# Lexical Analysis

**Input:** ***Program represented by a sequence of characters***

| **Tasks:** | **Compiler modul:** |
|---|---|
| | Input reader |
| Recognize and classify tokens | Scanner (central phase, finite state machine) |
| Skip irrelevant characters | |
| Encode tokens: | |
| | Identifier modul |
| Store token information | Literal modules |
| Conversion | String storage |

**Output:** ***Program represented by a sequence of encoded tokens***

# Representation of tokens

Uniform encoding of tokens by triples:

| **Syntax code** | **attribute** | **source position** |
|---|---|---|
| terminal code of the concrete syntax | value or reference into data module | to locate error messages of later compiler phases |

**Examples**:

```
double sum = 5.6e-5;
while (count < maxVect)
{ sum = sum + vect[count];
```

| | | |
|---|---|---|
| DoubleToken | | 12, 1 |
| Ident | 138 | 12, 8 |
| Assign | | 12, 12 |
| FloatNumber | 16 | 12, 14 |
| Semicolon | | 12, 20 |
| WhileToken | | 13, 1 |
| OpenParen | | 13, 7 |
| Ident | 139 | 13, 8 |
| LessOpr | | 13, 14 |
| Ident | 137 | 13, 16 |
| CloseParen | | 13, 23 |
| OpenBracket | | 14, 1 |
| Ident | 138 | 14, 3 |

# Specification of token notations

## Example: identifiers

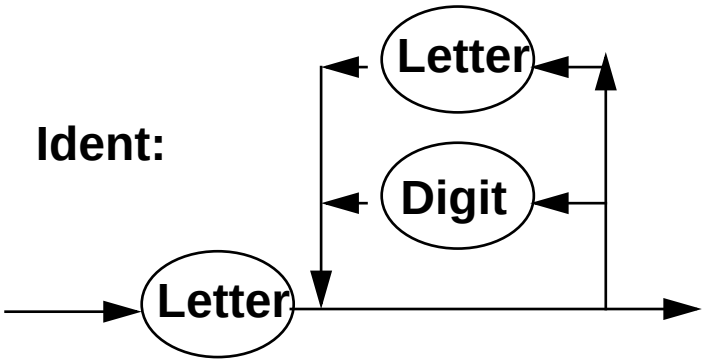
**Ident = Letter (Letter | Digit)***

**regular grammar**

**Ident ::= Letter X**
**X ::= Letter X**
**X ::= Digit X**
**X ::=**

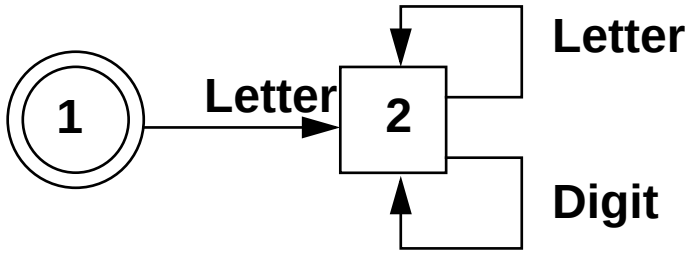
**regular expression**

**syntax diagram**



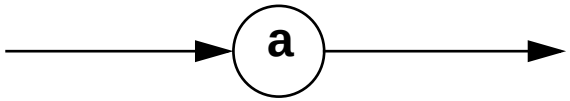
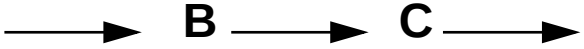
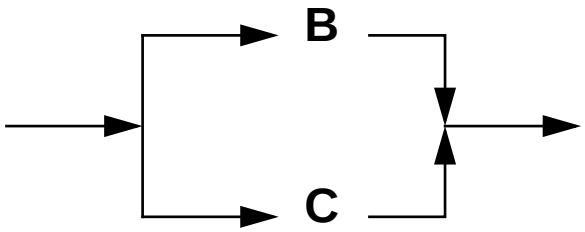
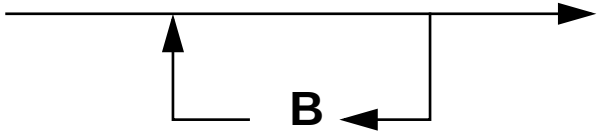
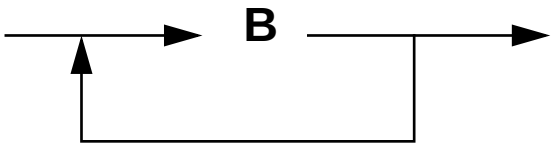

**acceptor:**

**finite state machine**



# Regular expressions mapped to syntax diagrams

**Transformation rules:**

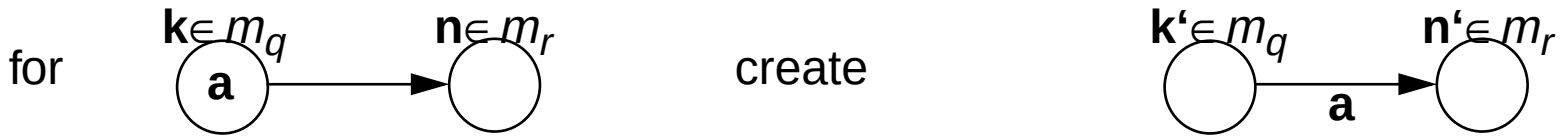
| regular expression A | syntax diagram for A | |
|---|---|---|
| *empty* |  | empty |
| a |   | single character |
| B C |   | sequence |
| B \| C |   | alternative |
| B* |   | repetition, may be empty |
| $B^+$ |   | repetition, non-empty |

# Construction of deterministic finite state machines

| **Syntax diagram** | **deterministic finite state machine** |
|---|---|
| nodes, arcs | transitions, states |
| set of nodes $m_q$ | state $q$ |
| sets of nodes $m_q$ and $m_r$ connected with the same character $a$ | transitions $q$ ---> $r$ with character $a$ |

**Construction:**

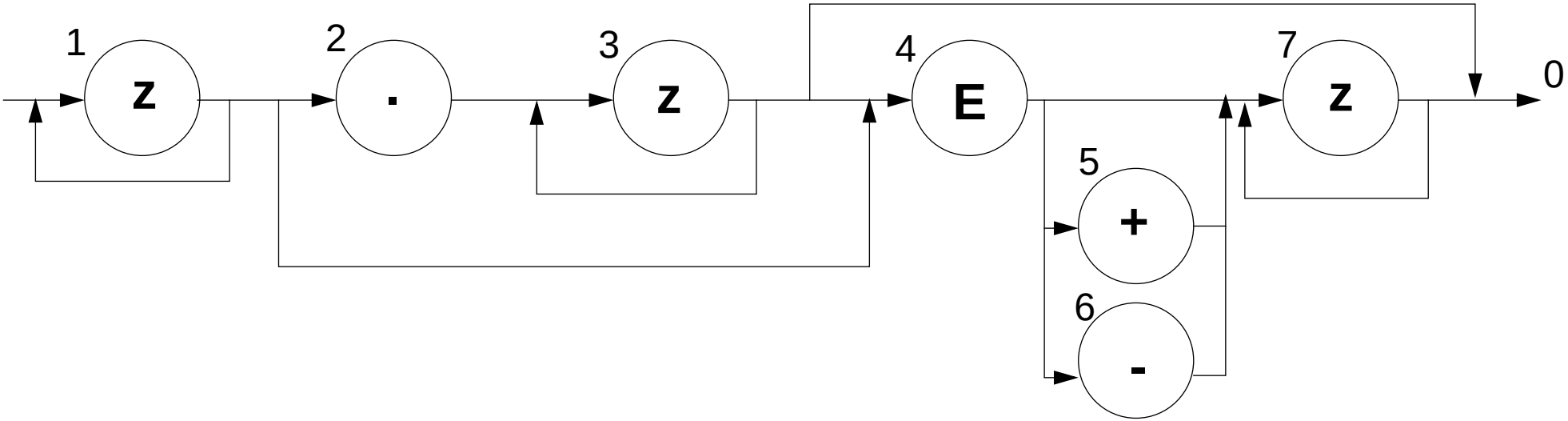
1. **enumerate nodes**; exit of the diagram gets the number *0*
2. **initial set of nodes** $m_1$ contains all nodes that are reachable from the begin of the diagram — **initial state** *1*
3. **construct new sets of nodes (states)** and **transitions:** For a character *a* and a set $m_q$ containing node *k* create set $m_r$ with all nodes *n*, according to the following schema:




4. **repeat step 3** until no new sets of nodes can be created
5. a state *q* is a **final state** iff *0* is in $m_q$.

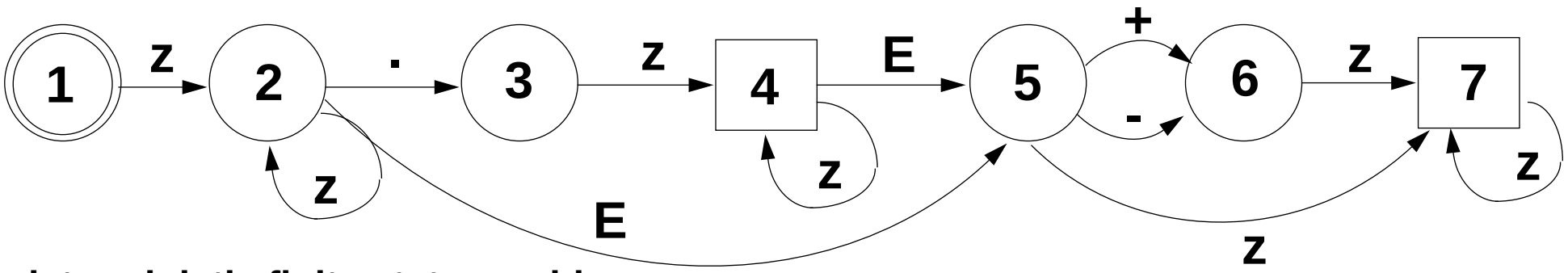
# Example: Floating point numbers in Pascal

## Syntax diagram




**{1}** **{1, 2, 4}** **{3}** **{3, 4, 0}** **{5, 6, 7}** **{7}** **{7, 0}**

**z** **z . E** **z** **z E** **+ - z** **z** **z**

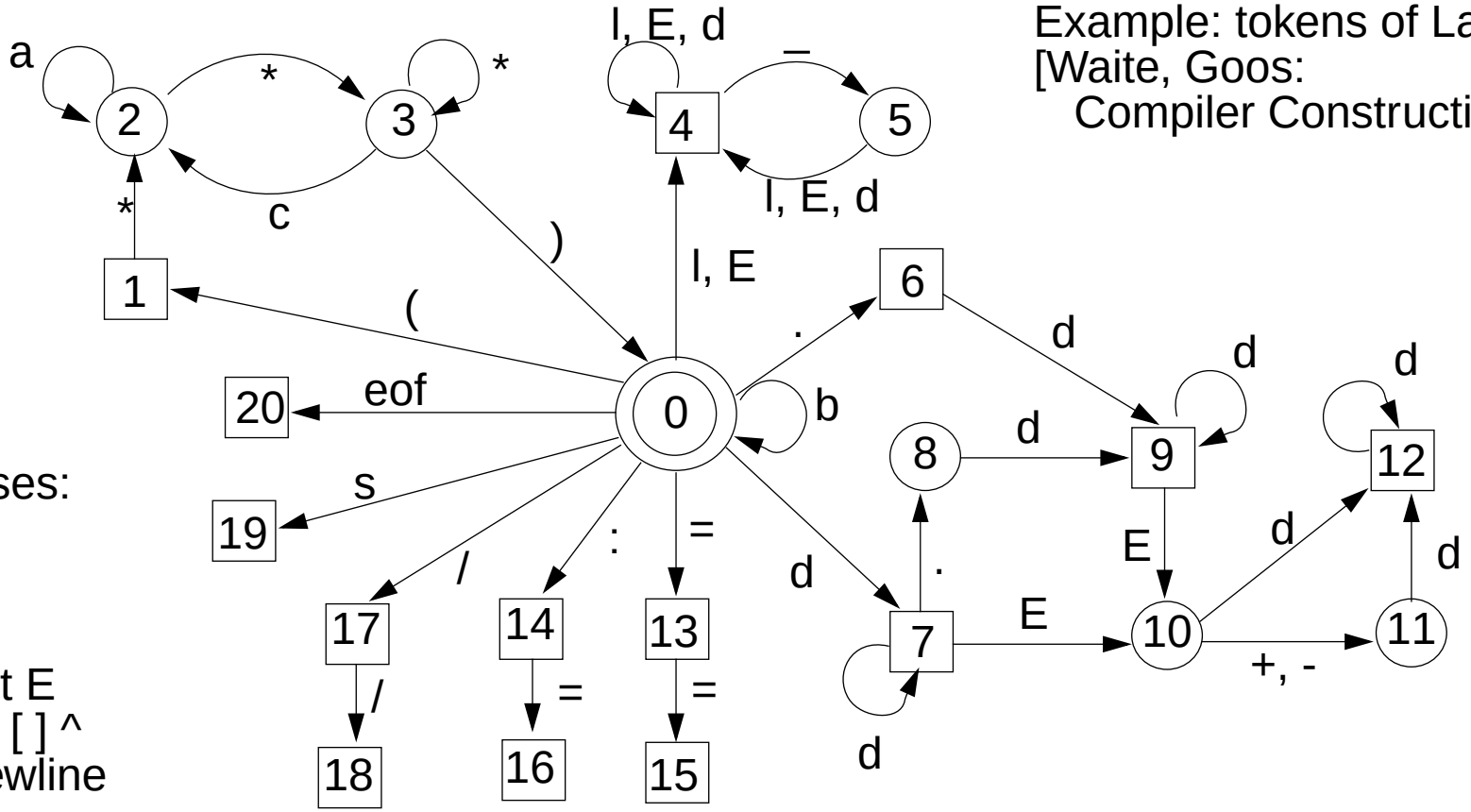



**deterministic finite state machine**

# Composition of token automata

Construct one finite state machine for each token. Compose them forming a single one:

- **Identify the initial states of the single automata**
  and identical structures evolving from there (transitions with the same character and states).
- **Keep the final states of single automata distinct,** they classify the tokens.
- **Add automata for comments and irrelevant characters** (white space)




Example: tokens of Lax
[Waite, Goos:
Compiler Construction]

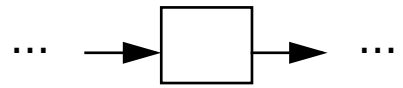
character classes:

a all but *
c all but * or )
d digits
l all letters but E
s + - * < > ; , ) [ ] ^
b blank tab newline

# Rule of the longest match

An automaton may contain **transitions from final states:**

When does the automaton stop?




**Rule of the longest match:**

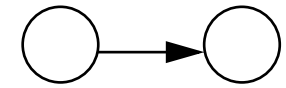
- **The automaton continues as long as there is a transition with the next character.**
- **After having stopped it sets back to the most recently passed final state.**
- **If no final state has been passed an error message is issued.**

Consequence: Some kinds of tokens have to be separated explicitly.

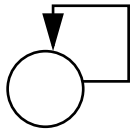
Check the concrete grammar for tokens that may occur adjacent!

# Scanner: Aspects of implementation

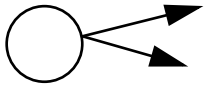
- **Runtime is proportional to the number of characters in the program**
- **Operations per character must be fast** - otherwise the Scanner dominates compilation time
- **Table driven** automata are too **slow:**
  Loop interprets table, 2-dimensional array access, branches
- **Directly programmed** automata is **faster;** transform **transitions into control flow:**



**sequence**



**repeat loop**



**branch**

- **Fast loops** for sequences of irrelevant **blanks**.
- Implementation of **character classes**:
  bit pattern or indexing - avoid slow operations with sets of characters.
- **Do not copy characters** from input buffer - maintain a pointer into the buffer, instead.

# Identifier module and literal modules

- **Uniform interface for all scanner support modules:**
  Input parameters: pointer to token text and its length;
  Output parameters: syntax code, attribute

- **Identifier module encodes identifier occurrences bijective (1:1), and recognizes keywords**
  Implementation: hash vector, extensible table, collision lists

- **Literal modules for floating point numbers, integral numbers, strings**

  **Variants for representation in memory:**
  token text; value converted into compiler data; value converted into target data

  **Caution:**
  Avoid overflow on conversion!
  Cross compiler: compiler representation may differ from target representation

- **Character string memory:**
  stores strings without limits on their lengths,
  used by the identifier module and the literal modules

# Scanner generators

**generate the central function of lexical analysis**

| | |
|---|---|
| **GLA** | University of Colorado, Boulder; component of the Eli system |
| **Lex** | Unix standard tool |
| **Flex** | Successor of Lex |
| **Rex** | GMD Karlsruhe |

**Token specification: regular expressions**

| | |
|---|---|
| **GLA** | library of precoined specifications;<br>recognizers for some tokens may be programmed |
| **Lex, Flex, Rex** | transitions may be made conditional |

**Interface:**

| | |
|---|---|
| **GLA** | as described in this chapter; cooperates with other Eli components |
| **Lex, Flex, Rex** | actions may be associated with tokens (statement sequences)<br>interface to parser generator Yacc |

**Implementation:**

| | |
|---|---|
| **GLA** | directly programmed automaton in C |
| **Lex, Flex, Rex** | table-driven automaton in C |
| **Rex** | table-driven automaton in C or in Modula-2 |
| **Flex, Rex** | faster, smaller implementations than generated by Lex |