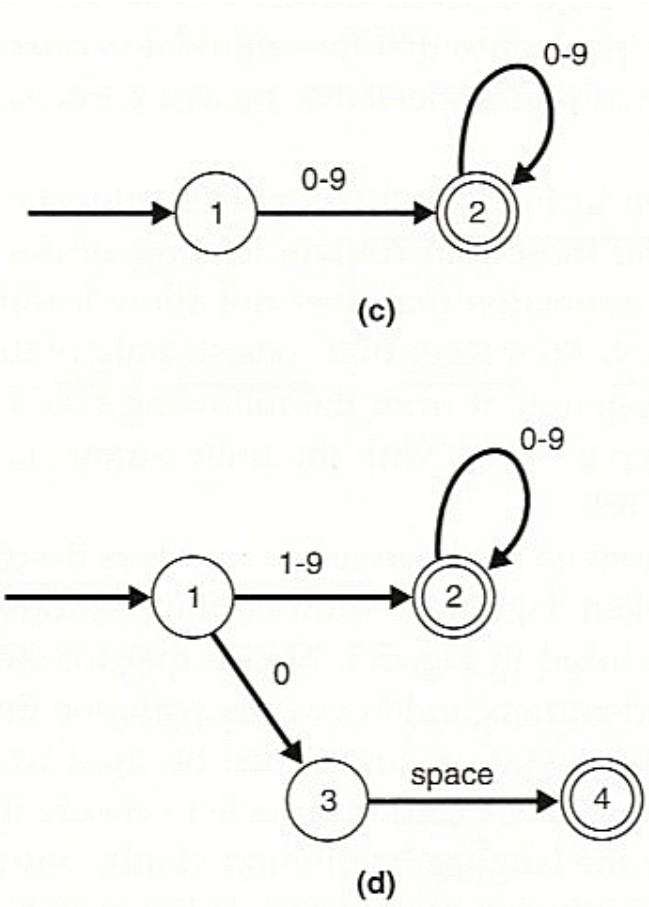
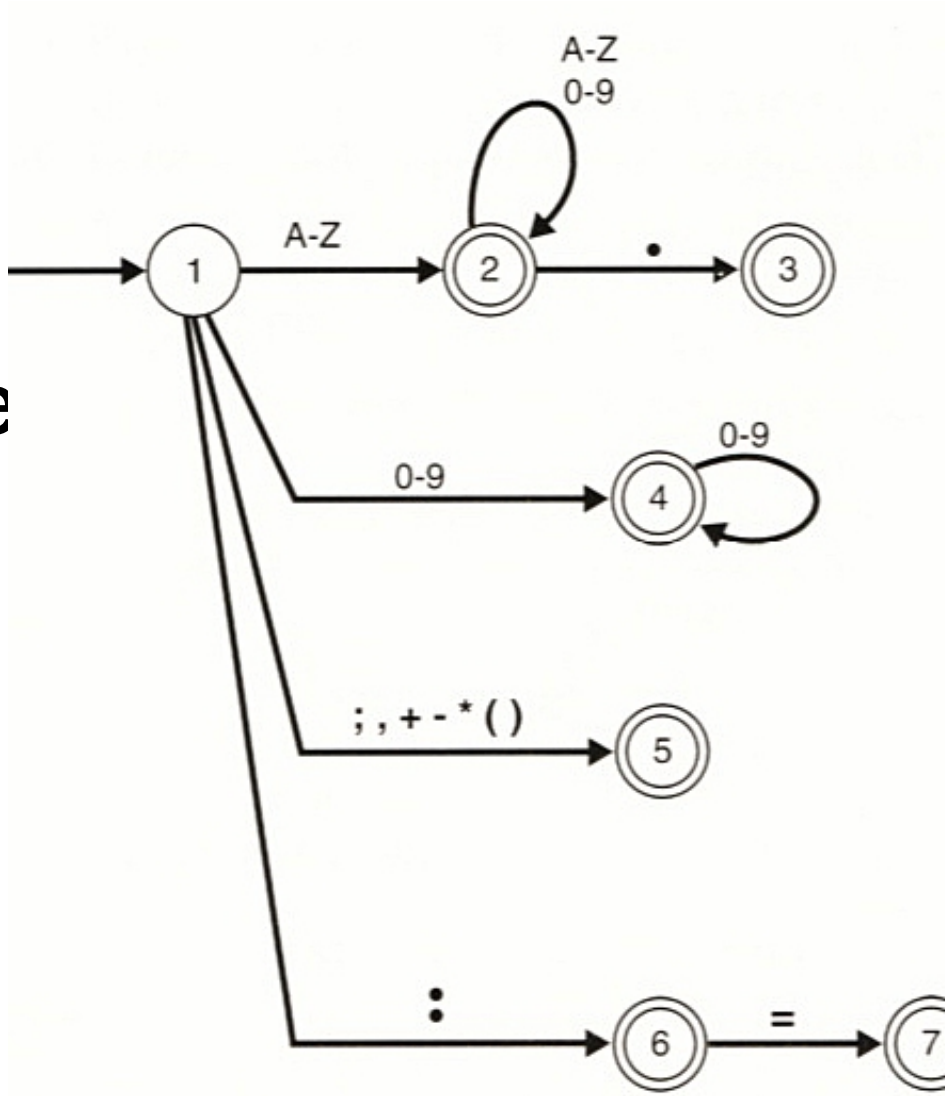


Figure 5.8 Finite automata for typical programming language tokens.

Scanner - Implementation

- Figure 5.10 (a)
  - Algorithmic code for identifier recognition
- Tabular representation of finite automaton for Figure 5.9.

State	A-Z	0-9	;,+-*()	:	=	.
1	2	4	5	6		
2	2	2				3
3						
4		4				
5						
6					7	
7						



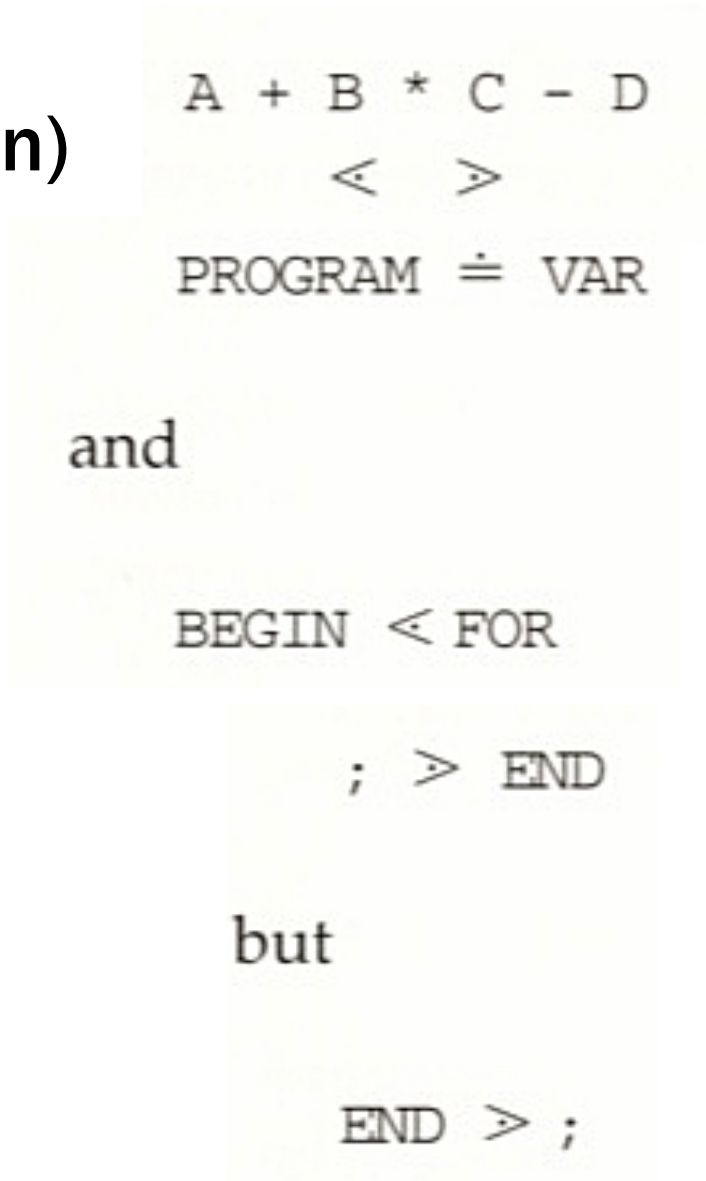
5.9 Finite automaton to recognize tokens from Fi

Syntactic Analysis

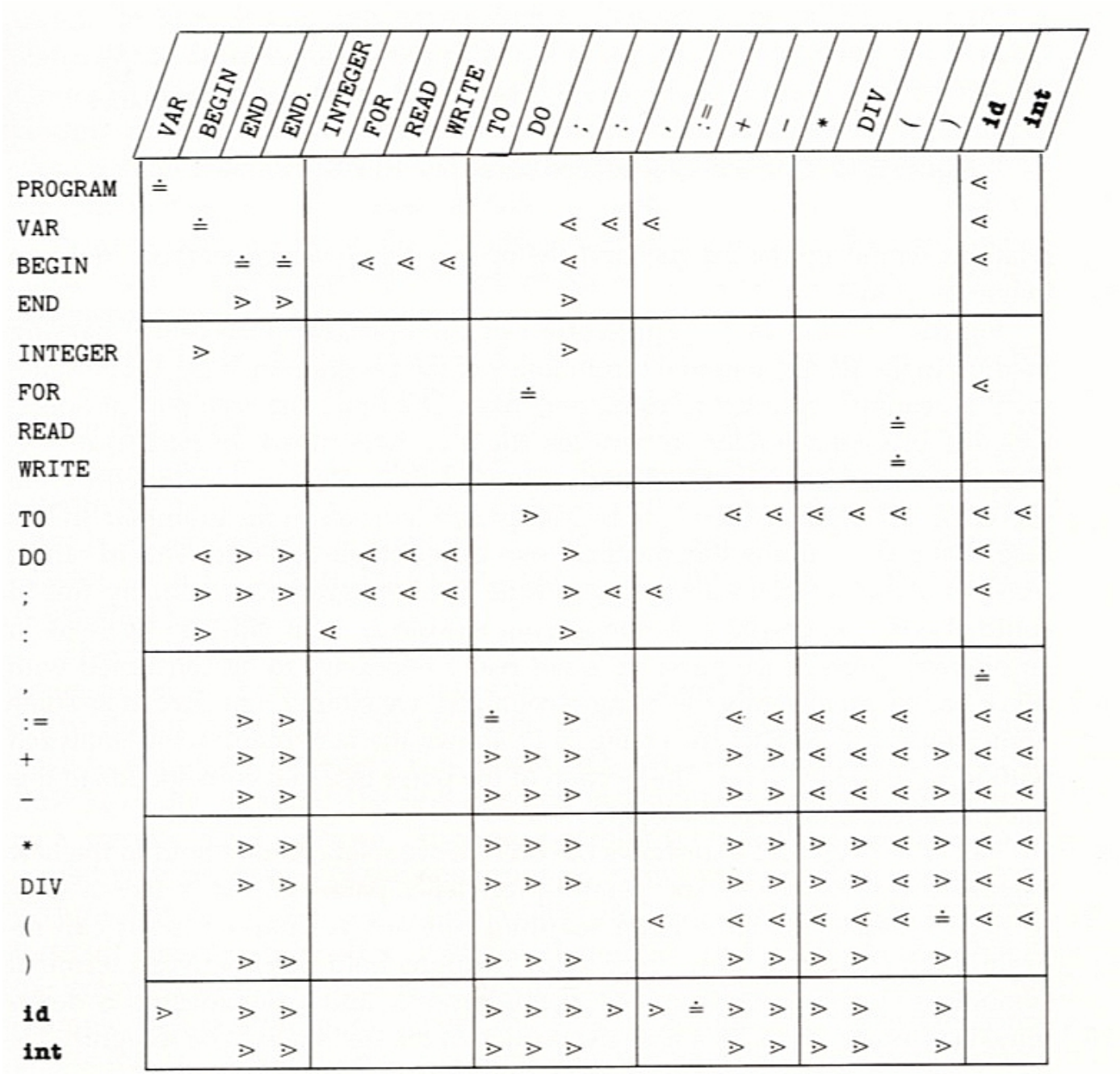
- Recognise source statements as language constructs or build the parse tree for the statements.
  - Bottom-up
    - Operator-precedence parsing
    - Shift-reduce parsing
    - LR(0) parsing
    - LR(1) parsing
    - SLR(1) parsing
    - LALR(1) parsing
  - Top-down
    - Recursive-descent parsing
    - LL(1) parsing

Operator-Precedence Parsing

- Operator
  - Any terminal symbol (or any token)
- Precedence
  - * $\gtrdot$ +
  - + $\lessdot$ *
- Operator-precedence
  - Precedence relations between operators



Precedence Matrix for the Fig. 5.2



	VAR	BEGIN	END	END.	INTEGER	FOR	READ	WRITE	TO	DO	:	;	,	:=	+	−	*	DIV	(	)	id	int
PROGRAM	≐																				⋖	
VAR		≐									⋖	⋖	⋖								⋖	
BEGIN			≐	≐		⋖	⋖	⋖			⋖										⋖	
END			⋗	⋗							⋗											
INTEGER		⋗									⋗											
FOR										≐											⋖	
READ																			≐			
WRITE																			≐			
TO									⋗						⋖	⋖					⋖	⋖
DO		⋖	⋗	⋗		⋖	⋖	⋖			⋗										⋖	
;		⋗	⋗	⋗		⋖	⋖	⋖			⋗	⋖	⋖								⋖	
:		⋗			⋖						⋗											
,																					≐	
:=			⋗	⋗					≐		⋗				⋖	⋖					⋖	⋖
+			⋗	⋗					⋗	⋗	⋗				⋗	⋗					⋖	⋖
−			⋗	⋗					⋗	⋗	⋗				⋗	⋗					⋖	⋖
*			⋗	⋗					⋗	⋗	⋗				⋗	⋗					⋖	⋖
DIV			⋗	⋗					⋗	⋗	⋗				⋗	⋗					⋖	⋖
(														⋖	⋖	⋖				≐	⋖	⋖
)			⋗	⋗					⋗	⋗	⋗				⋗	⋗						
id	⋗		⋗	⋗					⋗	⋗	⋗	⋗	⋗	≐	⋗	⋗						
int			⋗	⋗					⋗	⋗	⋗				⋗	⋗						

Figure 5.11 Precedence matrix for the grammar from Fig. 5.2.

Operator-Precedence Parse Example

BEGIN READ (VALUE) ;

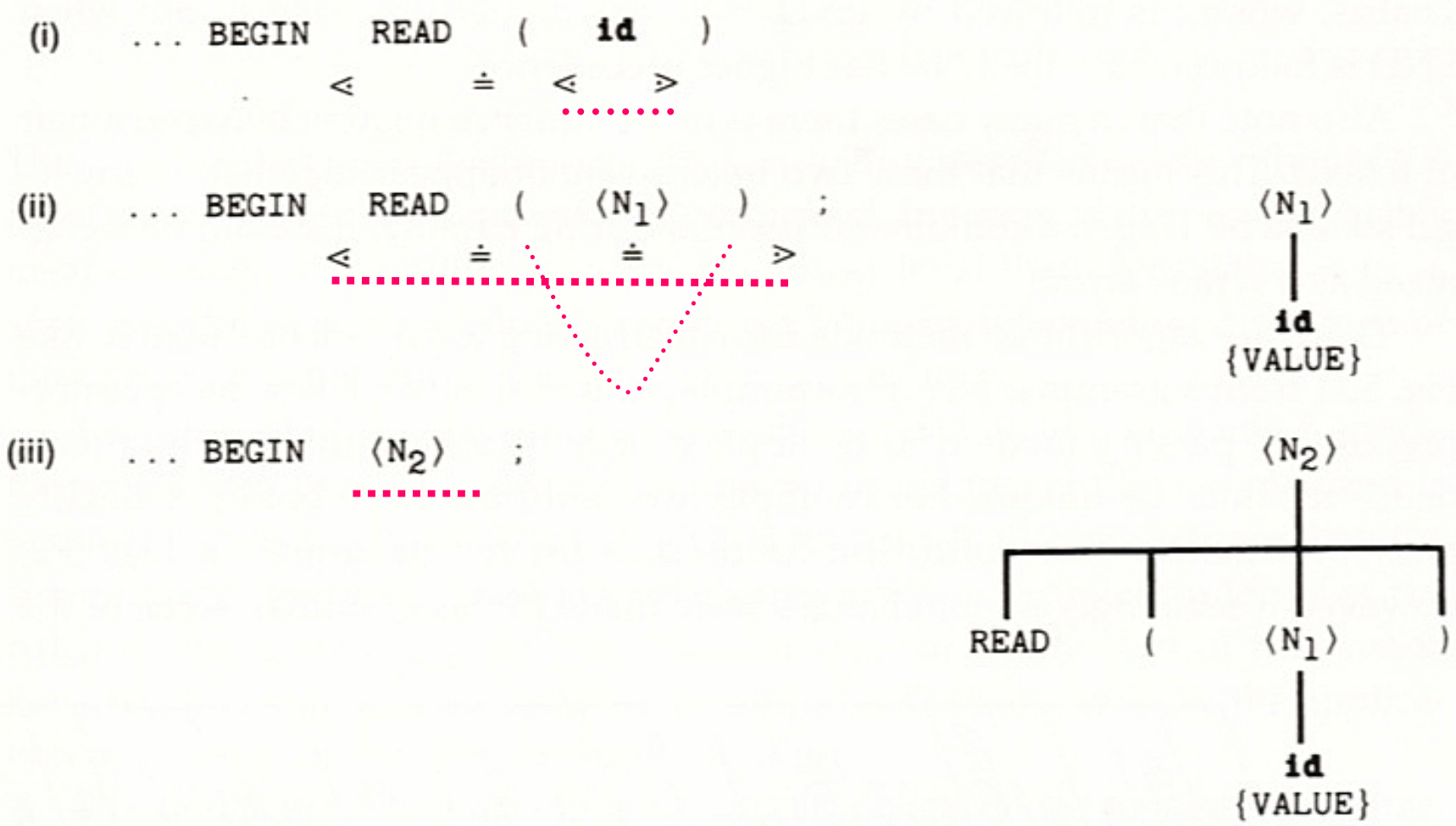
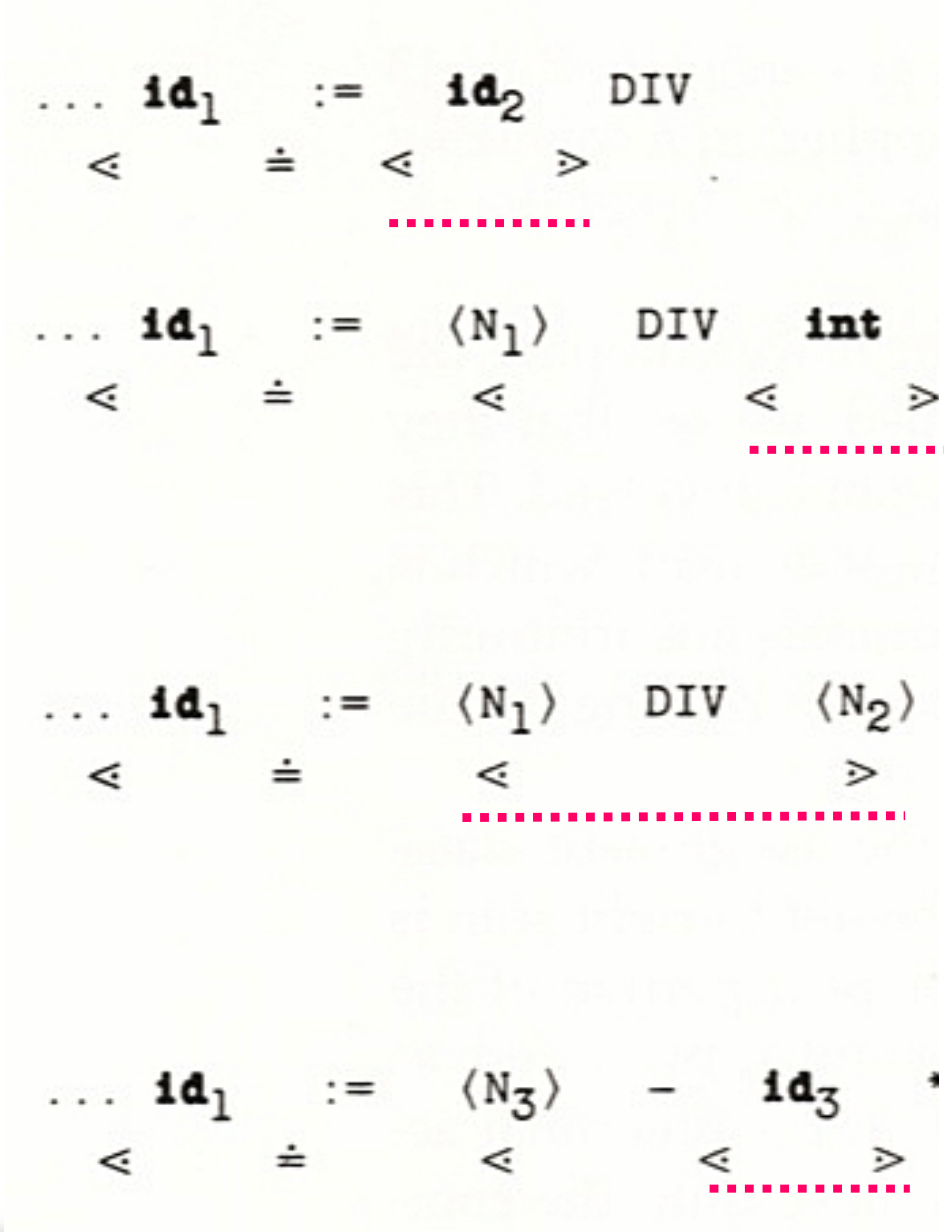
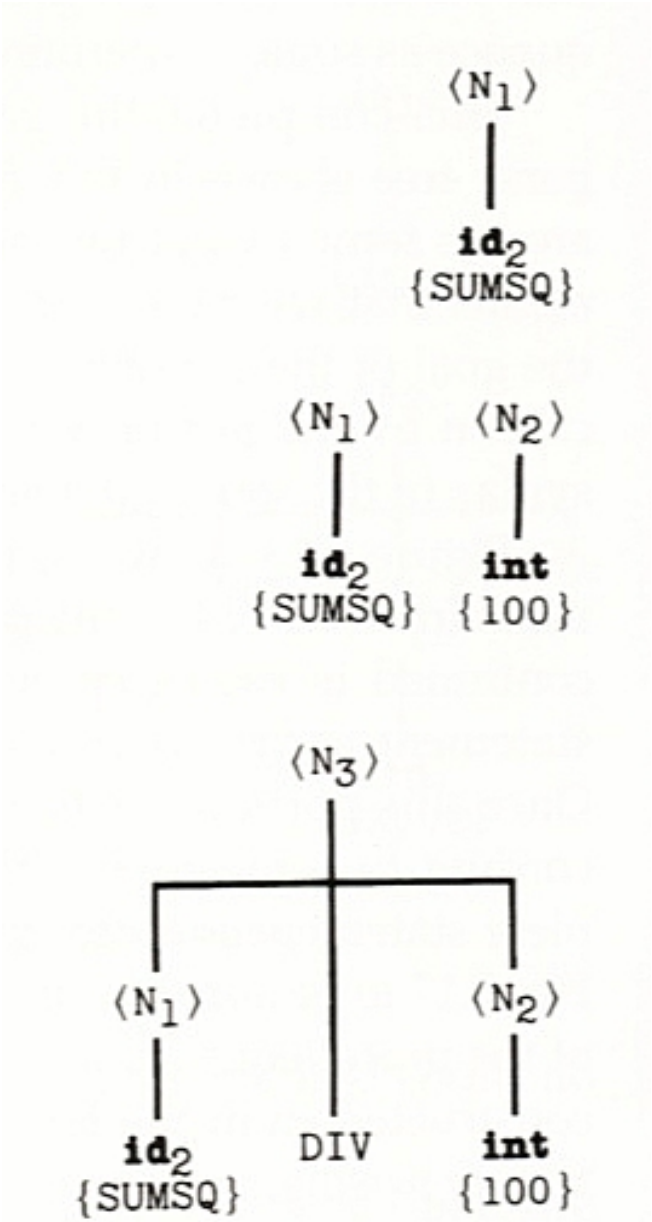


Figure 5.12 Operator-precedence parse of a READ statement.

Operator-Precedence Parse Example





Operator-Precedence Parse Example

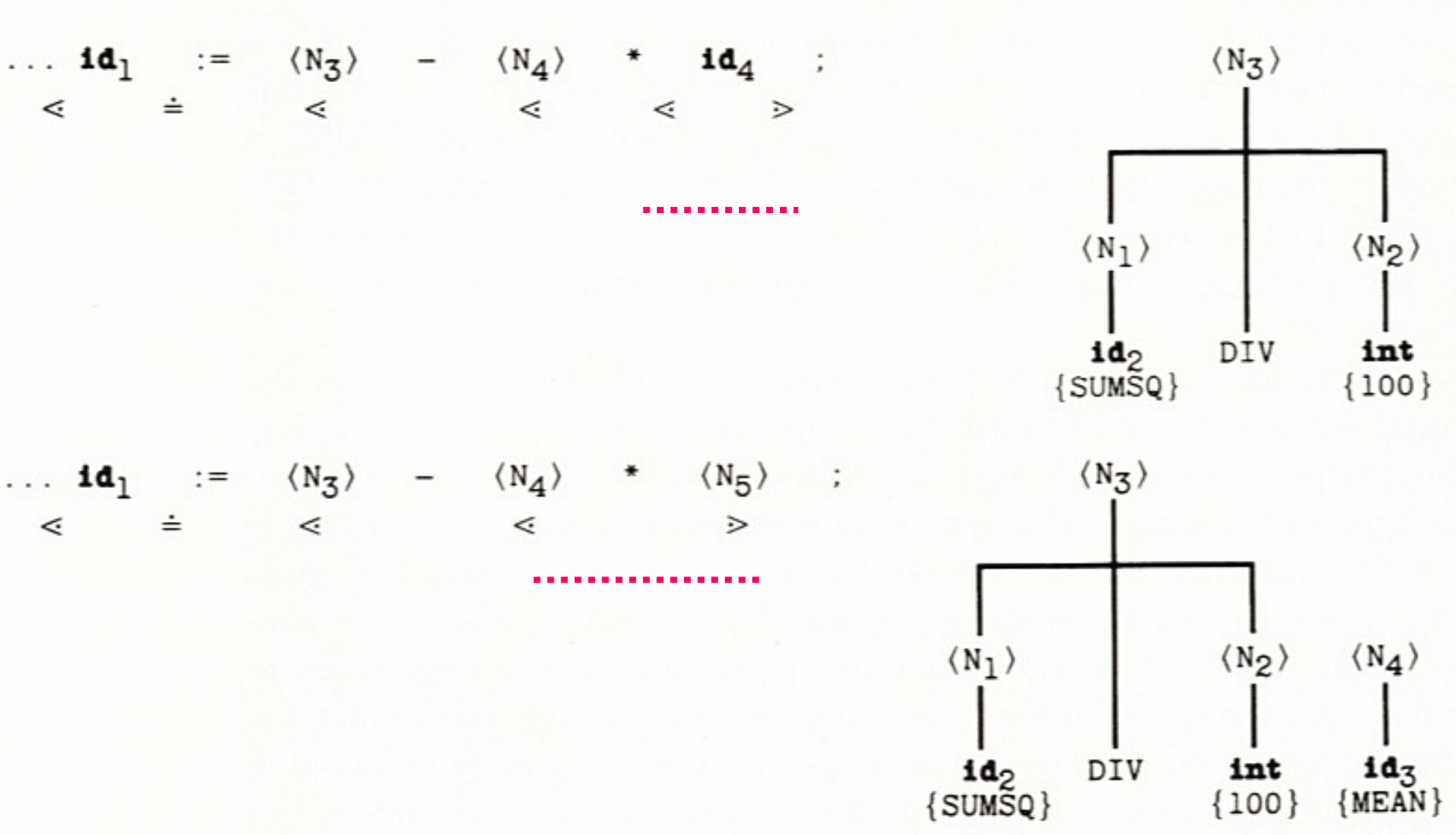
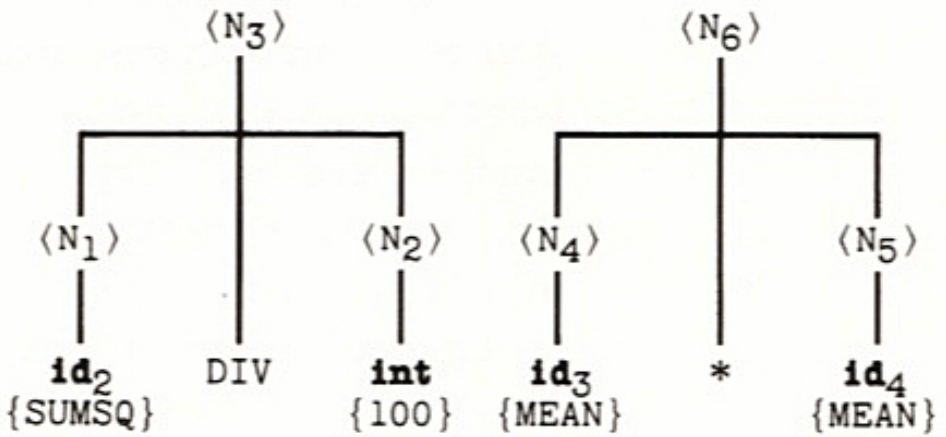


Figure 5.13 Operator-precedence parse of an assignment statement.

Operator-Precedence Parse Example

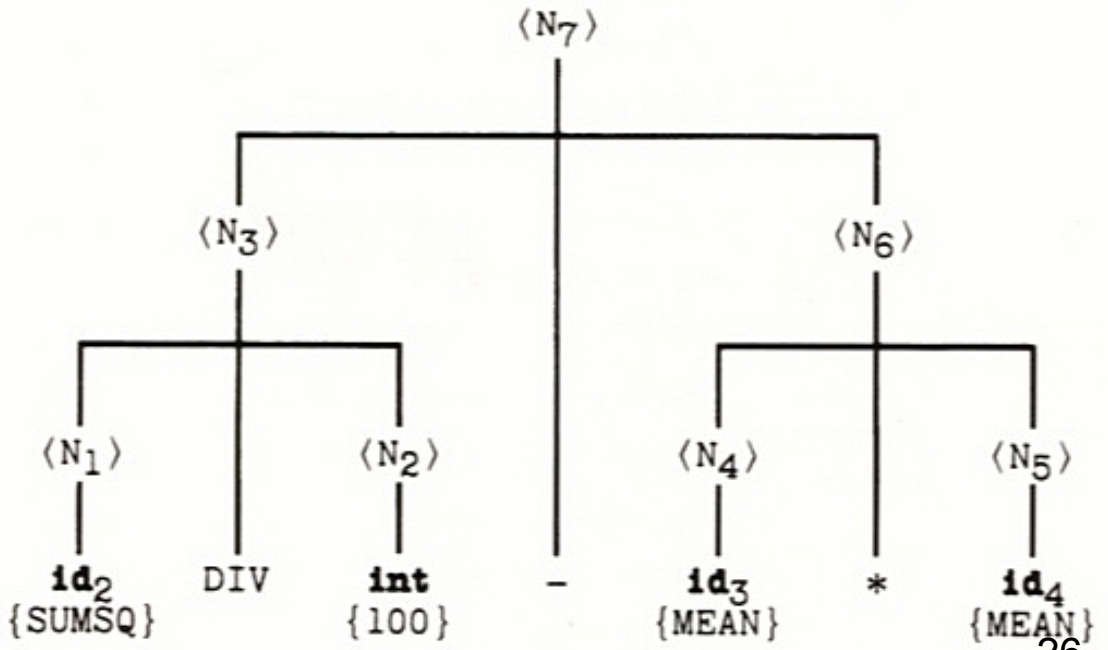
(vii) ... **id**$_1$:= ⟨N$_3$⟩ − ⟨N$_6$⟩ ;

< ≐ < >



(viii) ... **id**$_1$:= ⟨N$_7$⟩ ;

< ≐ >



Operator-Precedence Parsing

- Bottom-up parsing
- Generating precedence matrix
  - Aho et al. (1988)

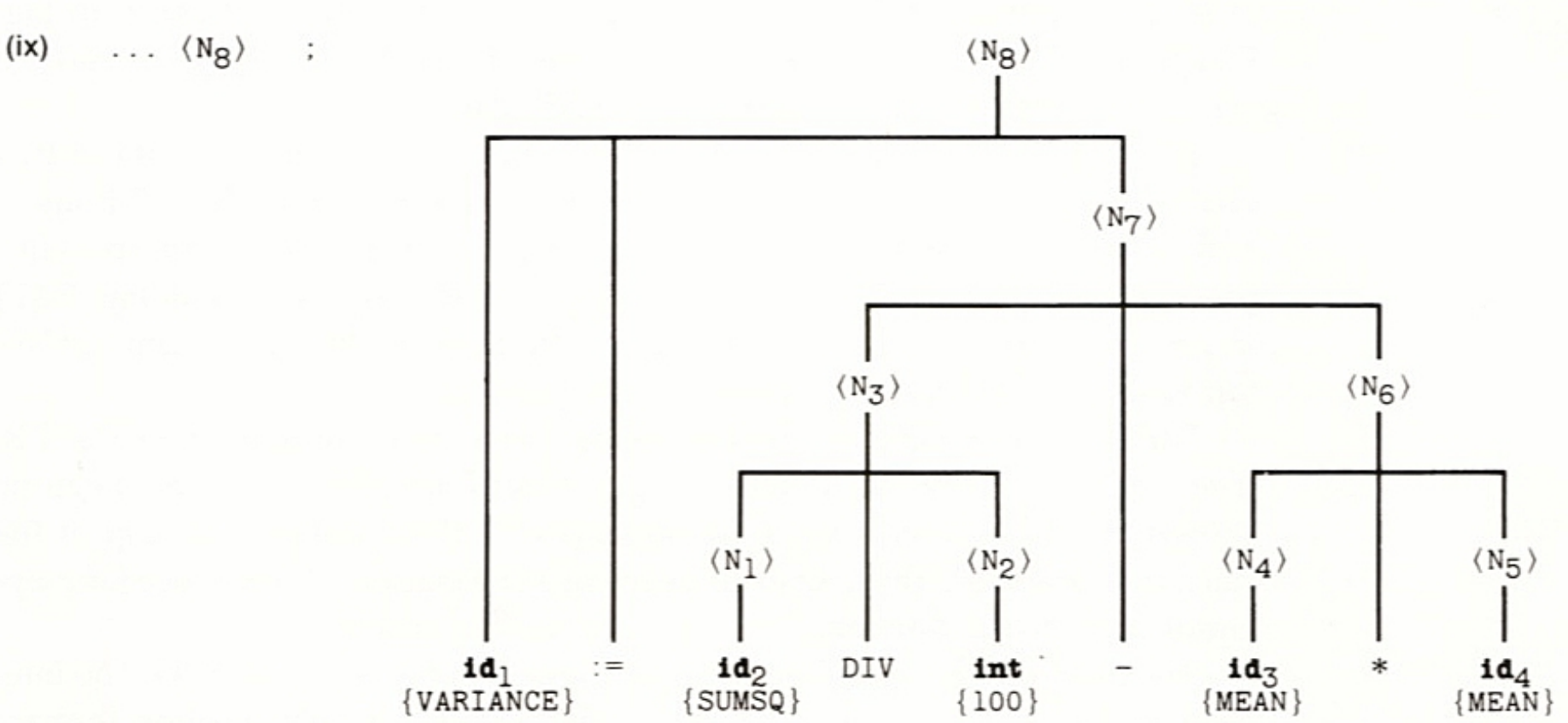


Figure 5.13 (*cont'd*)

Shift-reduce Parsing with Stack

» Figure 5.14

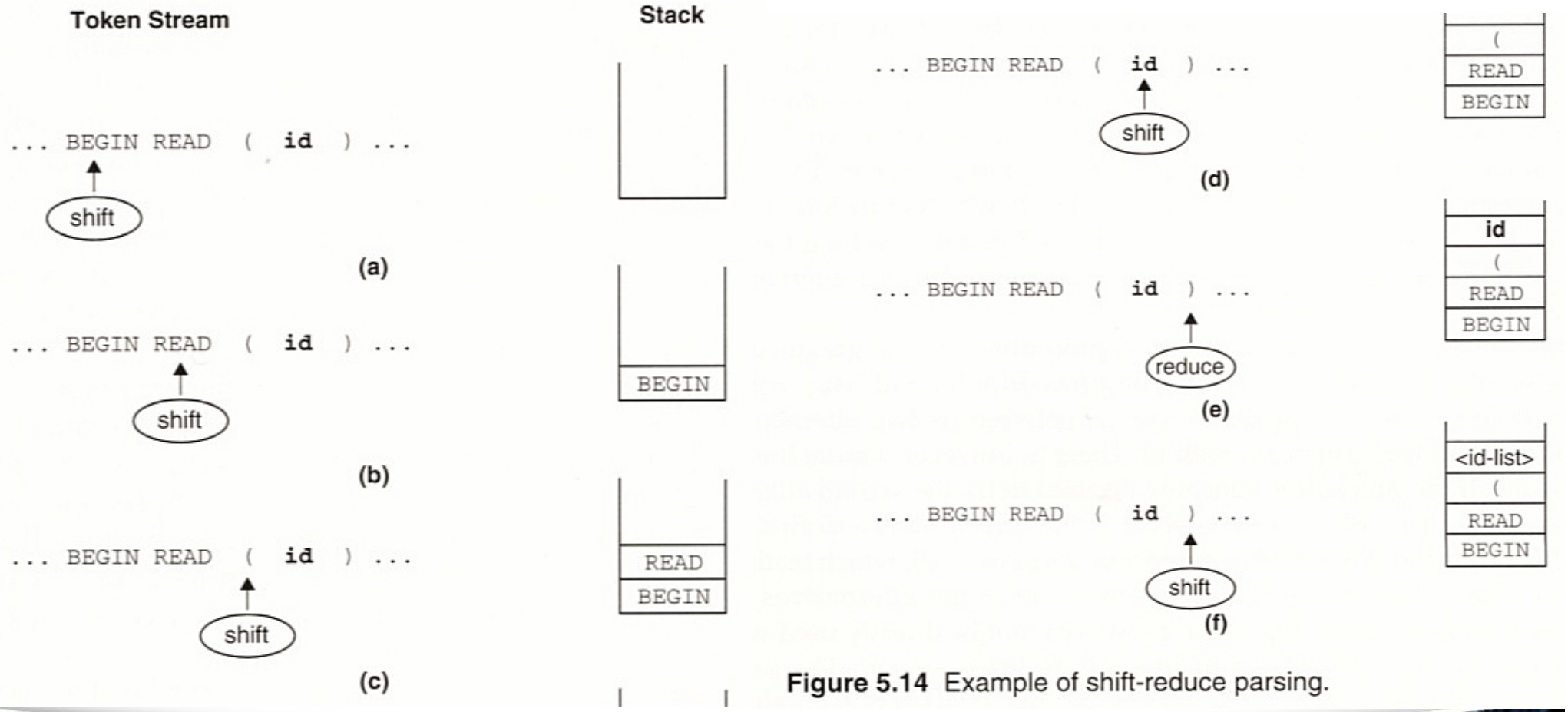


Figure 5.14 Example of shift-reduce parsing.

Recursive-Descent Parsing

- Each nonterminal symbol in the grammar is associated with a procedure.
  - <read> ::= READ (<id-list>)
  - <id-list>::= id | <id-list>,id
- Testing for alternatives:
  - <stmt> ::= <assign> | <read> | <write> | <for>

Recursive-Descent Parsing of READ

```
procedure READ
        begin
            FOUND := FALSE
            if TOKEN = 8 {READ} then
                begin
                    advance to next token
                    if TOKEN = 20 { ( } then
                        begin
                            advance to next token
                            if IDLIST returns success then
                                if TOKEN = 21 { ) } then
                                    begin
                                        FOUND := TRUE
                                        advance to next token
                                    end {if ) }
                        end {if ( }
                end {if READ}
            if FOUND = TRUE then
                return success
            else
                return failure
        end {READ}
```

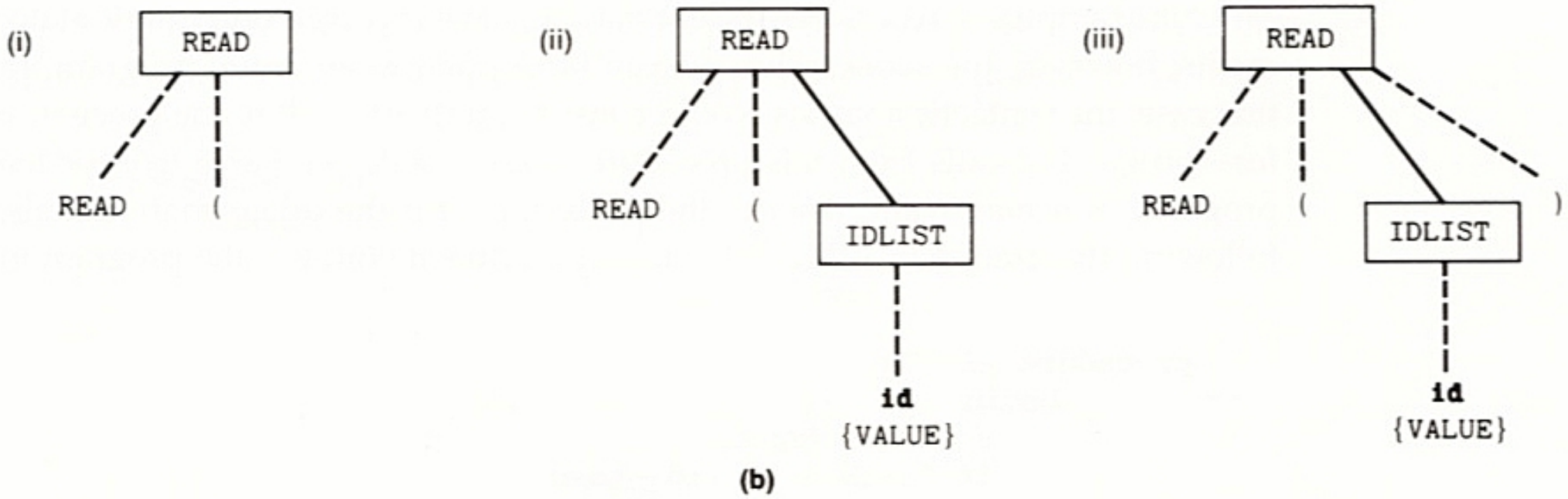
Recursive-Descent Parsing of IDLIST

```
procedure IDLIST
        begin
            FOUND := FALSE
            if TOKEN = 22 {id} then
                begin
                    FOUND := TRUE
                    advance to next token
                    while (TOKEN = 14 {,}) and (FOUND = TRUE) do
                        begin
                            advance to next token
                            if TOKEN = 22 {id} then
                                advance to next token
                            else
                                FOUND := FALSE
                        end {while}
                end {if id}
            if FOUND = TRUE then
               return success
            else
              return failure
        end {IDLIST}
```

(a)

Figure 5.16 Recursive-descent parse of a READ statement.

Recursive-Descent Parsing (cont'd.)



(b)

Figure 5.16 (*cont'd*)

Eliminating Left-Recursion

- **Left Recursion in lines 3, 6, 7, 10 and 11**

```
<id-list> ::= id { , id }
```

- **Modification:**

```
6  <id-list>      ::= id | <id-list> , id
```

  - **<dec-list> ::= <dec> | <dec-list>;<dec>**
- **Modification:**
  - **<dec-list> ::= <dec> {;<dec>}**

Recursive-Descent Parsing (cont'd.)

```
1    <prog>          ::= PROGRAM <prog-name> VAR <dec-list> BEGIN <stmt-list> END.
2    <prog-name>     ::= id
3a   <dec-list>      ::= <dec> { ; <dec> }
4    <dec>           ::= <id-list> : <type>
5    <type>          ::= INTEGER
6a   <id-list>       ::= id { , id }
7a   <stmt-list>     ::= <stmt> { ; <stmt> }
8    <stmt>          ::= <assign> | <read> | <write> | <for>
9    <assign>        ::= id := <exp>
10a  <exp>           ::= <term> { + <term> | - <term> }
11a  <term>          ::= <factor> { * <factor> | DIV < factor> }
12   <factor>        ::= id | int | ( <exp> )
13   <read>          ::= READ ( <id-list> )
14   <write>         ::= WRITE ( <id-list> )
15   <for>           ::= FOR <index-exp> DO <body>
16   <index-exp>     ::= id := <exp> TO <exp>
17   <body>          ::= <stmt> | BEGIN <stmt-list> END
```

Figure 5.15 Simplified Pascal grammar modified for recursive-descent parse.

Recursive-Descent Parsing of ASSIGN

```
procedure ASSIGN
        begin
            FOUND := FALSE
            if TOKEN = 22 {id} then
                begin
                    advance to next token
                    if TOKEN = 15 { := } then
                        begin
                            advance to next token
                            if EXP returns success then
                                FOUND := TRUE
                        end {if := }
                end {if id}
            if FOUND = TRUE then
                return success
            else
                return failure
        end {ASSIGN}
```

Recursive-Descent Parsing of EXP

```
procedure EXP
        begin
            FOUND := FALSE
            if TERM returns success then
                begin
                    FOUND := TRUE
                    while ((TOKEN = 16 {+}) or (TOKEN = 17 {-}))
                        and ( FOUND = TRUE ) do
                            begin
                                advance to next token
                                if TERM returns failure then
                                    FOUND := FALSE
                            end {while}
                end {if TERM}
            if FOUND = TRUE then
                return success
            else
                return failure
        end {EXP}
```

Figure 5.17 Recursive-descent parse of an assignment statement.

Recursive-Descent Parsing of TERM

```
procedure TERM
        begin
            FOUND := FALSE
            if FACTOR returns success then
                begin
                    FOUND := TRUE
                    while ({TOKEN = 18 {*}) or (TOKEN = 19 {DIV
                        and (FOUND = TRUE) do
                            begin
                                advance to next token
                                if FACTOR returns failure then
                                    FOUND := FALSE
                            end {while}
                end {if FACTOR}
            if FOUND = TRUE then
                return success
            else
                return failure
        end {TERM}
```

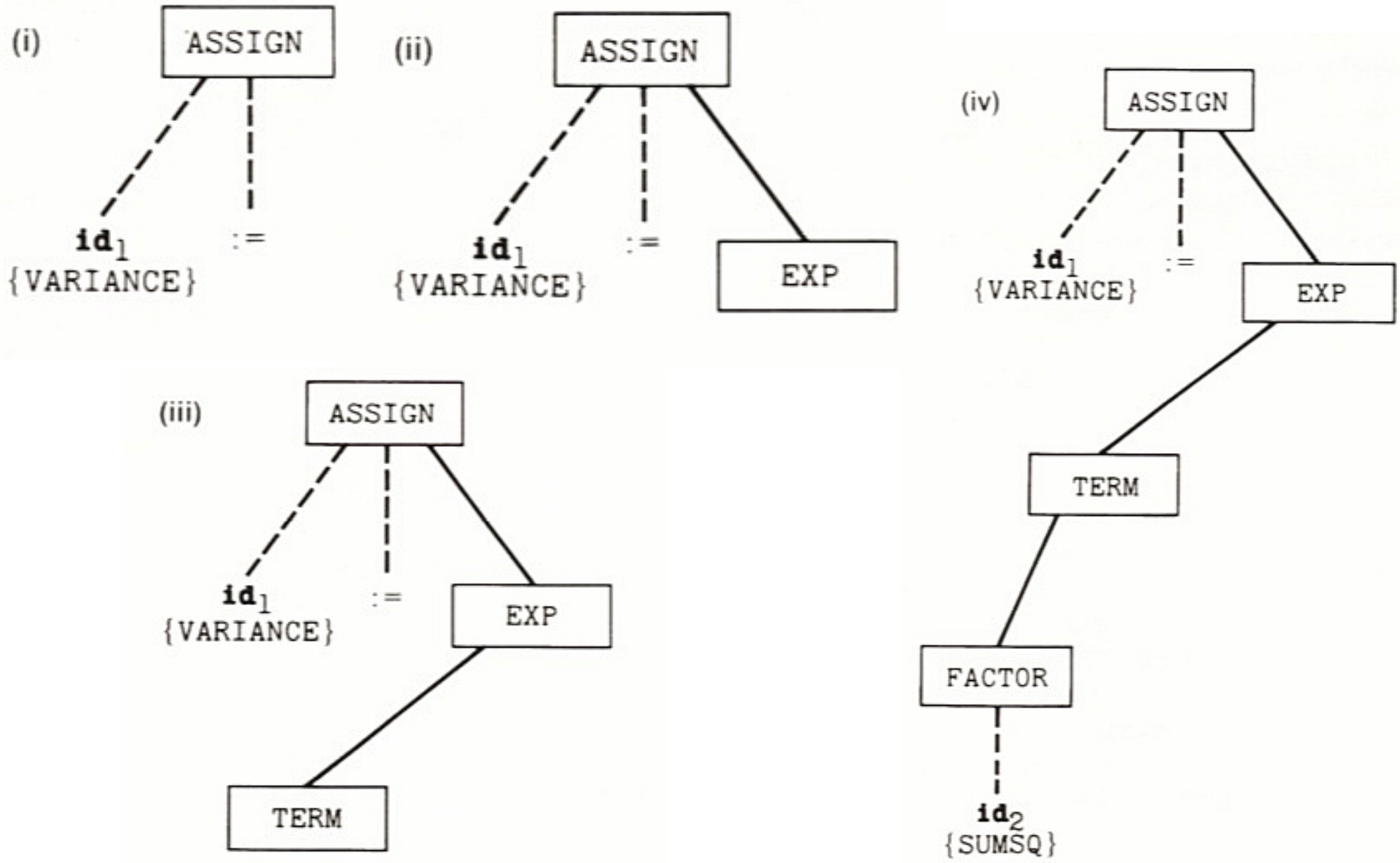
procedure FACTOR

begin

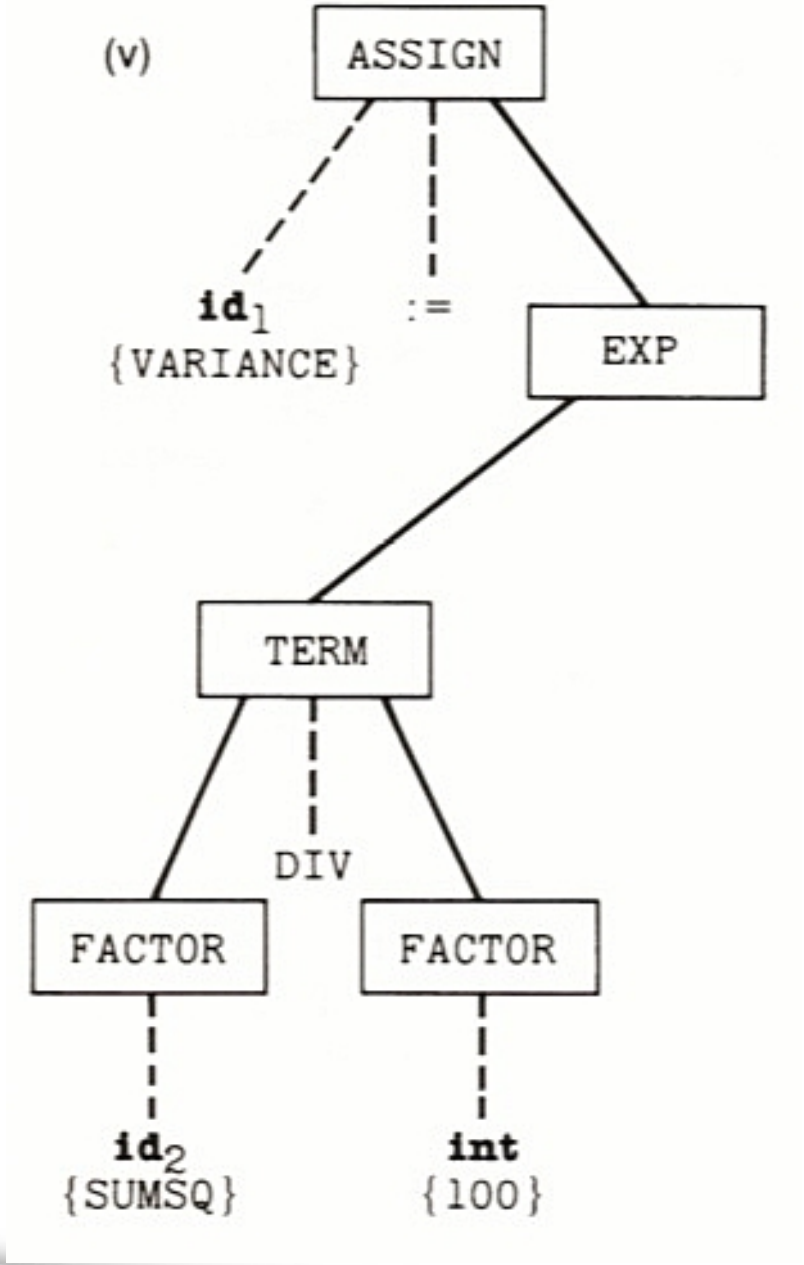
```
FOUND := FALSE
if (TOKEN = 22 {id}) or (TOKEN = 23 {int}) then
    begin
        FOUND := TRUE
        advance to next token
    end {if id or int}
else
    if TOKEN = 20 { ( } then
        begin
            advance to next token
            if EXP returns success then
                if TOKEN = 21 { ) } then
                    begin
                        FOUND := TRUE
                        advance to next token
                    end {if )}
        end {if ( }
if FOUND = TRUE then
    return success
else
    return failure
```

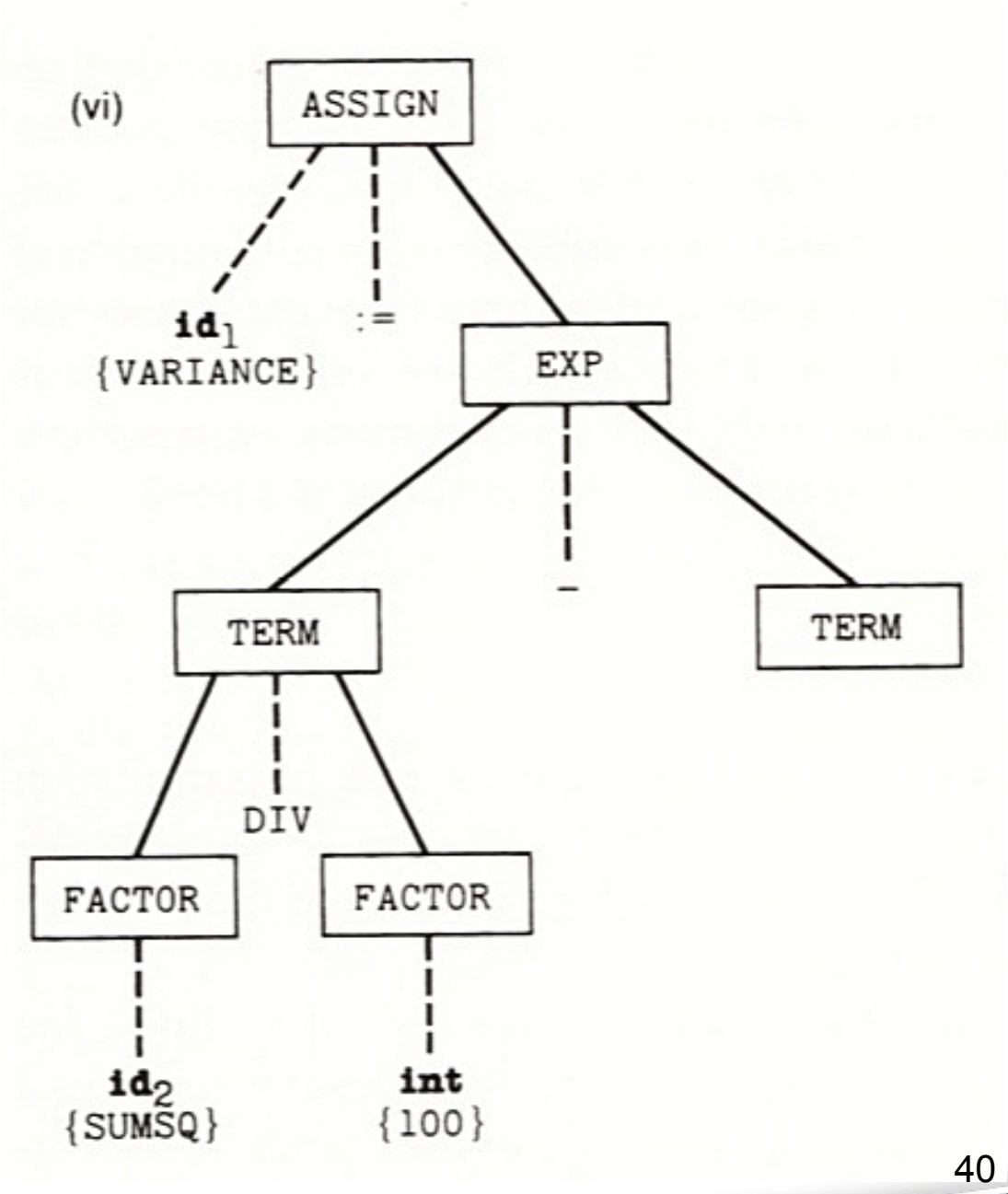
end {FACTOR}

Recursive-Descent Parsing (cont'd.)

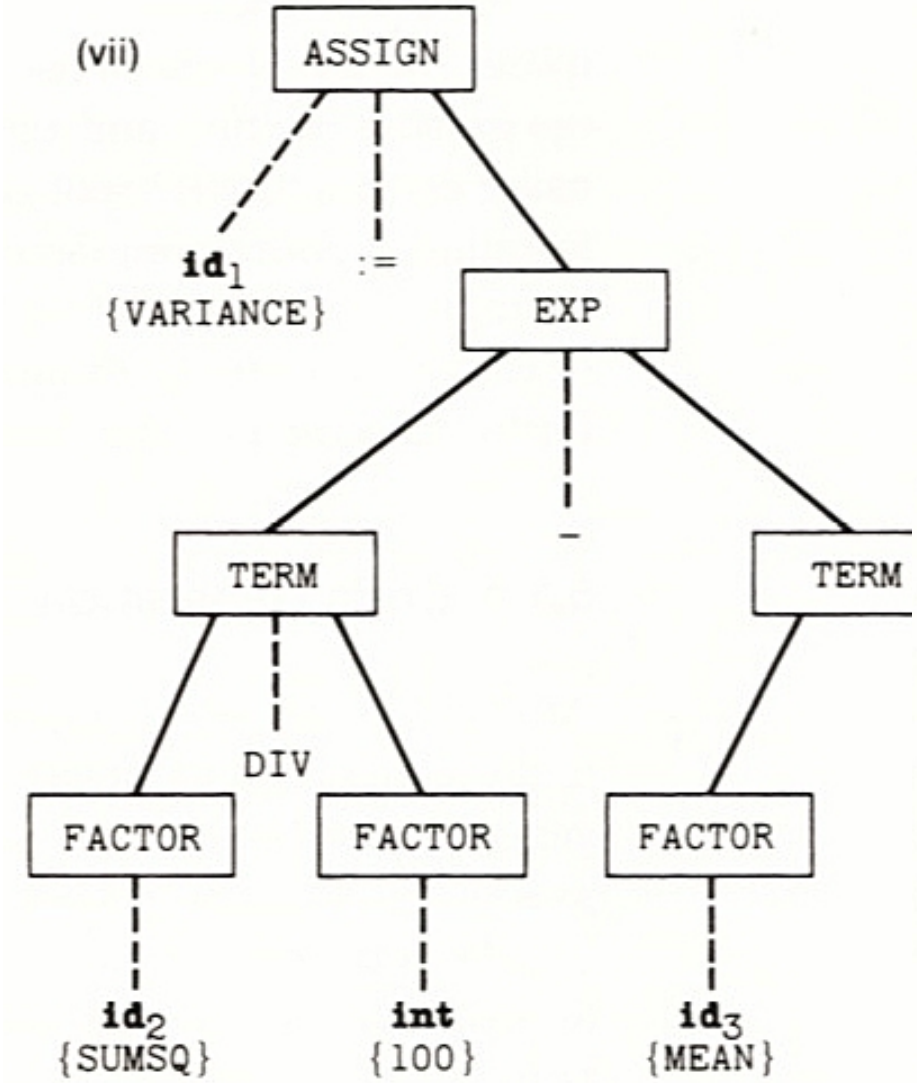


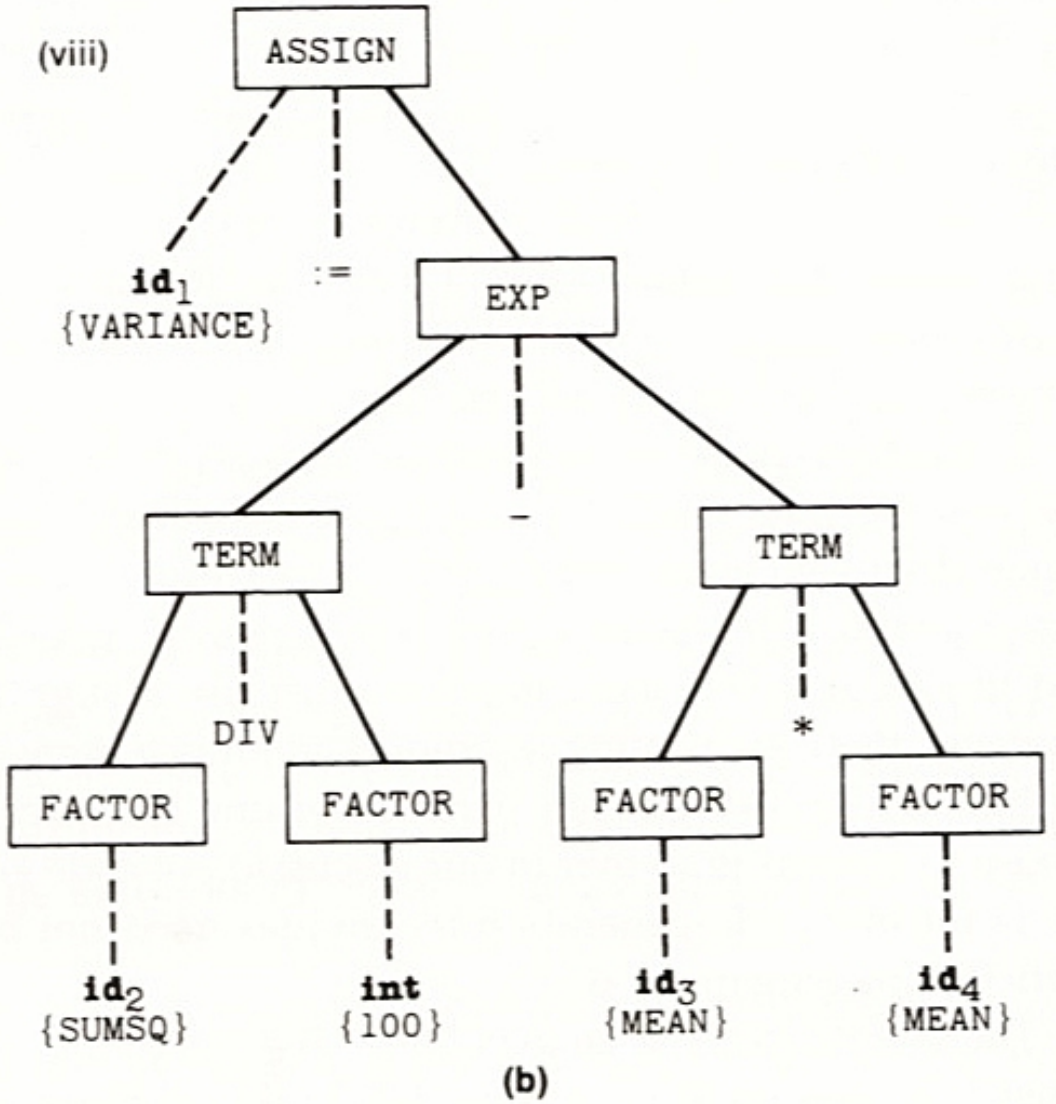
Recursive-Descent Parsing (cont'd.)





Recursive-Descent Parsing (cont'd.)





(b)

EXAMPLE:

Fahrenheit := 32 + celsius * 1.8

| f | a | h | r | e | n | h | e | i | t | : | = | 3 | 2 | + | c | e | l | s | l | o | u | s | * | 1 | . | 8 | ; |

Getchar()

Lexical analyser (scanner) (converts from character stream into a stream of tokens.)

[id, 1] [: =][int, 32][+][id, 2][*][int, 1.8][;]

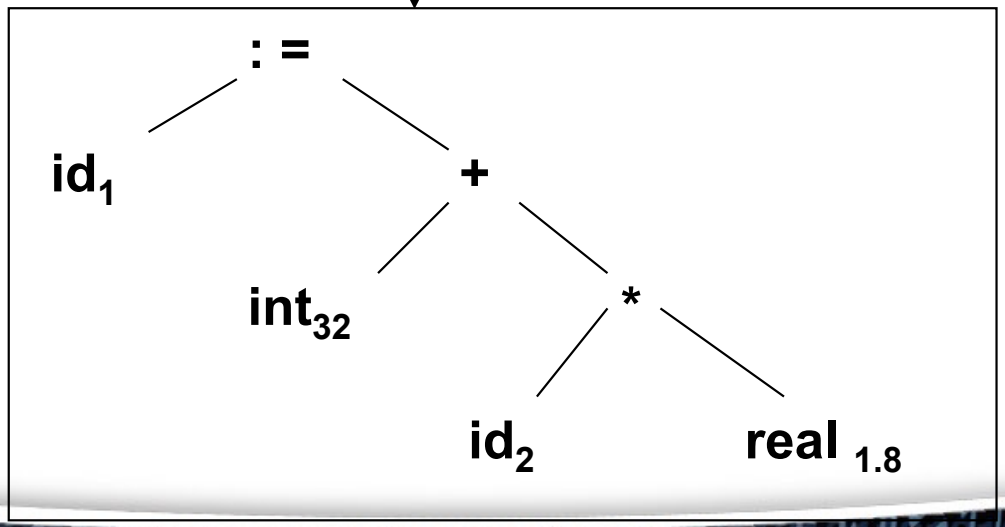
index in symbol table

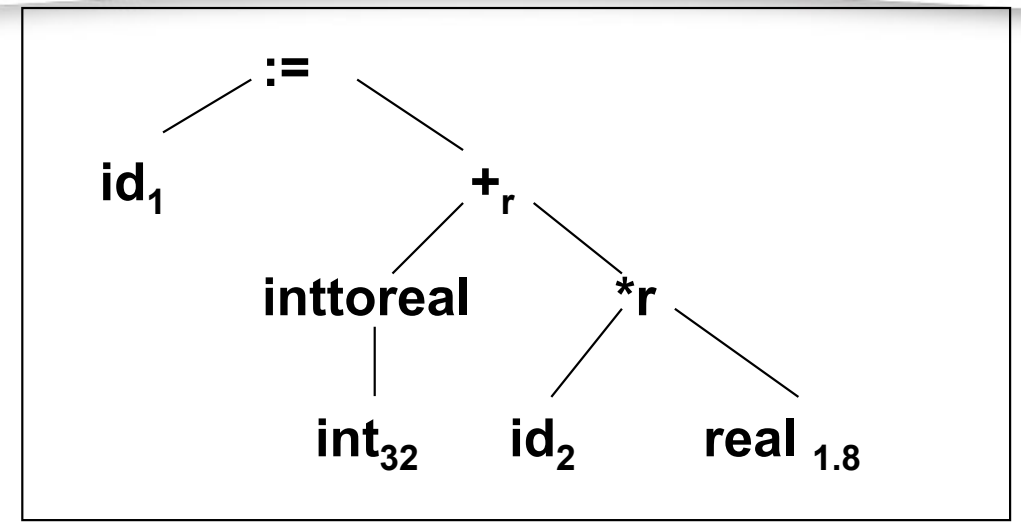
Symbol Table

1	fahrenheit	real
2	celsius	real

name attribute

Syntax analyser (parser)
(Construct syntactic structure of the program)





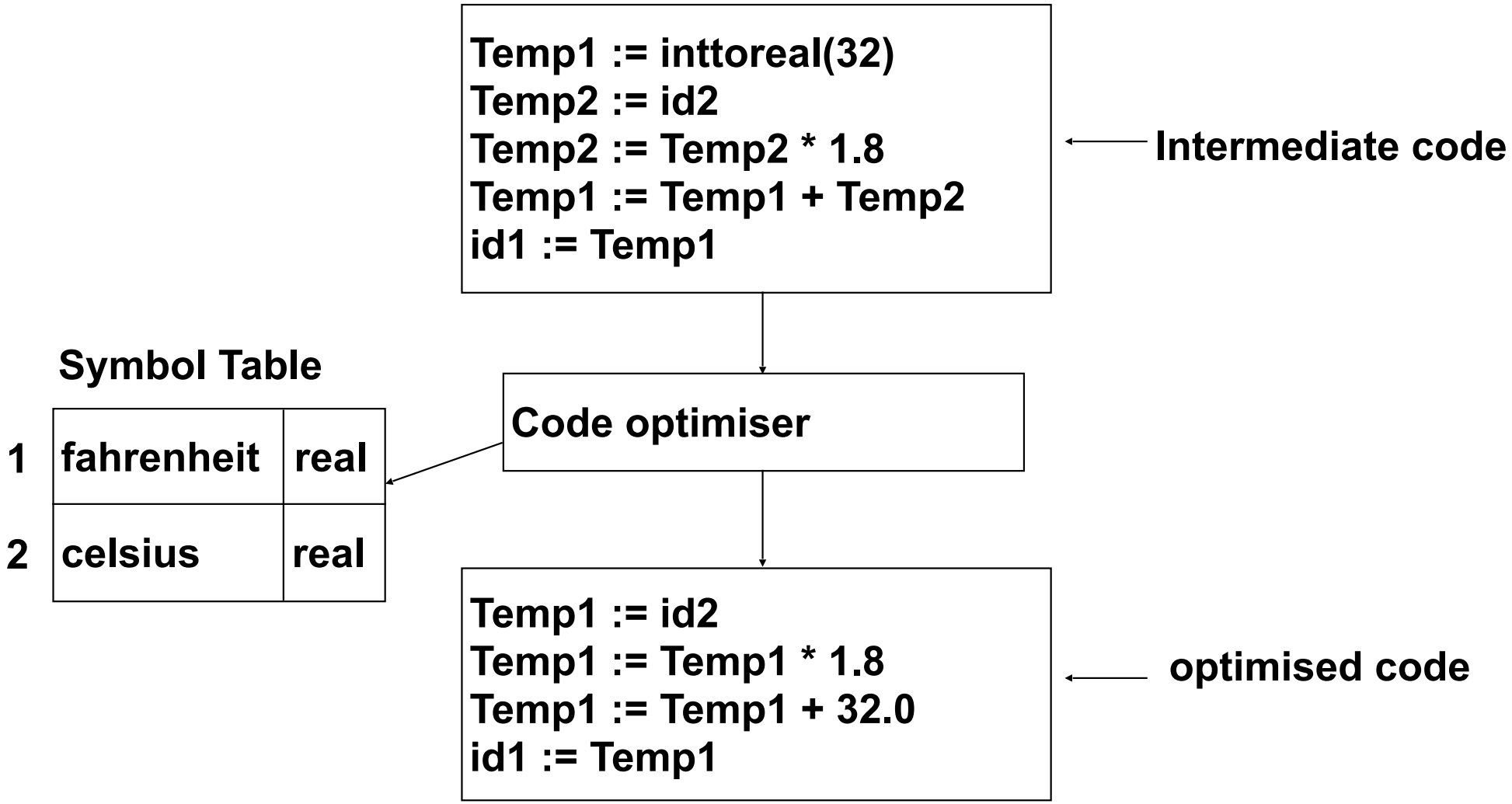
Symbol Table

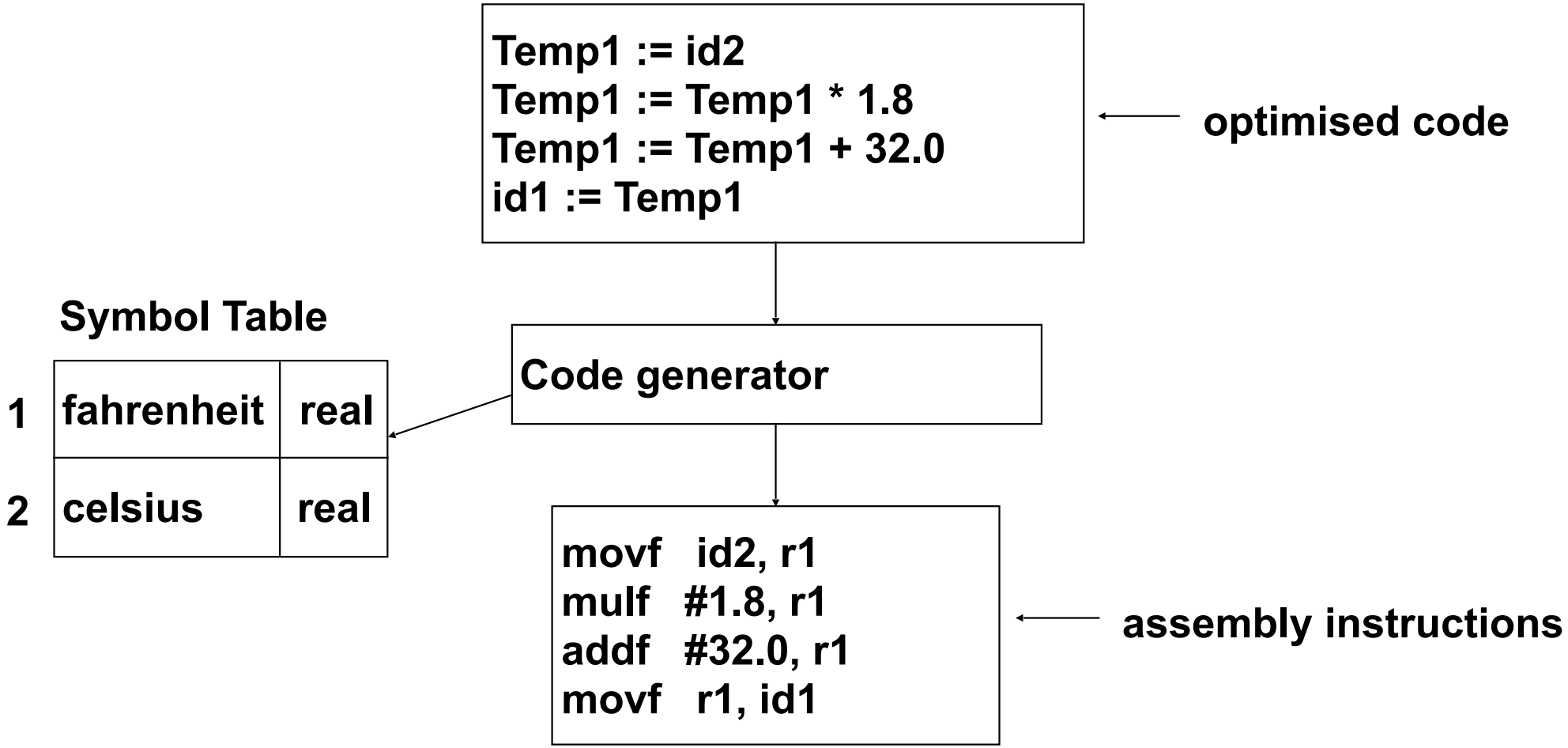
1	fahrenheit	real
2	celsius	real

Intermediate code generator

```
Temp1 := inttoreal(32)
Temp2 := id2
Temp2 := Temp2 * 1.8
Temp1 := Temp1 + Temp2
id1 := Temp1
```

← **Intermediate code**


Temp1 := inttoreal(32)
Temp2 := id2
Temp2 := Temp2 * 1.8
Temp1 := Temp1 + Temp2
id1 := Temp1
Intermediate code
Symbol Table
1 fahrenheit real
2 celsius real
Code optimiser
Temp1 := id2
Temp1 := Temp1 * 1.8
Temp1 := Temp1 + 32.0
id1 := Temp1
optimised code


Temp1 := id2
Temp1 := Temp1 * 1.8
Temp1 := Temp1 + 32.0
id1 := Temp1
optimised code
Symbol Table
1 fahrenheit real
2 celsius real
Code generator
movf id2, r1
mulf #1.8, r1
addf #32.0, r1
movf r1, id1
assembly instructions