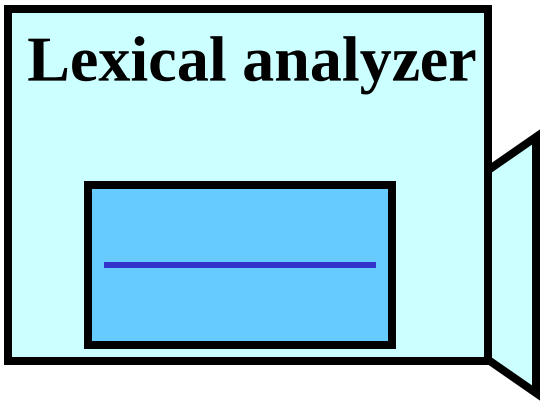
Applications: Lexical Analysis

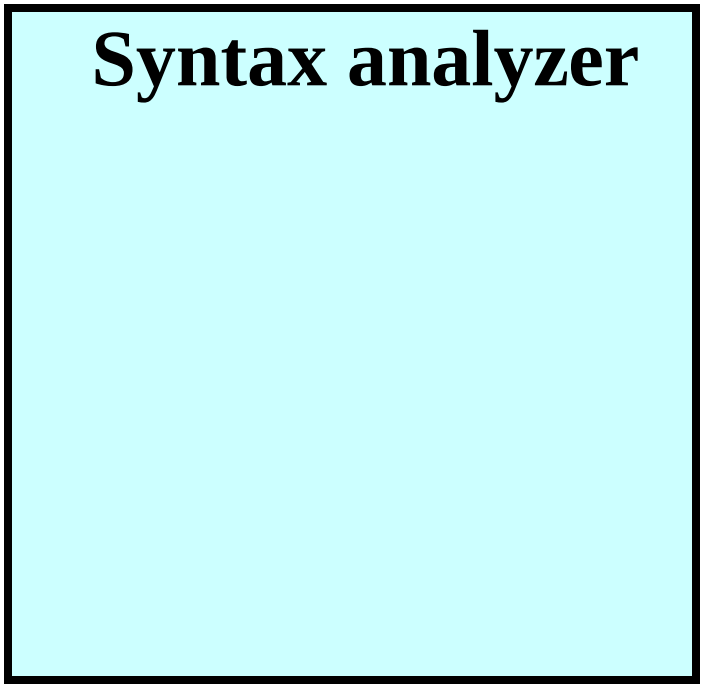
Lexical Analyzer (Scanner)

Example:

Source program:

```
Pos := Rate*60
```





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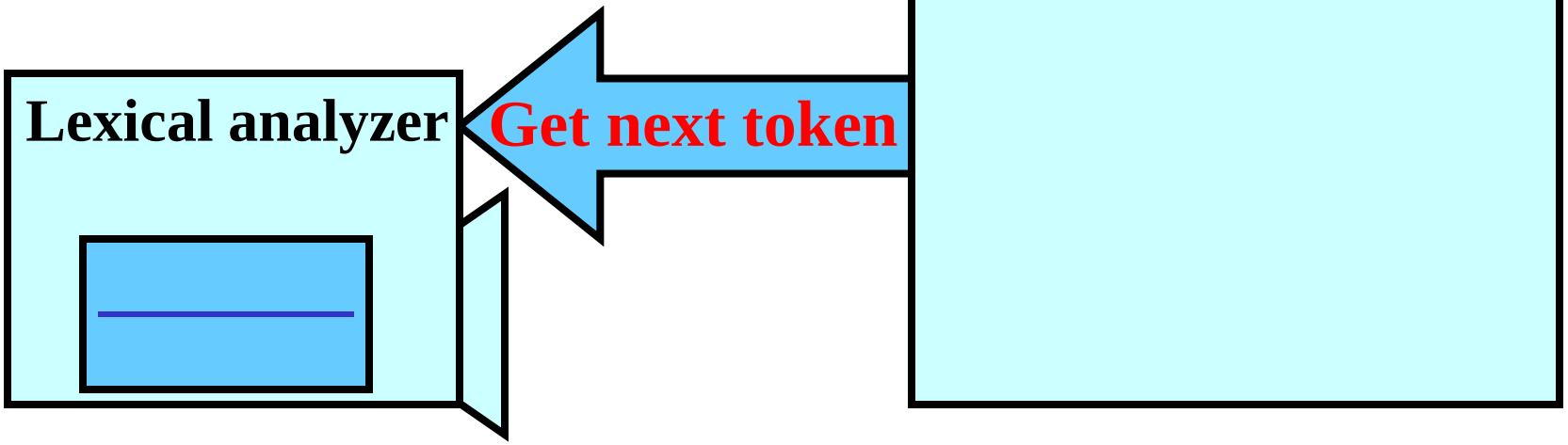

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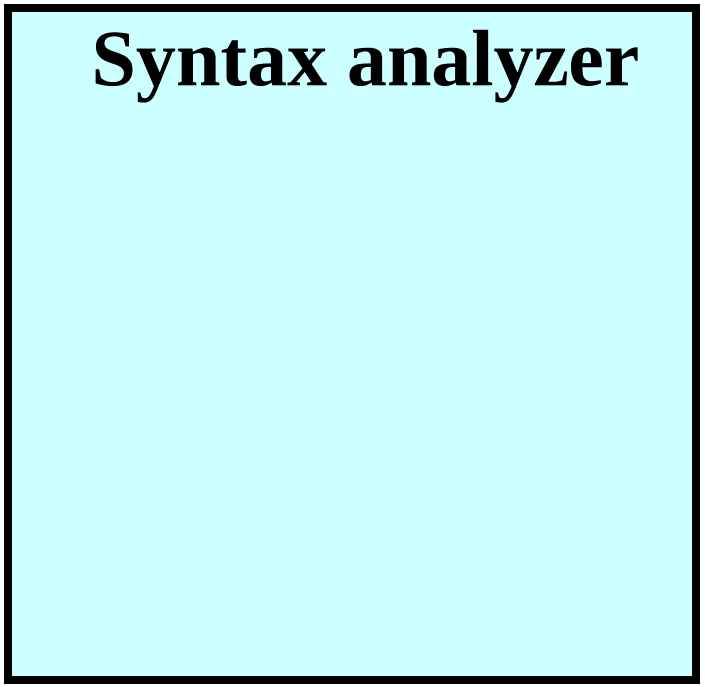

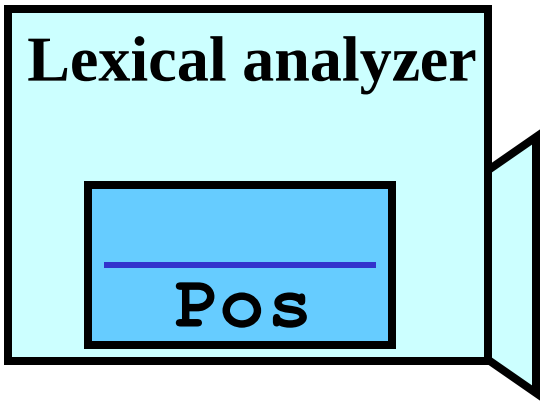

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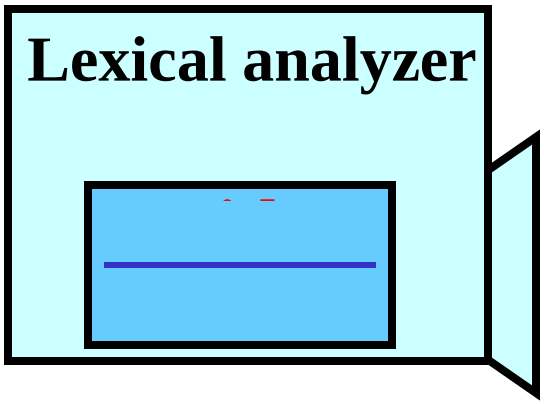

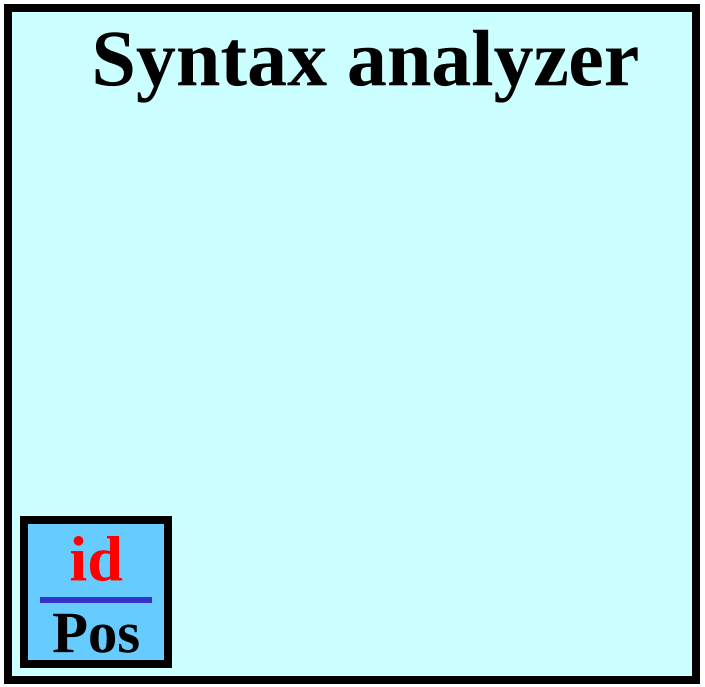

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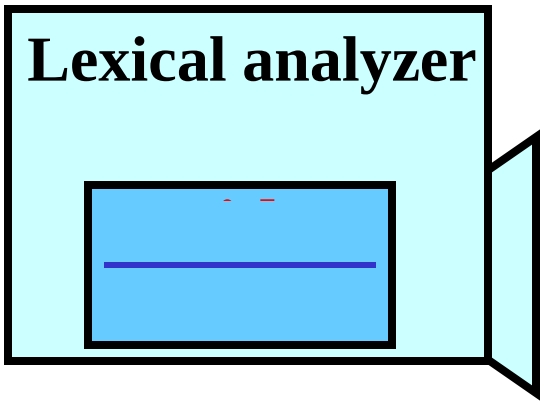

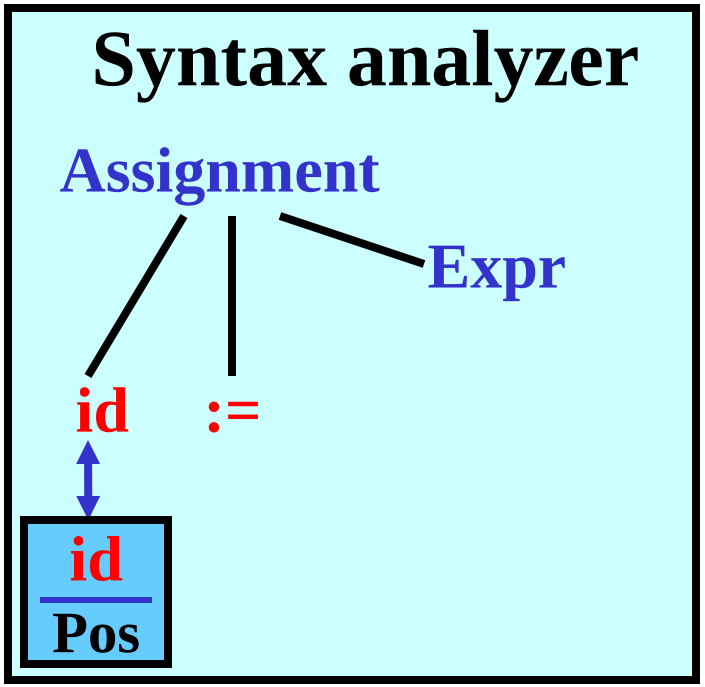

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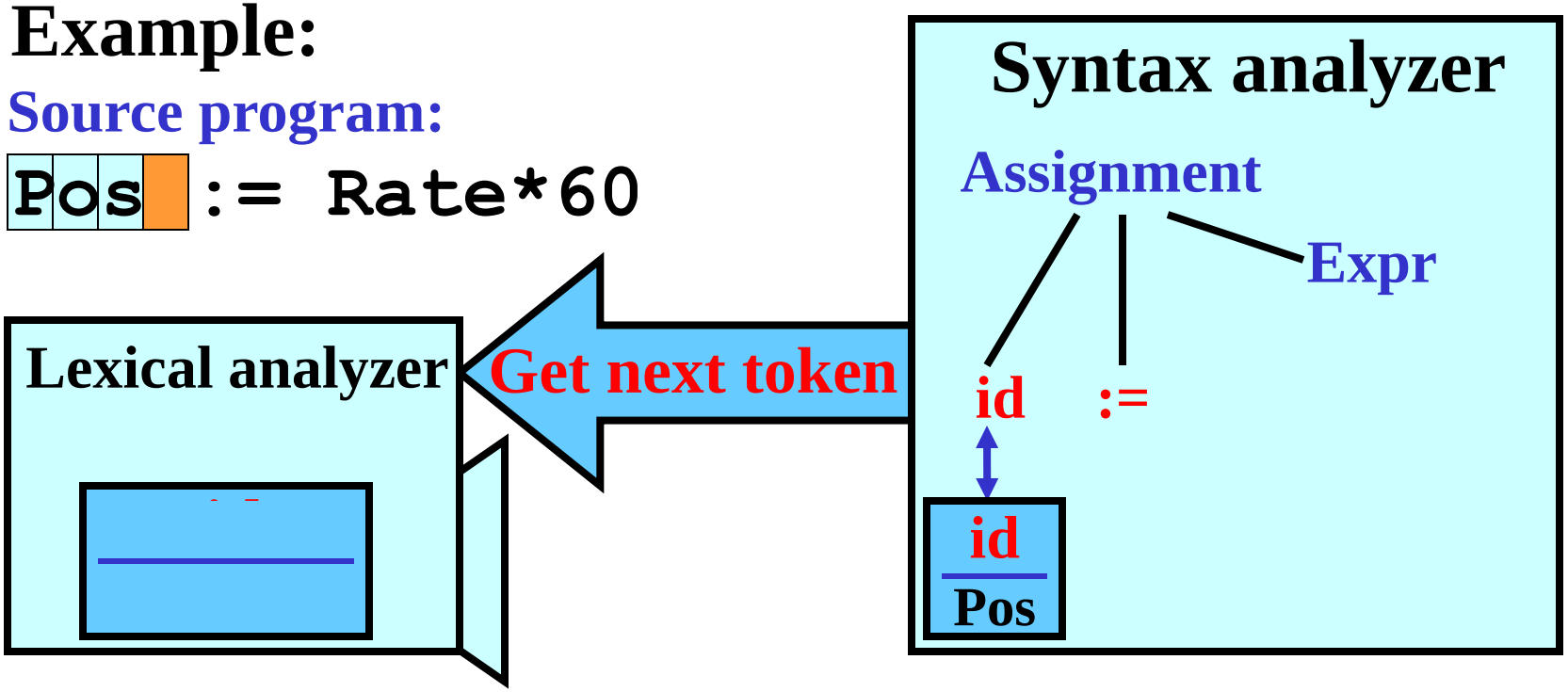

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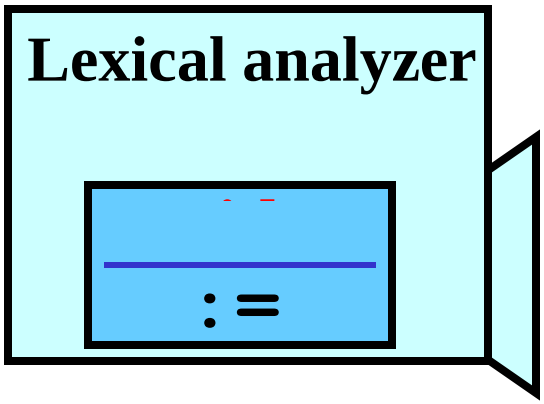

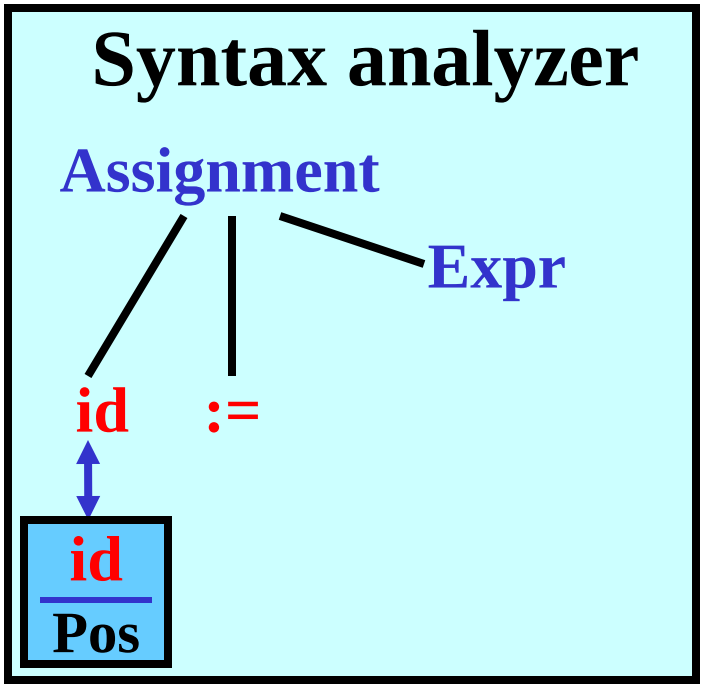

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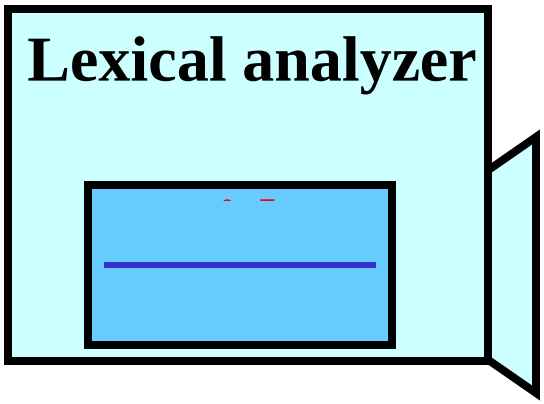

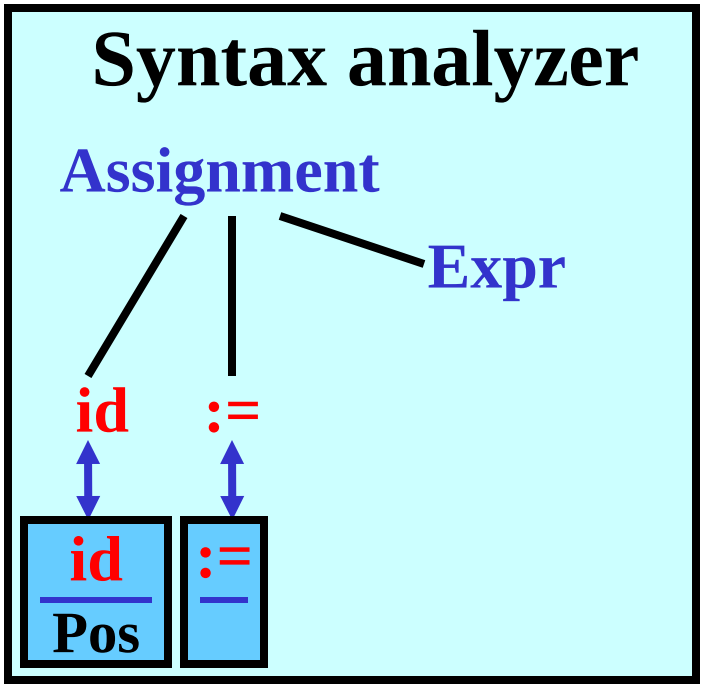

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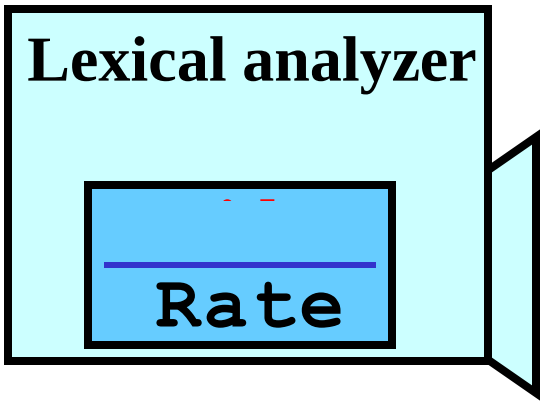

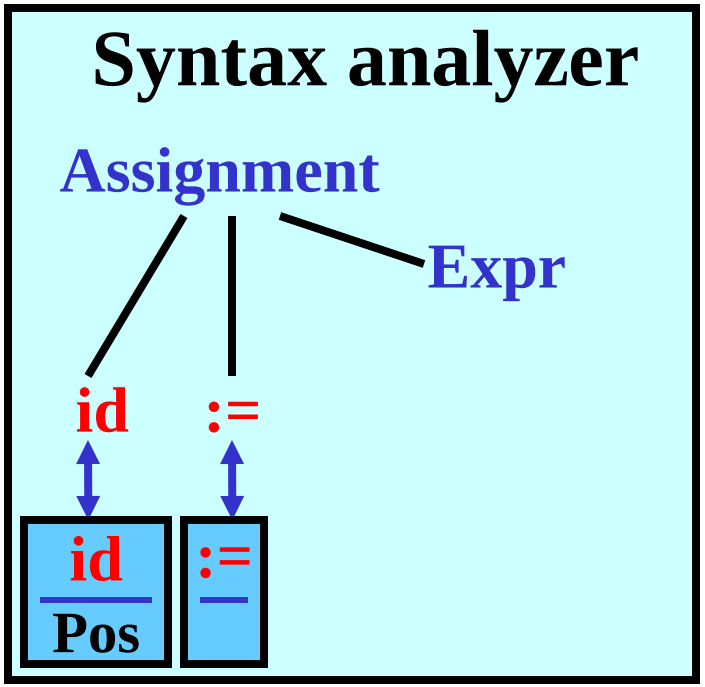

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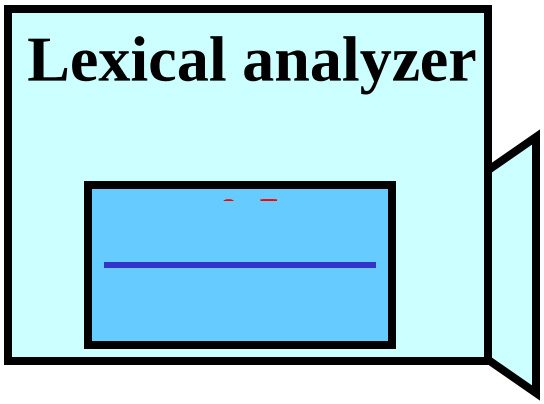

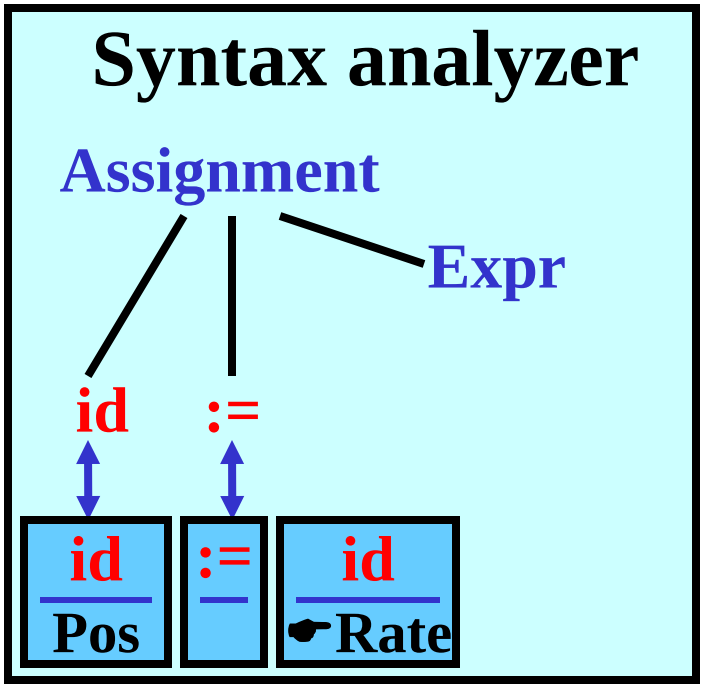

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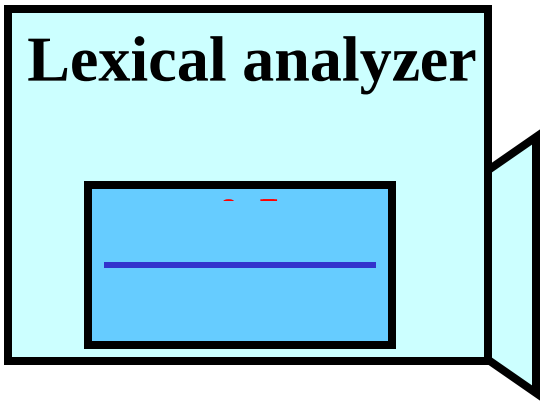

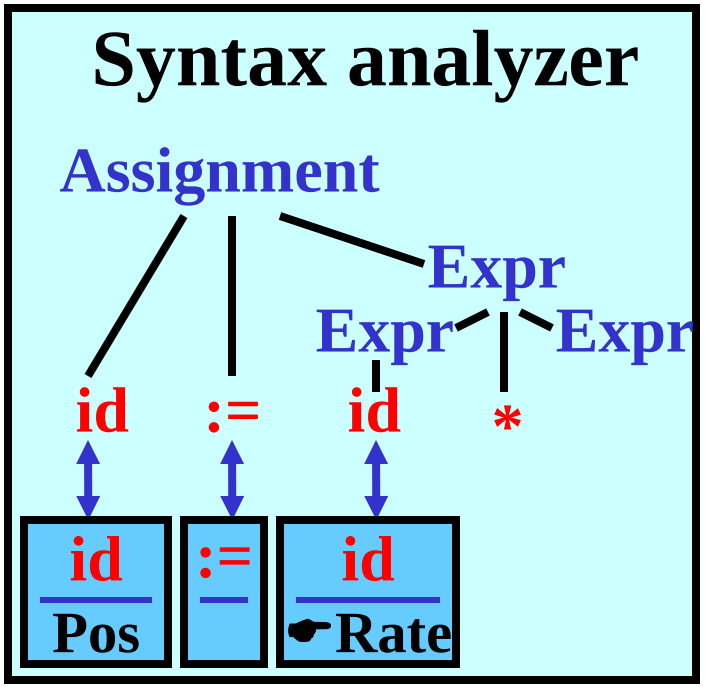

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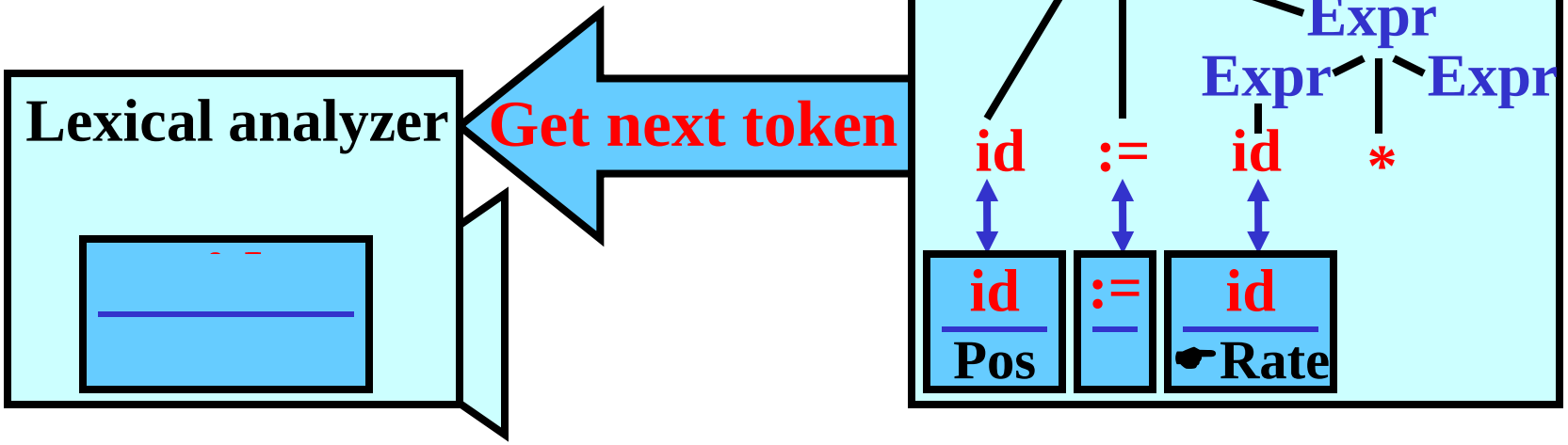

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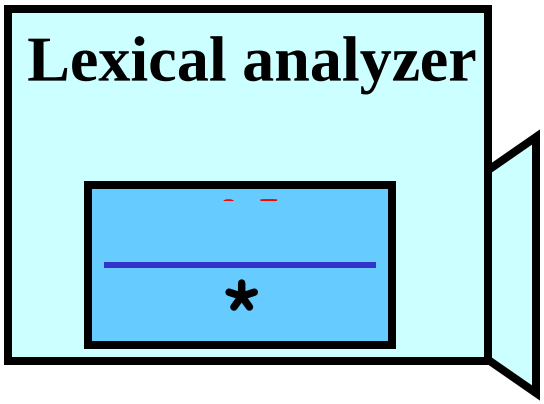

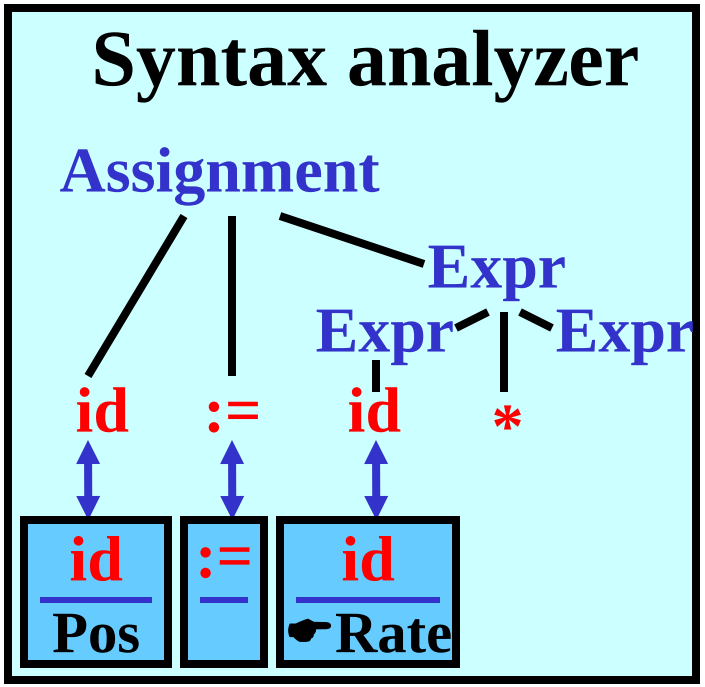

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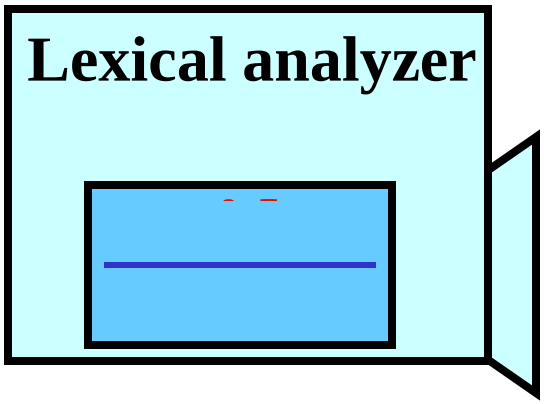

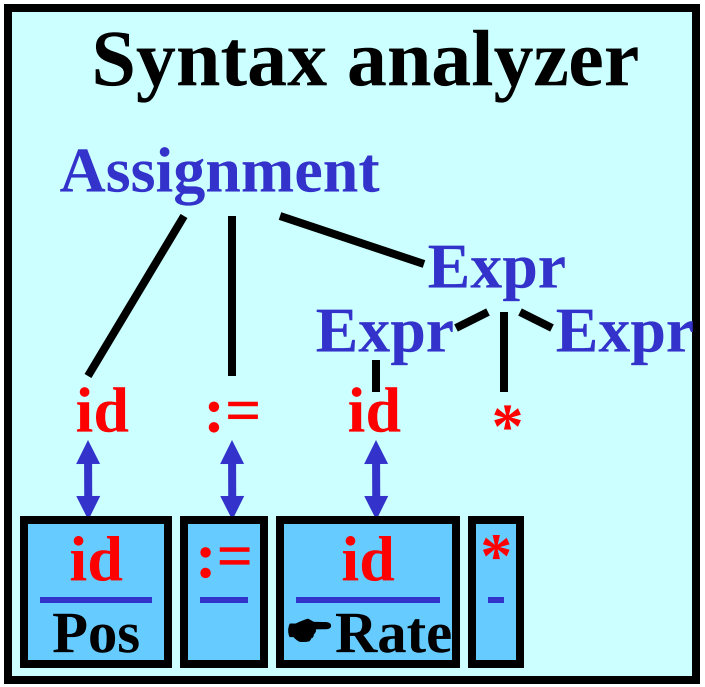

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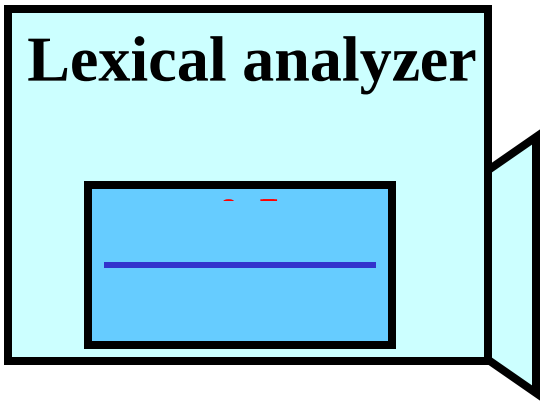

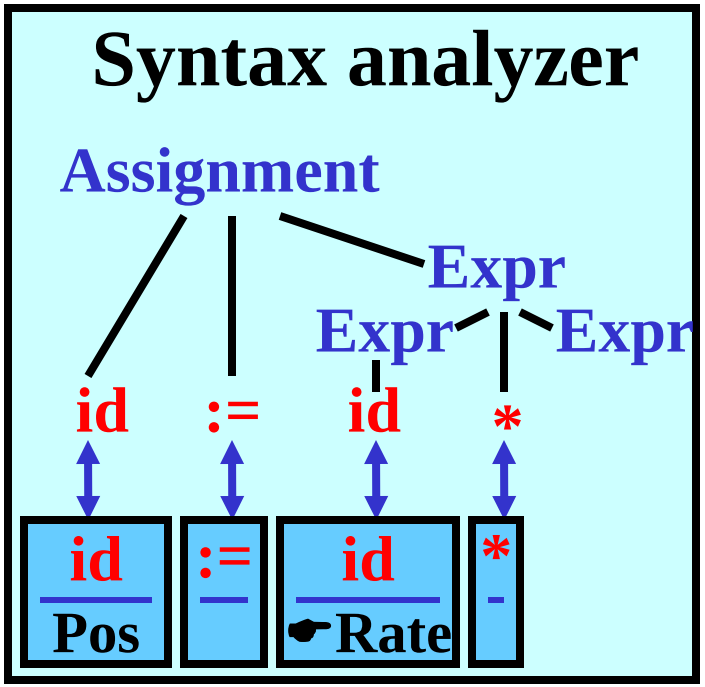

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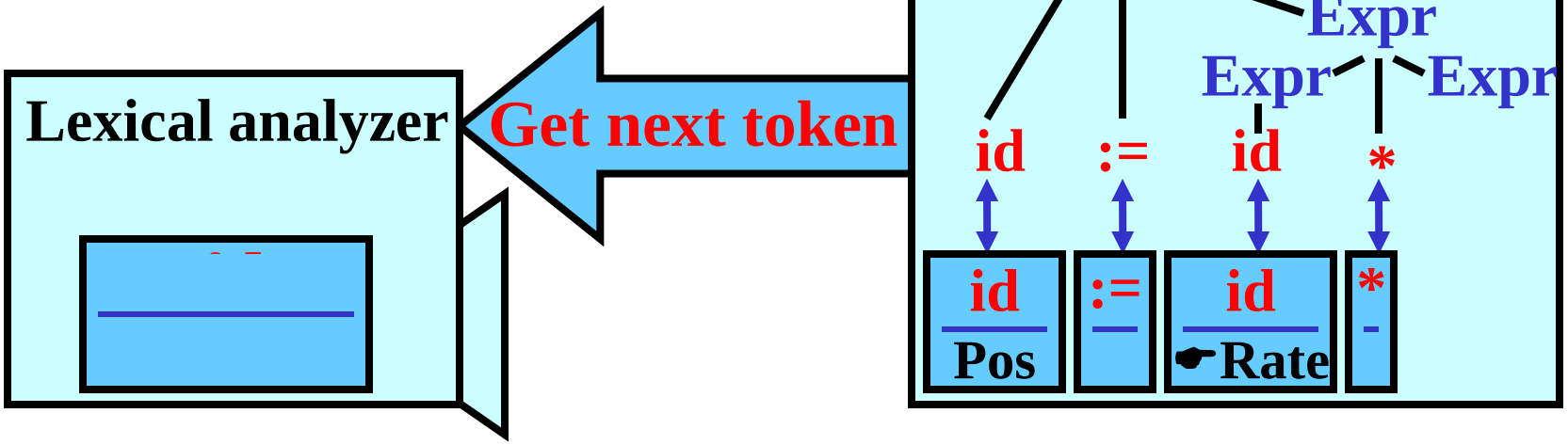

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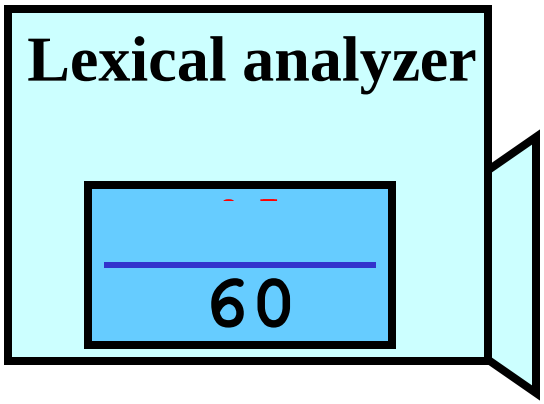

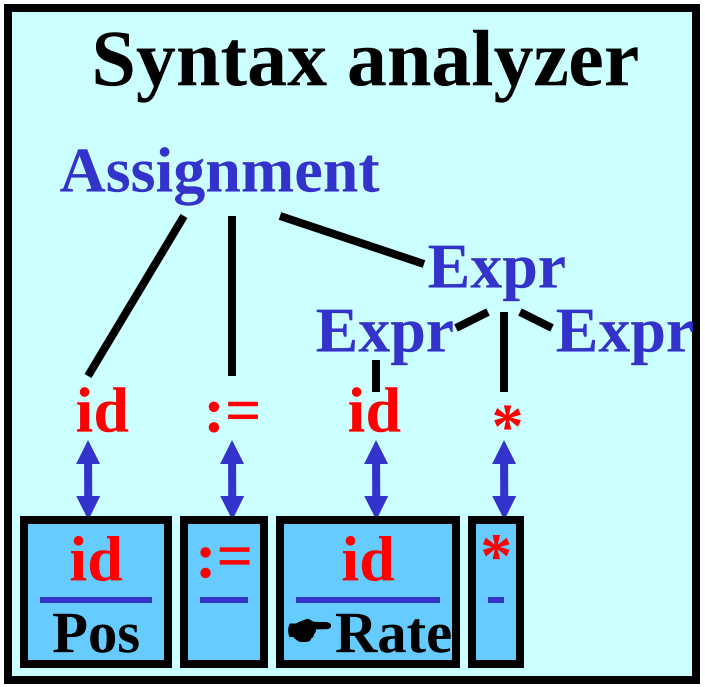

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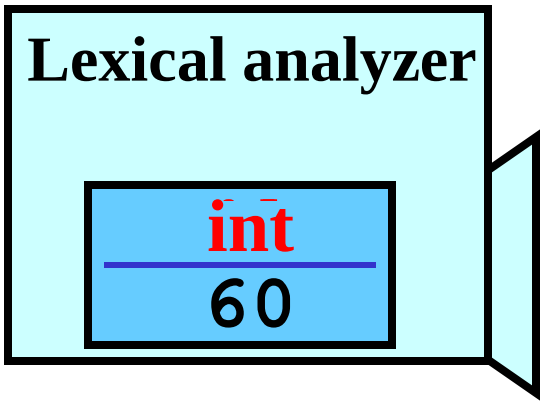

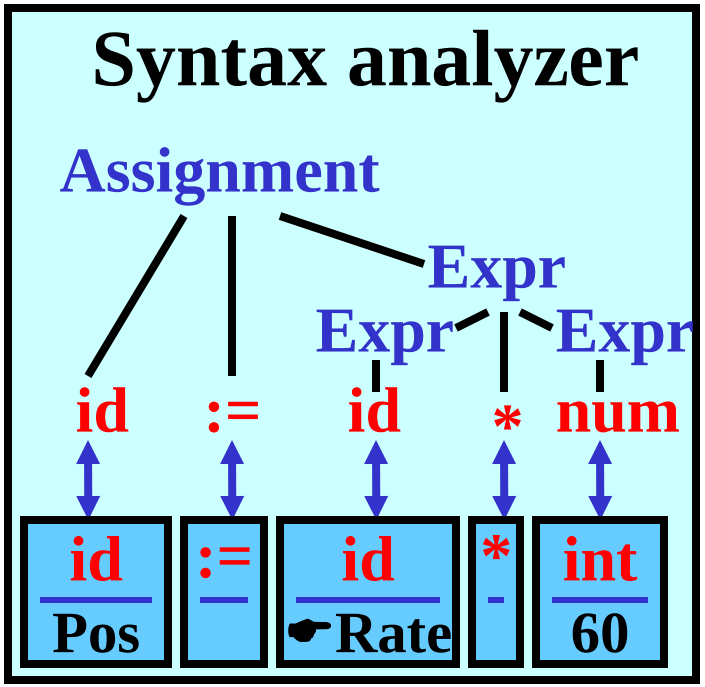

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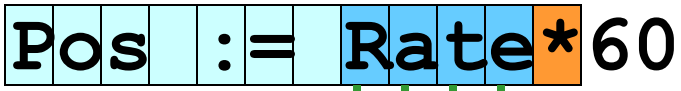
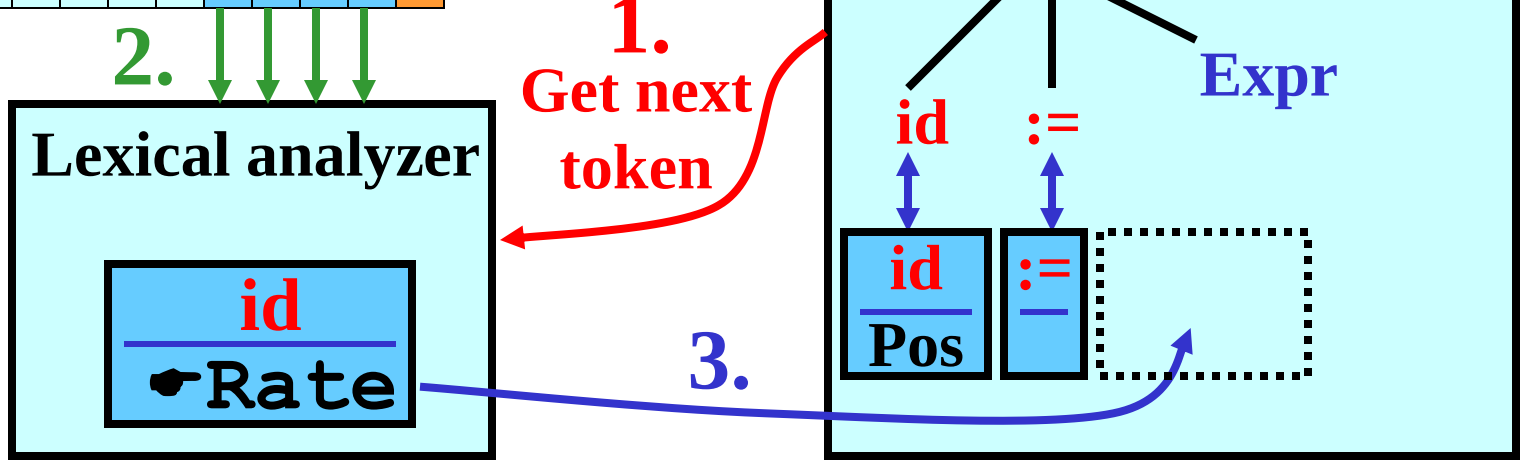




Scanner: Tasks

Main task

- recognition and classification of lexemes
- representing lexemes by their tokens

Other tasks

- removal of comments and whitespaces
- communication with symbol tables

Relation to Models for RLs

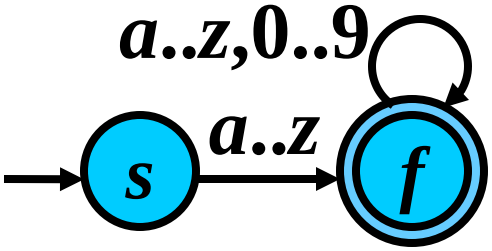
- **Regular expressions** specify lexemes
- **DFAs** underlie scanners

Lexemes Recognized by DFAs 1/2

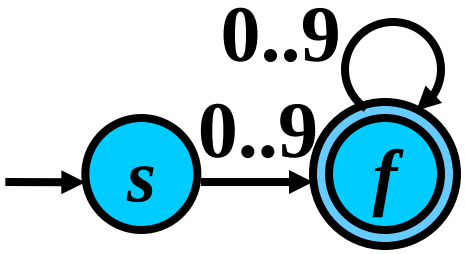
1) Recognition of lexemes by using DFA

Example:

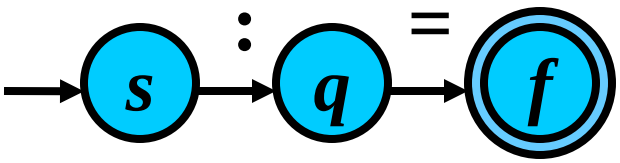
Identifier:



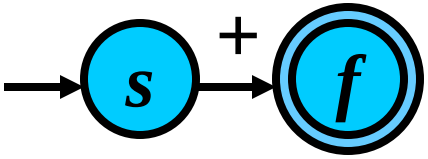
Integer:



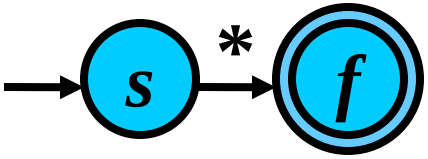
Assignment:



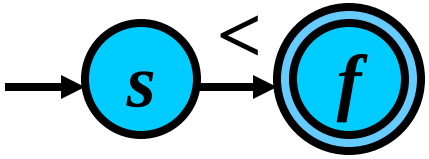
Operator +:



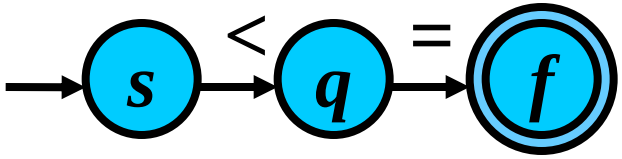
Operator *:



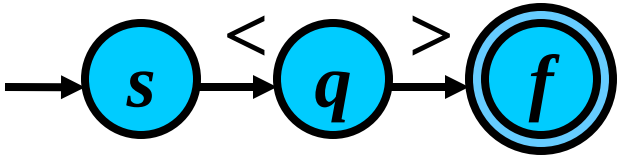
Comparator <:



Comparator <=:



Comparator <>:



Lexemes Recognized by DFAs 2/2

2) Construction of an FA that accepts all lexemes:

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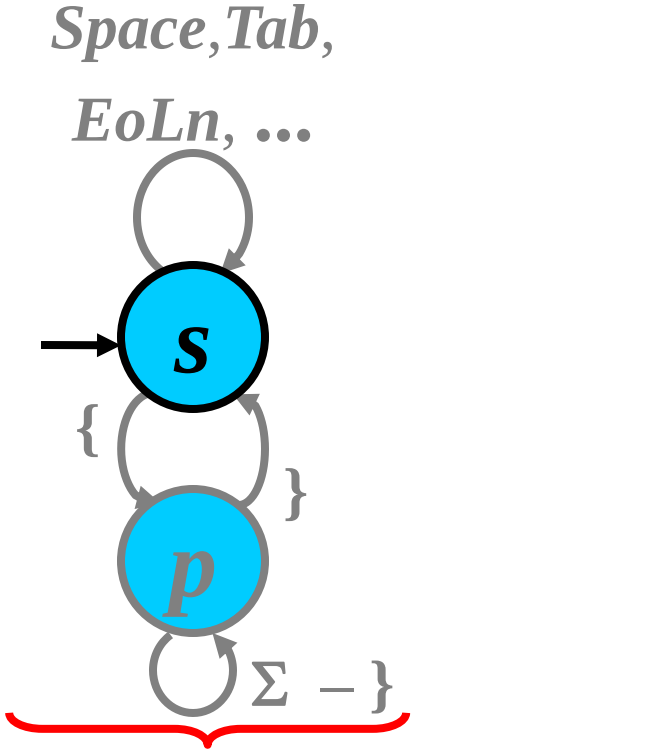

Comments and whitespaces are skipped before a new lexeme

Lexemes Recognized by DFAs 2/2

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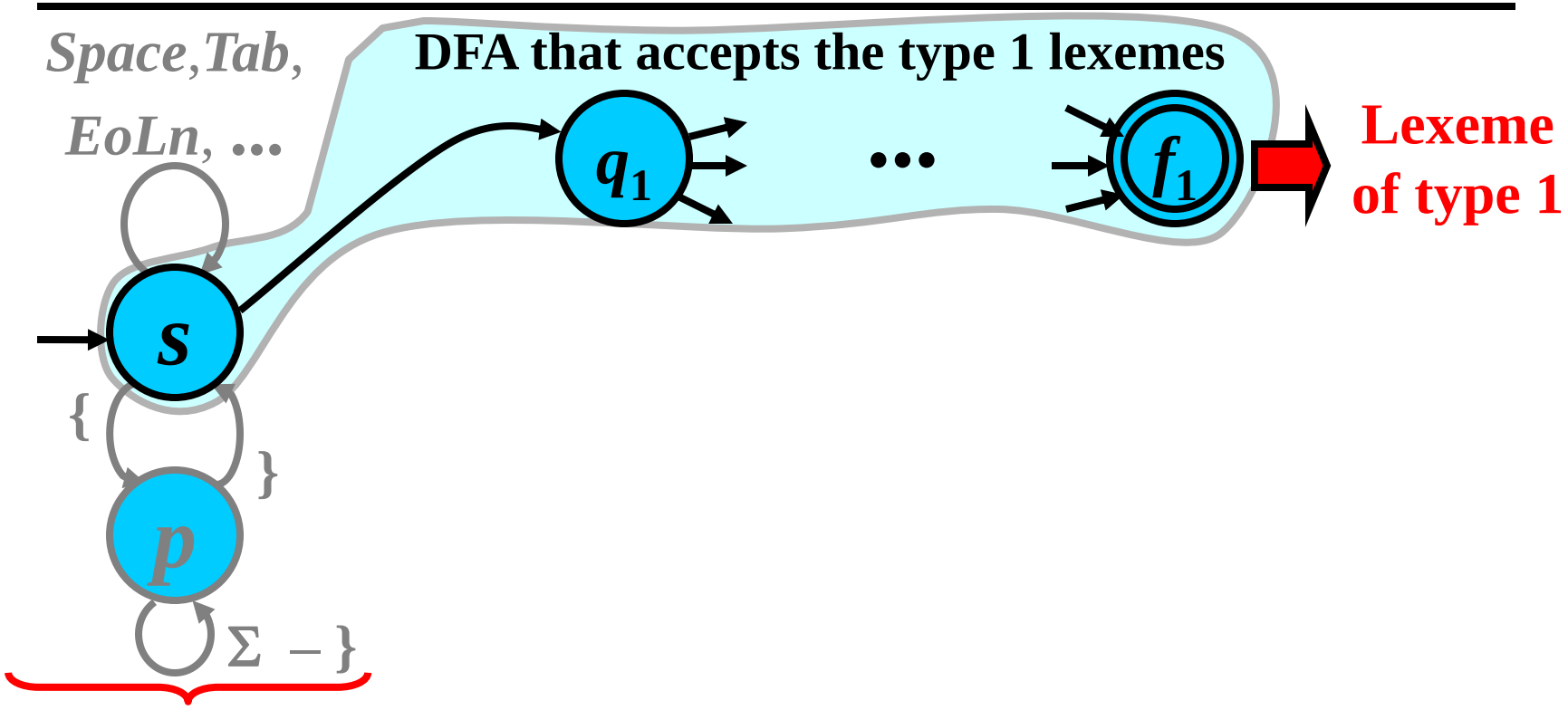

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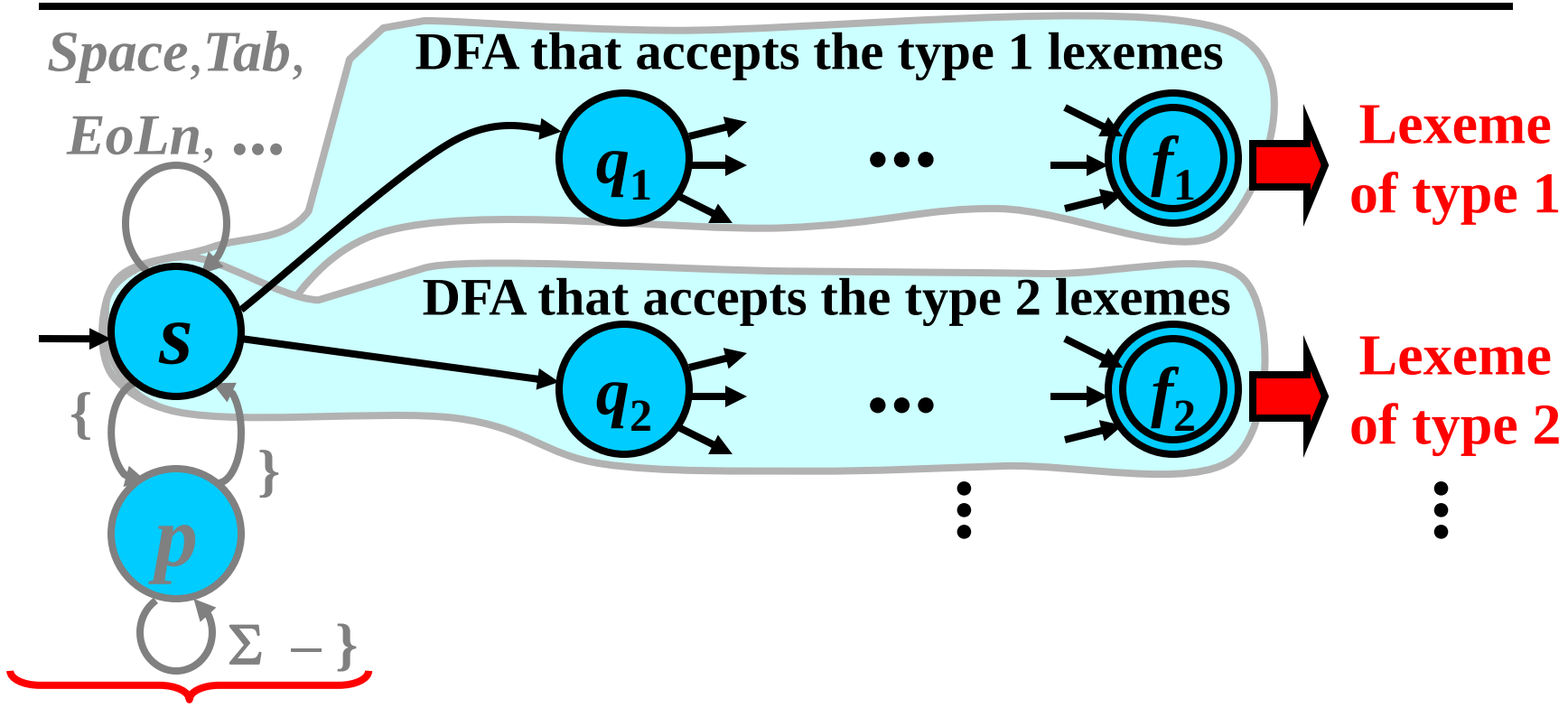

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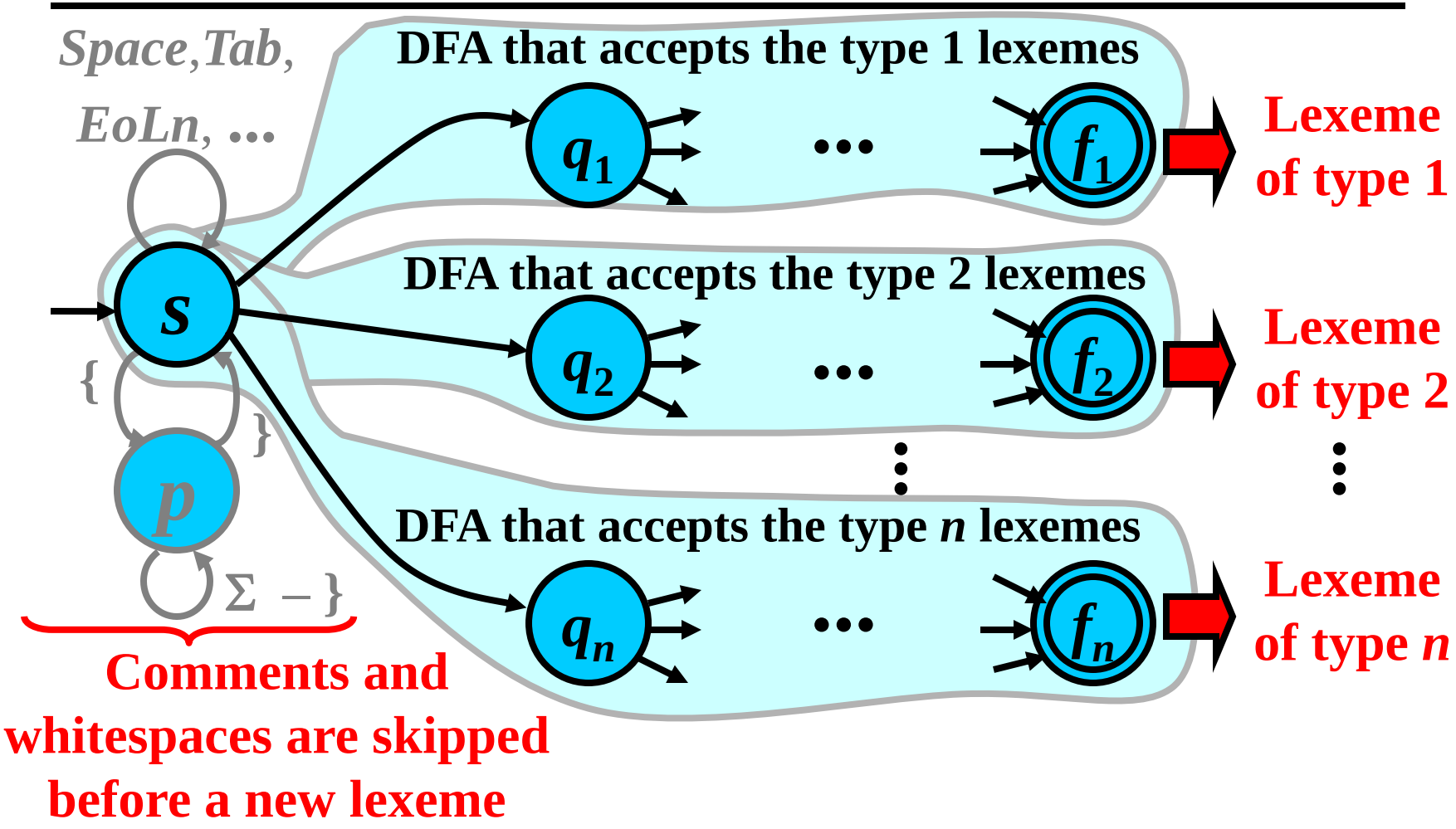

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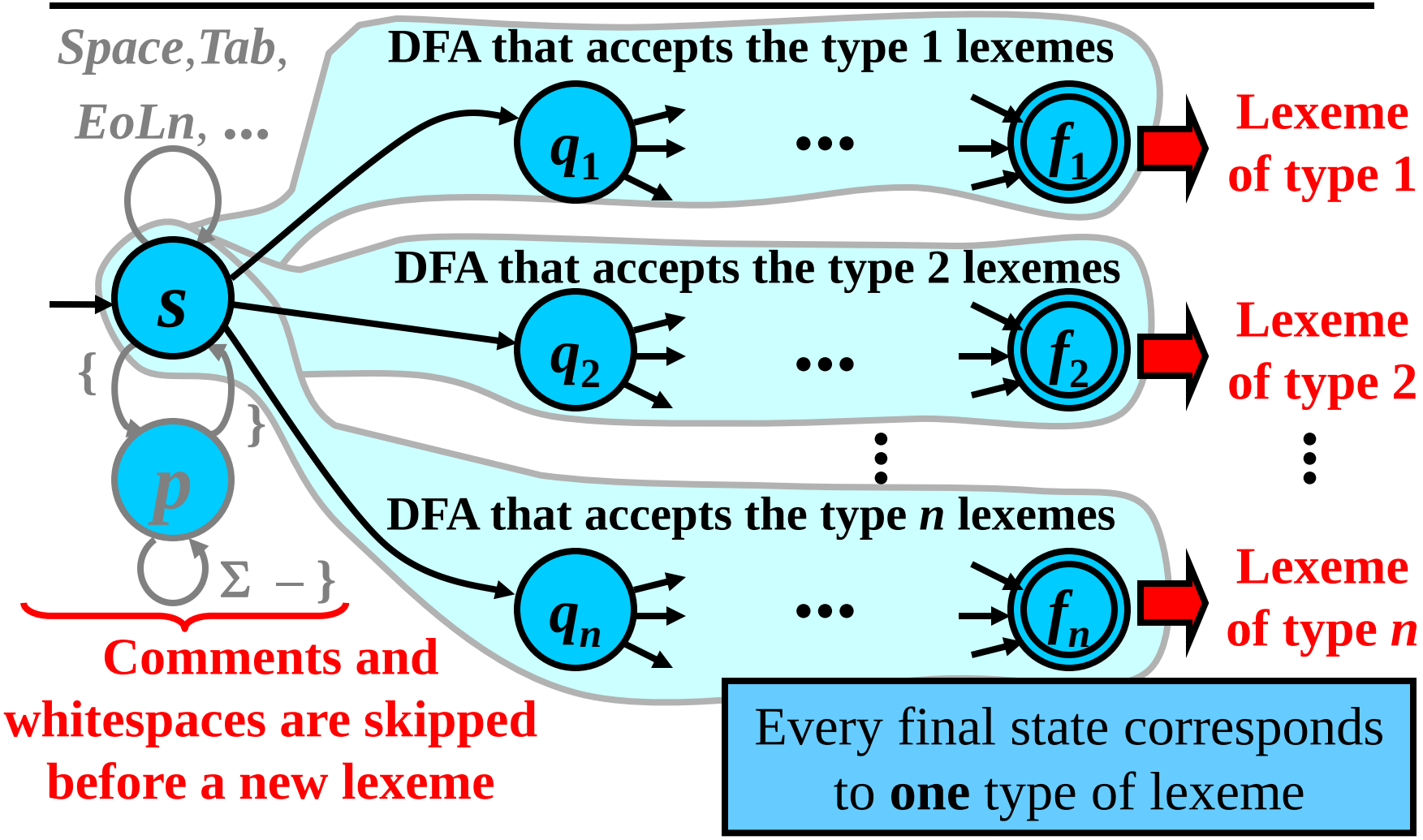
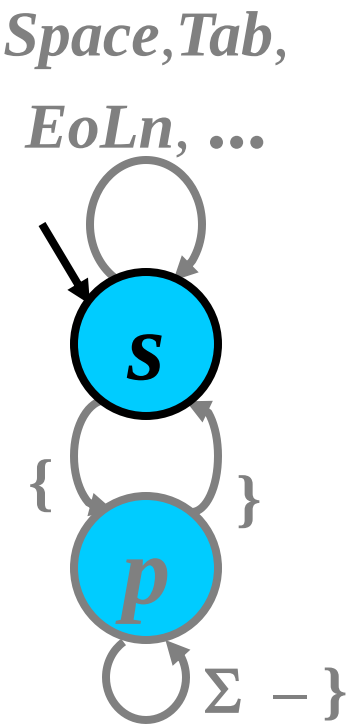


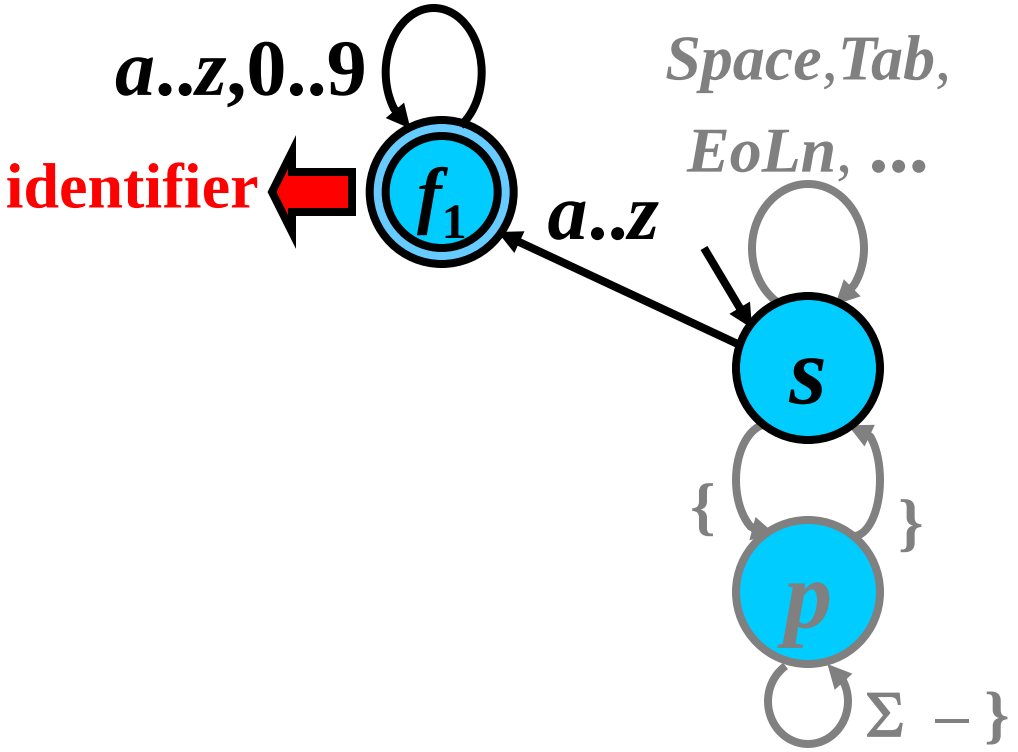
DFA for Lexemes : Example 1/2

- FA that accepts these lexemes:



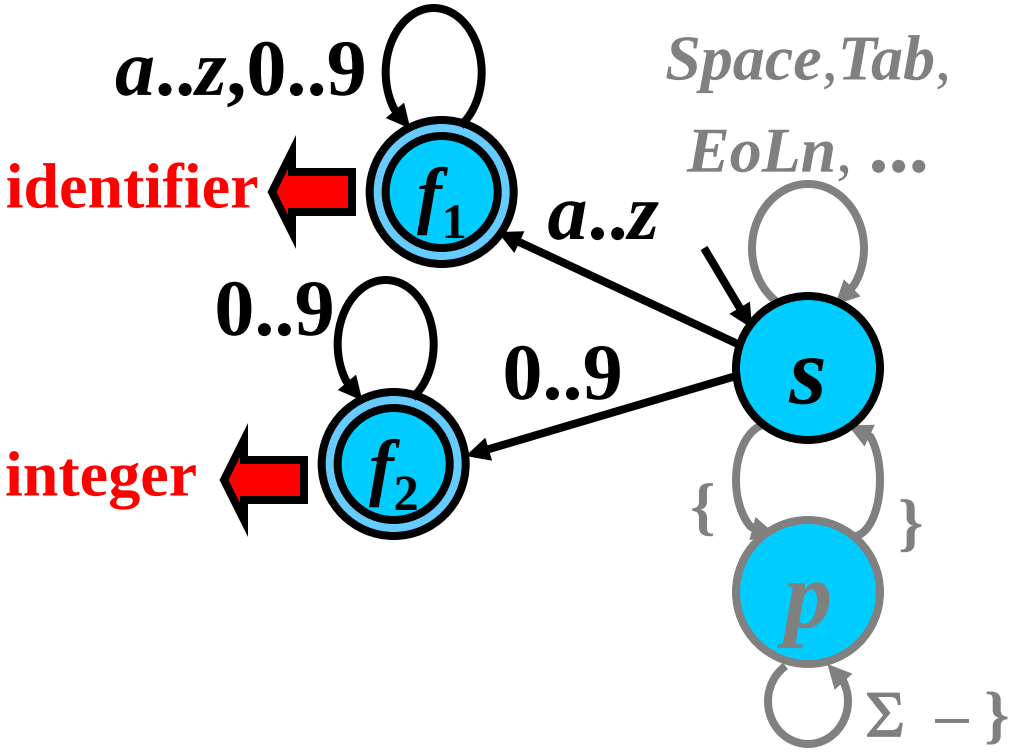
DFA for Lexemes : Example 1/2

- FA that accepts these lexemes:
  identifier,



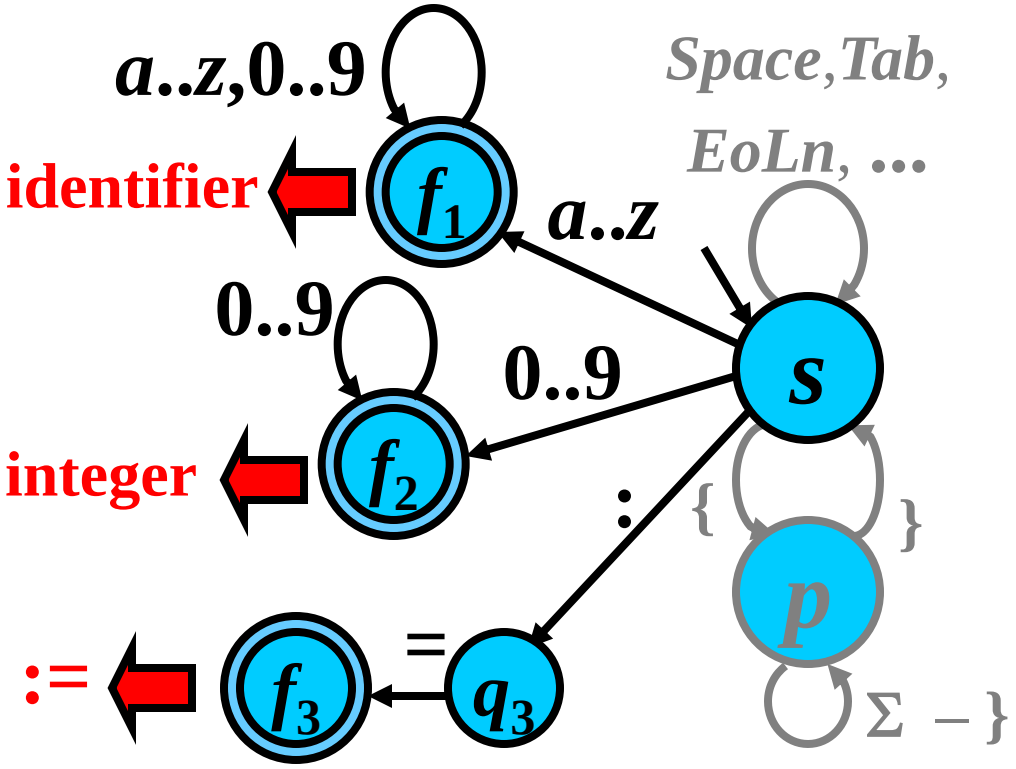
DFA for Lexemes : Example 1/2

- FA that accepts these lexemes:
  identifier, integer,



DFA for Lexemes : Example 1/2

- FA that accepts these lexemes:
  identifier, integer, :=,



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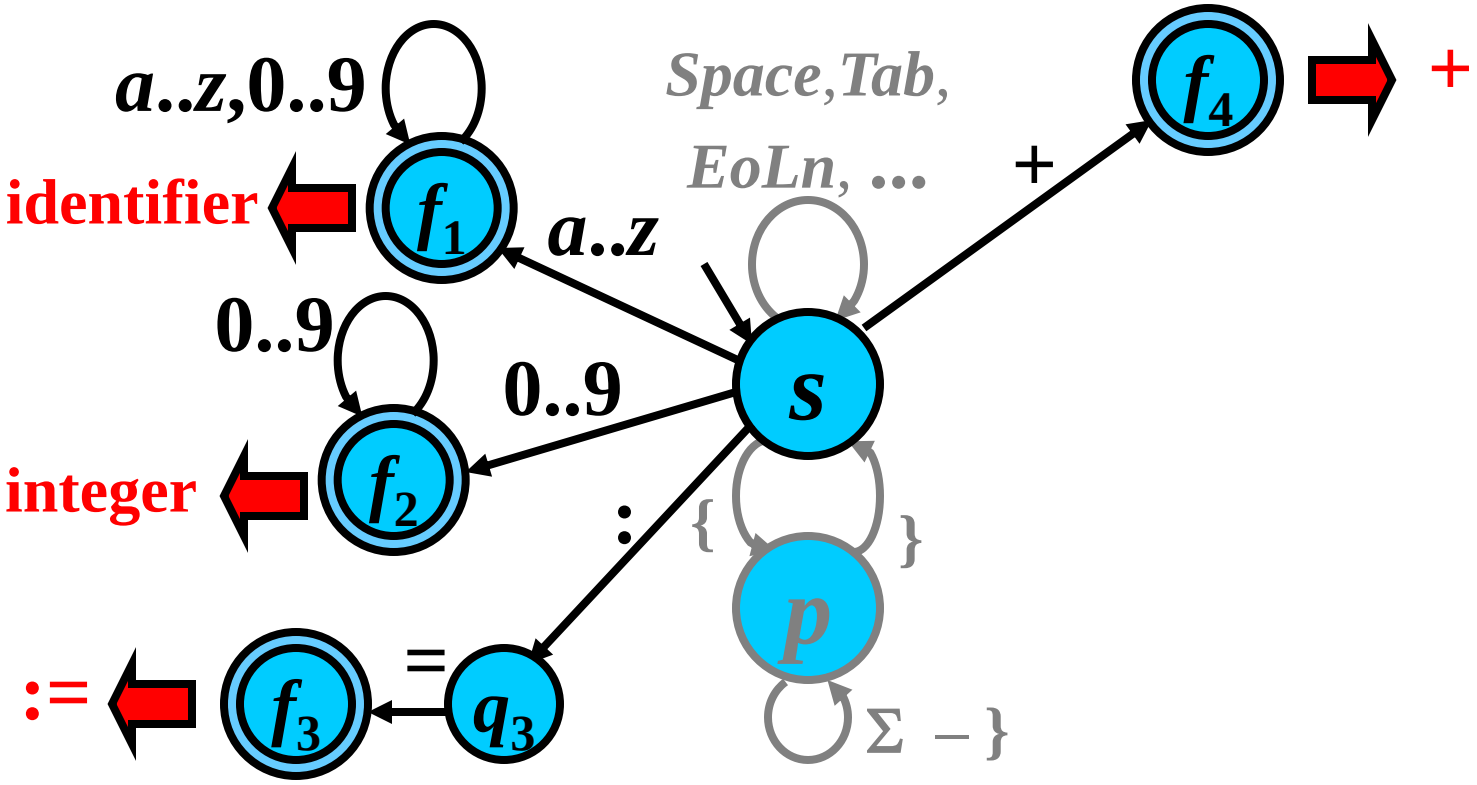

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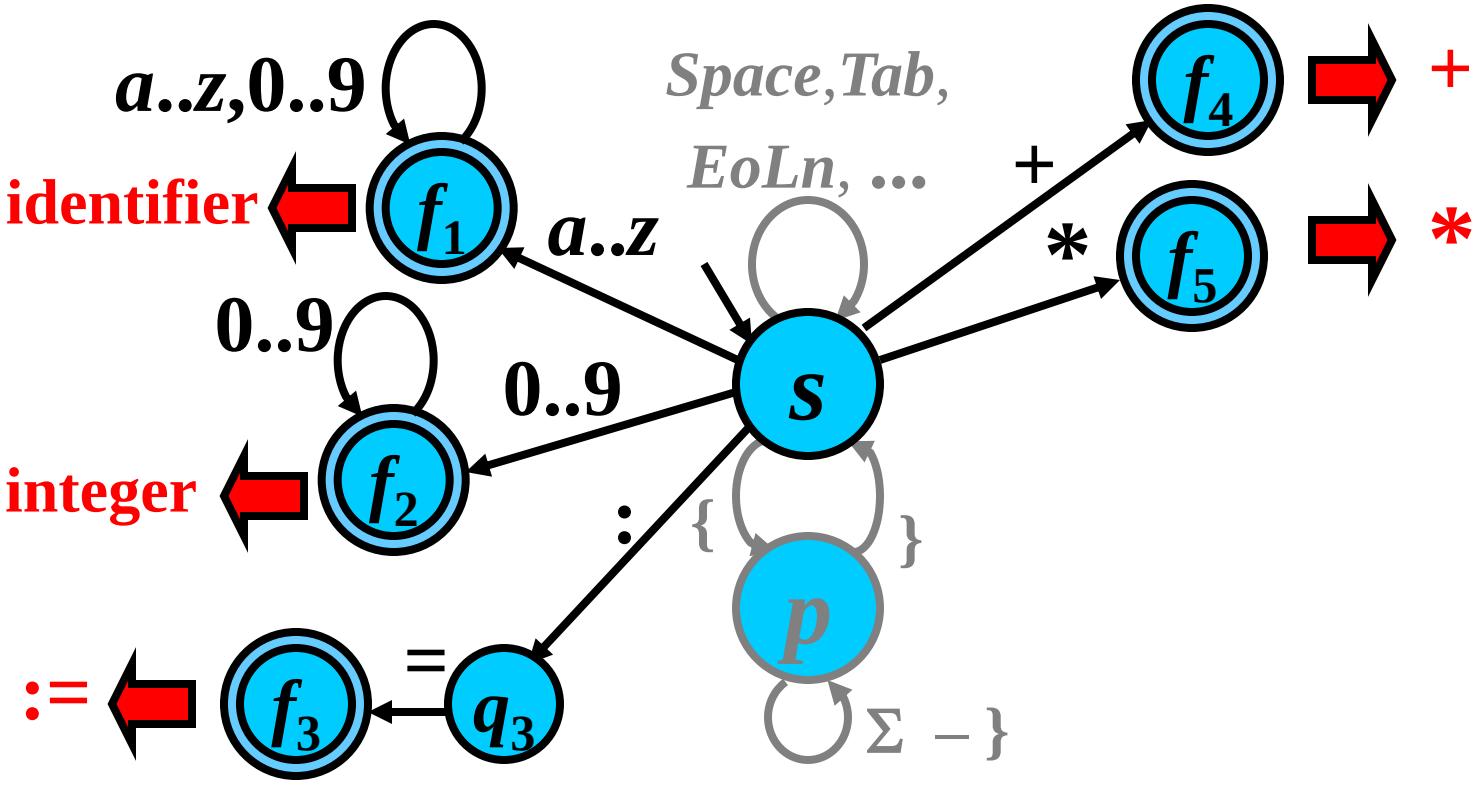

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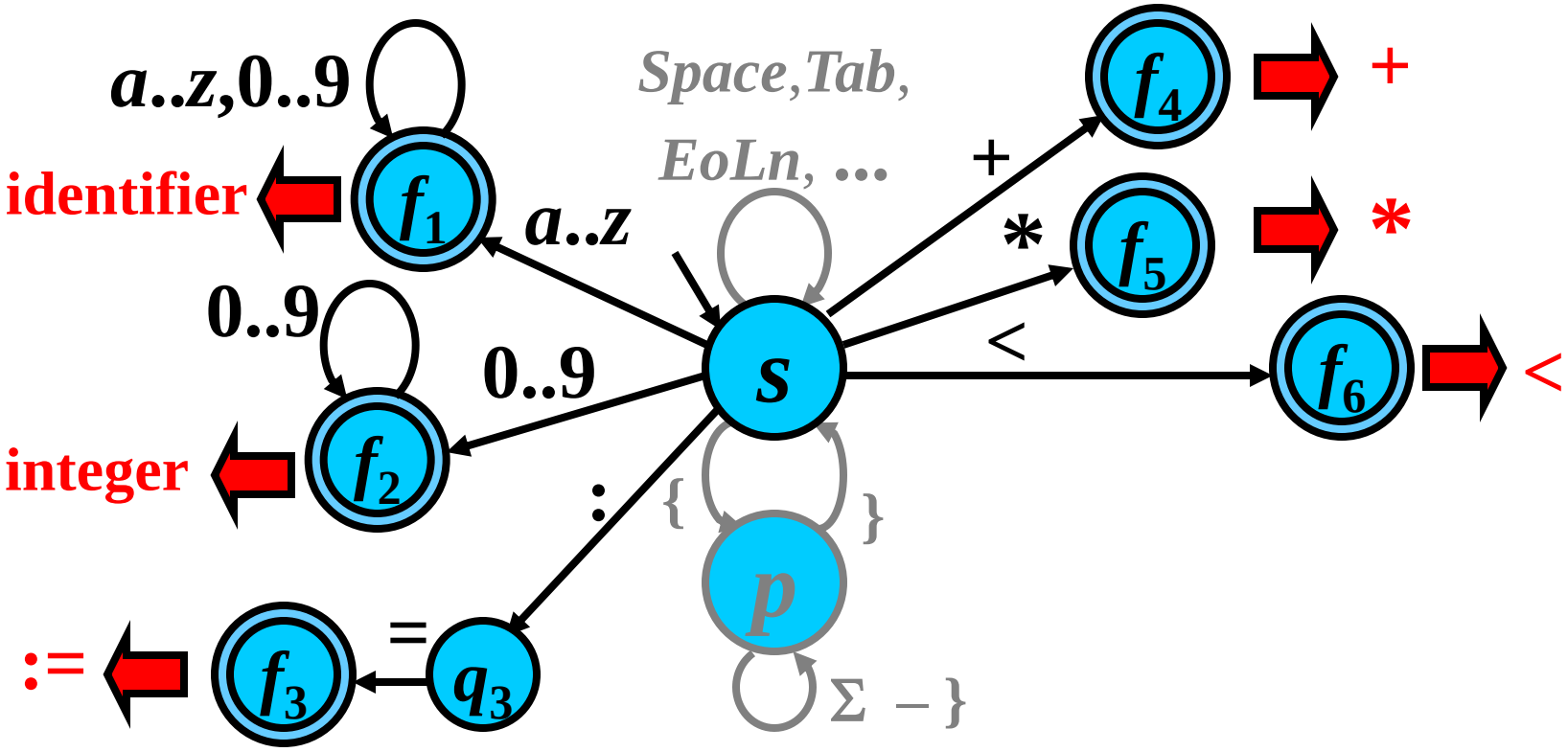
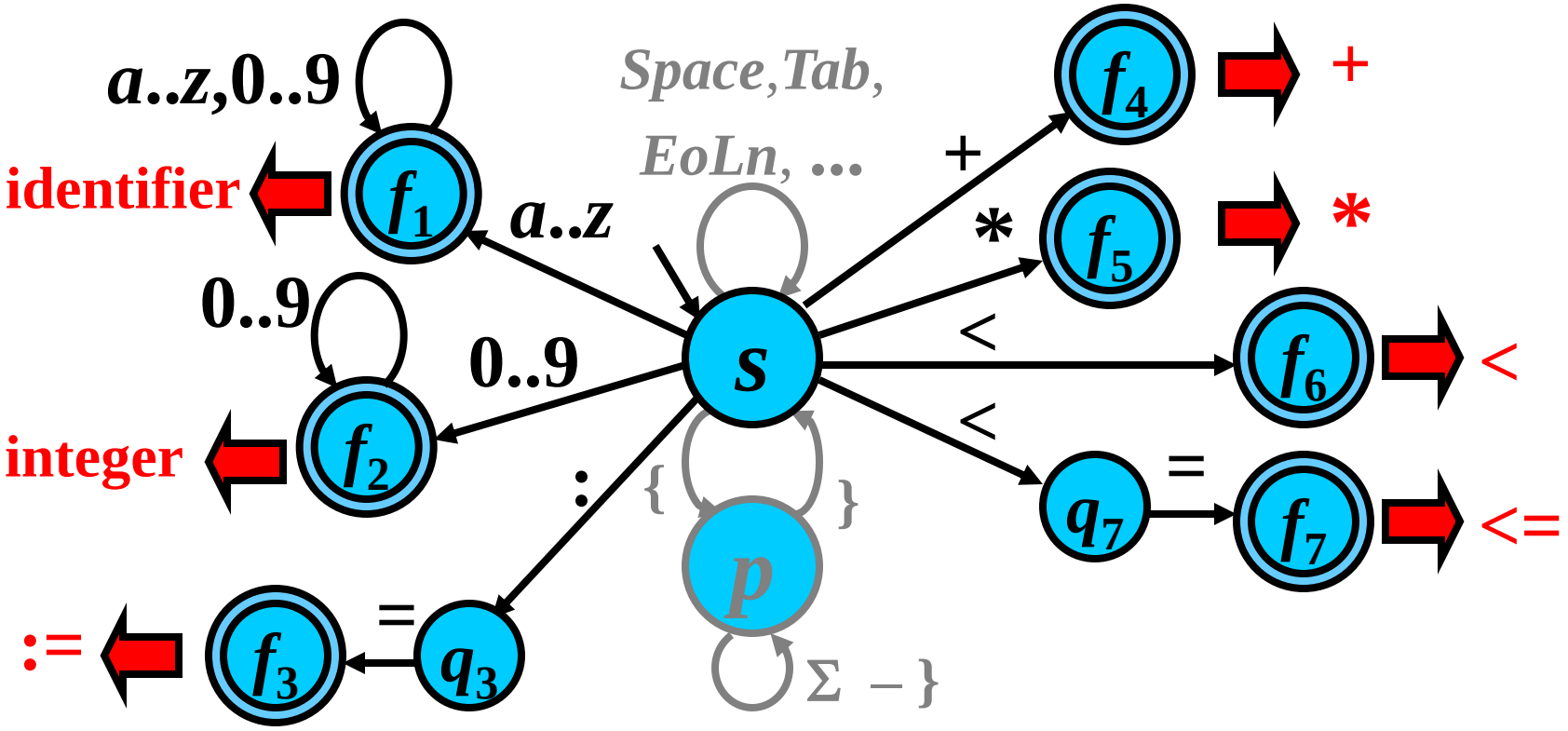


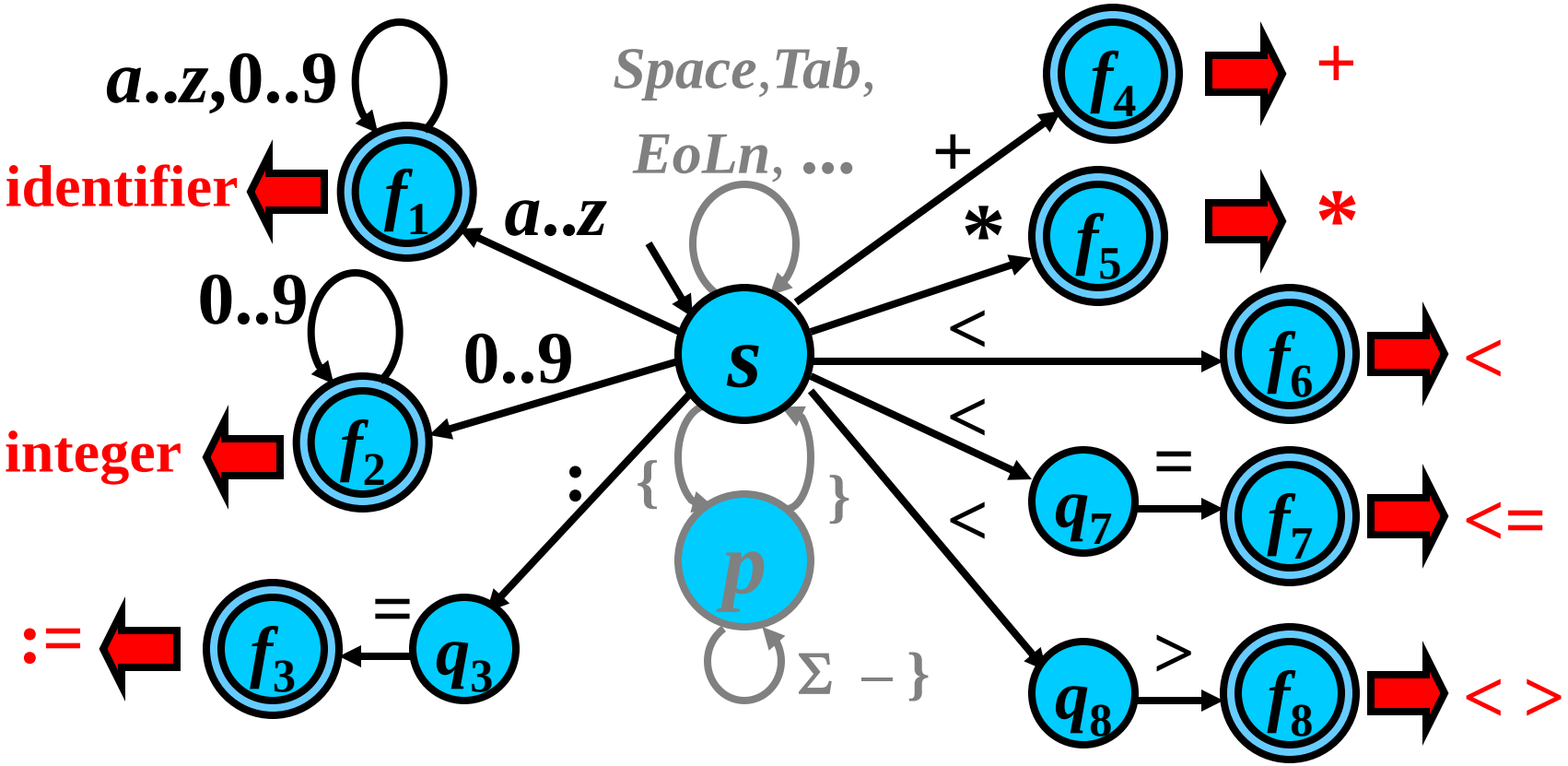
DFA for Lexemes : Example 1/2

- FA that accepts these lexemes:
  identifier, integer, :=, +, *, <, <=,



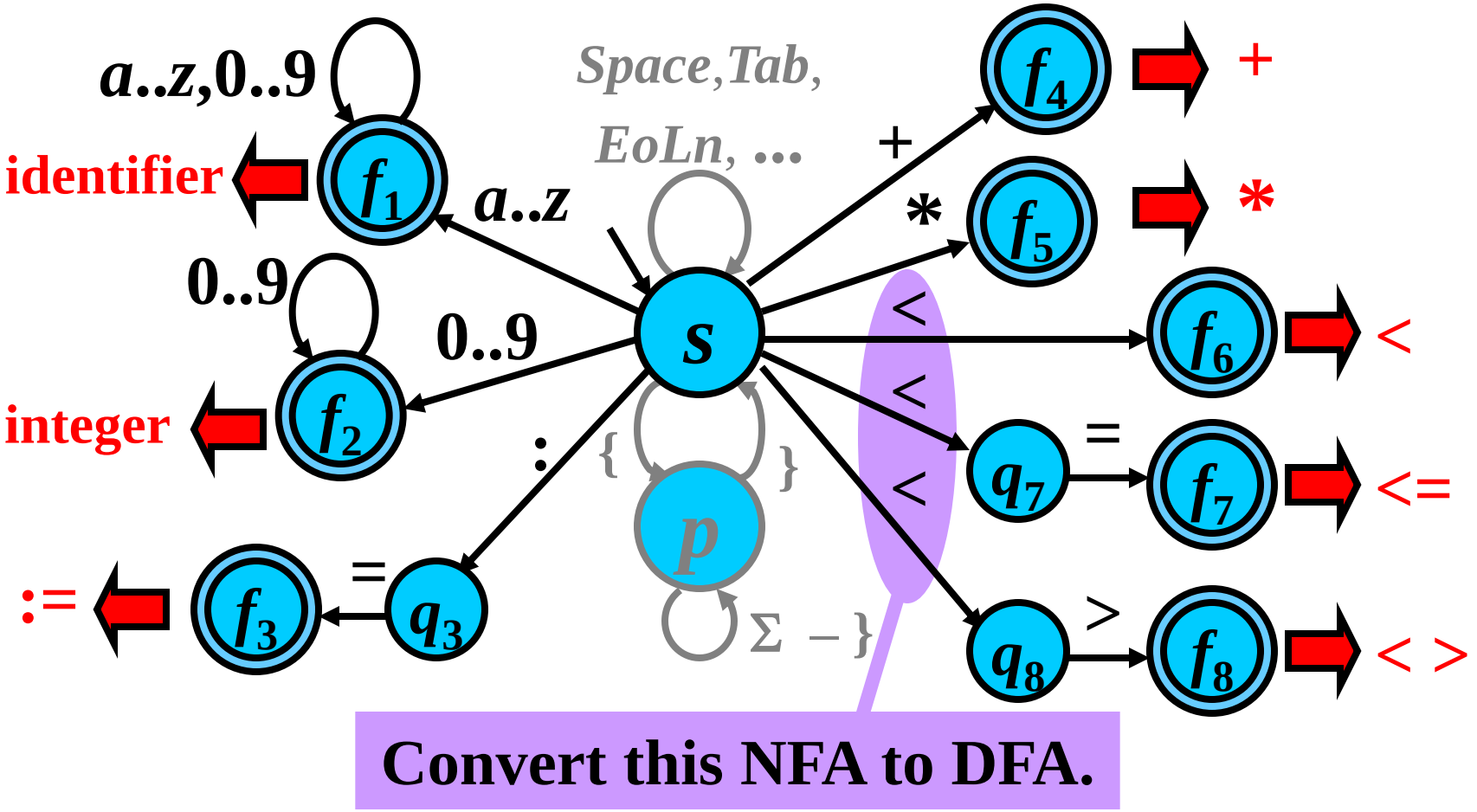
DFA for Lexemes : Example 1/2

- FA that accepts these lexemes:
  identifier, integer, :=, +, *, <, <=, < >



DFA for Lexemes : Example 1/2

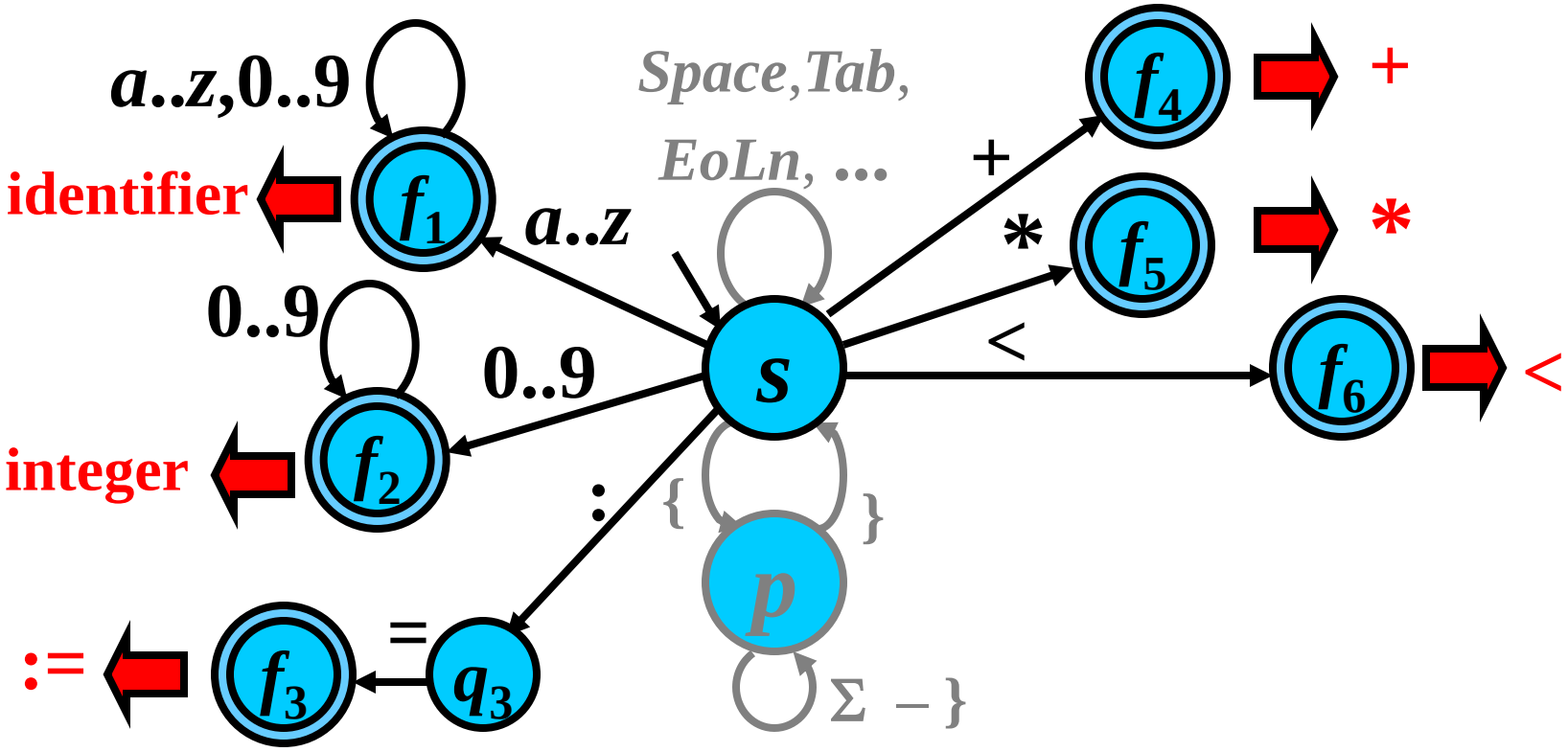
- FA that accepts these lexemes:
  identifier, integer, :=, +, *, <, <=, < >



DFAs for Lexemes: Example 2/2

- Equivalent DFA:

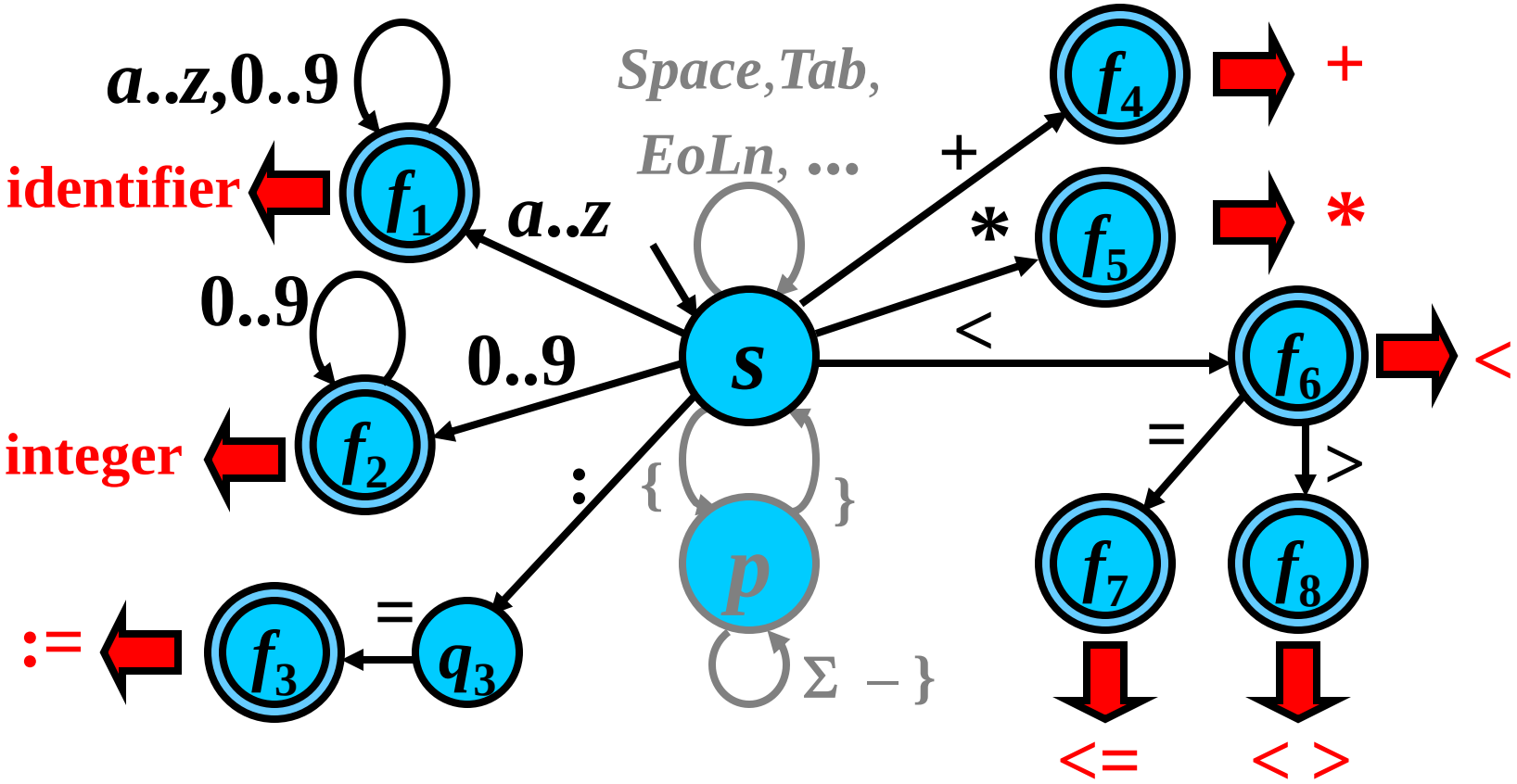
identifier, integer, :=, +, *, <, <=, < >



DFAs for Lexemes: Example 2/2

- Equivalent DFA:

identifier, integer, :=, +, *, <, <=, < >

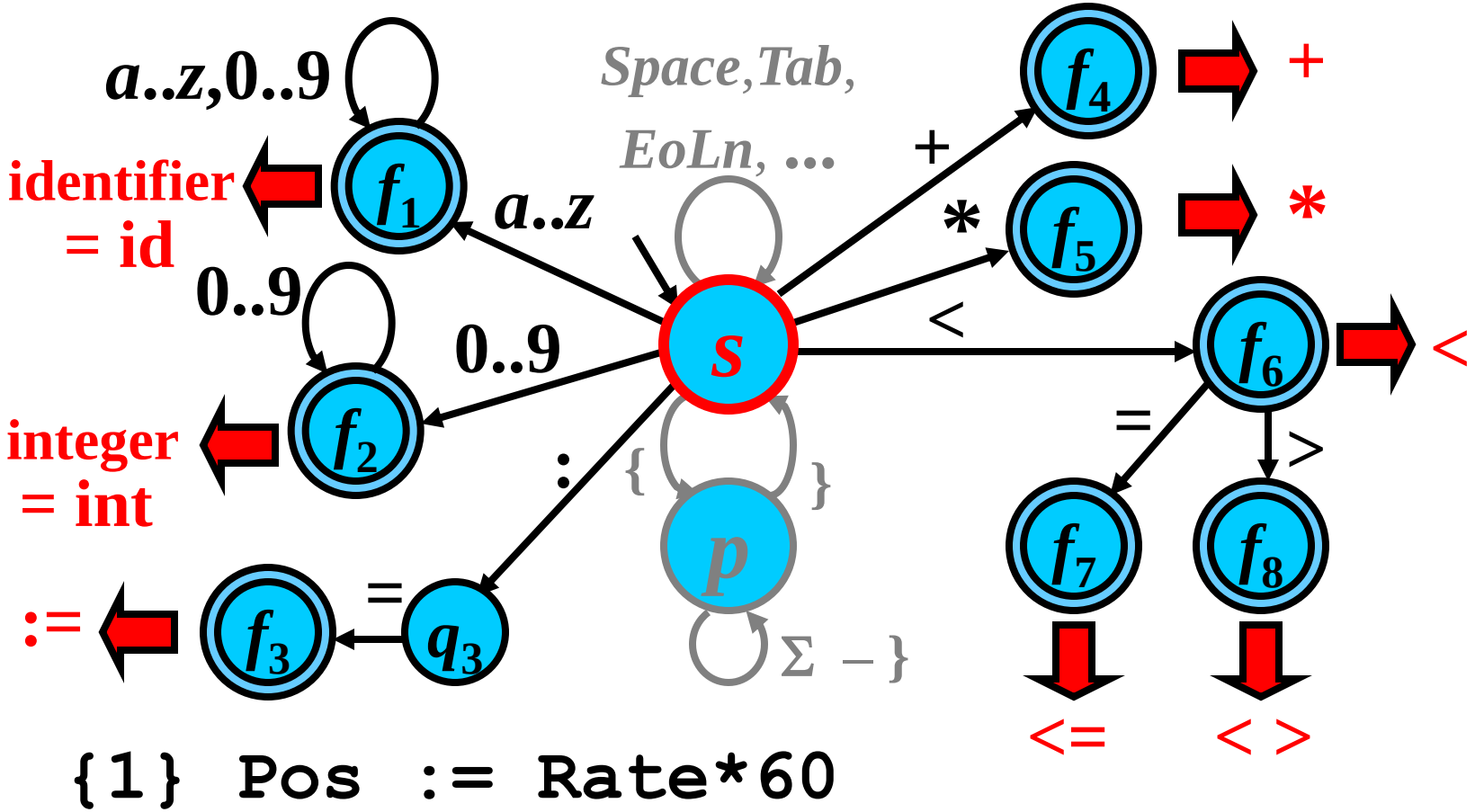


Algorithm: Type of Lexeme

- **Input:** DFA *M* for the source-program lexemes
- **Output:** determination of the lexeme type

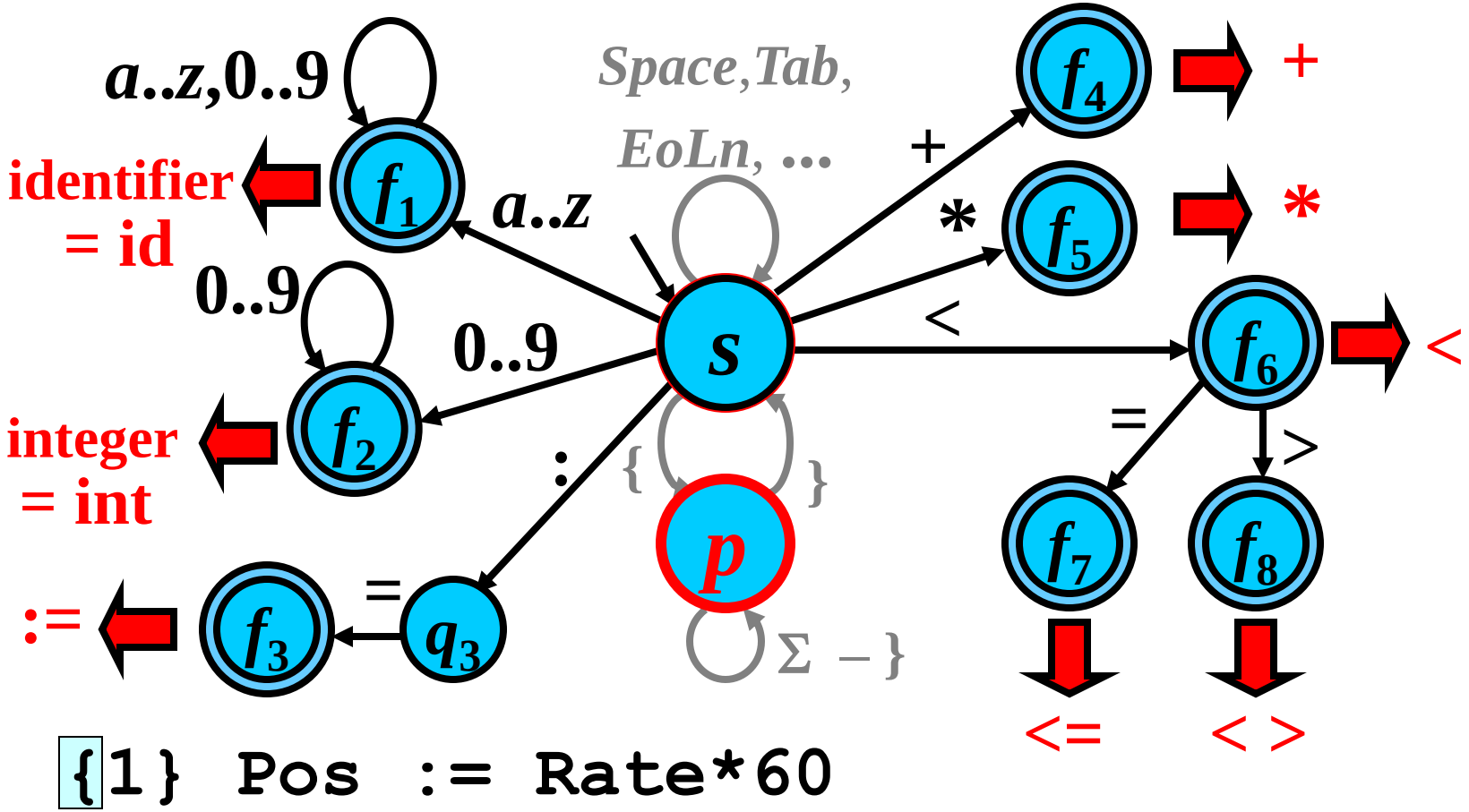
- **Method:**
- **while** ***a*** is the next symbol (character) in SP
  and *M* can make a move with ***a*** **do:**
    - read ***a***
    - make the move with ***a***
- **if** *M* is in a final state **then**
    determine the corresponding lexeme type
  else handle the lexical error (write message etc)

Type of Lexemes: Example

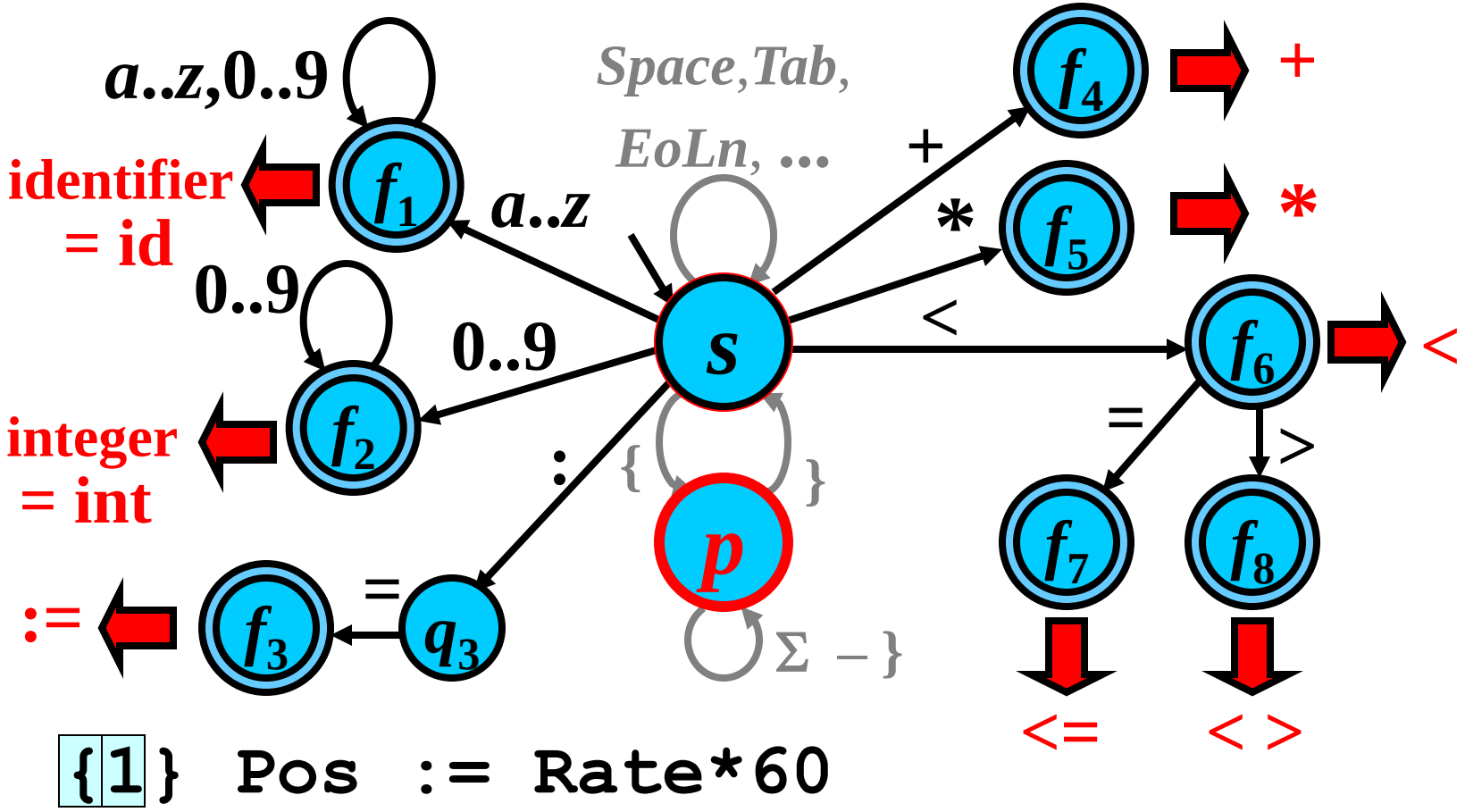



```
{1} Pos := Rate*60
```

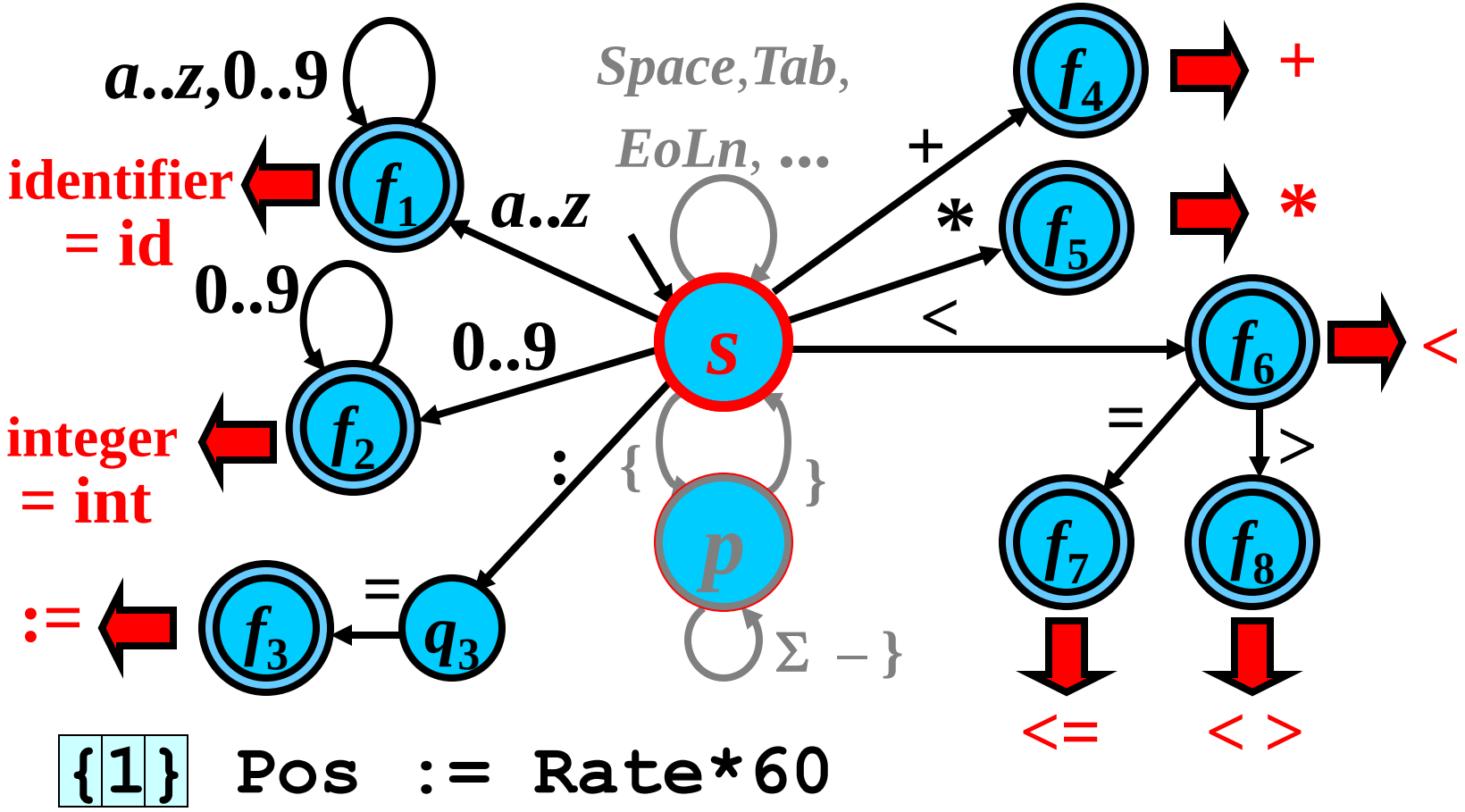
Type of Lexemes: Example



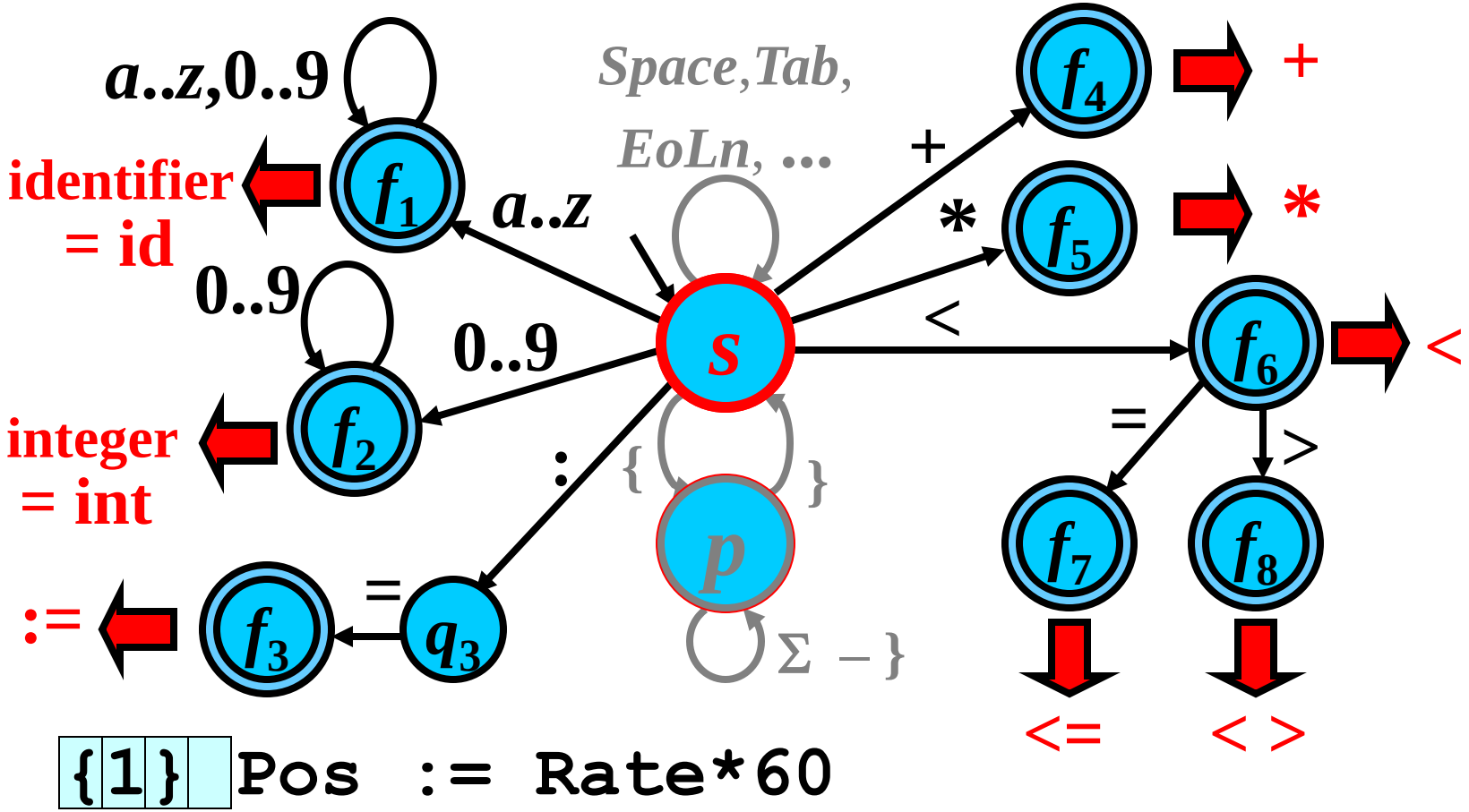
Type of Lexemes: Example



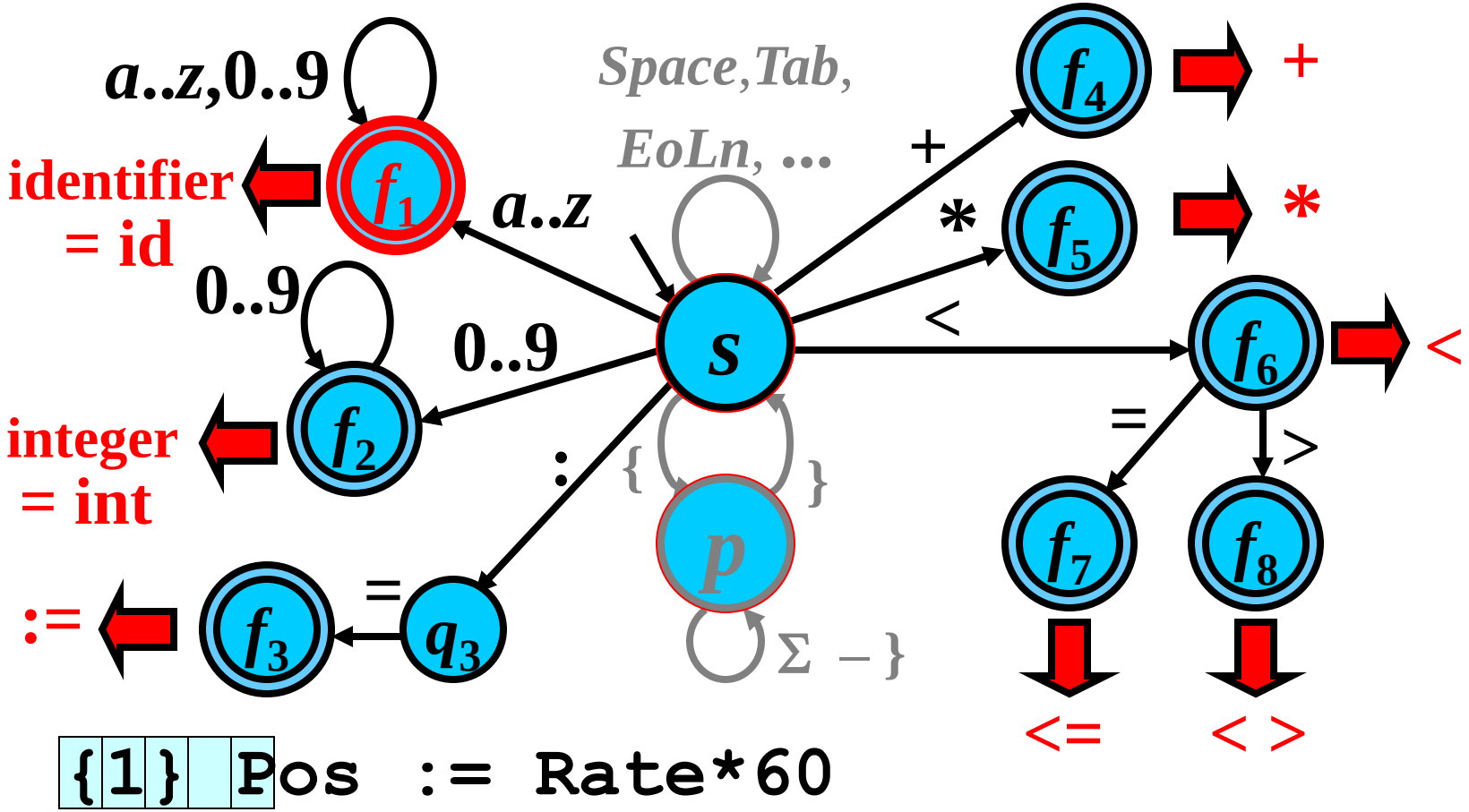
Type of Lexemes: Example



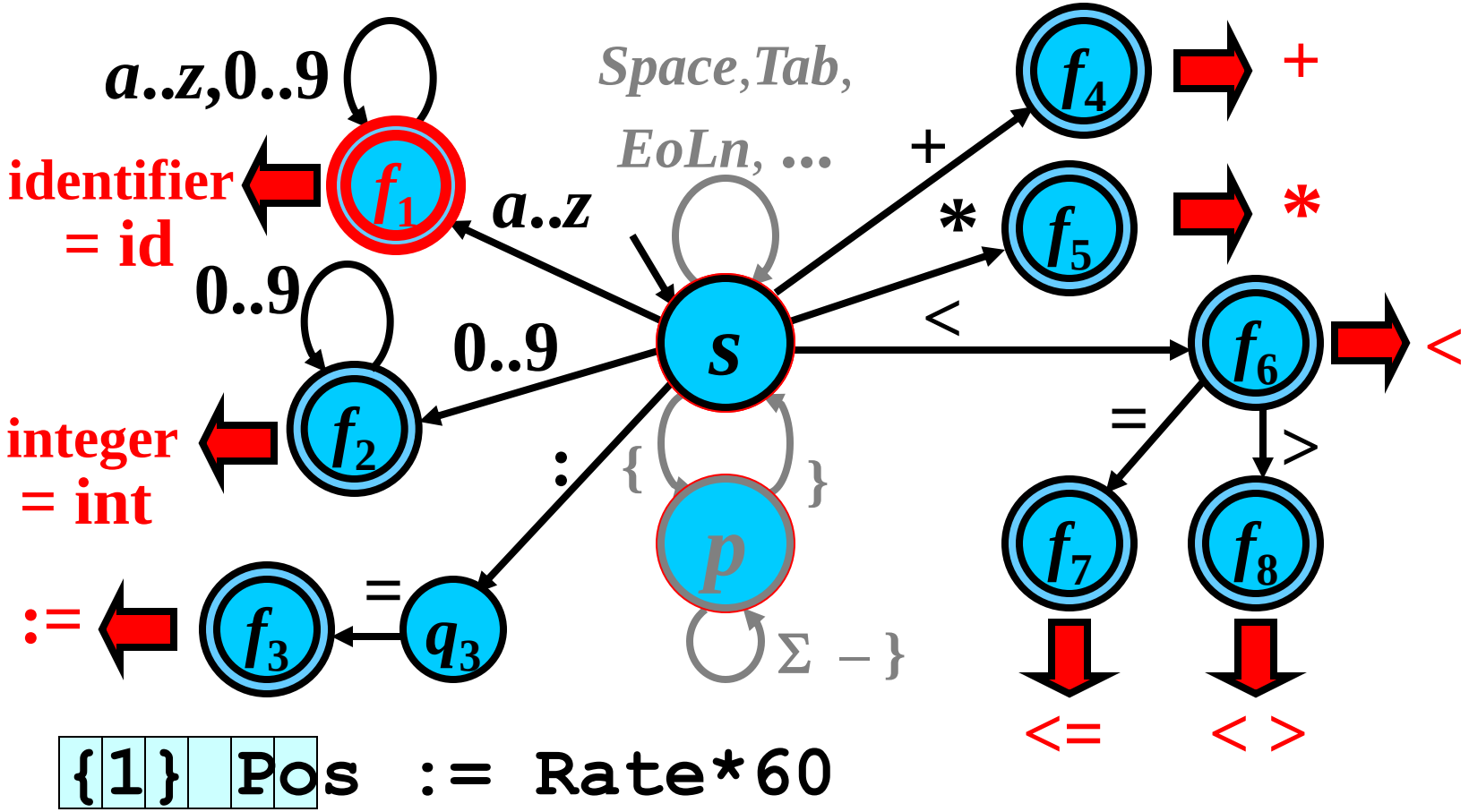
Type of Lexemes: Example



Type of Lexemes: Example



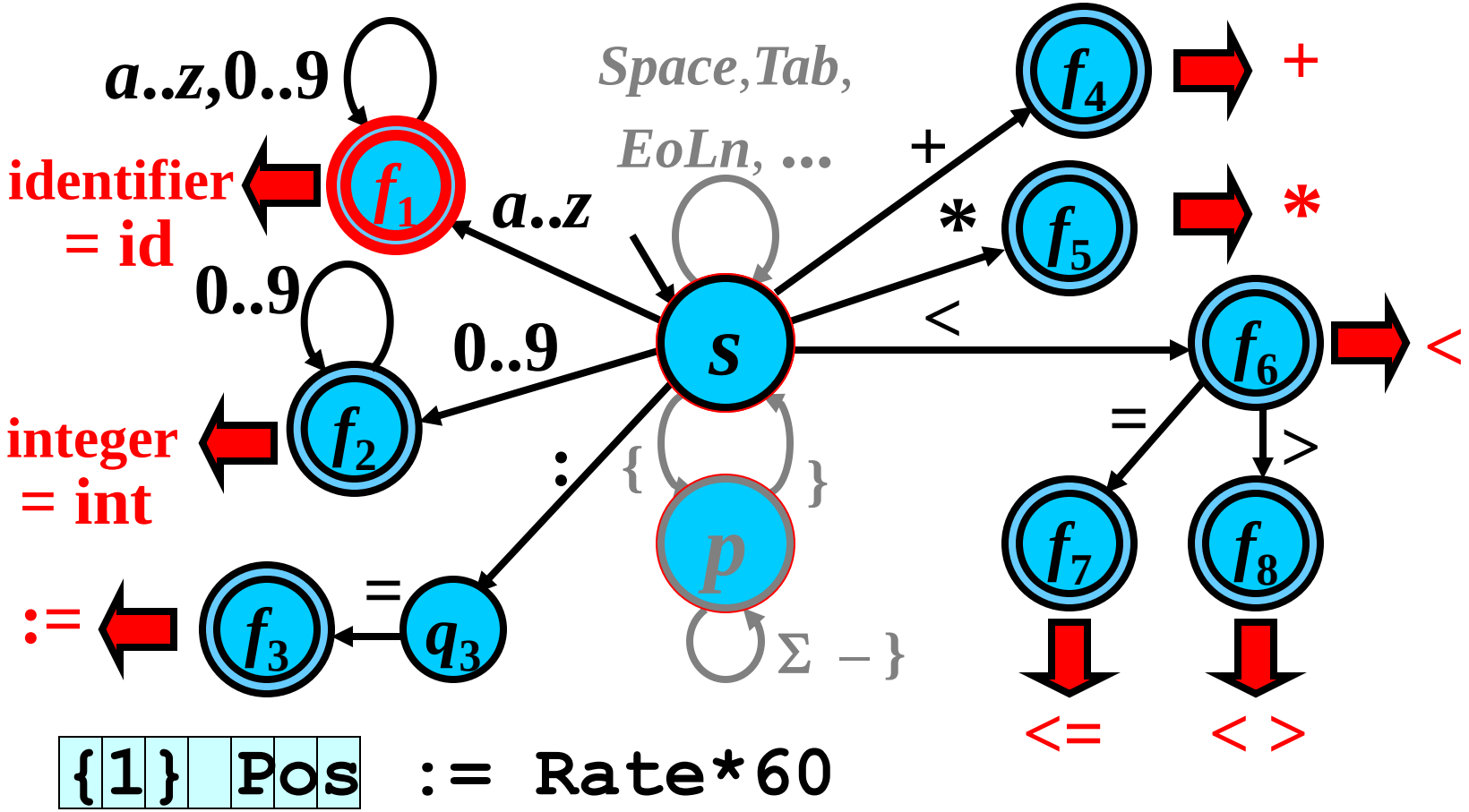
Type of Lexemes: Example




```
{1}  Pos := Rate*60
```

```
Po
```

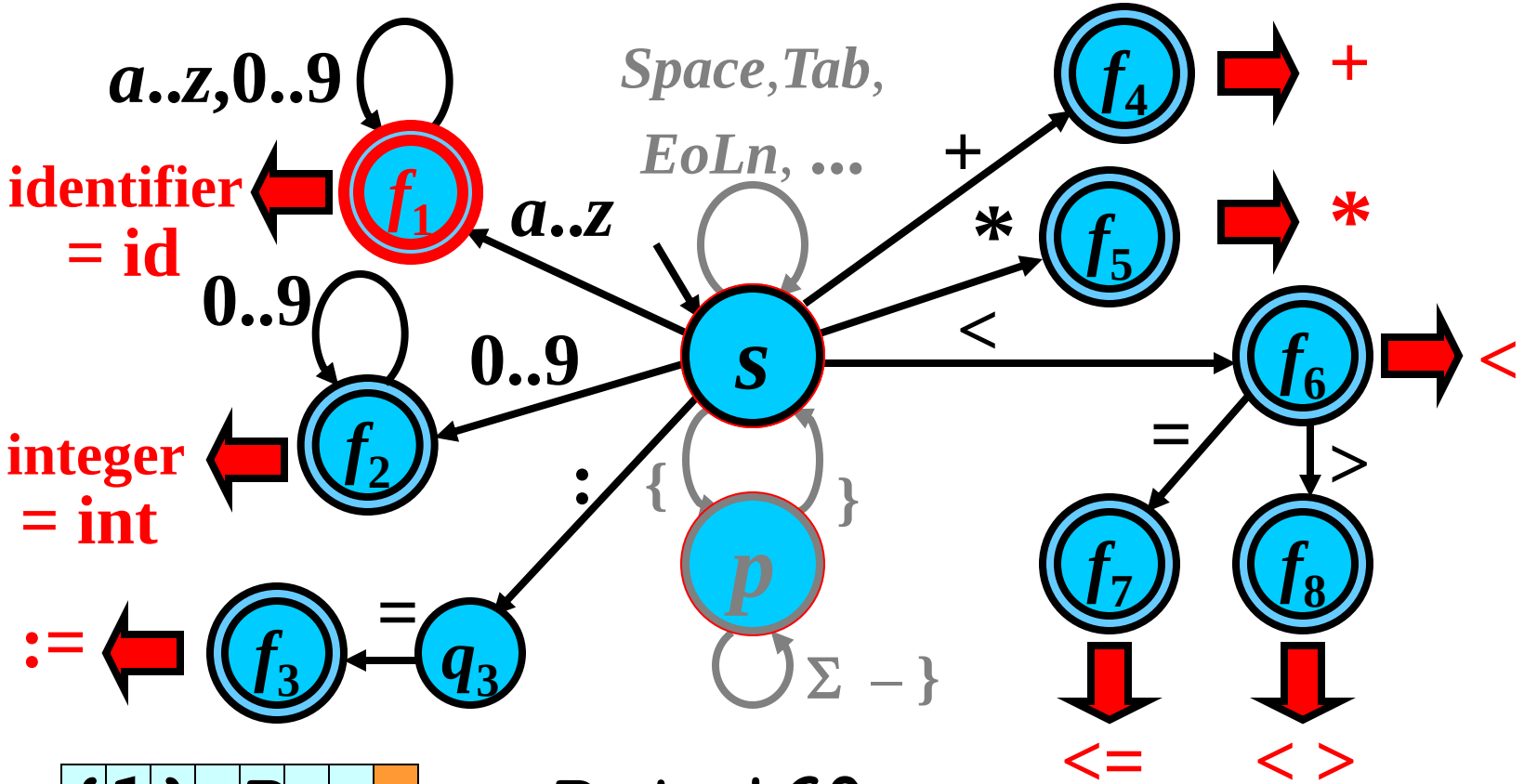
Type of Lexemes: Example




```
{1} Pos := Rate*60
```

```
Pos
```

Type of Lexemes: Example

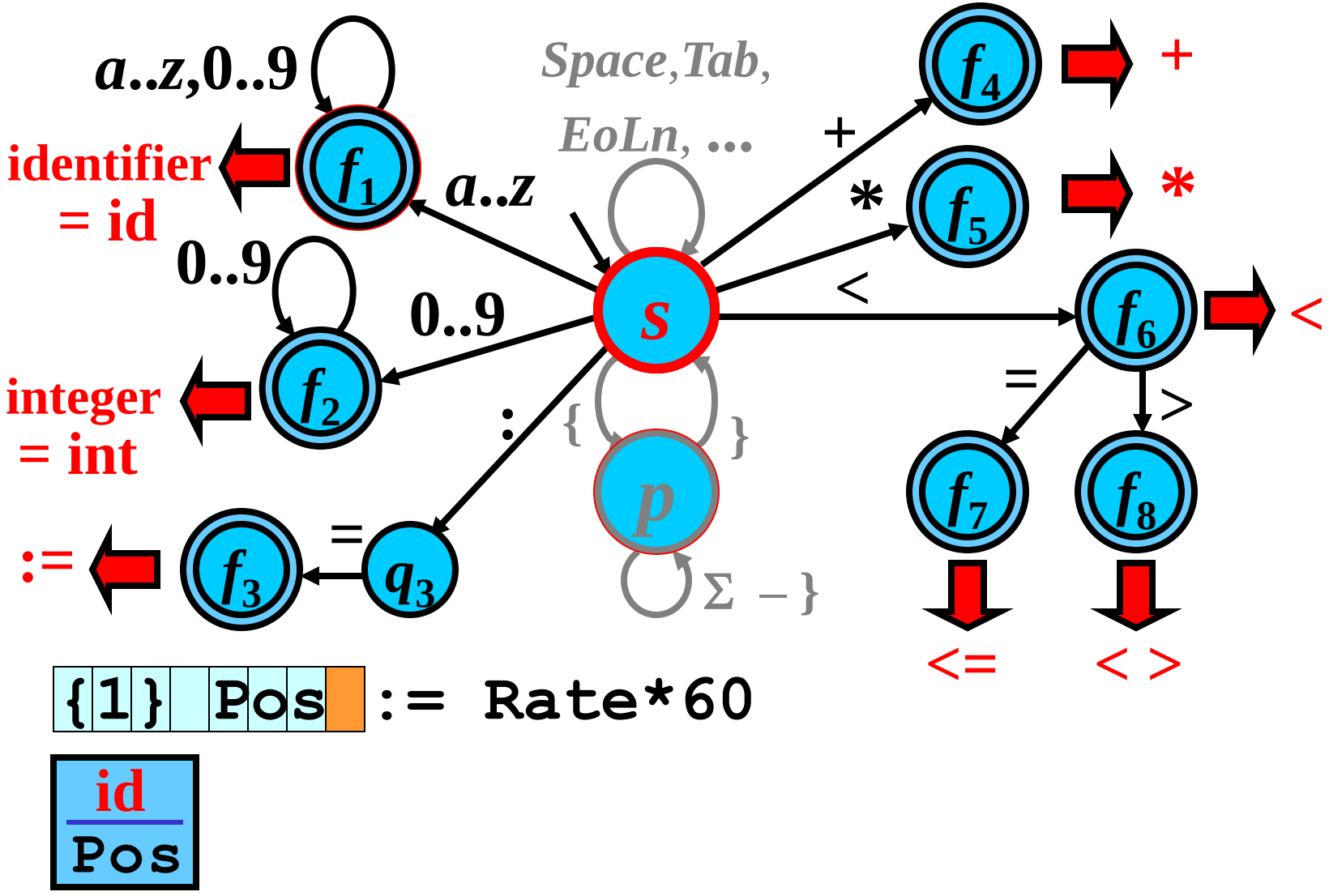


{1} Pos := Rate*60

id
Pos

No next configuration!

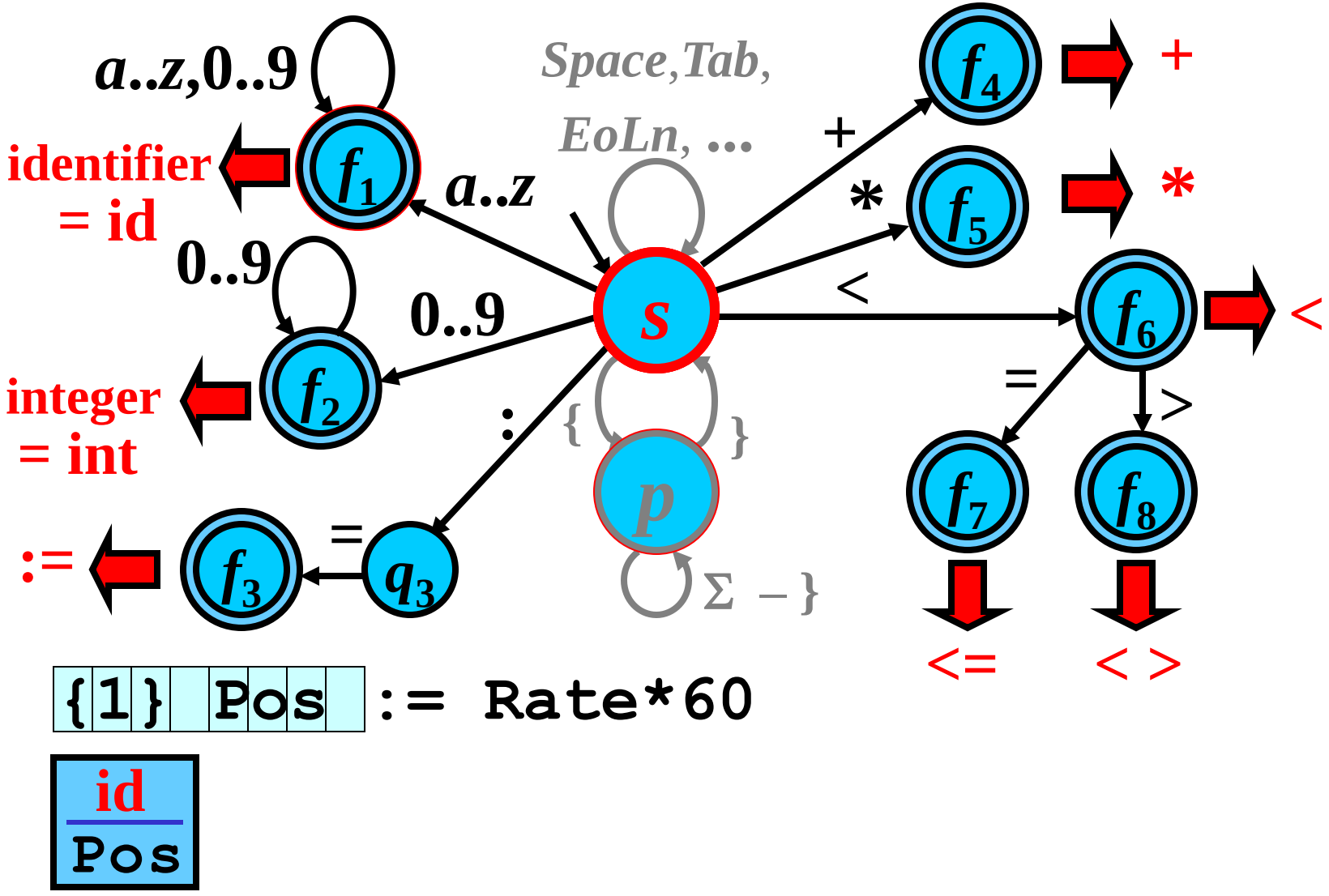
Type of Lexemes: Example



{1} Pos := Rate*60

id
Pos

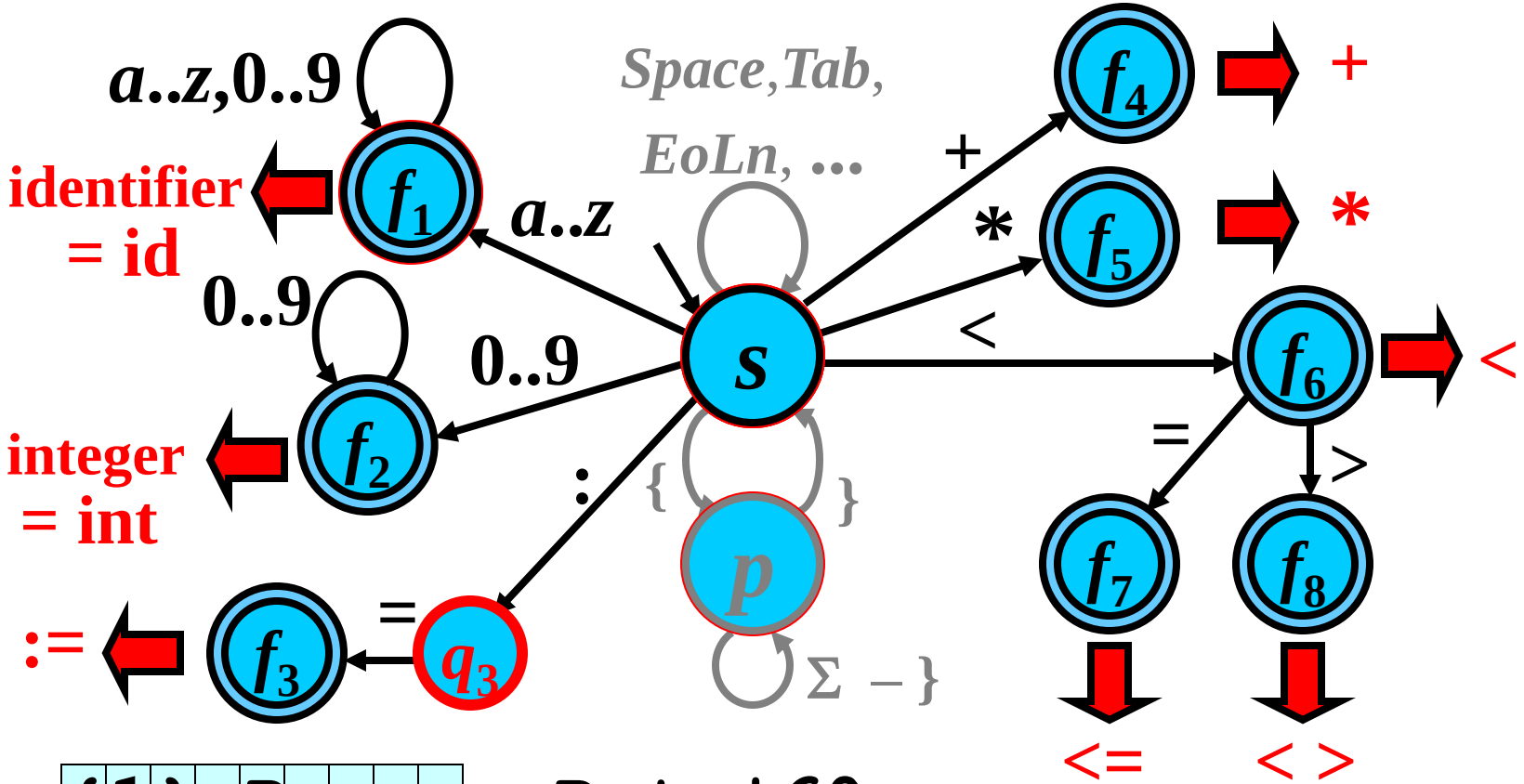
Type of Lexemes: Example



{1} Pos := Rate*60

id
Pos

Type of Lexemes: Example

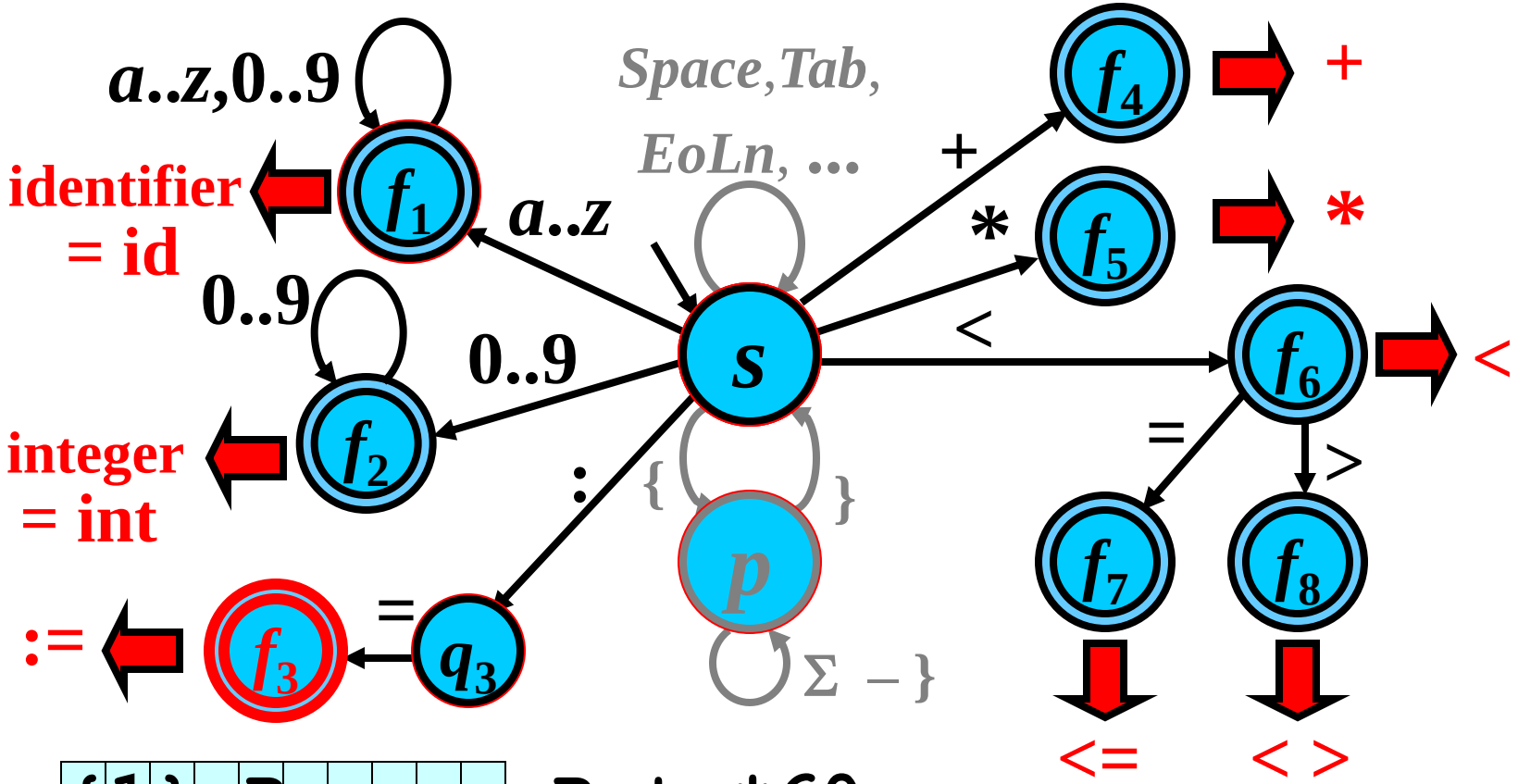



```
{1} Pos := Rate*60
```

id
Pos

:

Type of Lexemes: Example

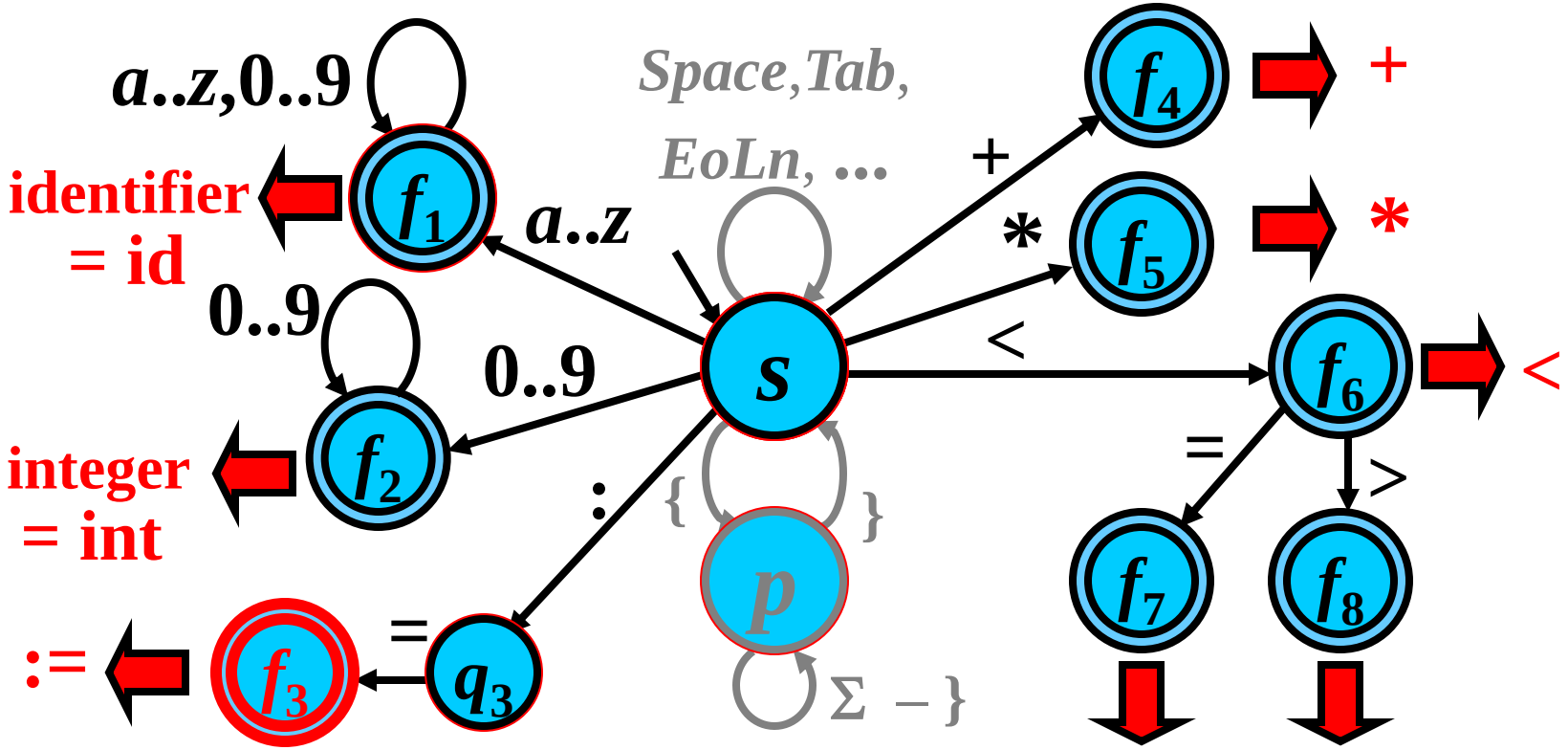



```
{1}  Pos  := Rate*60
```

id
Pos

:=

Type of Lexemes: Example

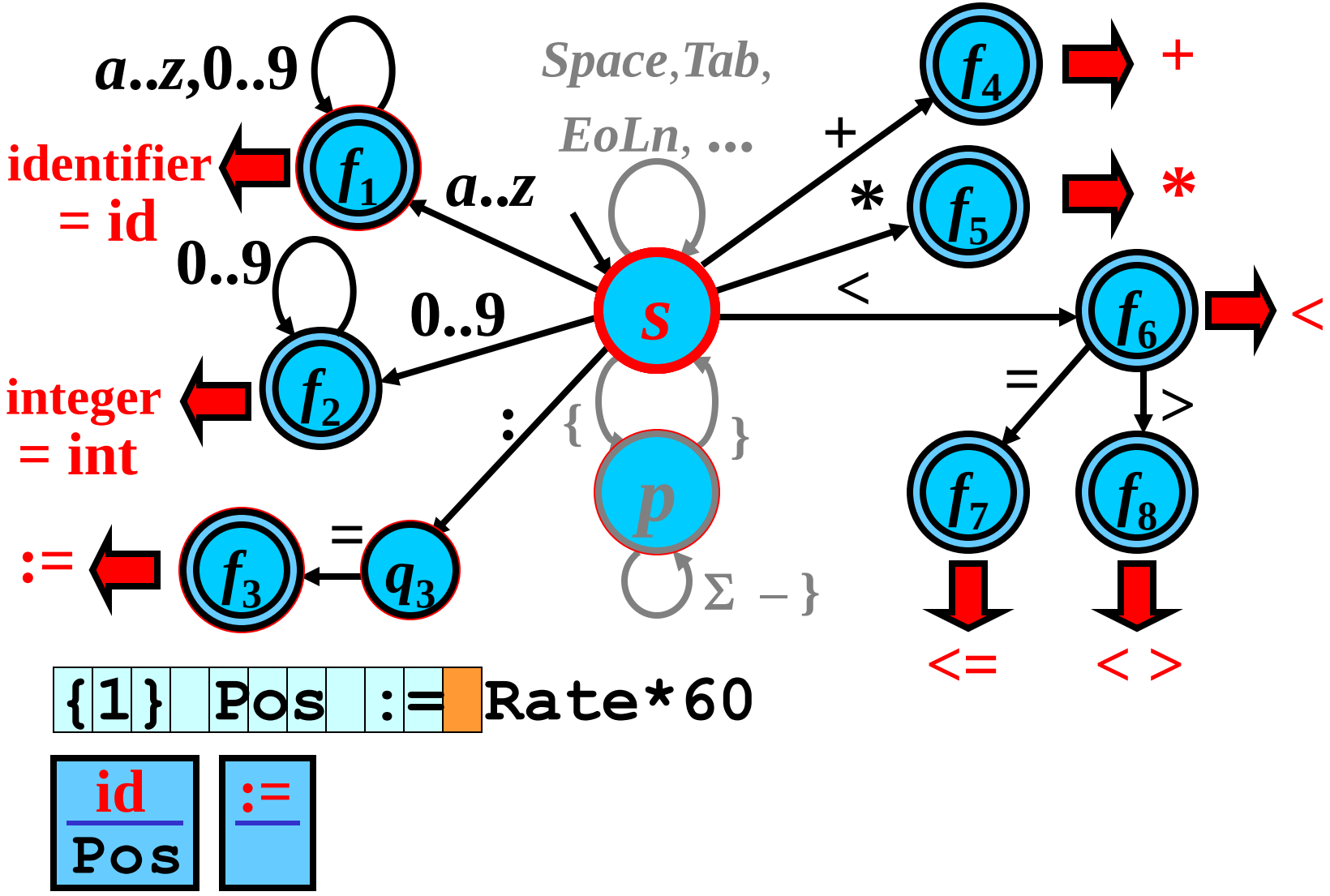


{1} Pos := Rate*60

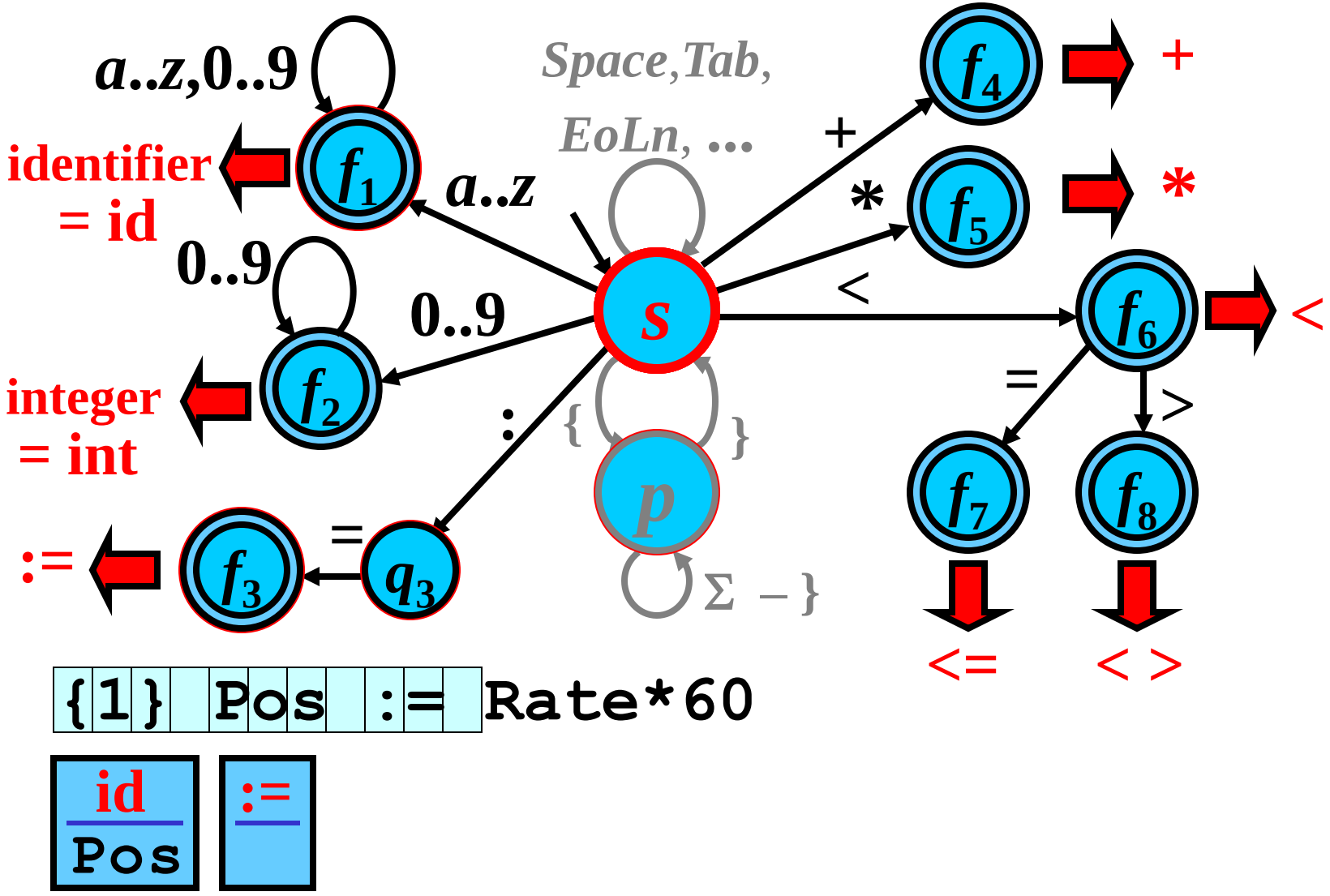
id	:=
Pos	

No next configuration!

Type of Lexemes: Example



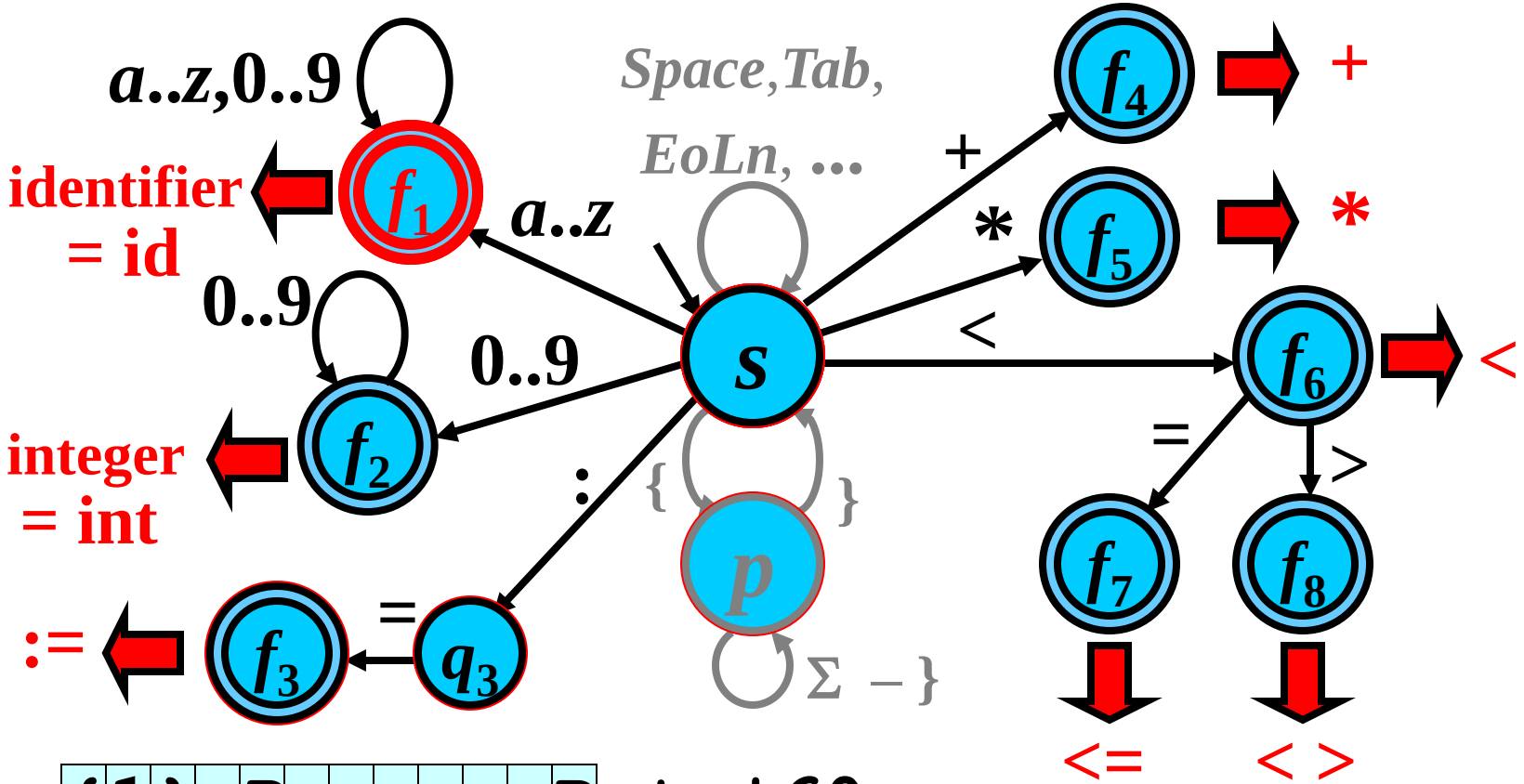
Type of Lexemes: Example



{1} Pos := Rate*60

id	:=
Pos	

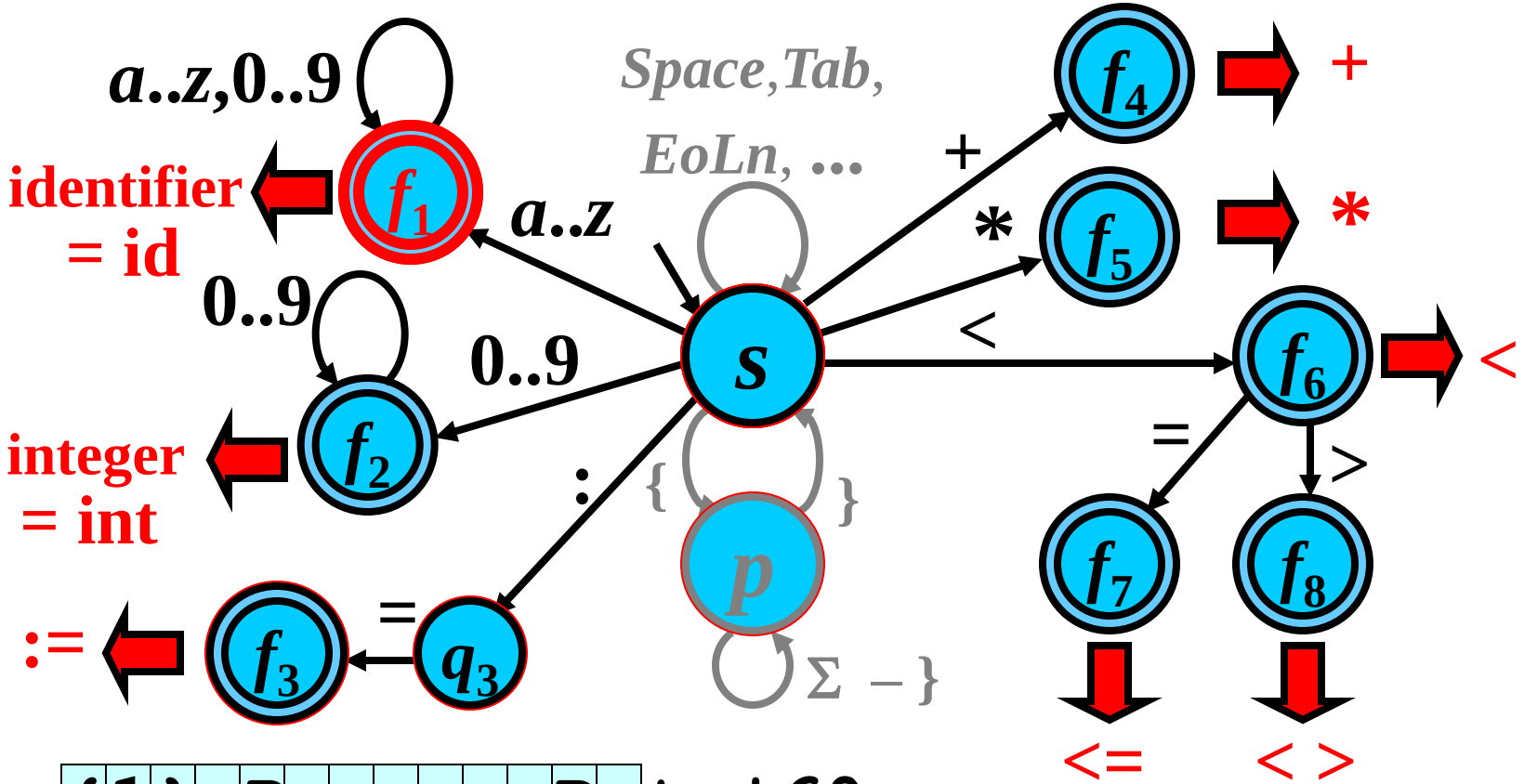
Type of Lexemes: Example



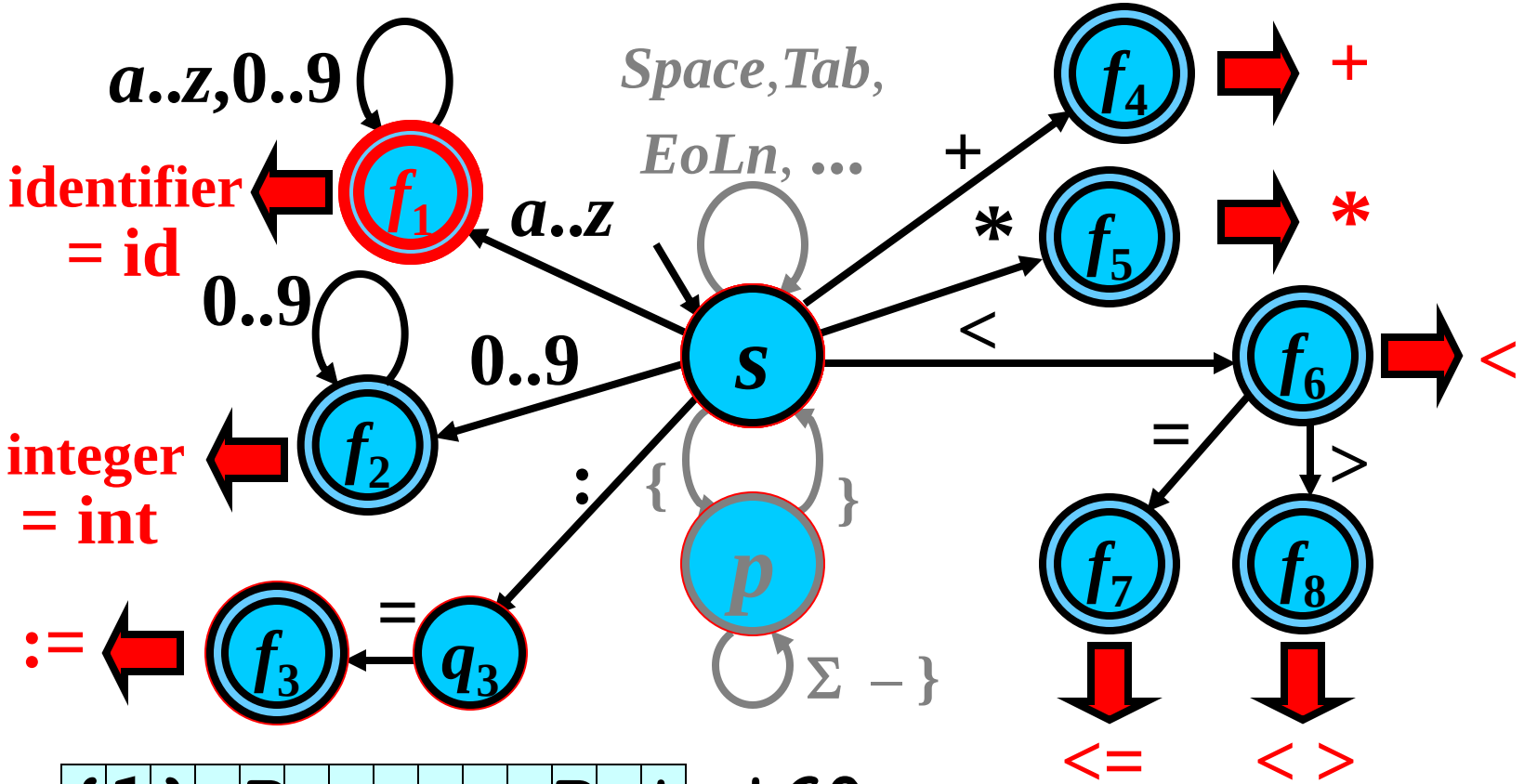
{1} Pos := Rate*60

id	:=	R
Pos		

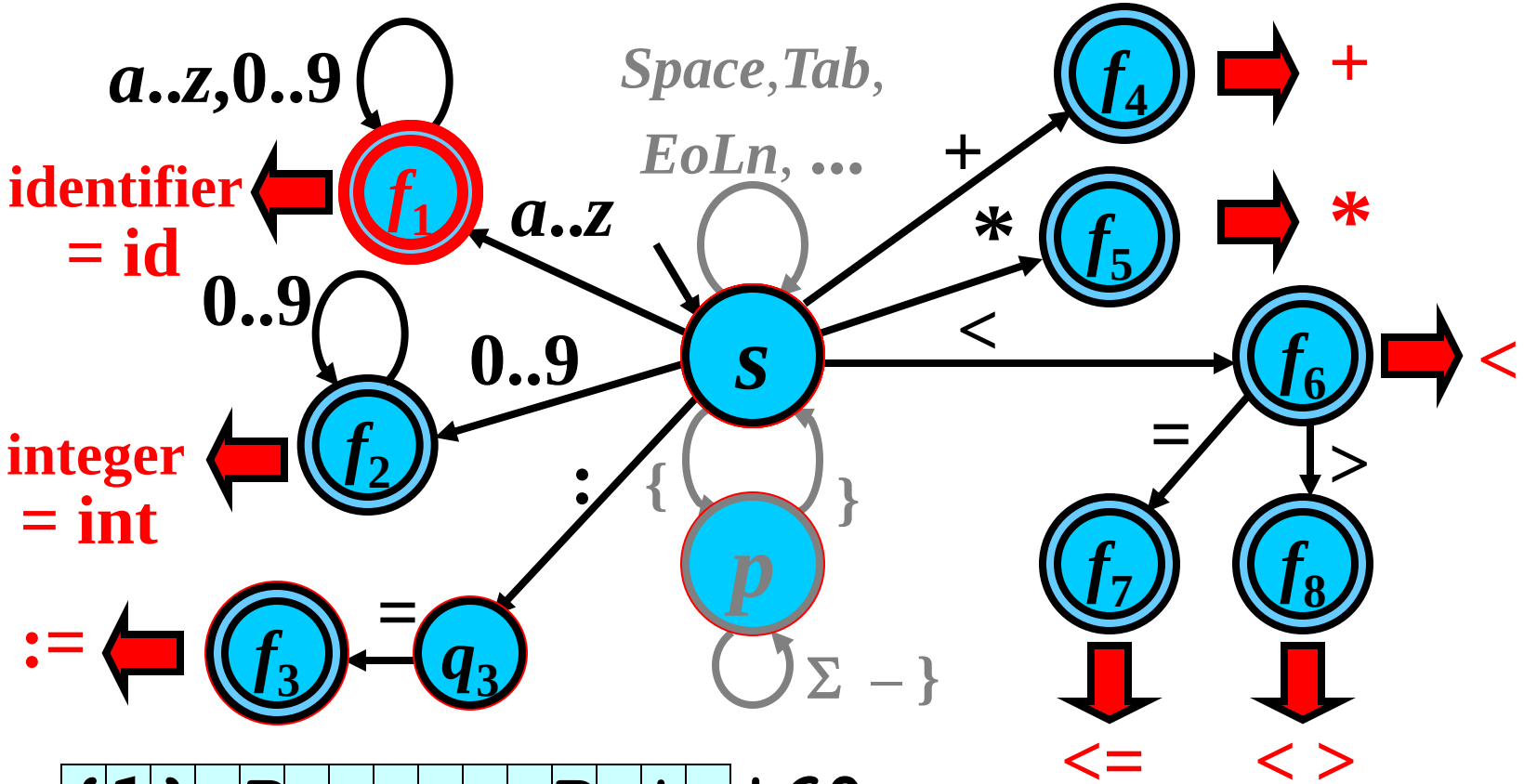
Type of Lexemes: Example



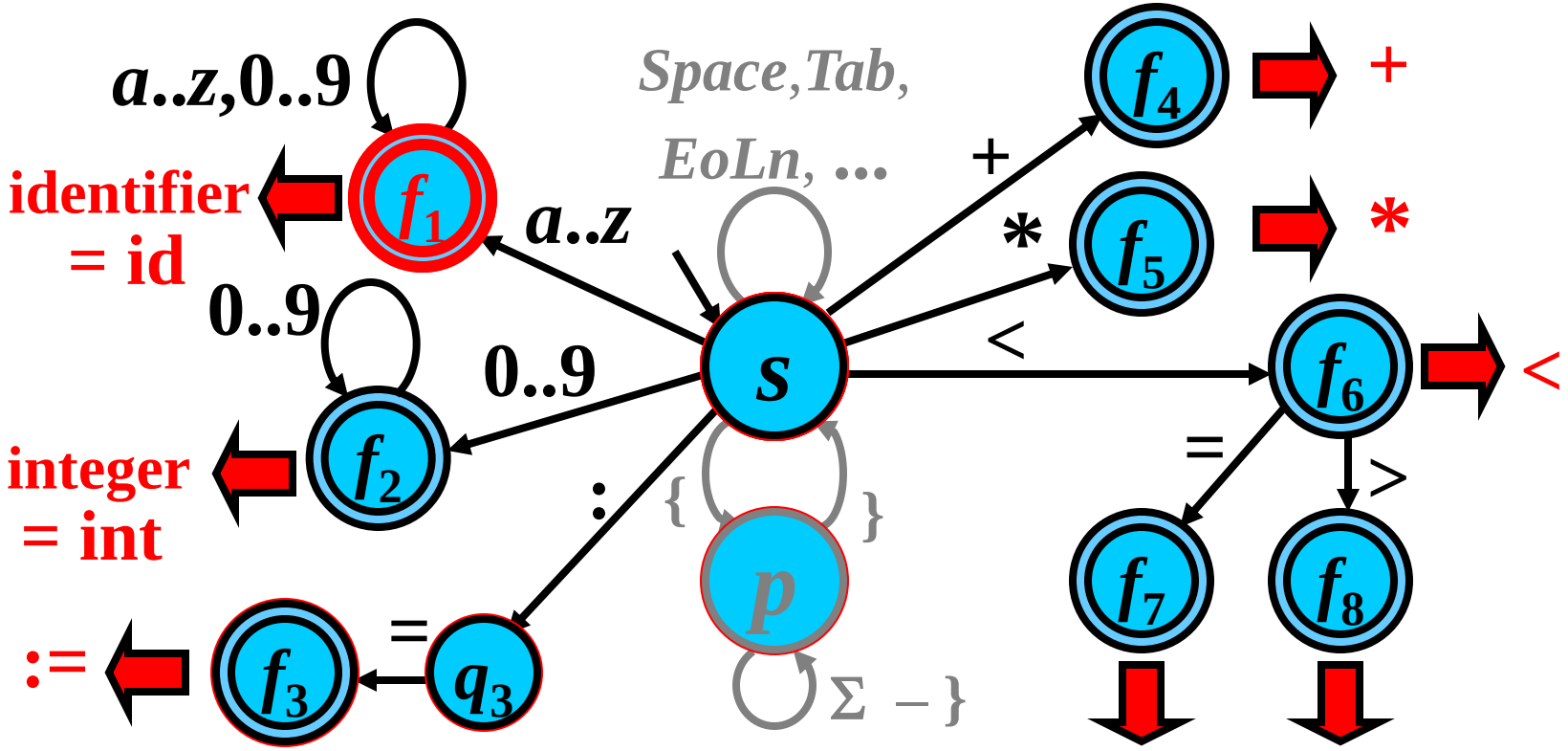
Type of Lexemes: Example



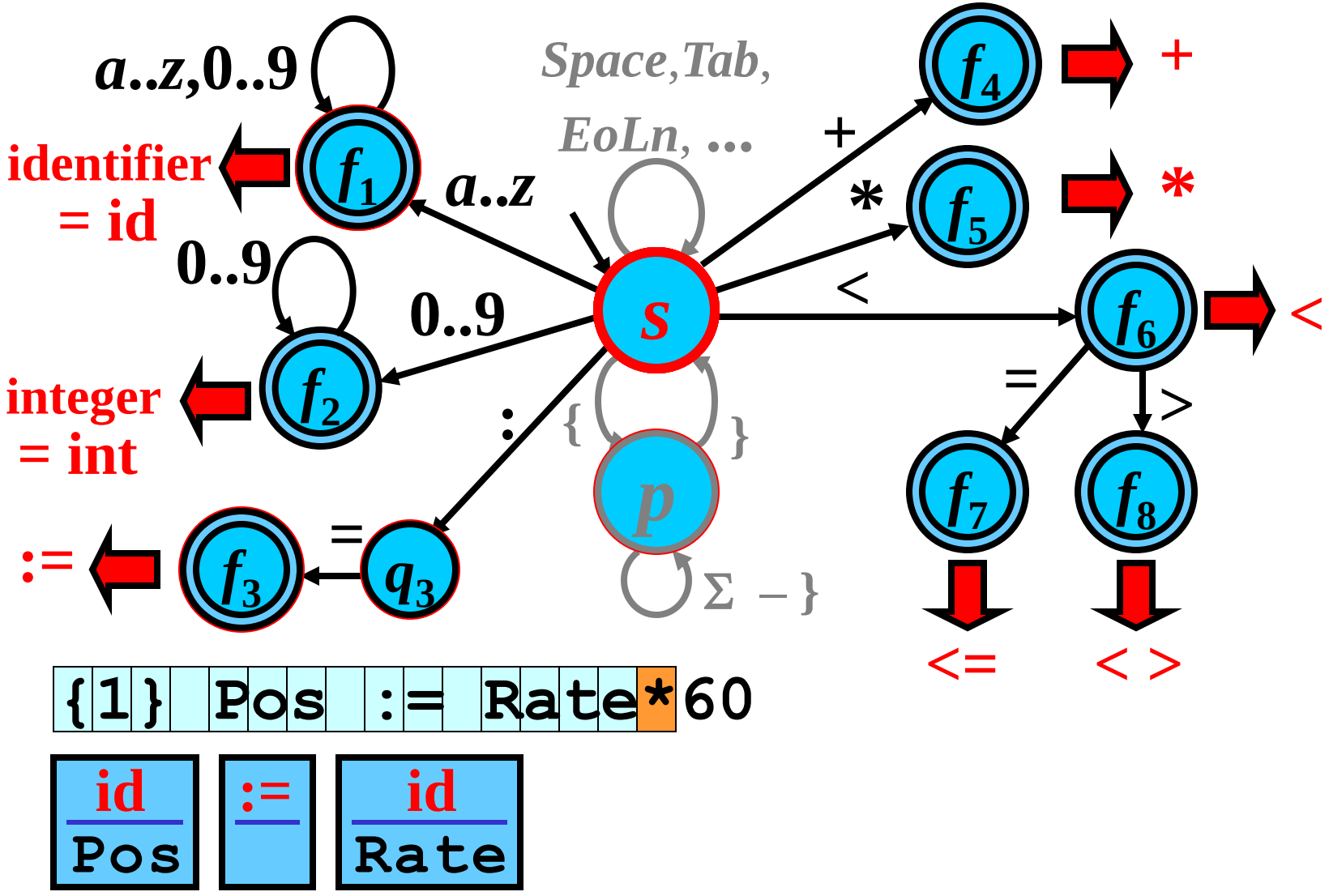
Type of Lexemes: Example



Type of Lexemes: Example



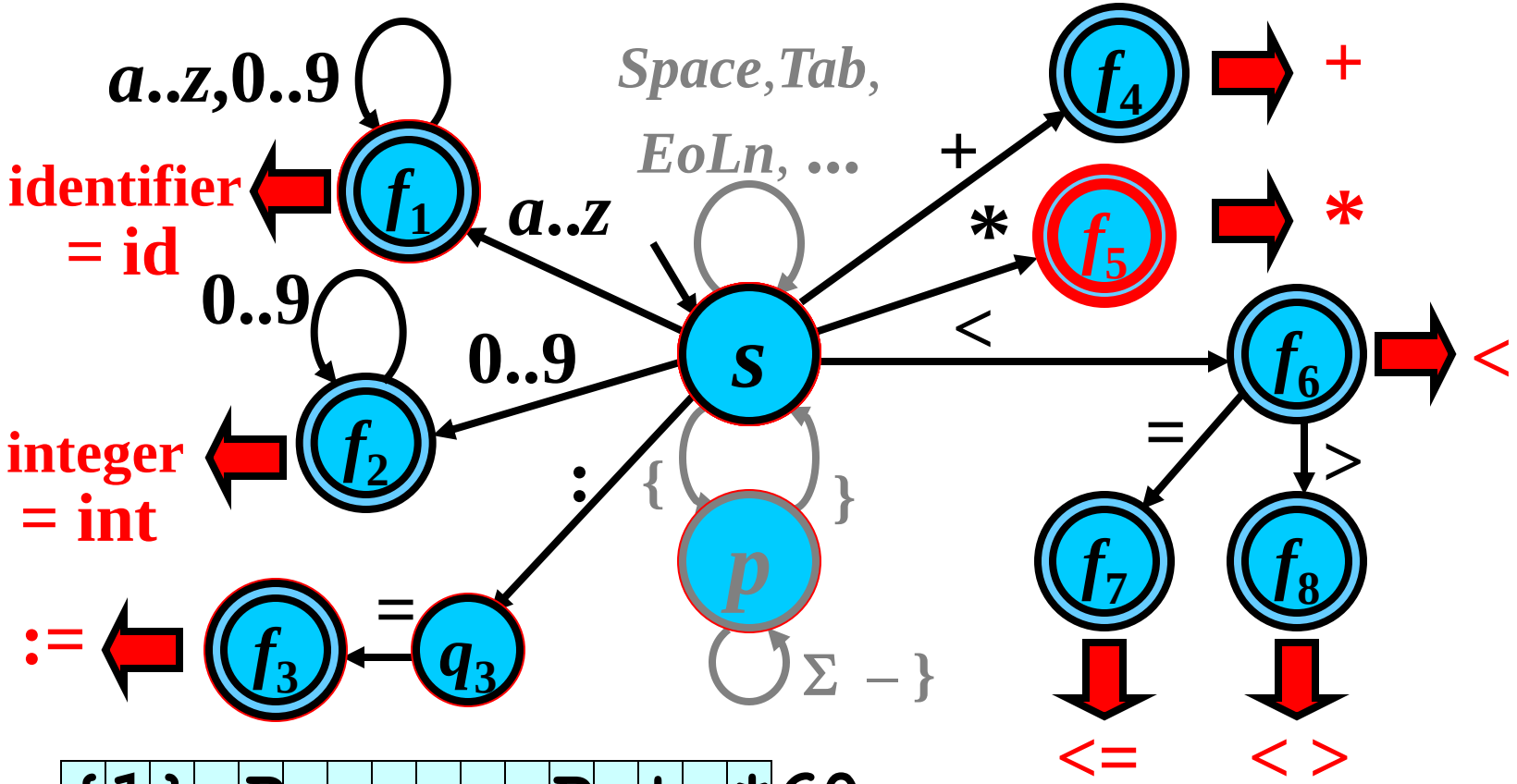
Type of Lexemes: Example



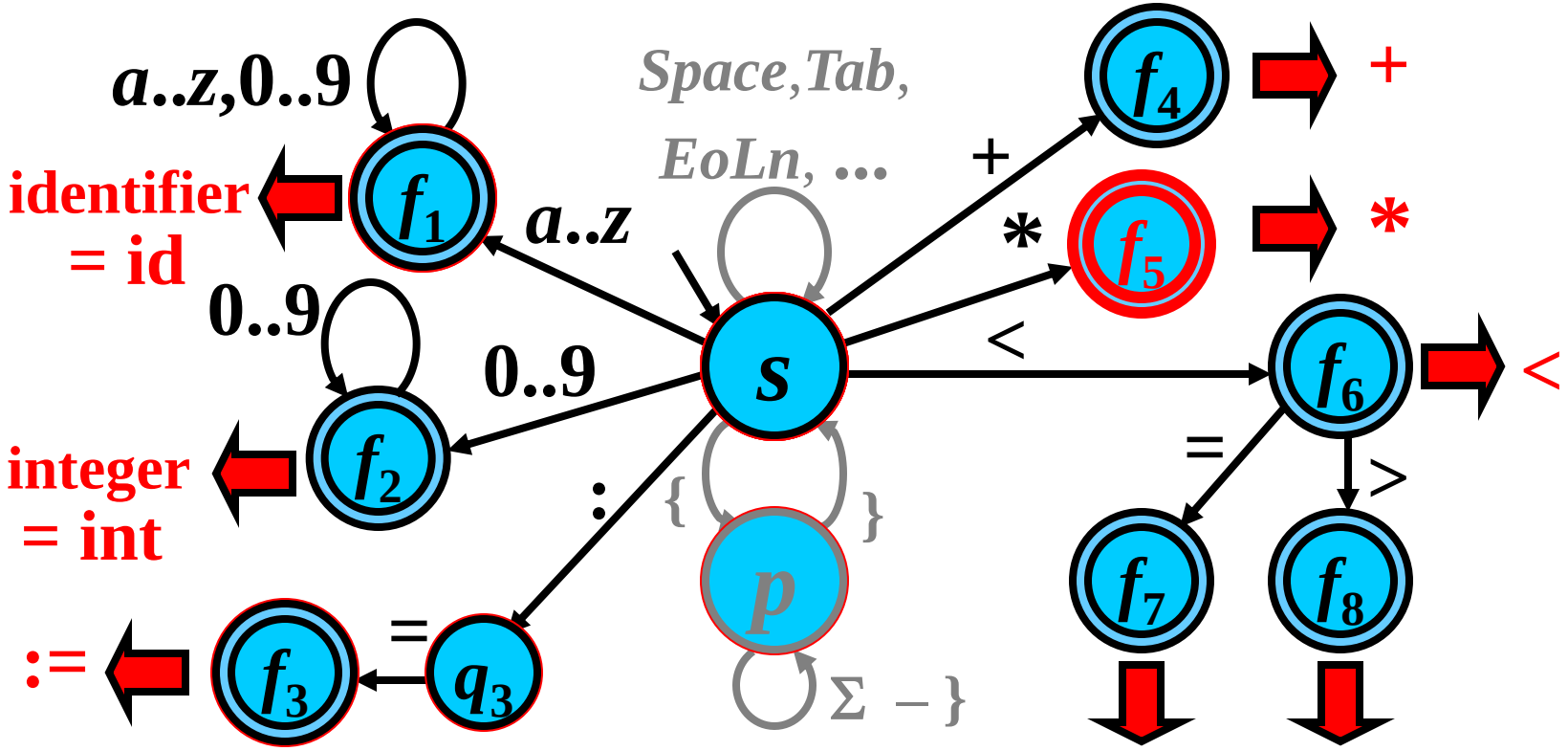
{1} Pos := Rate*60

id	:=	id
Pos		Rate

Type of Lexemes: Example



Type of Lexemes: Example

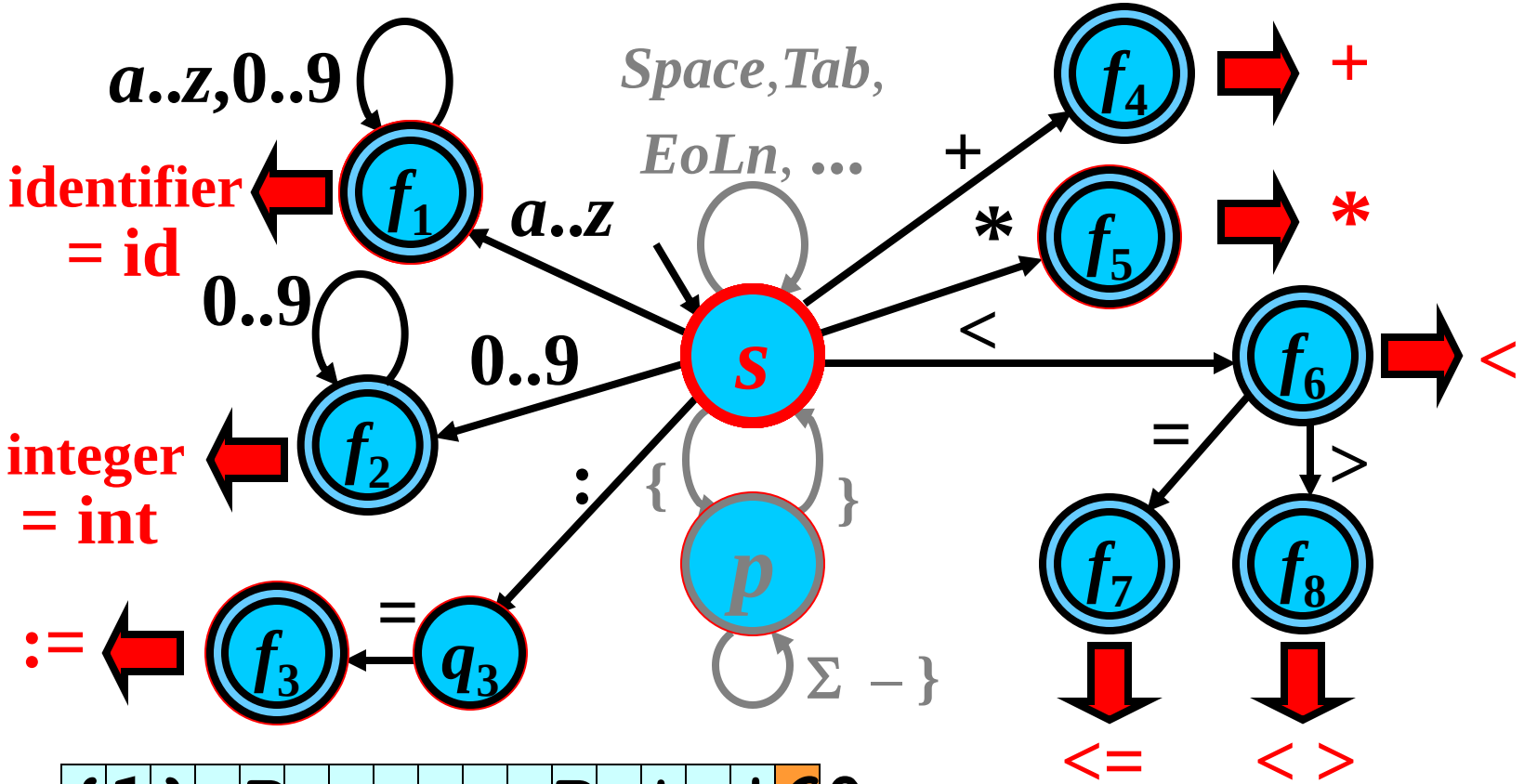


{1}	Pos	:=	Rate	*	60

id	:=	id	*
Pos		Rate	

No next configuration!

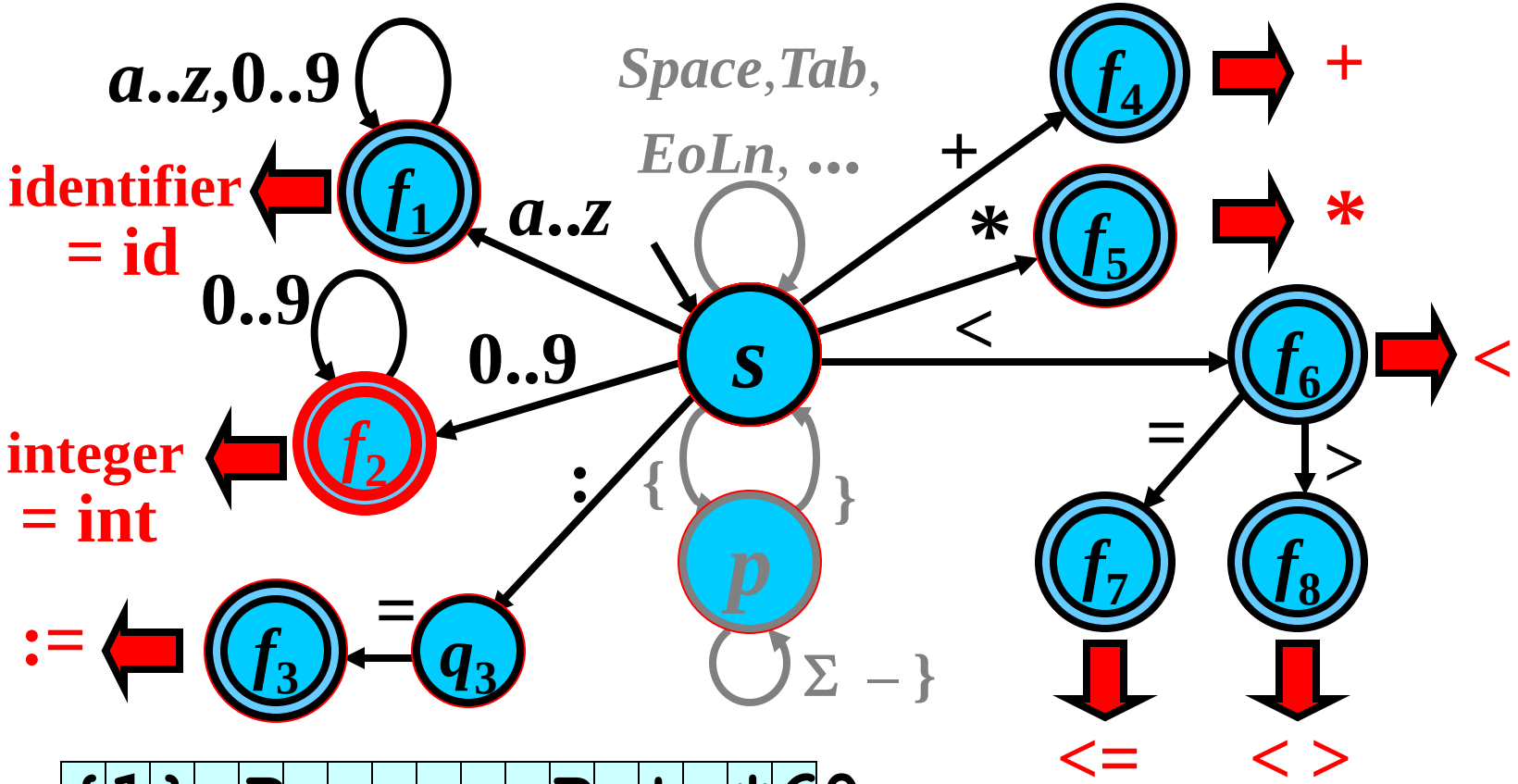
Type of Lexemes: Example



{1}	Pos	:=	Rate	*	60

id	:=	id	*
Pos		Rate	

Type of Lexemes: Example

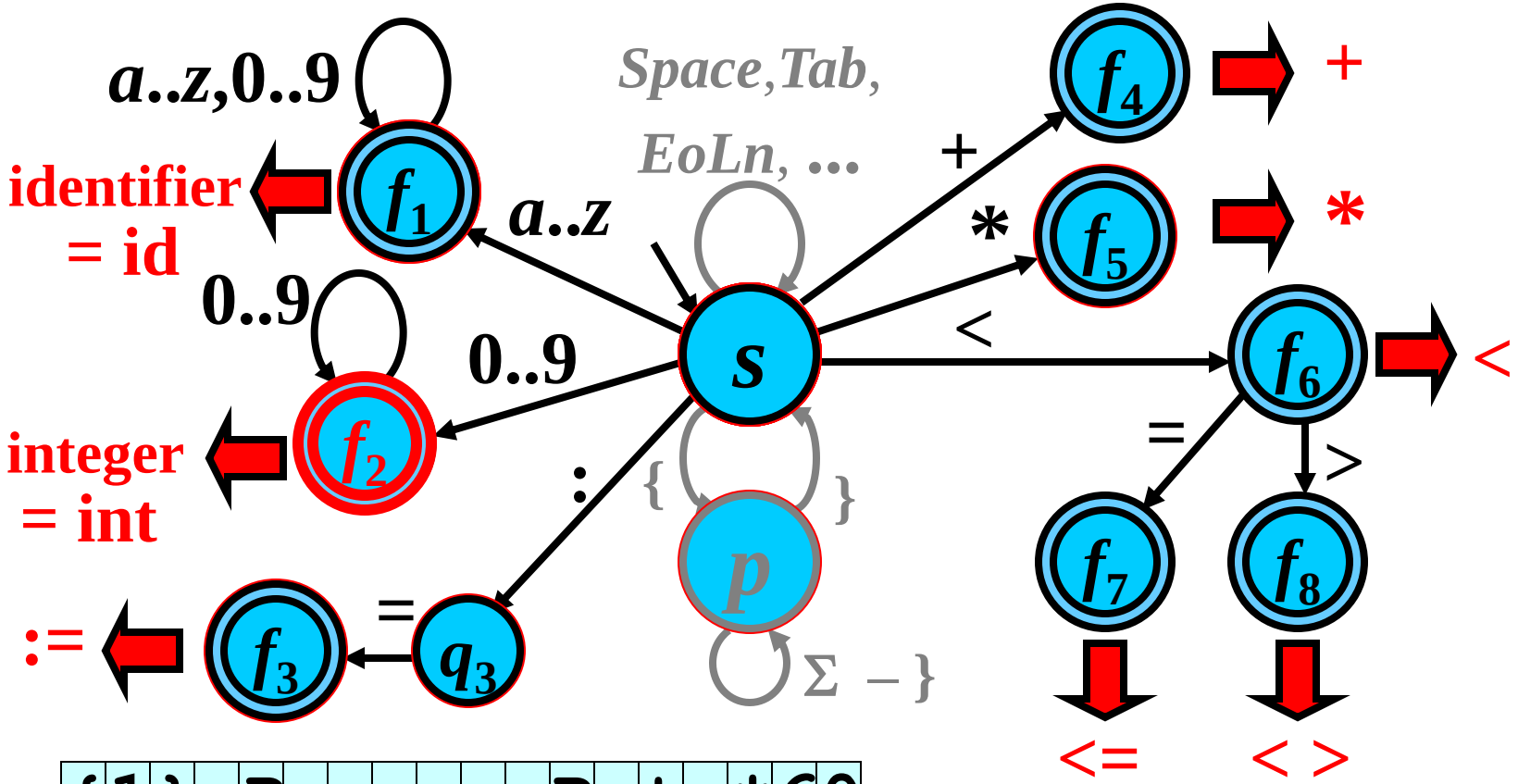


{1}	Pos	:=	Rate	*	60

id	:=	id	*
Pos		Rate	

6

Type of Lexemes: Example

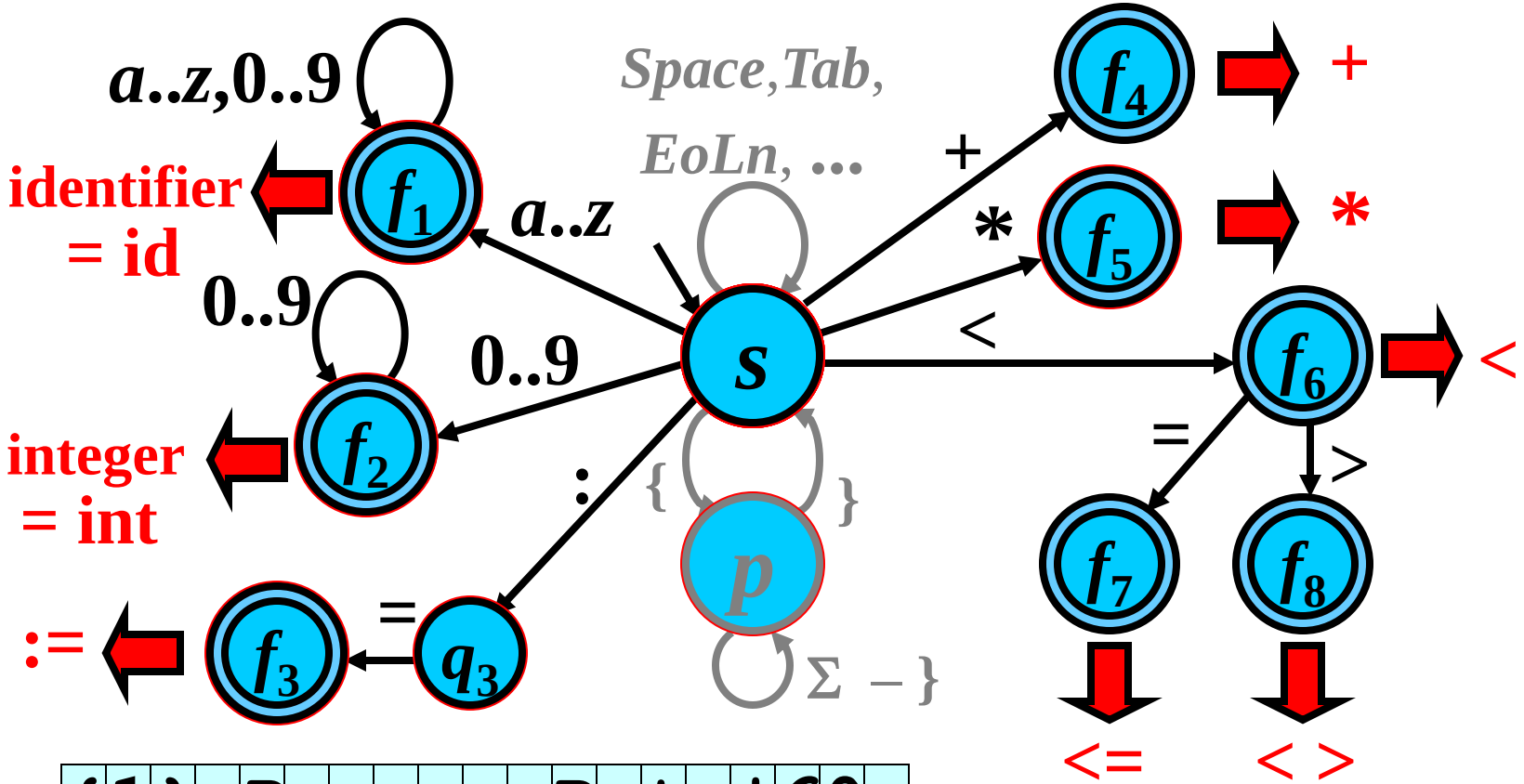


{1}	Pos	:=	Rate	*	60

id	:=	id	*
Pos		Rate	

60

Type of Lexemes: Example



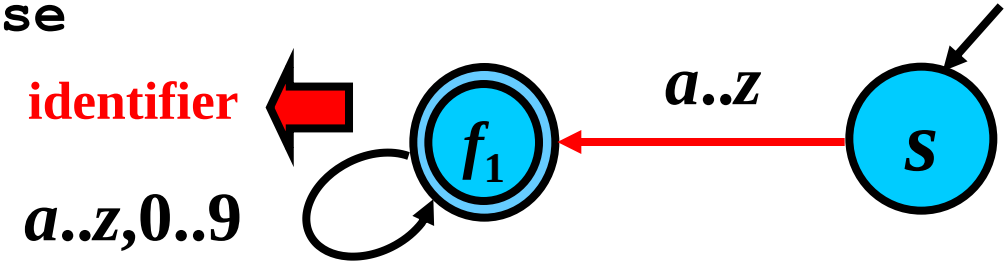
{1}	Pos	:=	Rate	*	60	.

id	:=	id	*	int
Pos		Rate		60

End of file

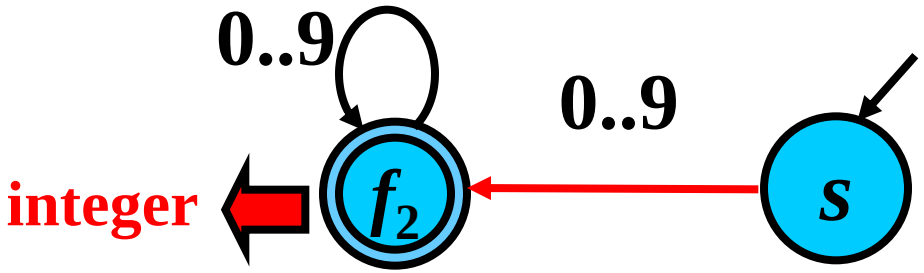
Implementation of DFA 1/10

```
procedure get_Next_Token(var TOKEN: ....);

...                                    {declaration, ...}

str    := '';                          {read string}
state  := S;                           {actual state}
repeat
  symbol = getchar();                  {read next character}
  case state of
    s : begin                          {start state}
          if symbol in ['a'..'z'] then
          begin
            state:= f1;                {identifier}
            str  := symbol;
          end else
```



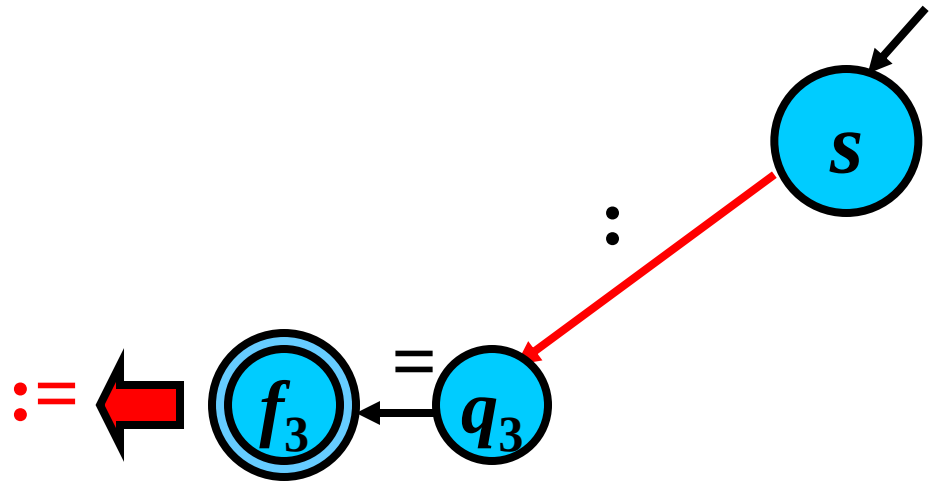
Implementation of DFA 2/10

```
case state of
  s : begin                          {start state}

        ...

        if symbol in ['0'..'9'] then
        begin
          state:= f2;                {integer}
          str  := symbol;
        end else
```



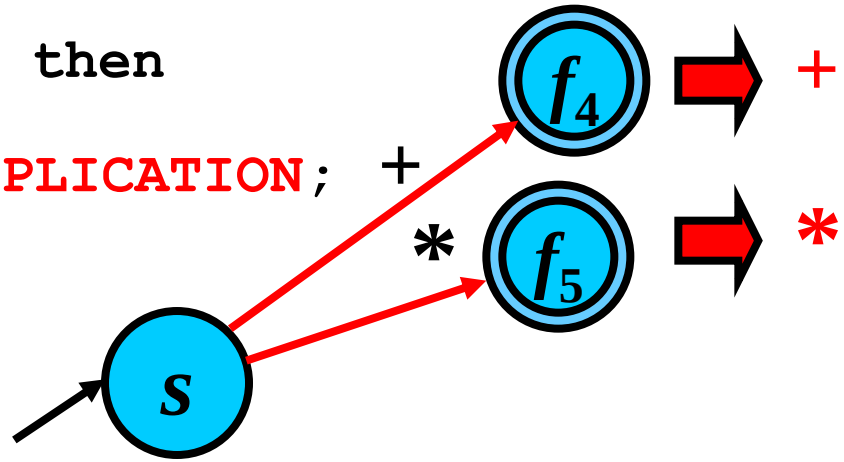
Implementation of DFA 3/10

```
case state of
  s : begin                          {start state}

        ...

        if symbol = ':' then
          state:= q3;                {assignment}
        else
```



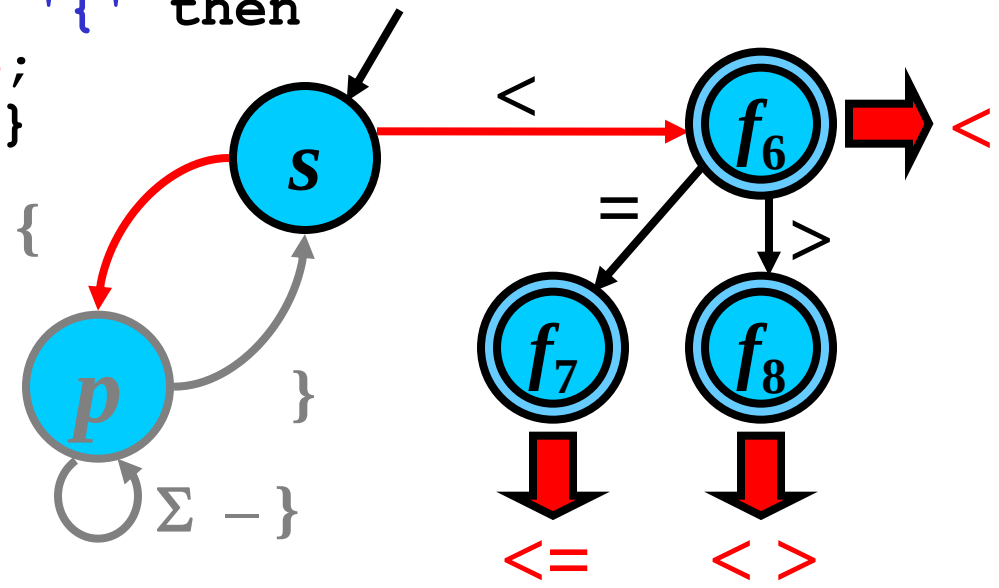
Implementation of DFA 4/10

```
case state of
  s : begin                          {start state}

        ...

        if symbol = '+' then
        begin
          TOKEN:= ADDITION;
          break;
        end else
        if symbol = '*' then
        begin
          TOKEN:= MULTIPLICATION;
          break;
        end else
```



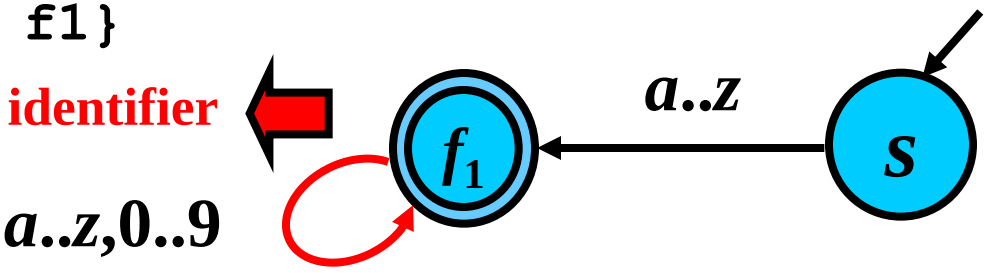
Implementation of DFA 5/10

```
case state of
  s : begin                          {start state}

        ...

        if symbol = '<' then
          state:= f6;
        else
        if symbol = '{' then
          state:= p;
      end; {state s}
```



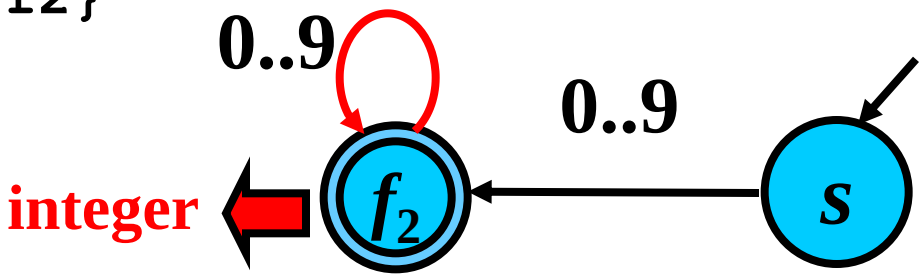
Implementation of DFA 6/10

```
case state of
  ...
  f1: begin                          {identifier}
        if symbol in ['a'..'z', '0'..'9'] then
          str  := str + symbol;
        else
        begin
          ungetchar(symbol);      {return symbol}
          if is_keyword(str) then      {keyword}
            TOKEN := get_keyword(str);
          else
            TOKEN := IDENTIFIER;
          break;
        end;
      end; {state f1}
```



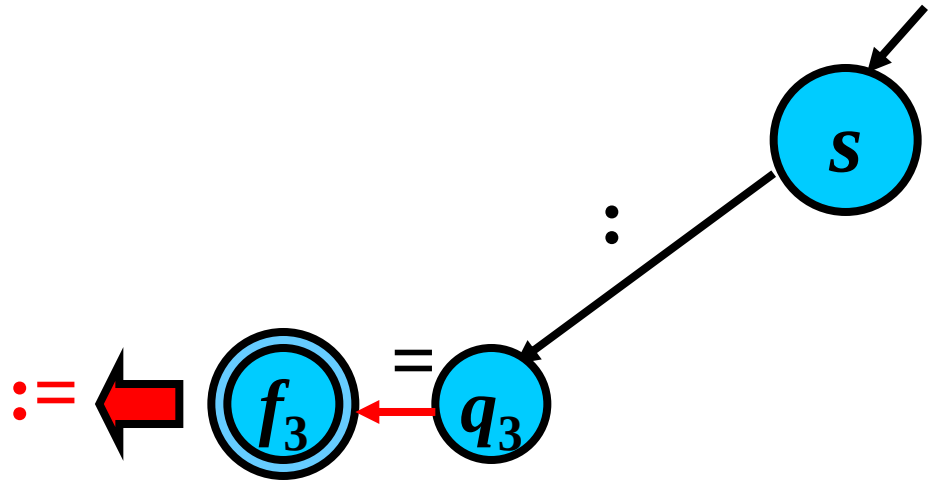
Implementation of DFA 7/10

```
case state of
  ...
  f2: begin                          {integer}
        if symbol in ['0'..'9'] then
          str  := str + symbol;
        else
        begin
          ungetchar(symbol);      {return symbol}
            TOKEN := INTEGER;
            {conversion value of str to integer}
          break;
        end;
      end; {state f2}
```



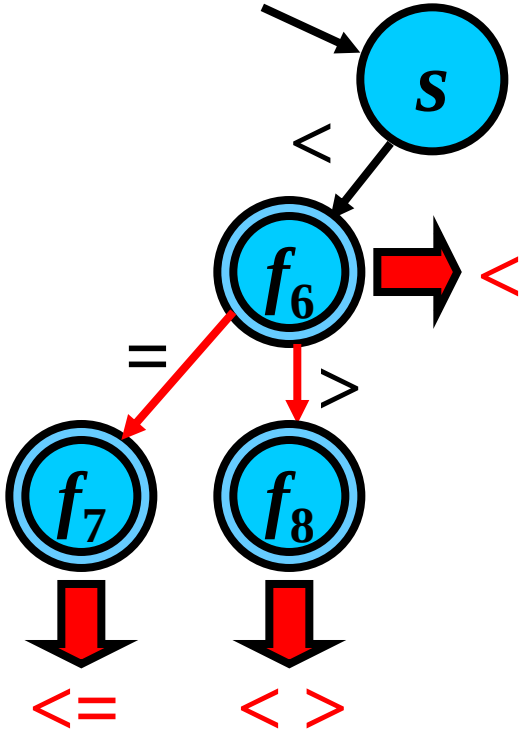
Implementation of DFA 8/10

```
case state of
  ...
  q3: begin                          {assignment}
        if symbol = '=' then
        begin
          TOKEN := ASSIGNMENT;
          break;
      end; {state q3}
```



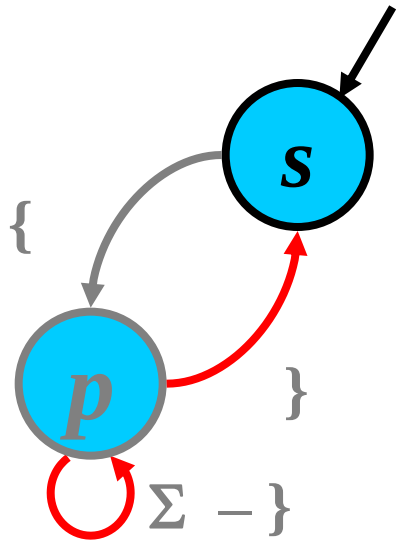
Implementation of DFA 9/10

```
case state of
  ...
  f6: begin
        if symbol = '=' then
        begin
          TOKEN := LEQ;     {<=}
          break;
        end else
        if symbol = '>' then
        begin
          TOKEN := NEQ;     {<>}
          break;
        end else
          ungetchar(symbol); {return symbol}
          TOKEN := LTN;     {<}
          break;
        end;
      end; {state f6}
```



Implementation of DFA 10/10

```
  case state of
    ...
    p : begin                          {comment}
          if symbol = '}' then
            state := s;                {start state}
        end; {state p}

until EOF;

...

end;
```



Tokens in Practice

- tokens represent every SP lexeme in a uniform way
- in general, their form is

[type, attribute]

---

1) Token **attributes** may vary

[id, Pos], **[int, 60]**, **[*,]**

pointer **integer** **nothing**

---

2) The same form of tokens

[1, 2], **[2, 3]**, **[3, 1]**

NOTE: In practice, we often use tokens whose attributes vary.

The Same Form of Tokens

[id, ☛Pos] [int, 60] [*,]

[,]

[,]

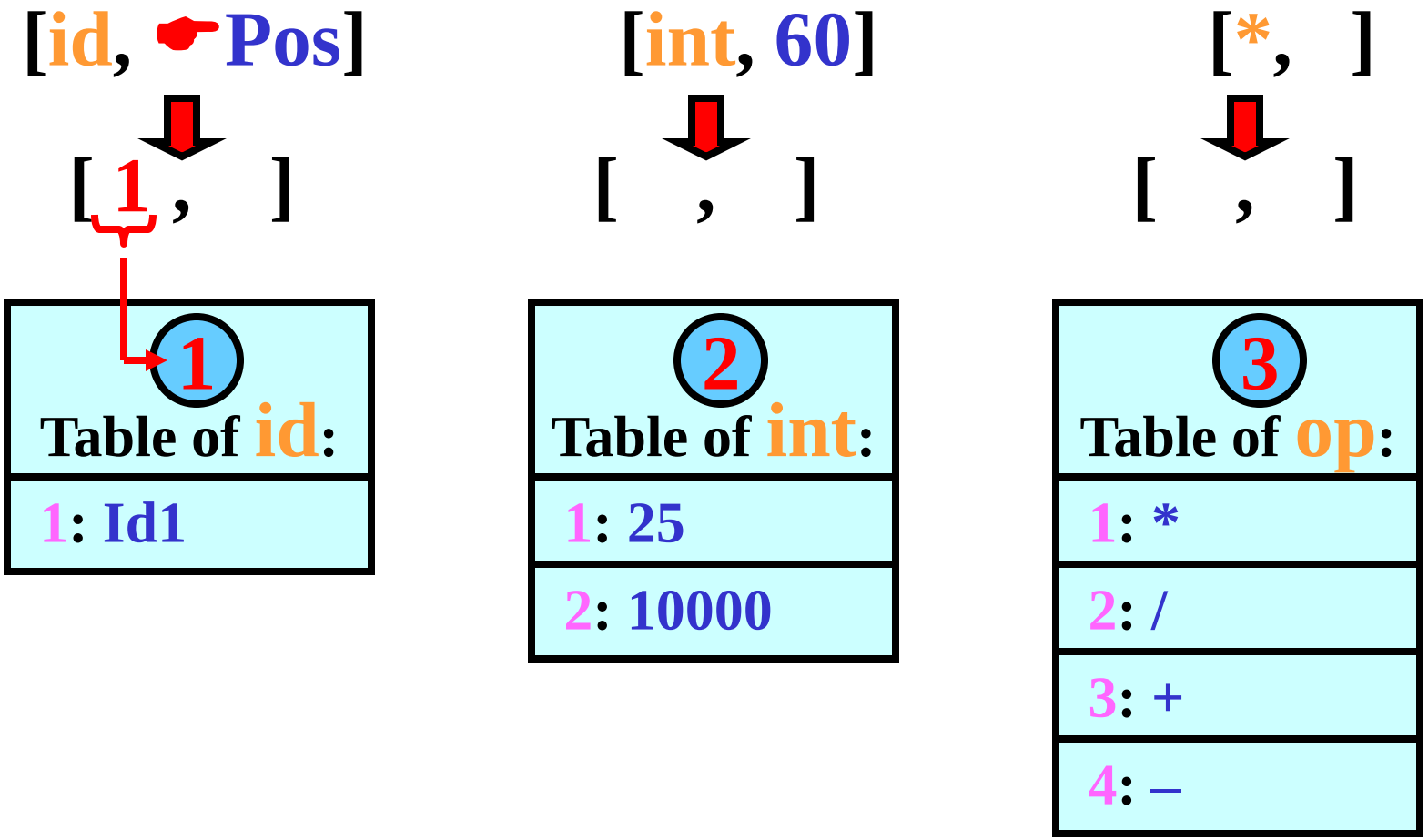
[,]

1 Table of id:
1: Id1

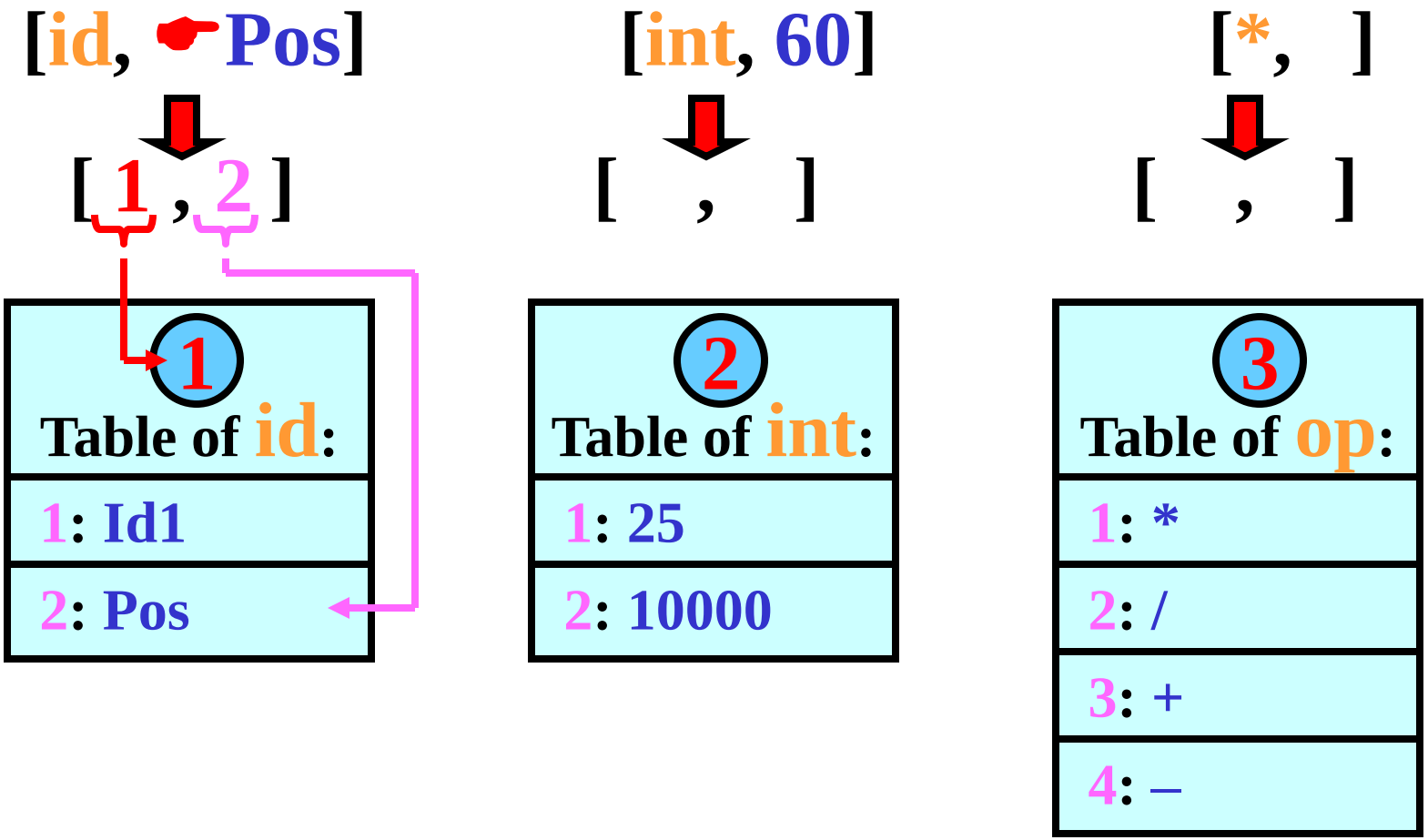
2 Table of int:
1: 25
2: 10000

3 Table of op:
1: *
2: /
3: +
4: –

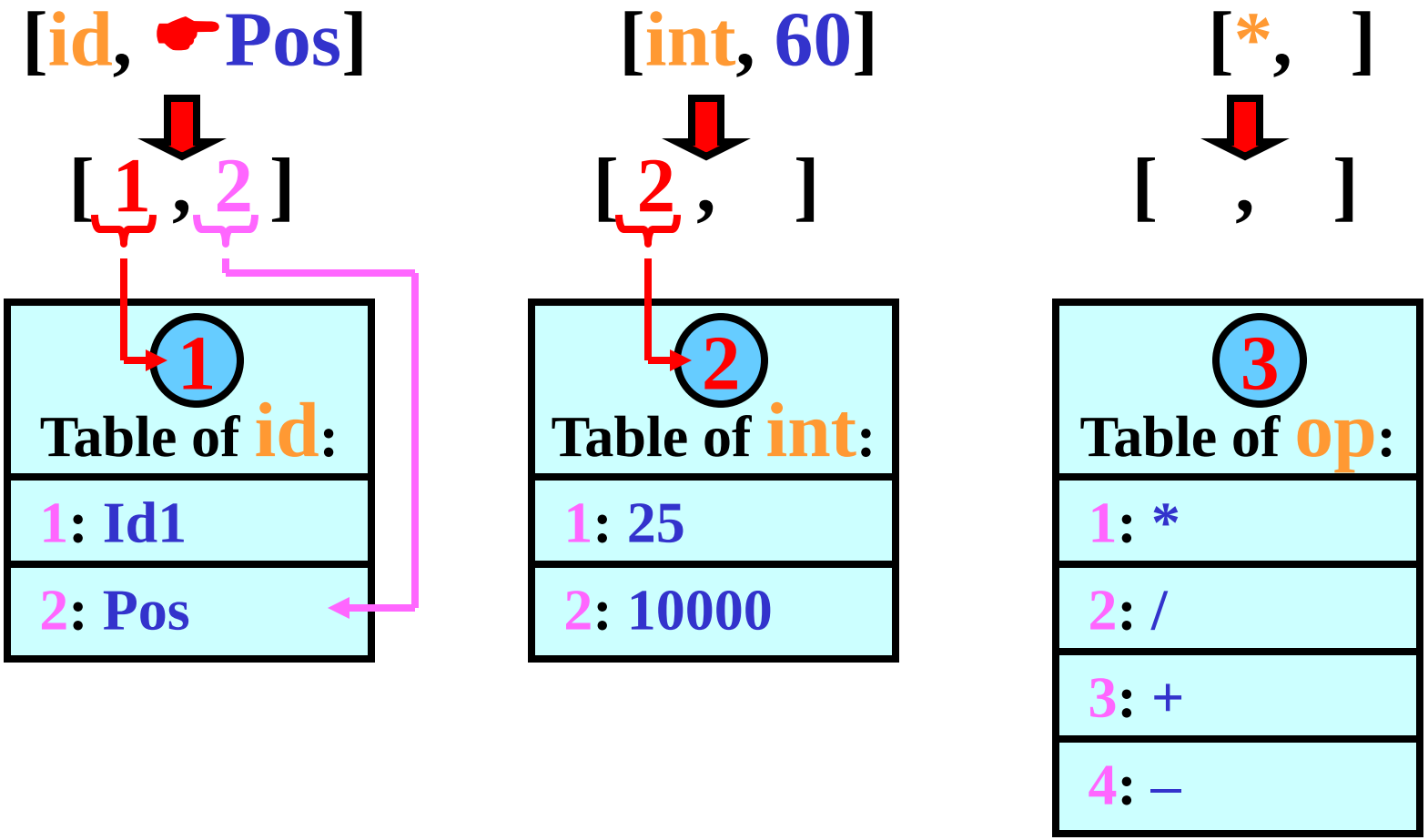
The Same Form of Tokens



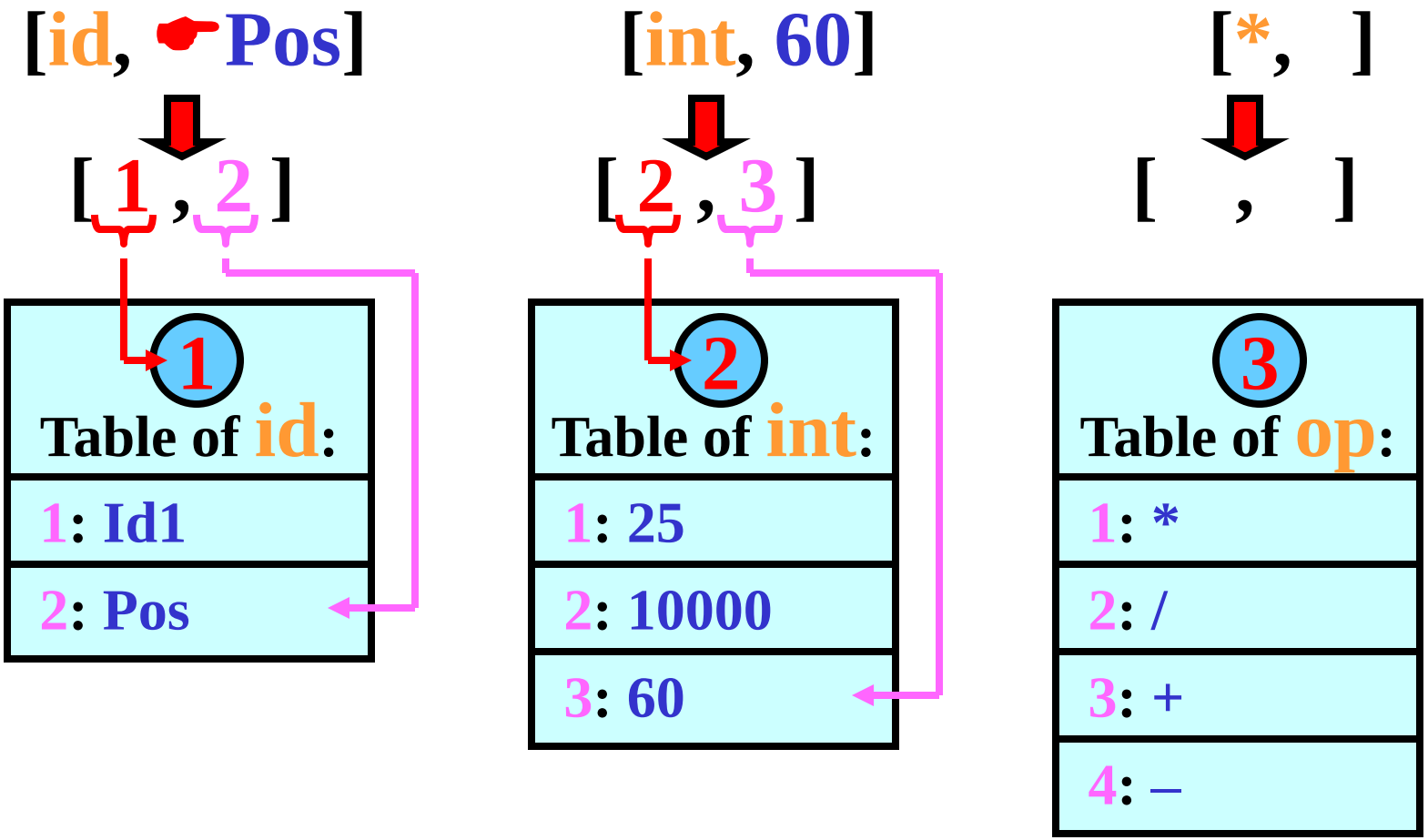
The Same Form of Tokens



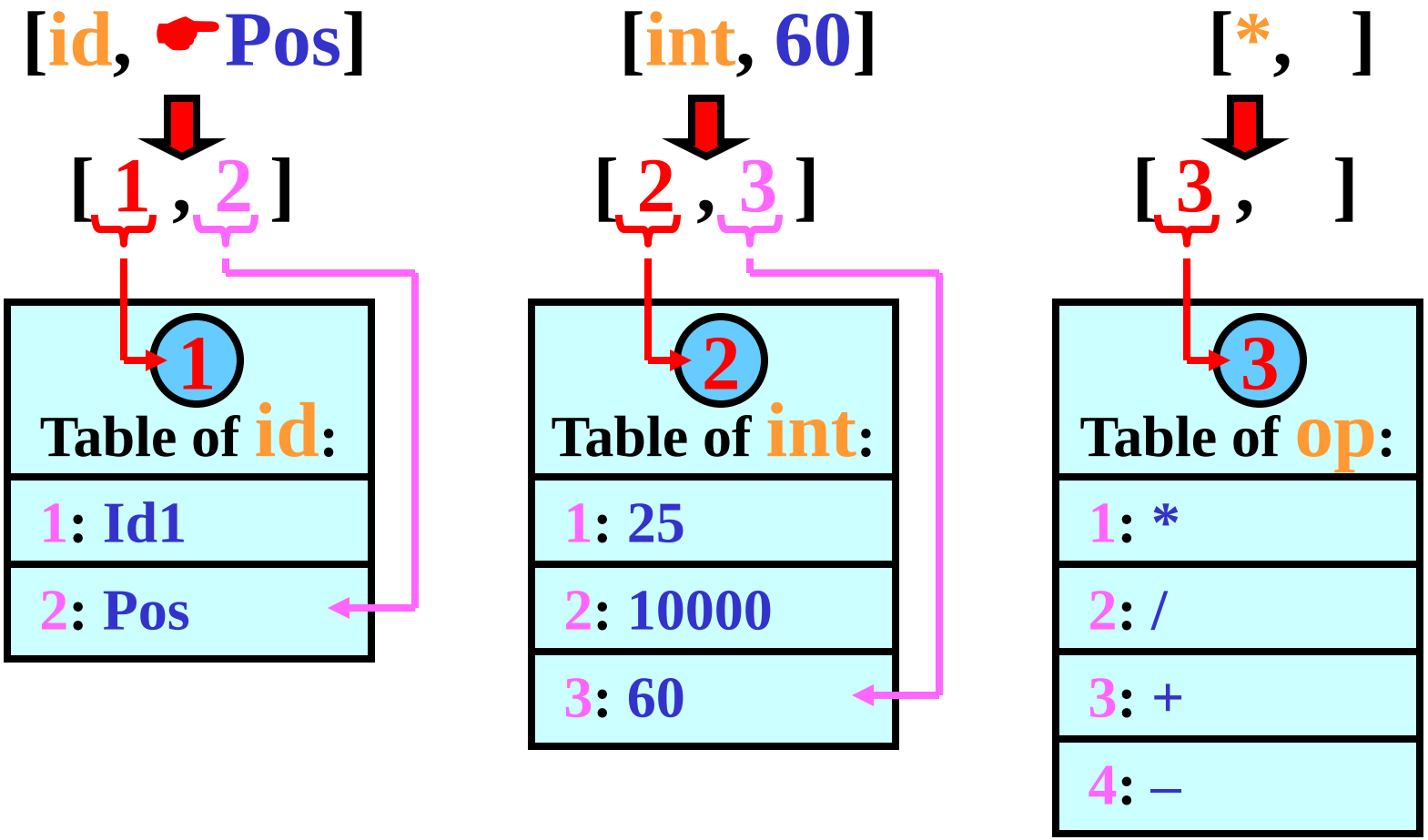
The Same Form of Tokens



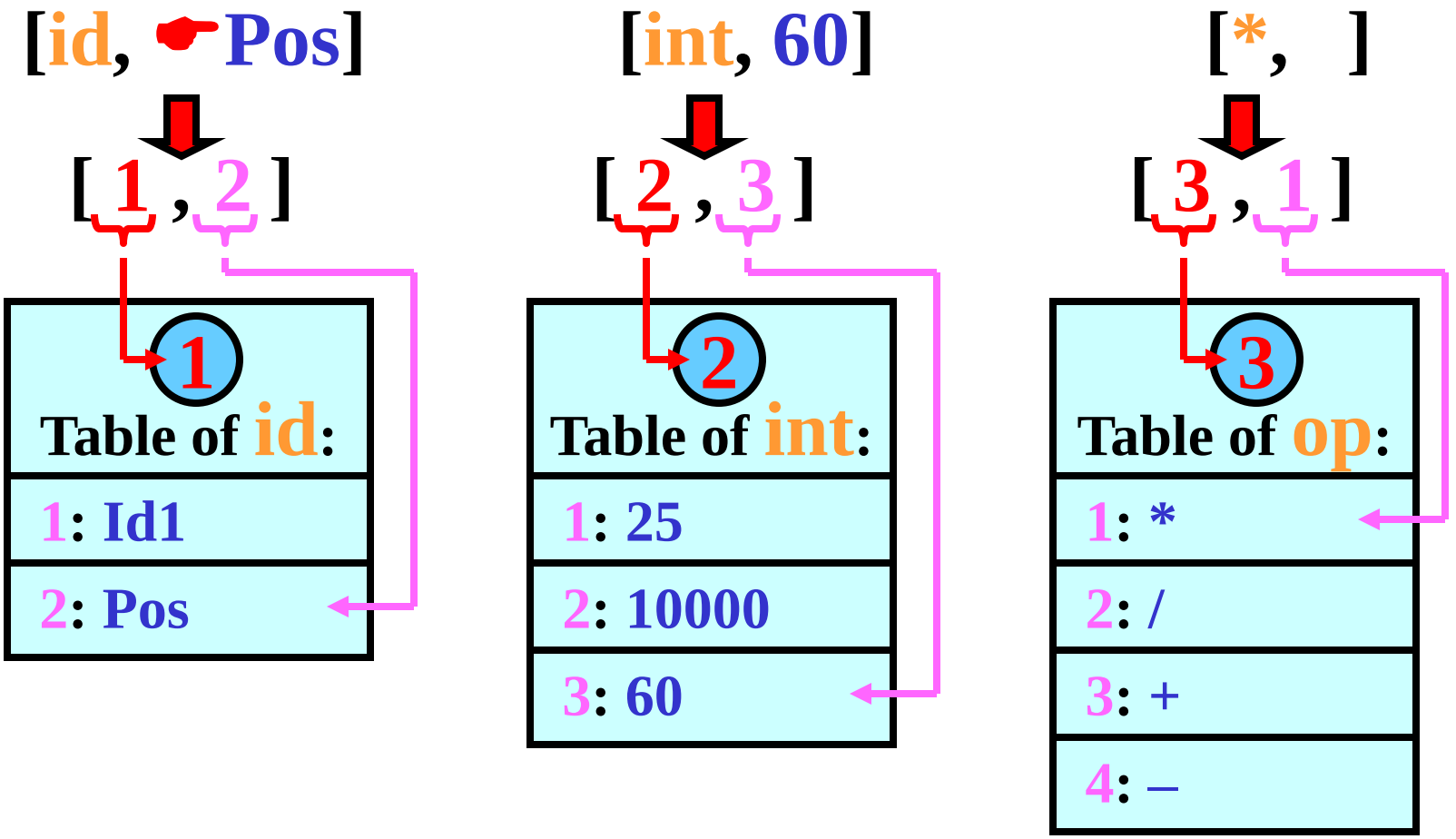
The Same Form of Tokens



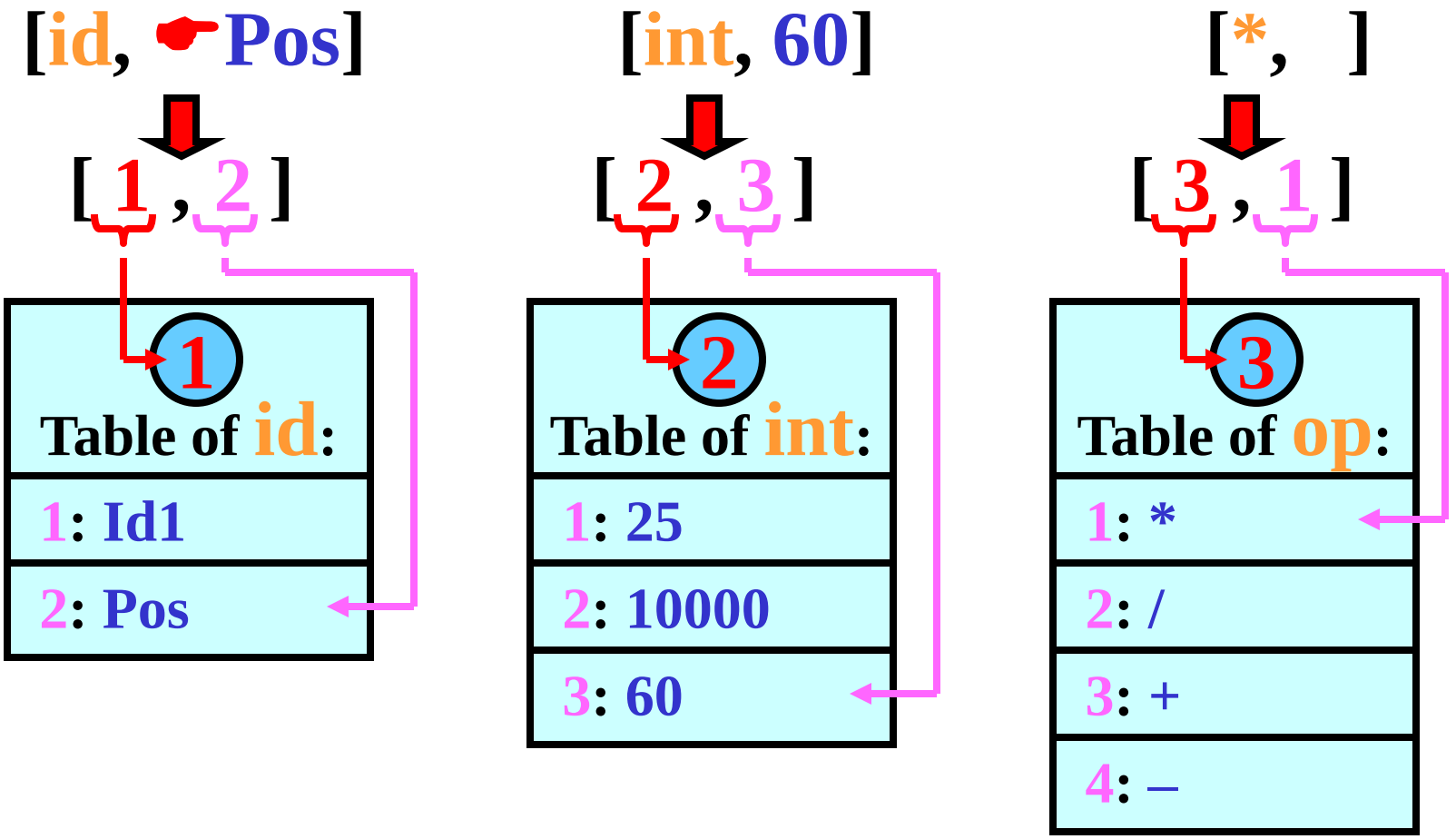
The Same Form of Tokens



The Same Form of Tokens



The Same Form of Tokens



Uniform form of tokens: [1, 2]; [2, 3]; [3, 1]

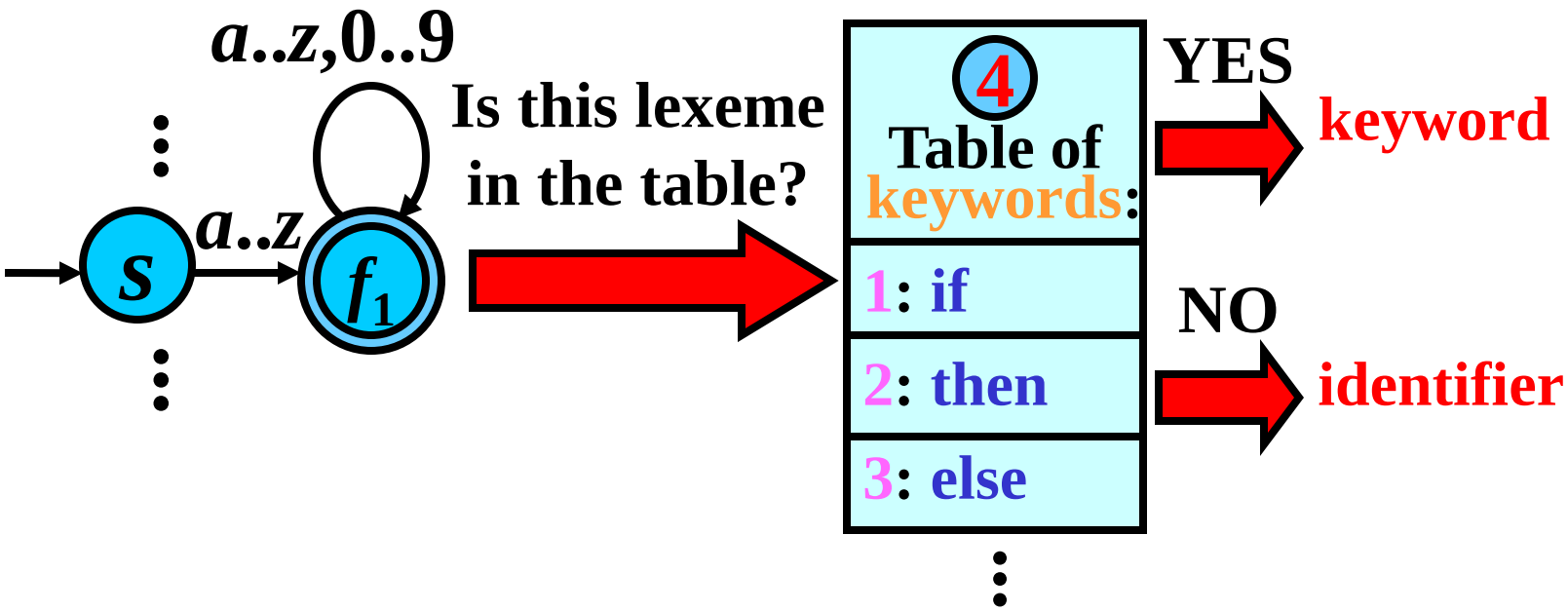
Homogenous structure

Identifiers × Keywords

Question: How to distinguish identifiers from keywords?

`if` ⇒ **keyword** × `ifj` ⇒ **identifier**

Answer: By a table of keywords.
(Tokens have the same form)



Symbol Table (Identifier Table)

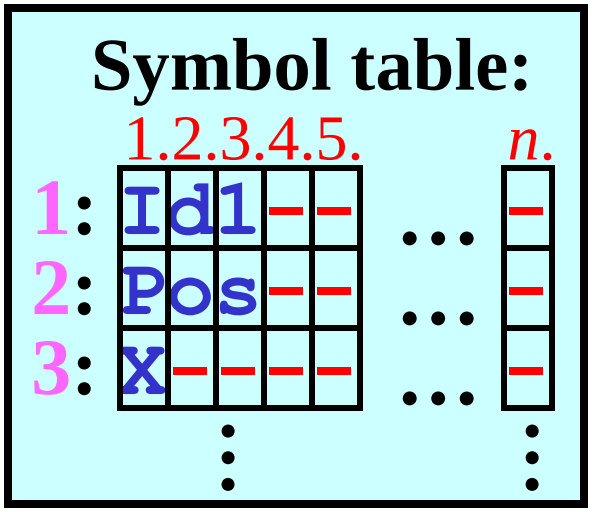
Practical problem:

1) Short identifiers:

- Empty spaces in memory (**–**)

2) Long identifiers:

- Length(Id) ≤ ***n***



Symbol Table (Identifier Table)

Practical problem:

1) Short identifiers:

- Empty spaces in memory (–)

2) Long identifiers:

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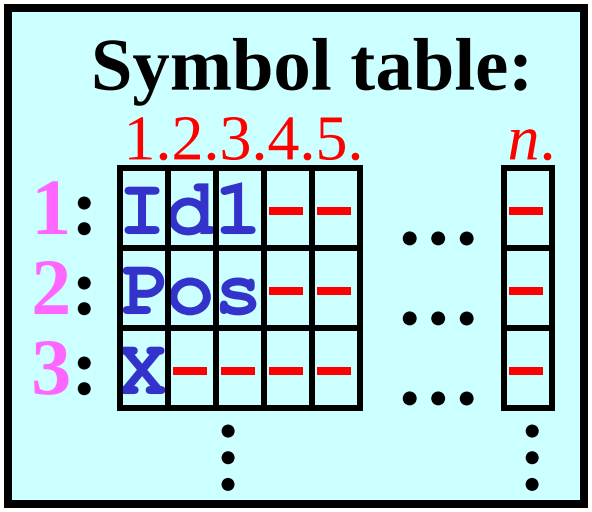
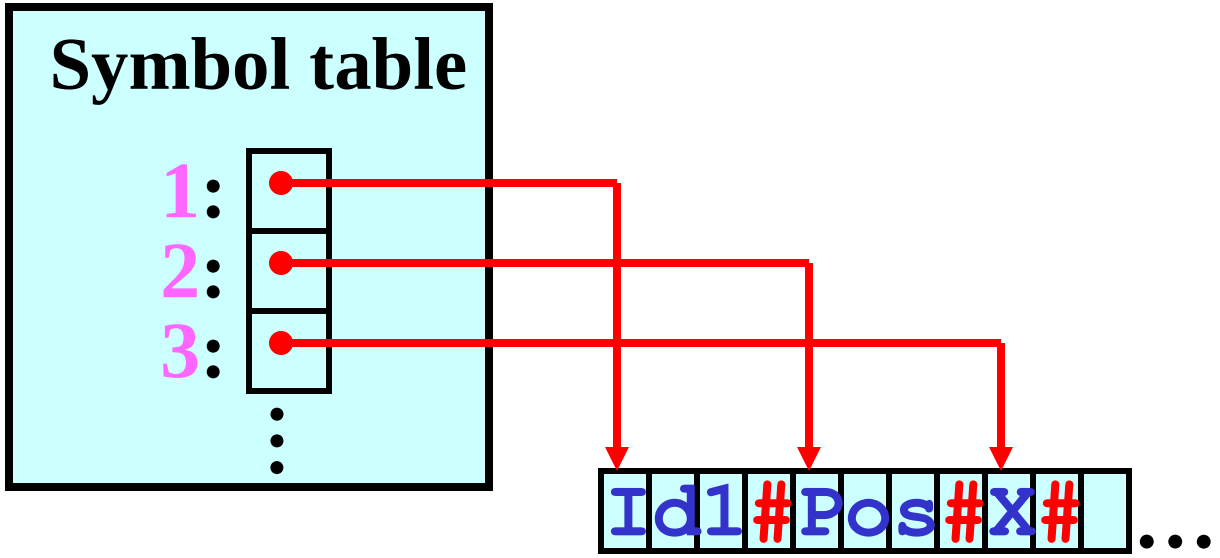


Solution:



Symbol Table: Structure

- We need many pieces of information about identifiers in ST:
  - **Variable:** name, type, length, …
  - **Constant:** type and value of constant
  - **Procedure:** the number and type of parameters

⋮

Symbol Table: Structure

- We need many pieces of information about identifiers in ST:
  - **Variable:** name, type, length, …
  - **Constant:** type and value of constant
  - **Procedure:** the number and type of parameters
  - ⋮

Final structure of the symbol table:

Symbol table		
	Name	**Info**
1:	**Id1**	**Variable; Type: integer**
2:	**Pi**	**Constant; Type: real, Value: 3.1415927**

Scope of Identifiers

- **Problem:**

```
Program P1;
```

Symbol table

Scope of Identifiers

- **Problem:**

```
Program P1;
var x, y: integer;
```

Symbol table		
1:	x	…
2:	y	…

Scope of Identifiers

- **Problem:**

```
Program P1;
var x, y: integer;

Procedure Proc1;
```

Symbol table		
1:	x	…
2:	y	…
3:	Proc1	…

Scope of Identifiers

- **Problem:**

```
Program P1;
var x, y: integer;

Procedure Proc1;
var x, y: integer;
```

Symbol table		
1:	x	…
2:	y	…
3:	Proc1	…
4:	x	…
5:	y	…

Scope of Identifiers

- **Problem:**

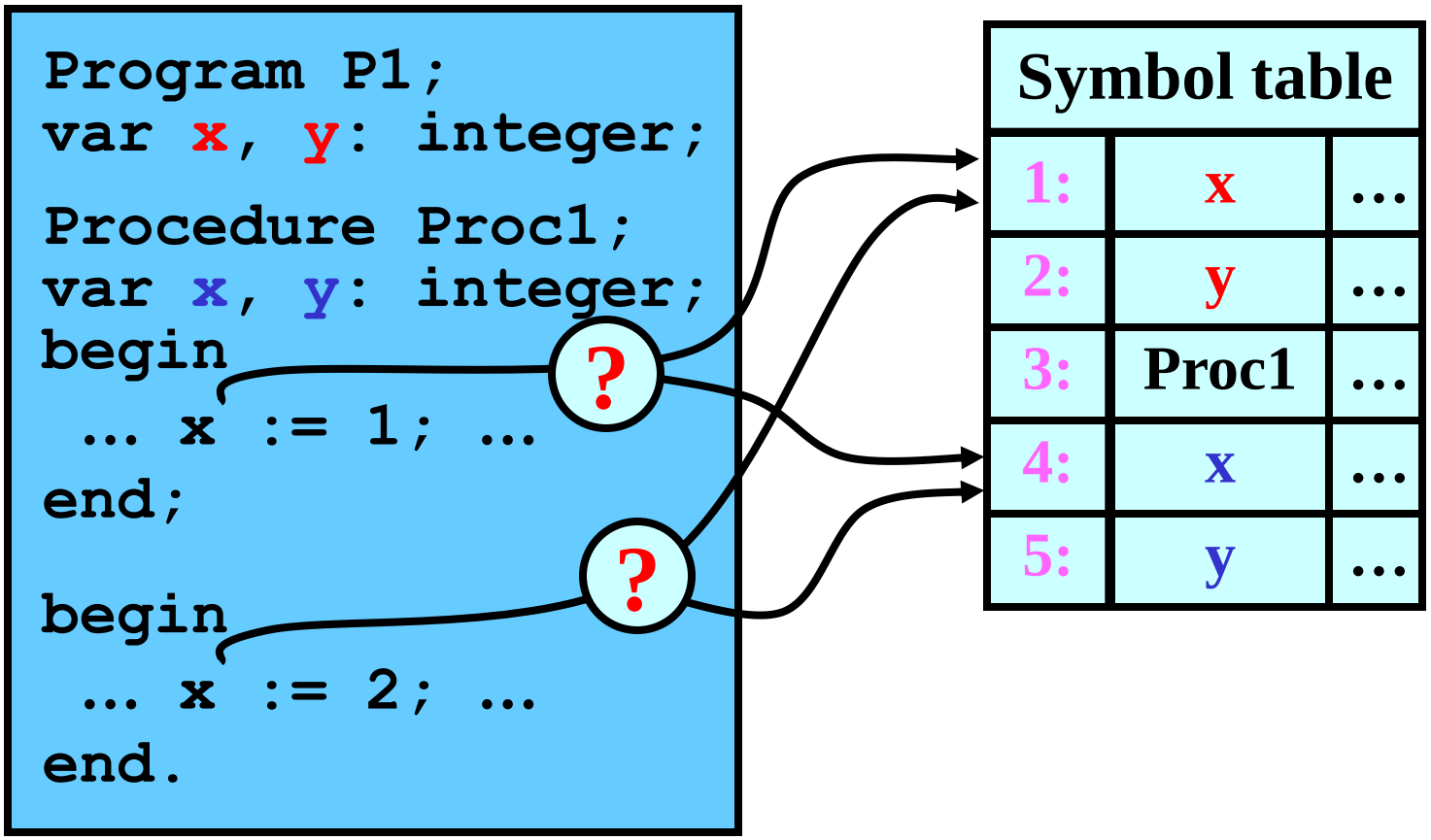
```
Program P1;
var x, y: integer;

Procedure Proc1;
var x, y: integer;
begin
  … x := 1; …
end;
```

Symbol table		
1:	x	…
2:	y	…
3:	Proc1	…
4:	x	…
5:	y	…

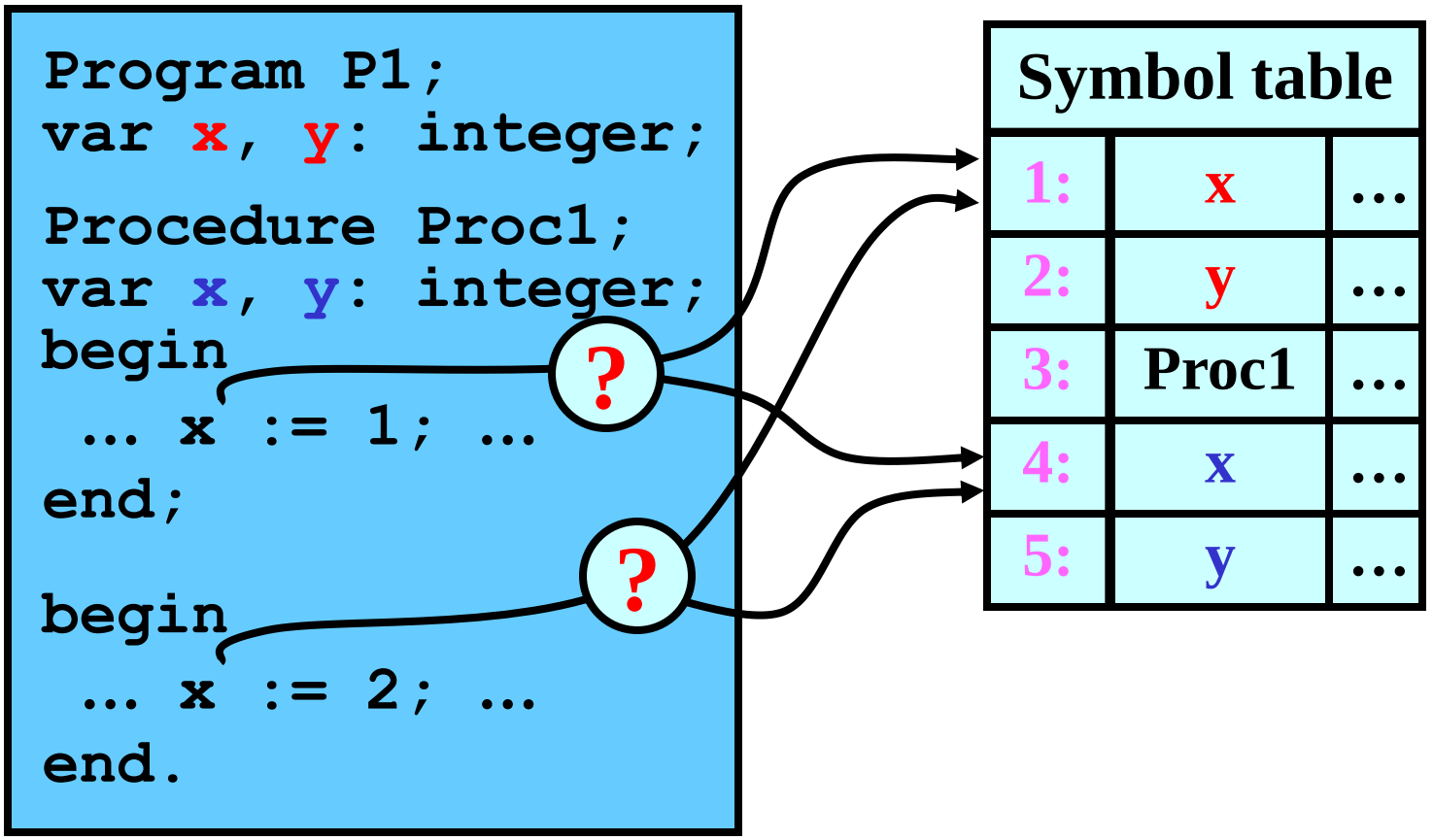
Scope of Identifiers

- **Problem:**



Scope of Identifiers

- **Problem:**



- **Solution:** **Scope Rules** (Stack structure of ST)

Scope Rules

Symbol Table=
ST-stack:

Auxiliary Table =
AT-stack:

Scope Rules

Main Block (B0)

Symbol Table=
ST-stack:

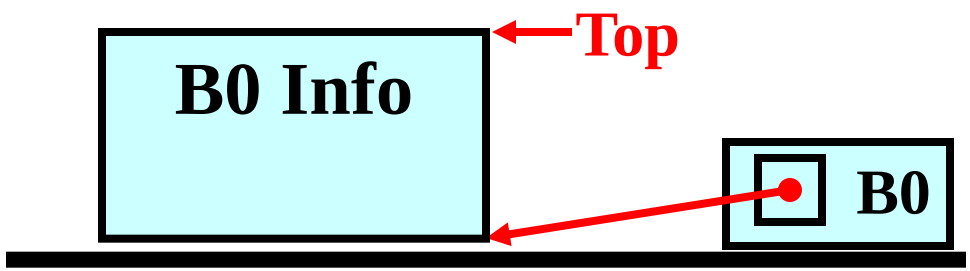
Auxiliary Table =
AT-stack:

Scope Rules

Main Block (B0)

Symbol Table=
ST-stack:

Auxiliary
Table =
AT-stack:



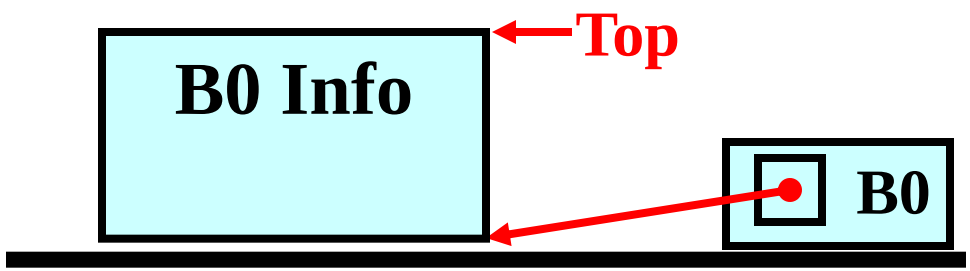
Scope Rules

Main Block (B0)

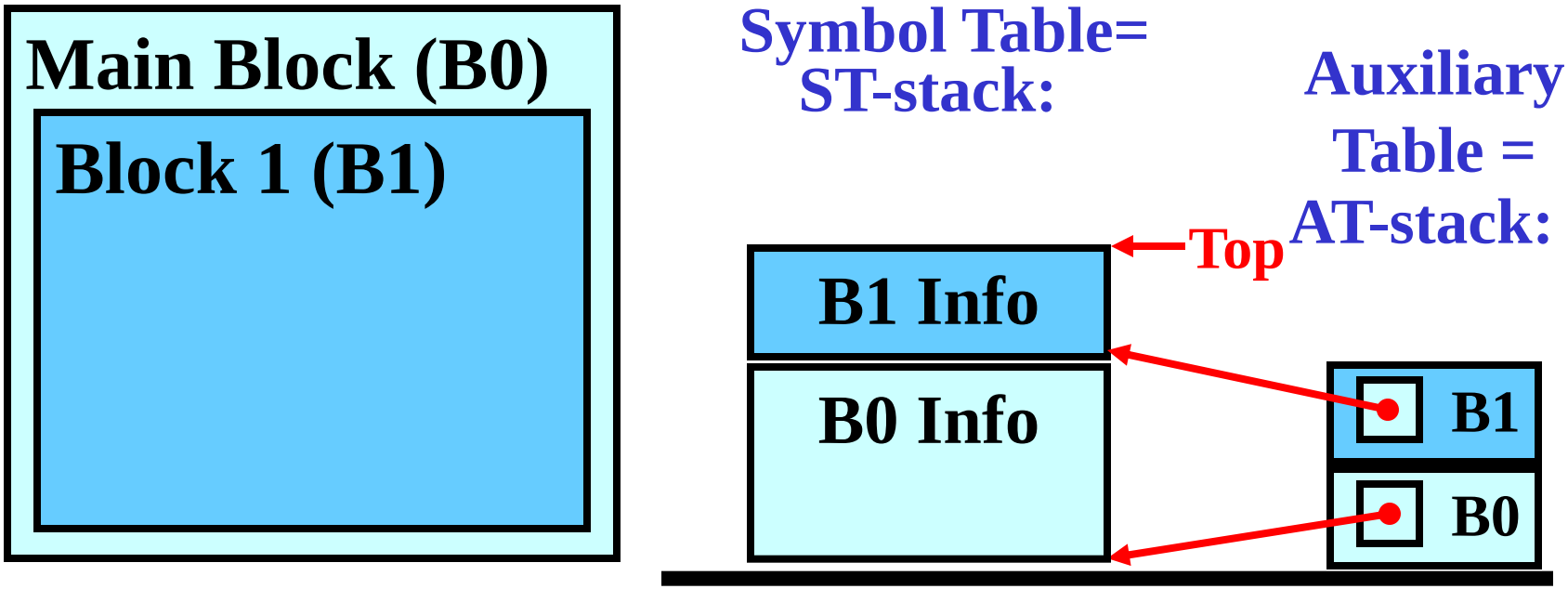
Block 1 (B1)

Symbol Table= ST-stack:

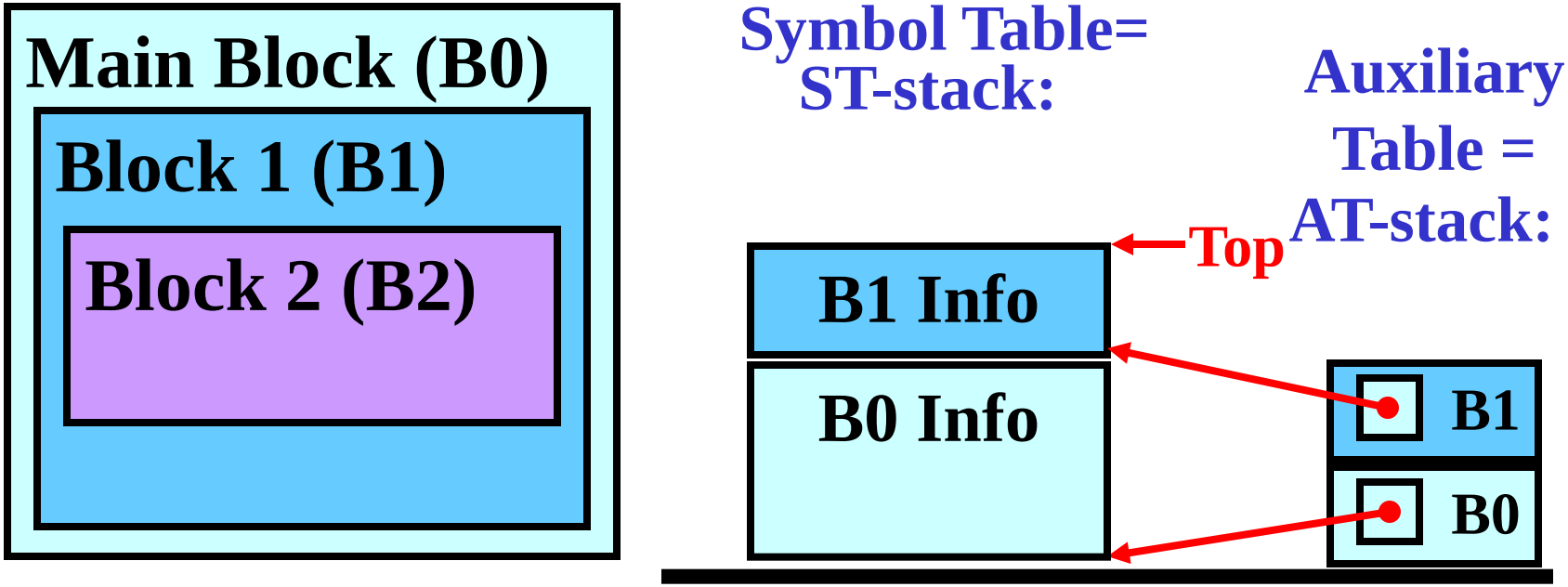
Auxiliary Table = AT-stack:



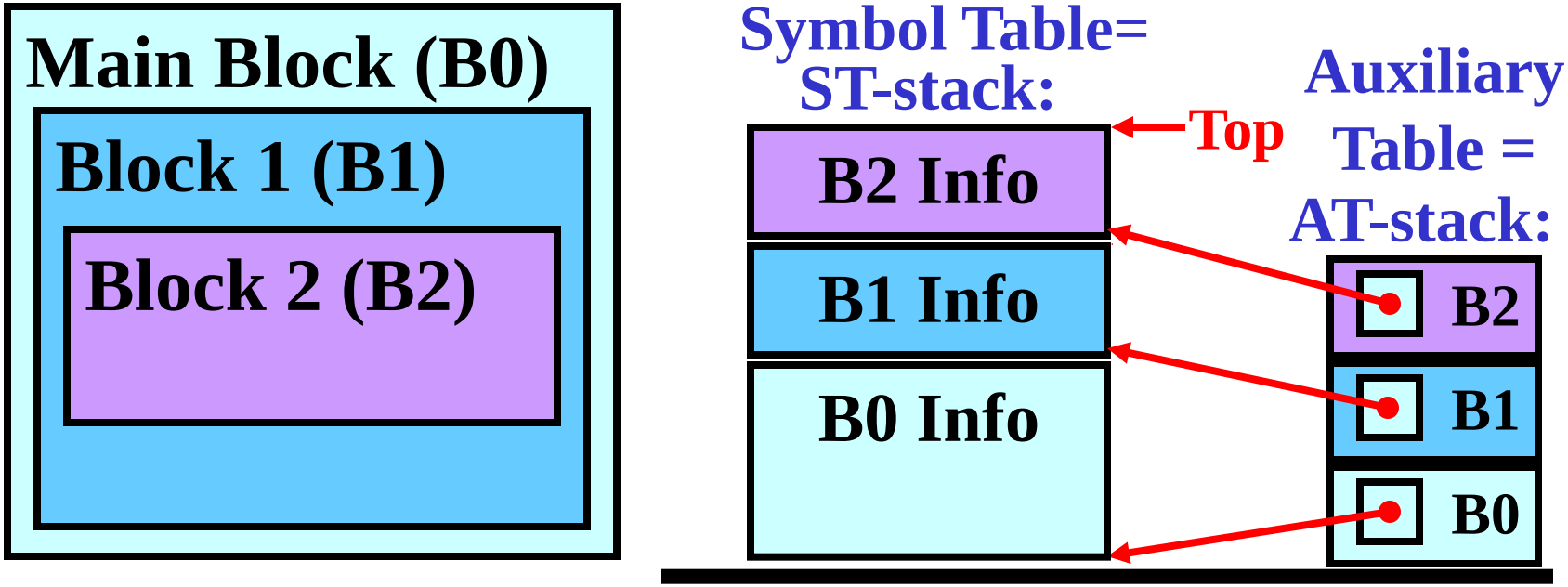
Scope Rules


Main Block (B0)
Block 1 (B1)
Symbol Table=
ST-stack:
Auxiliary
Table =
AT-stack:
Top
B1 Info
B0 Info
B1
B0

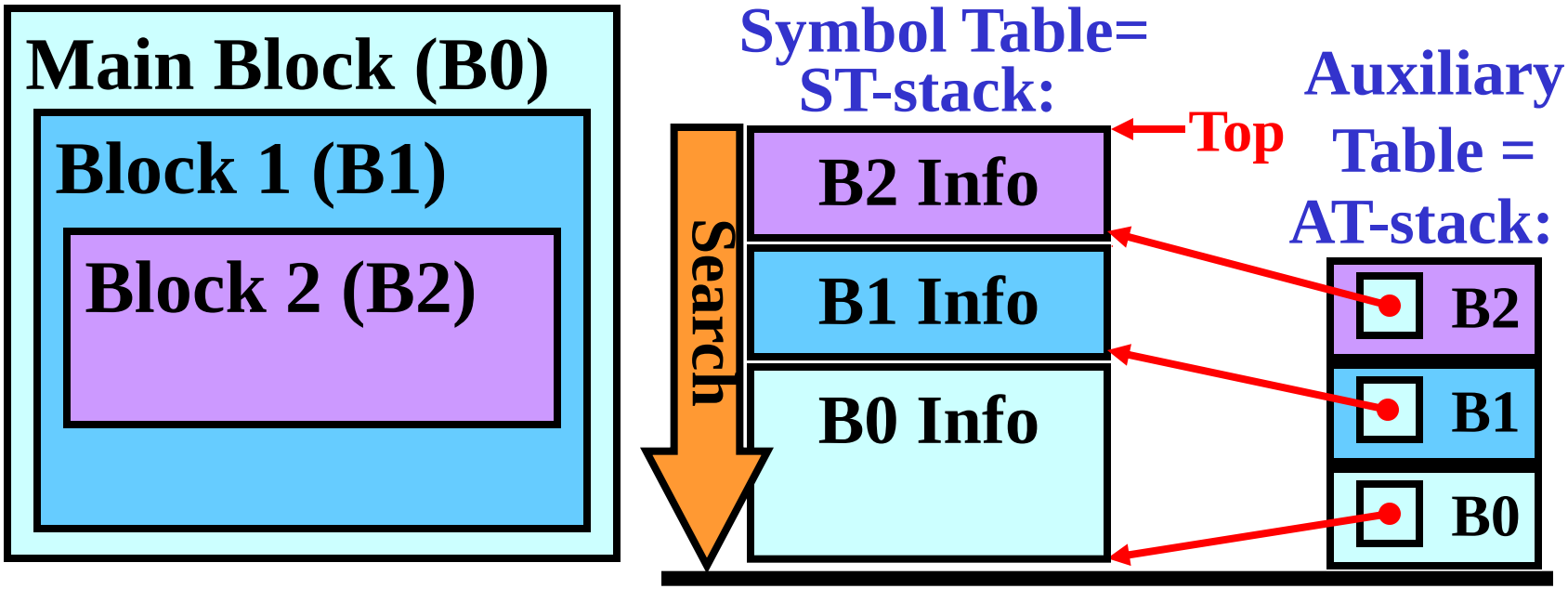
Scope Rules


Main Block (B0)
Block 1 (B1)
Block 2 (B2)
Symbol Table=
ST-stack:
Auxiliary
Table =
AT-stack:
Top
B1 Info
B0 Info
B1
B0

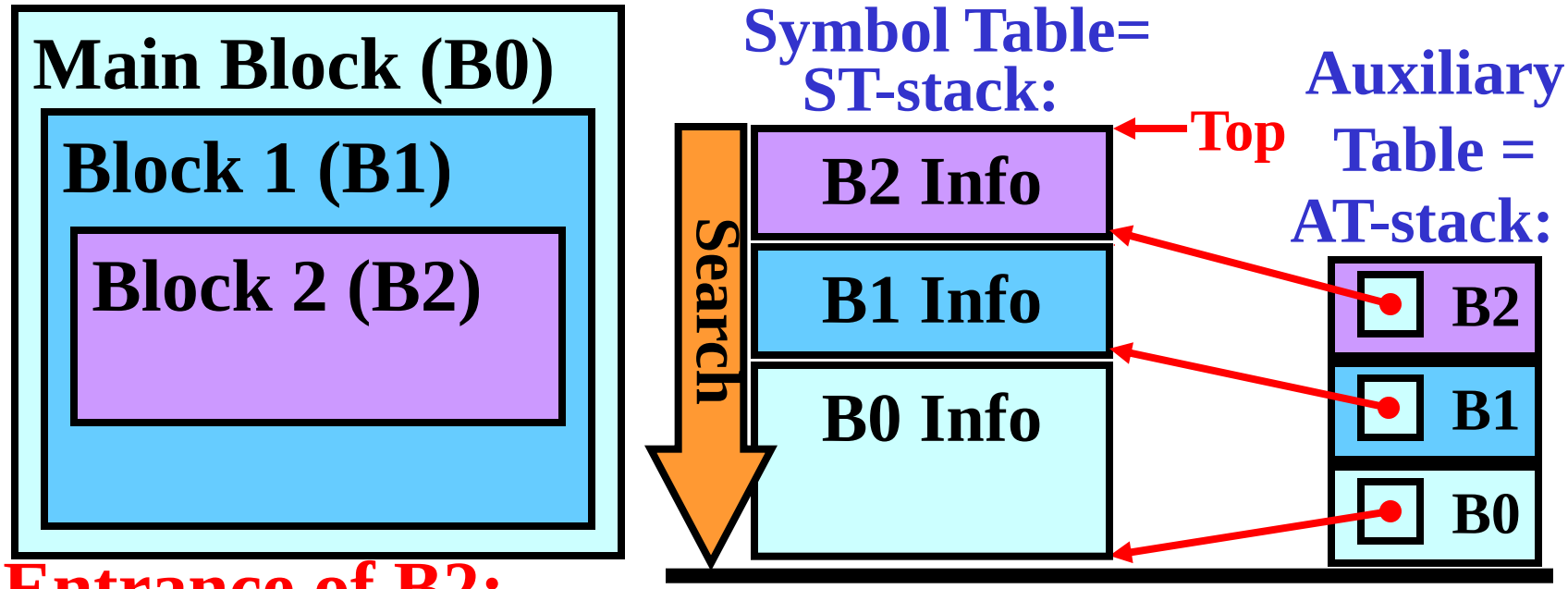
Scope Rules


Main Block (B0)
Block 1 (B1)
Block 2 (B2)
Symbol Table=
ST-stack:
Top
B2 Info
B1 Info
B0 Info
Auxiliary
Table =
AT-stack:
B2
B1
B0

Scope Rules


Main Block (B0)
Block 1 (B1)
Block 2 (B2)
Symbol Table=
ST-stack:
Top
Search
B2 Info
B1 Info
B0 Info
Auxiliary
Table =
AT-stack:
B2
B1
B0

Scope Rules



Entrance of B2:

- Push a pointer to the ST-stack top onto AT-stack

Exit from B2:

- The top of B1 Info becomes the ST-stack top
- Remove the B2 pointer from the AT-stack top

Search in ST:

- from the top towards the bottom

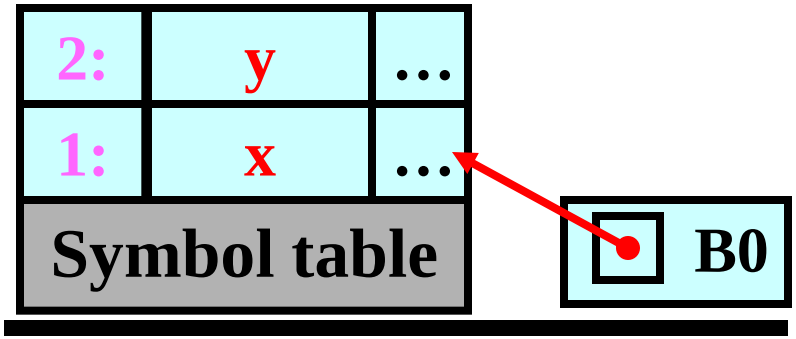
Scope Rules: Example

```
Program P1;
```

Symbol table

Scope Rules: Example

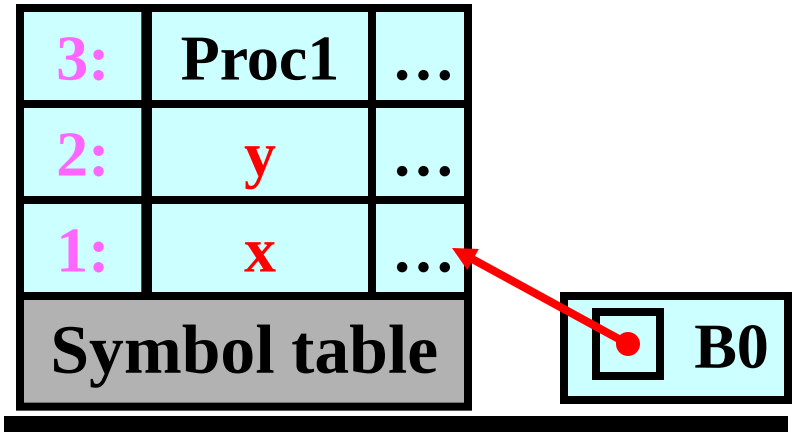
```
Program P1;
var x, y: integer;
```



Scope Rules: Example

```
Program P1;
var x, y: integer;

Procedure Proc1;
```



Scope Rules: Example

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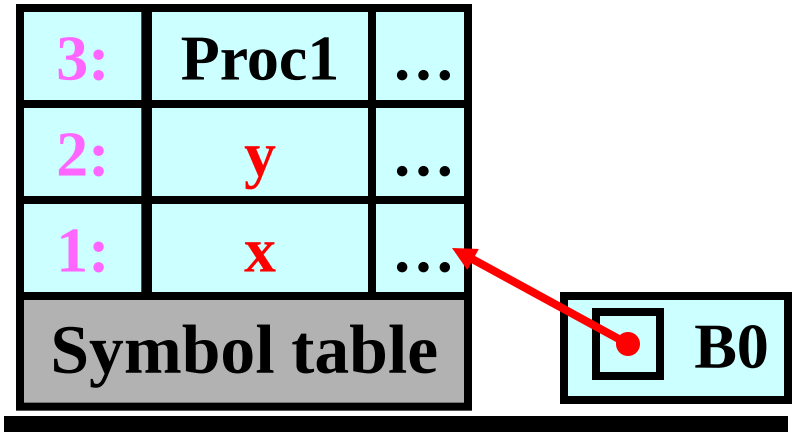
Program P1;
var x, y: integer;

Procedure Proc1;
var x, y: integer;
```



Scope Rules: Example

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var x, y: integer;

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var x, y: integer;
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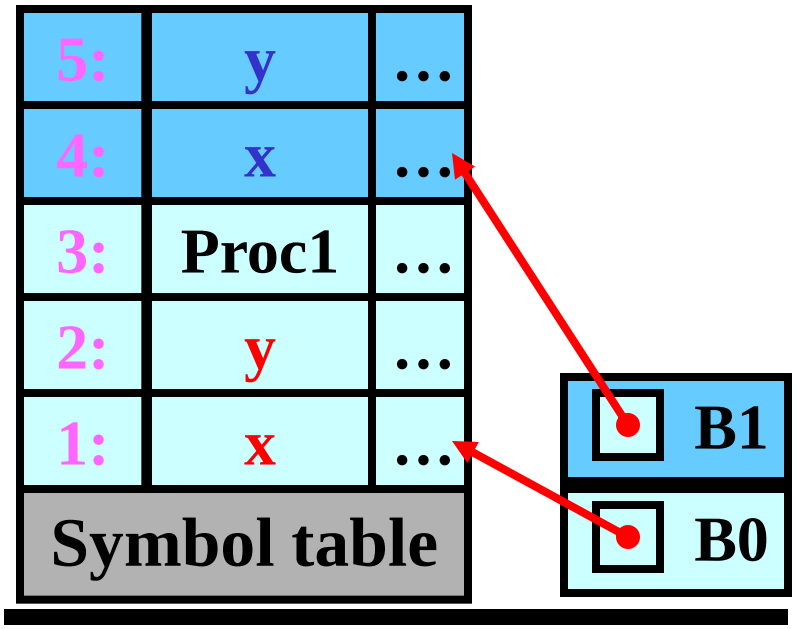
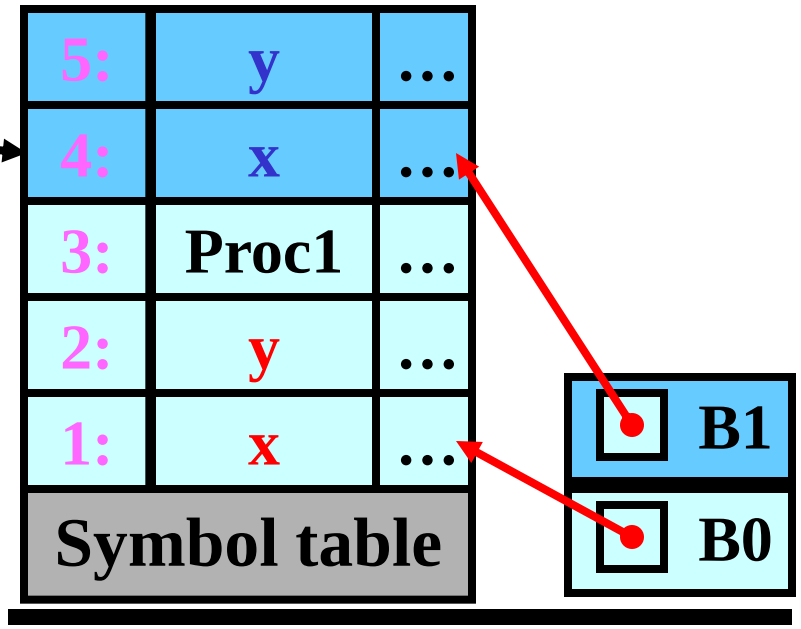


Scope Rules: Example

```
Program P1;
var x, y: integer;

Procedure Proc1;
var x, y: integer;
begin
   … x := 1; …
end;
```

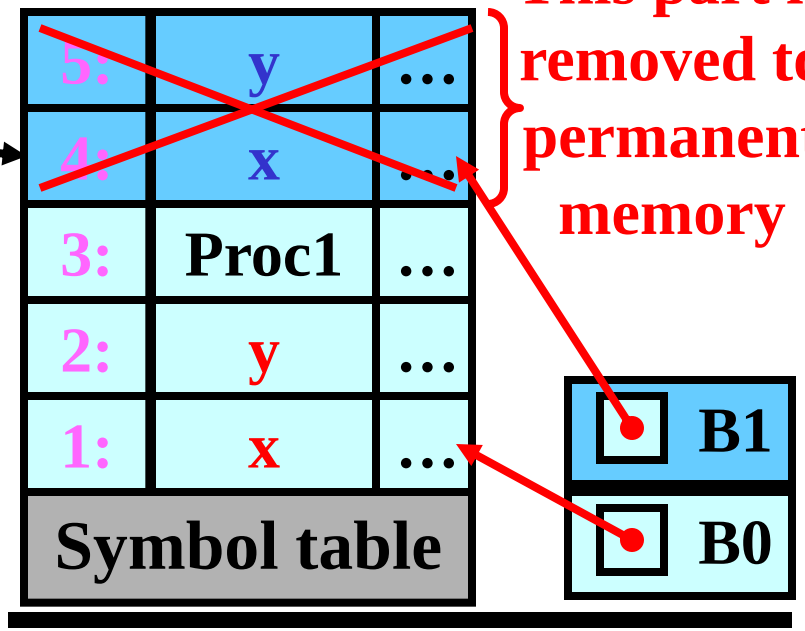


Scope Rules: Example

```
Program P1;
var x, y: integer;

Procedure Proc1;
var x, y: integer;
begin
   … x := 1; …
end;

begin
   … x := 2; …
end.
```



Scope Rules: Example

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```

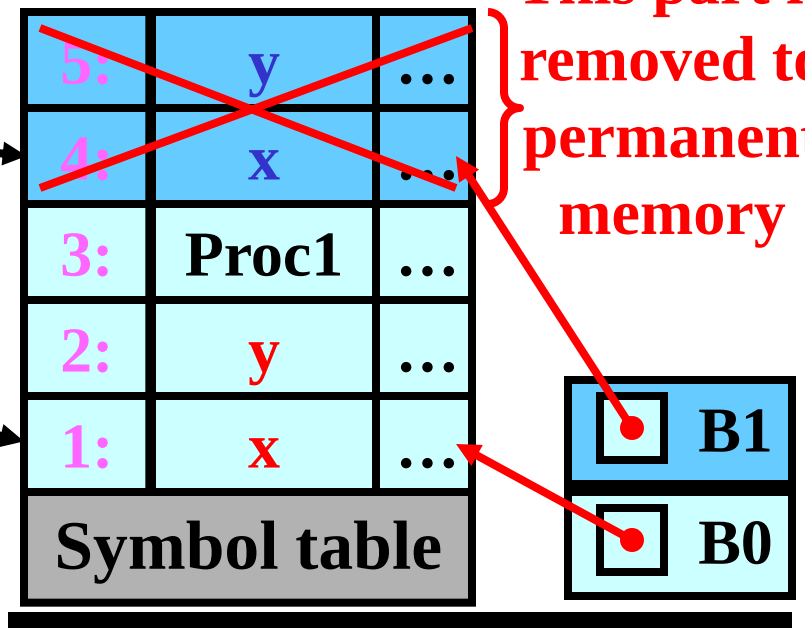

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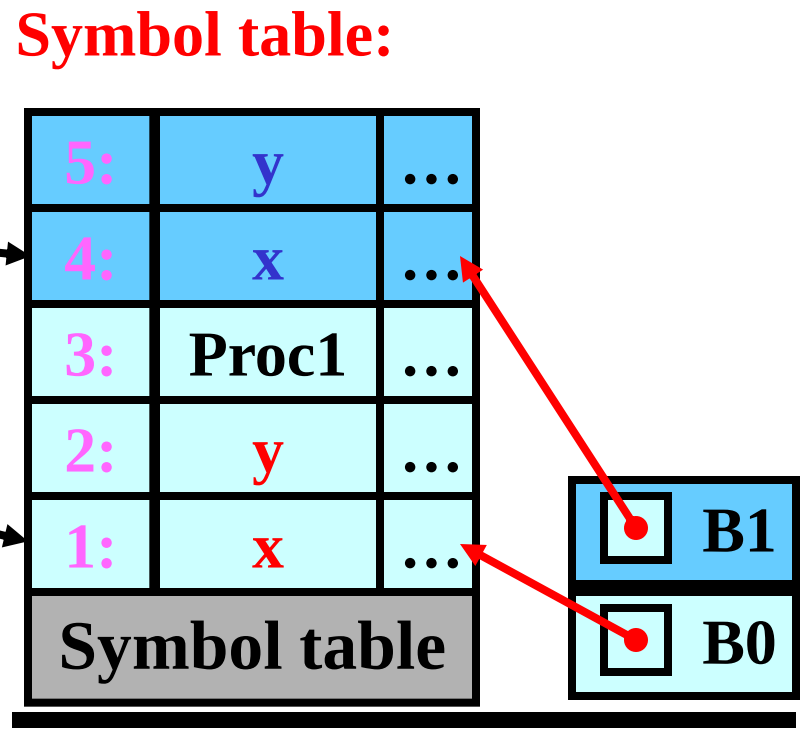
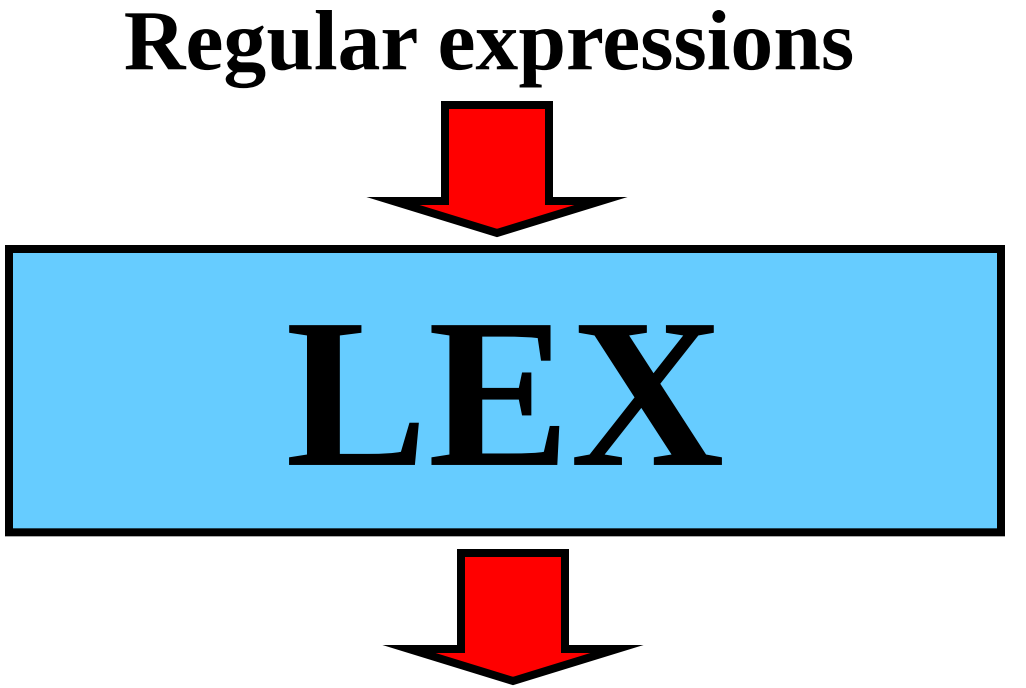


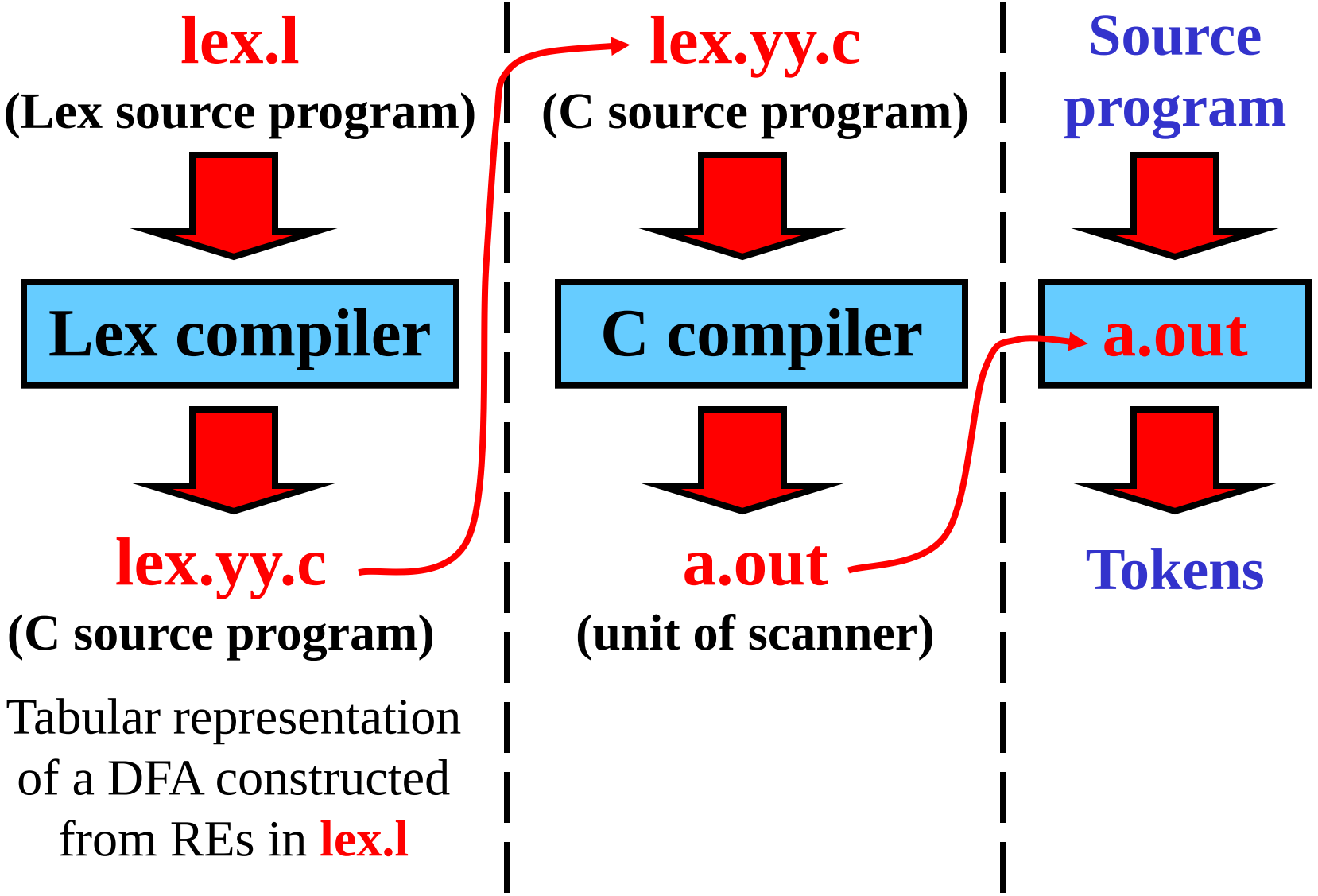
Lex: Basic Idea

- Automatic construction of a **scanner** from **RE**
- Lex compiler and Lex language

Illustration:



Lex: Phases of Compilation



Structure of Lex Source Program

/* **Section I:** Declaration */

$d_1, d_2, \ \ldots \ , d_i$

%% /* End of Section I*/

/* **Section II:** Translation rules */

$r_1, r_2, \ \ldots \ , r_j$

%% /* End of Section II*/

/* **Section III:** Auxiliary procedures*/

$p_1, p_2, \ \ldots \ , p_k$

Basic Regular Expressions in Lex

RE in LEX	Equivalent RE in theory of formal languages
`a`	a
`rs`	$r.s$
`r|s`	$r + s$
`r*`	r^*
`r+`	r^+
`r?`	$r + \varepsilon$
`[a-z]`	$a + b + c + \ldots + z$
`[0-9]`	$0 + 1 + 2 + \ldots + 9$

Section I: Declaration

1) Definitions of manifest constants = token types

2) Definitions based on REs are in the form:

```
Name_of_RE          RE
```

- `Name_of_RE` represents `RE`
- `{Name_of_RE}` is a reference to `Name_of_RE` used in other REs

Section I: Declaration

1) Definitions of manifest constants = token types

2) Definitions based on REs are in the form:

```
Name_of_RE        RE
```

- **Name_of_RE** represents **RE**
- **{Name_of_RE}** is a reference to **Name_of_RE** used in other REs

Example:

```
#define    IF    256    /* constant for IF */
#define    THEN  257    /* constant for THEN */
#define    ID    258    /* constant for ID */
#define    INT   259    /* constant for NUM */
letter     [a-z]
digit      [0-9]
id         {letter}({letter}|{digit})*
integer    {digit}+
```

Section II: Translation Rules

- Translation rules are in the form:

RE	Action

- **Action** is a program routine that specifies what to do when a lexeme is specified by **RE**

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RE	Action

- **Action** is a program routine that specifies what to do when a lexeme is specified by **RE**

Example:

```
if          return(IF);
then        return(THEN);
{id}        { yylval = install_id();
              return(ID); }
{integer}   { yylval = install_int();
              return(INT); }
```

yylval: value returned by install_id() = attribute of token

Section III: Auxiliary Procedures

- Auxiliary procedures are needed by translation rules

Section III: Auxiliary Procedures

- Auxiliary procedures are needed by translation rules

Example:

```
…
{id}        { yylval = install_id();
              return(ID); }
…
%%
…
int install_id() {
      /* Procedure to install the lexeme into the symbol
         table and return a pointer thereto */
}
…
```

Complete Source Program in Lex

```
#define    IF    256    /* constant for IF */
#define    THEN  257    /* constant for THEN */
#define    ID    258    /* constant for ID */
#define    INT   259    /* constant for NUM */
int yylval;             /* yylval is visible for parser */
letter     [a-z]
digit      [0-9]
id         {letter}({letter}|{digit})*
integer    {digit}+
%%
if         return(IF);
then       return(THEN);
{id}       {yylval = install_id() ;return(ID) ;}
{integer}  {yylval = install_int();return(INT);}
%%
int install_id()   { ... }
int install_int()  { ... }
```