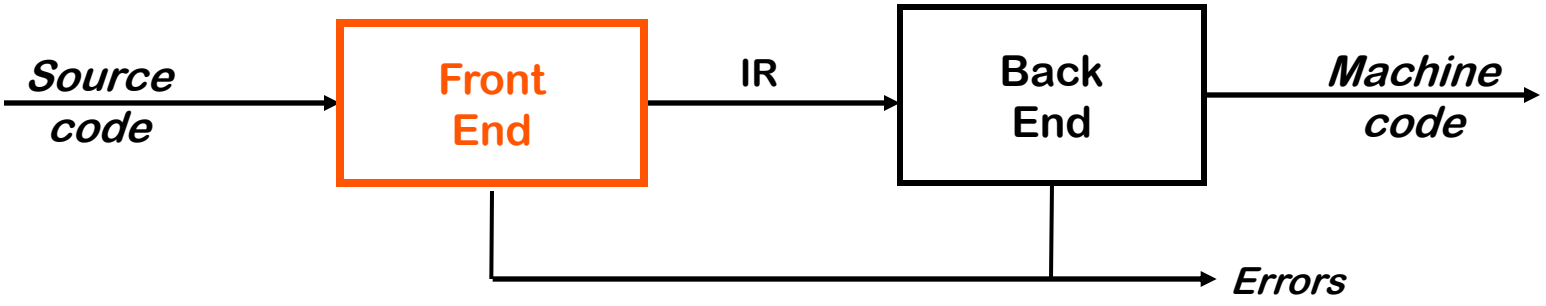
Lexical Analysis

Introduction

The Front End

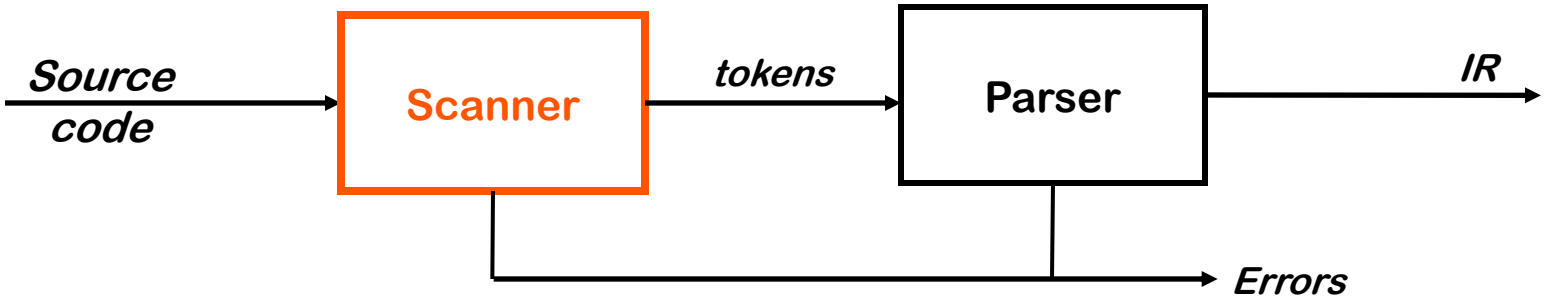


The purpose of the front end is to deal with the input language

- Perform a membership test: code ∈ source language?
- Is the program well-formed (semantically) ?
- Build an IR version of the code for the rest of the compiler

The front end is not monolithic

The Front End



Scanner

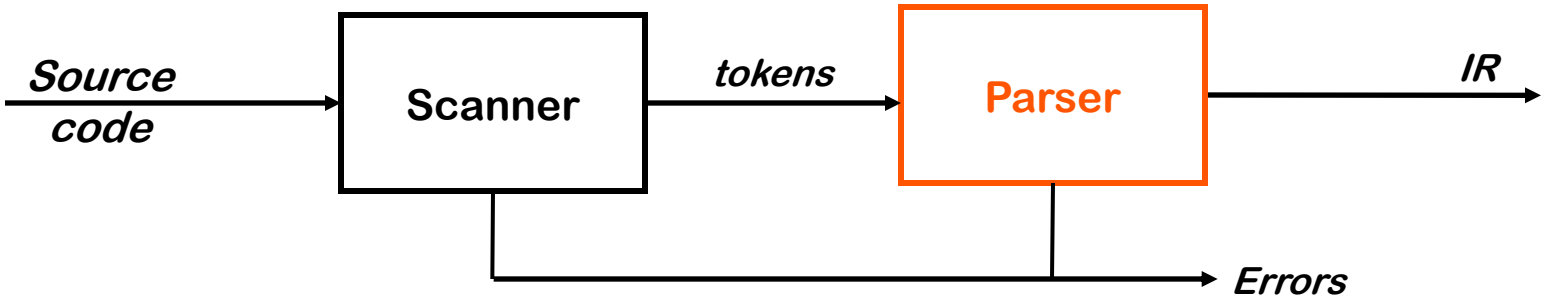
- Maps stream of characters into words
  - Basic unit of syntax
  - **x = x + y ;** *becomes*

    <id,x> <eq,=> <id,x> <pl,+> <id,y> <sc,; >
- Characters that form a word are its *lexeme*
- Its *part of speech* (or *syntactic category*) is called its *token type*
- Scanner discards white space & (often) comments

Speed is an issue in scanning

⇒ use a specialized recognizer

The Front End



Parser

- Checks stream of classified words (*parts of speech*) for grammatical correctness
- Determines if code is syntactically well-formed
- Guides checking at deeper levels than syntax
- Builds an IR representation of the code

We'll come back to parsing in a couple of lectures

The Big Picture

- Language syntax is specified with *parts of speech*, not *words*
- Syntax checking matches *parts of speech* against a grammar

1. *goal* → *expr*
2. *expr* → *expr op term*
3. | *term*
4. *term* → number
5. | id
6. *op* → +
7. | –

S = *goal*

T = { number, id, +, - }

N = { *goal*, *expr*, *term*, *op* }

P = { 1, 2, 3, 4, 5, 6, 7}

The Big Picture

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S = *goal*

T = { number, id, +, - }

N = { *goal*, *expr*, *term*, *op* }

P = { 1, 2, 3, 4, 5, 6, 7}

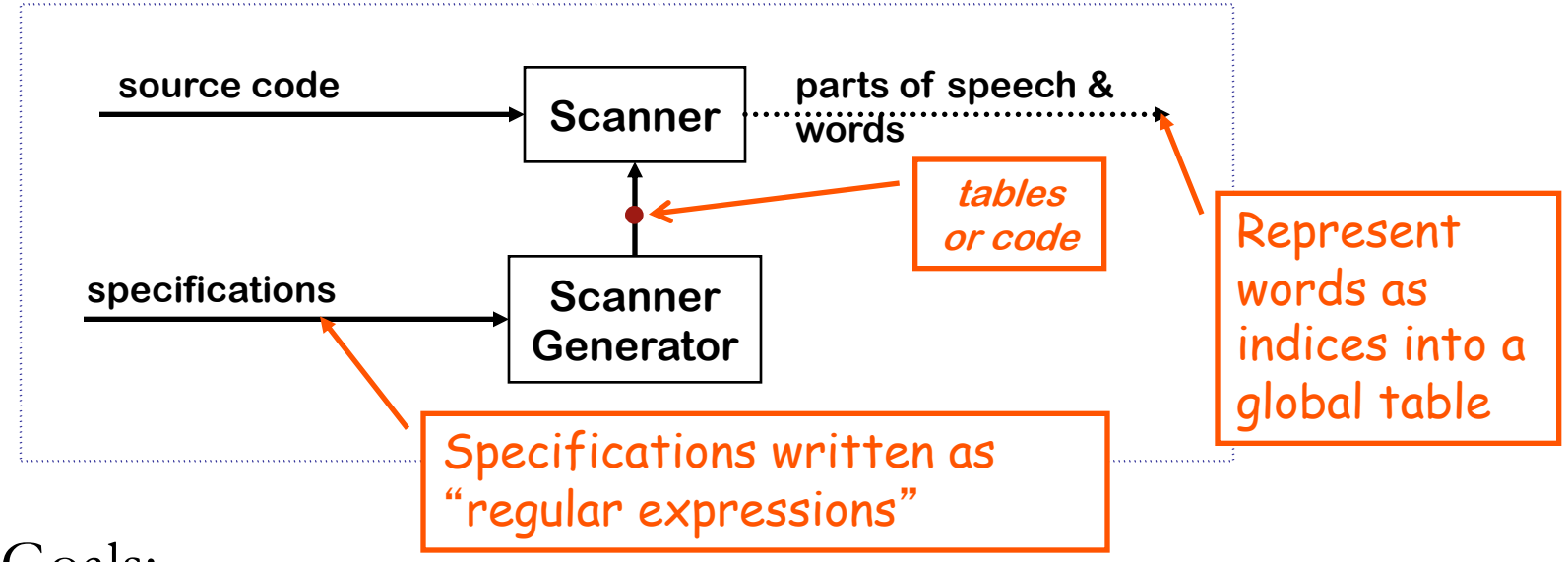
No words here!

Parts of speech, not words!

The Big Picture

Why study Lexical Analysis?

- We want to avoid writing Scanners by hand
- We want to harness the theory classes



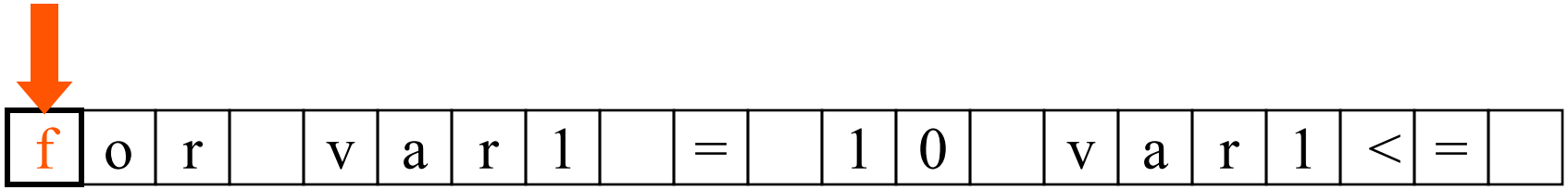
- Goals:
  - To simplify specification & implementation of scanners
  - To understand the underlying techniques and technologies

What is a Lexical Analyzer?

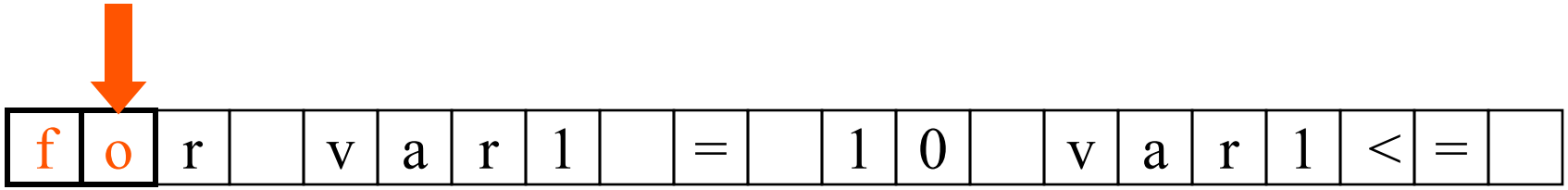
Source program text  Tokens

- Example of Tokens
  - Operators = + - > ({ := == <>
  - Keywords if while for int double
  - Numeric literals 43 4.565 -3.6e10 0x13F3A
  - Character literals 'a' '~' '\''
  - String literals "4.565" "Fall 10" "\"\" = empty"
- Example of non-tokens
  - White space space(' ') tab('\t') end-of-line('\n')
  - Comments /*this is not a token*/

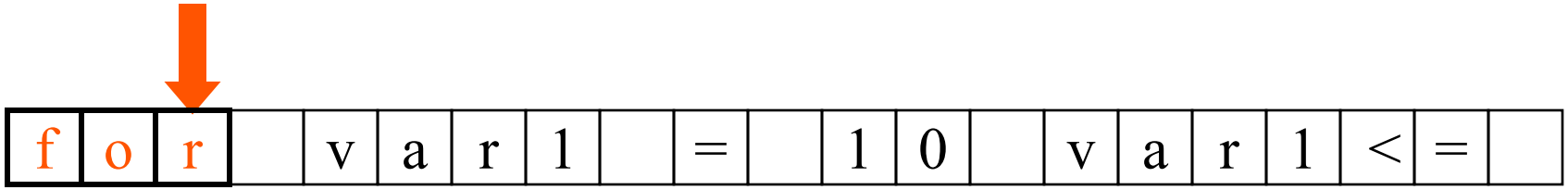
Lexical Analyzer in Action



Lexical Analyzer in Action



Lexical Analyzer in Action



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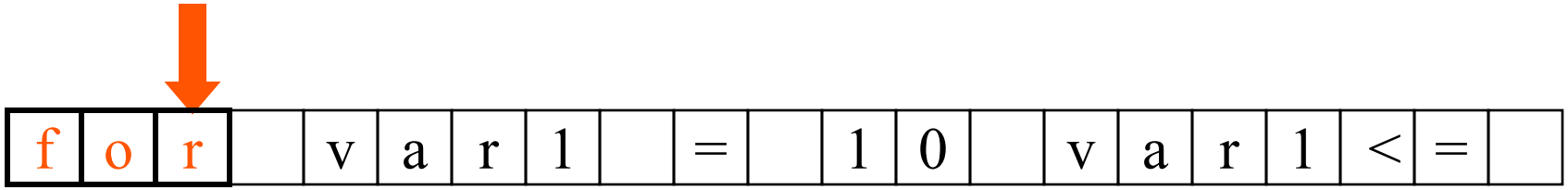
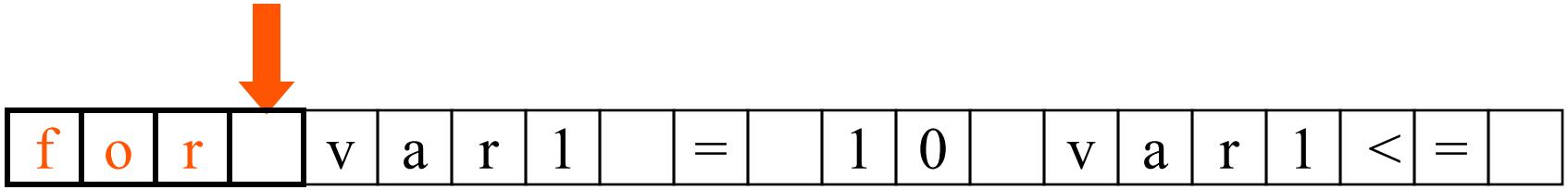


for_key

Lexical Analyzer in Action



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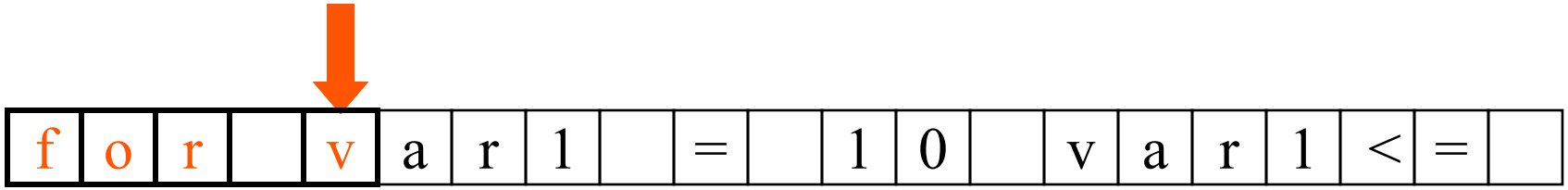

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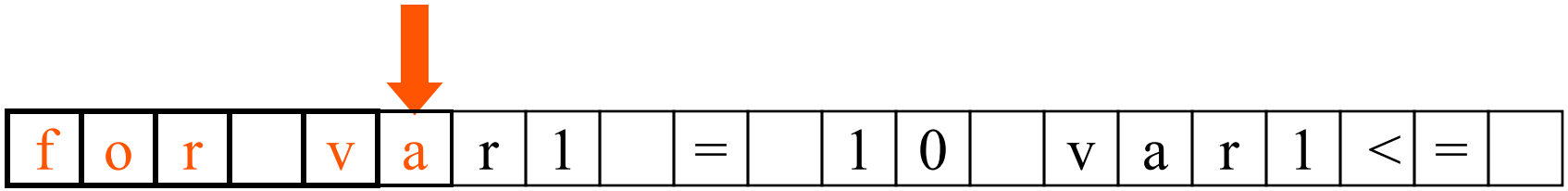

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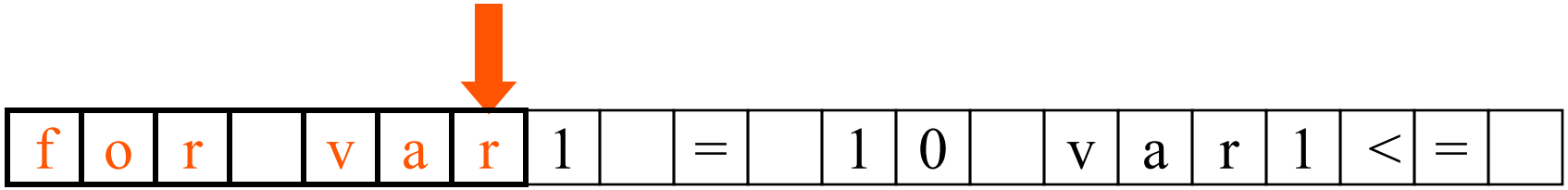

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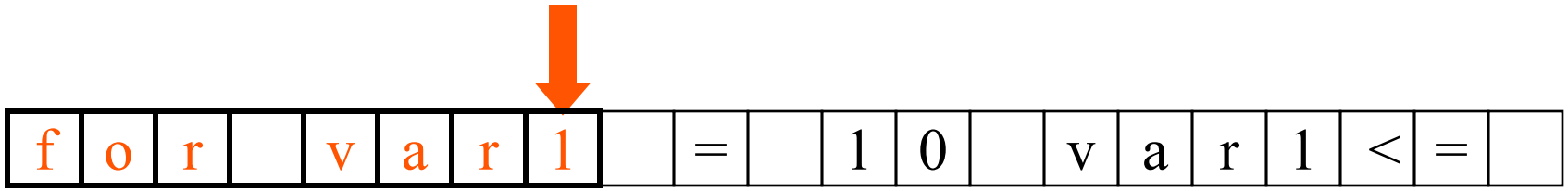
Lexical Analyzer in Action



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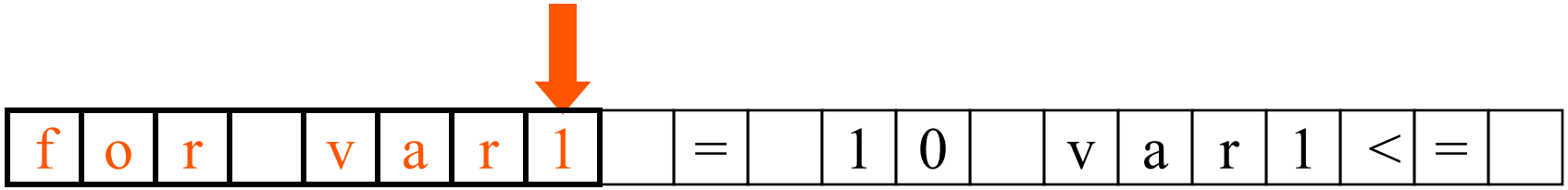
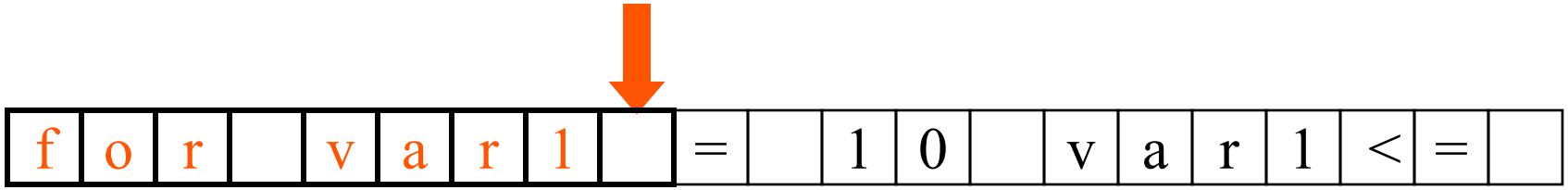
Lexical Analyzer in Action



for_key ID("var1")

Lexical Analyzer in Action



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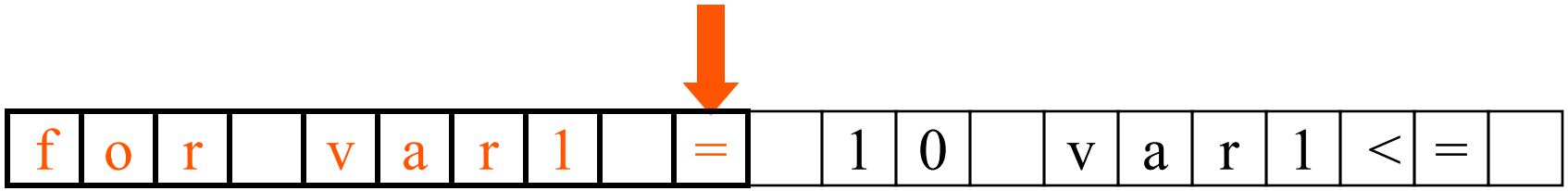

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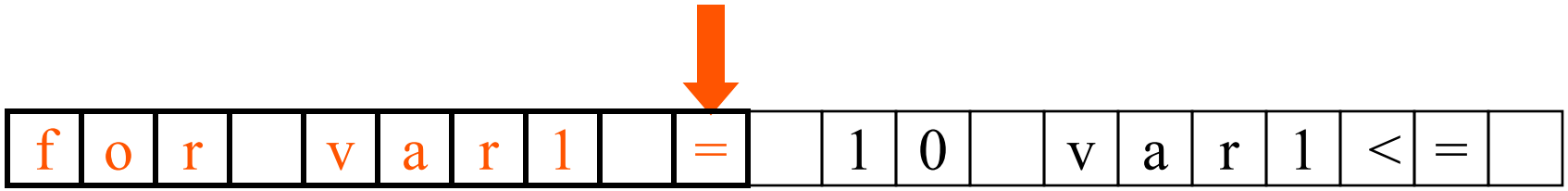

for_key ID("var1") eq_op

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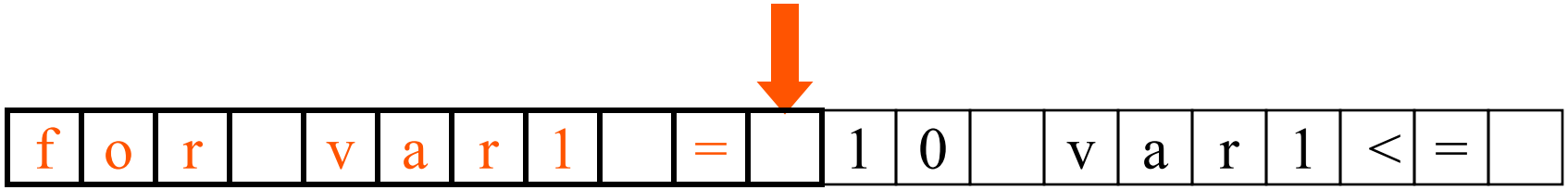

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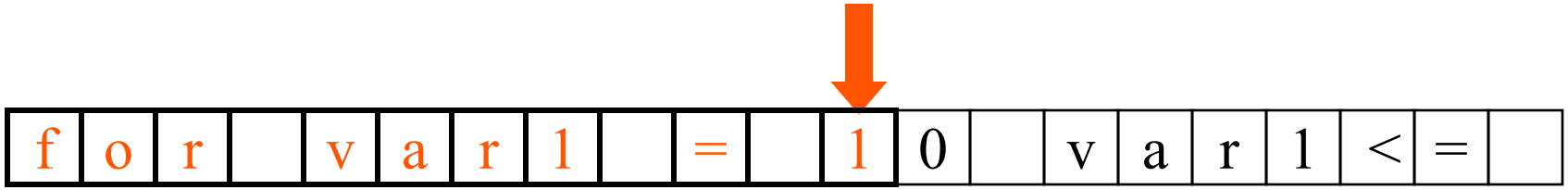

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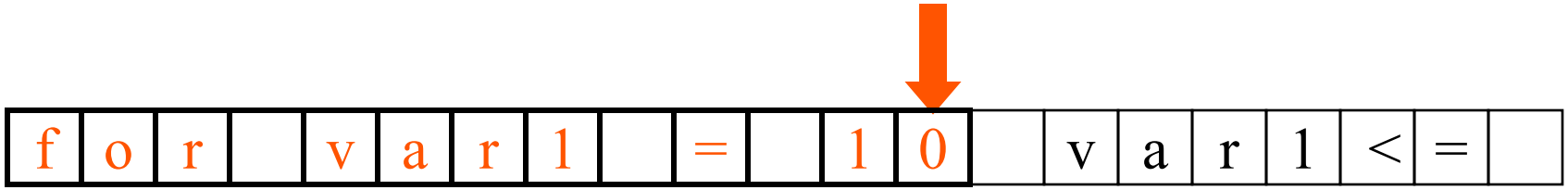

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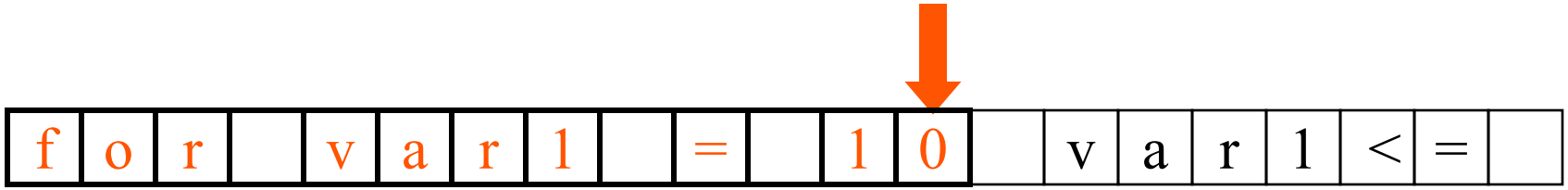
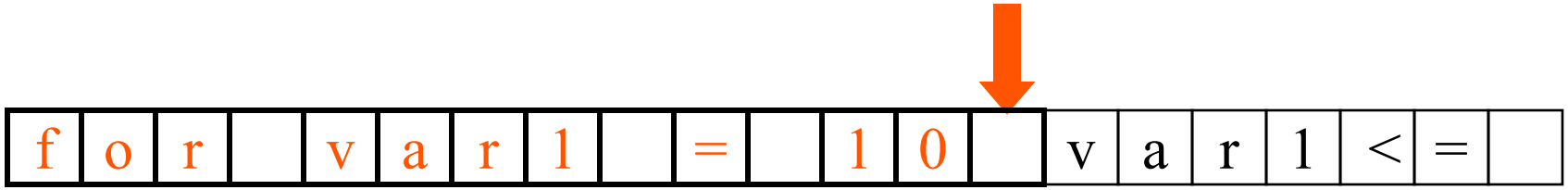


for_key ID("var1") eq_op Num(10)

Lexical Analyzer in Action



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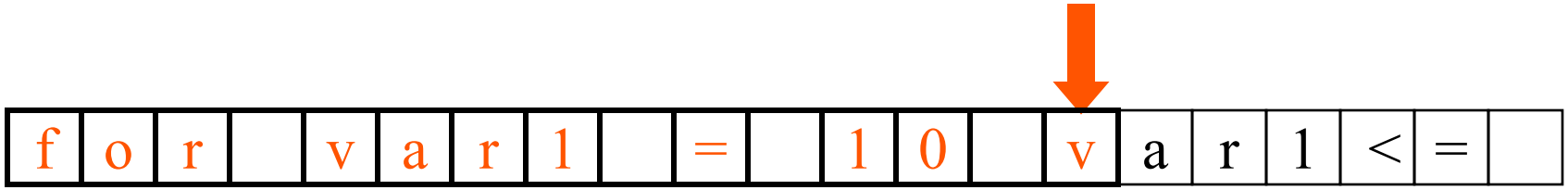

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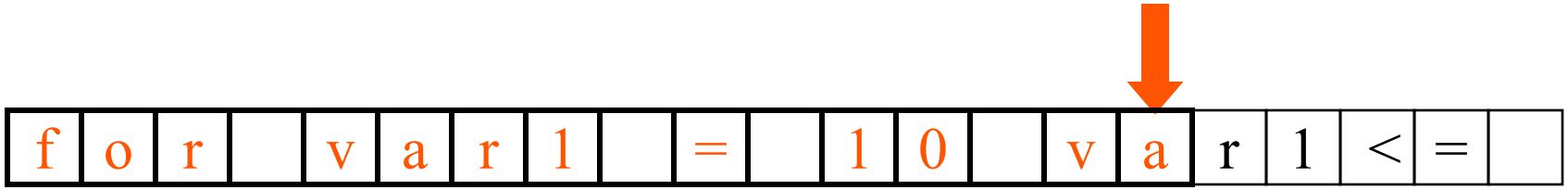

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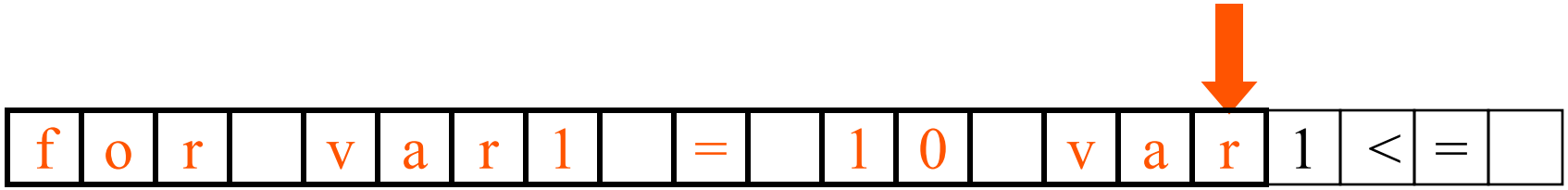

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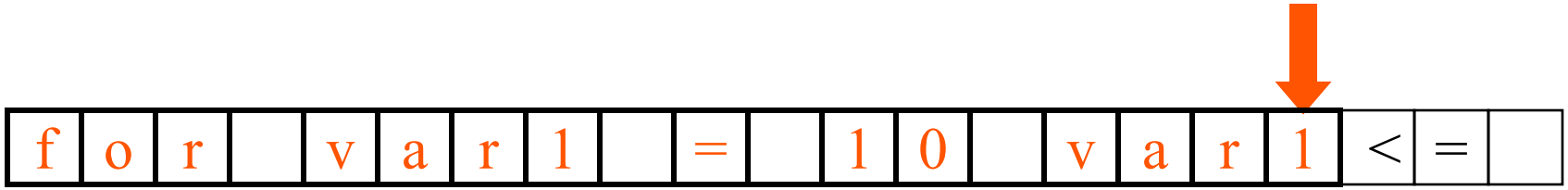

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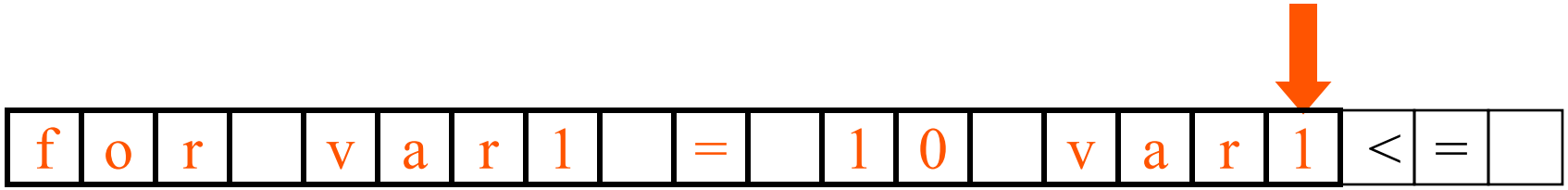

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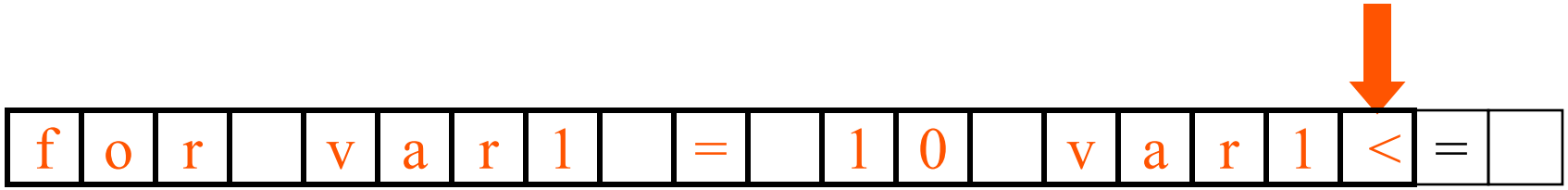

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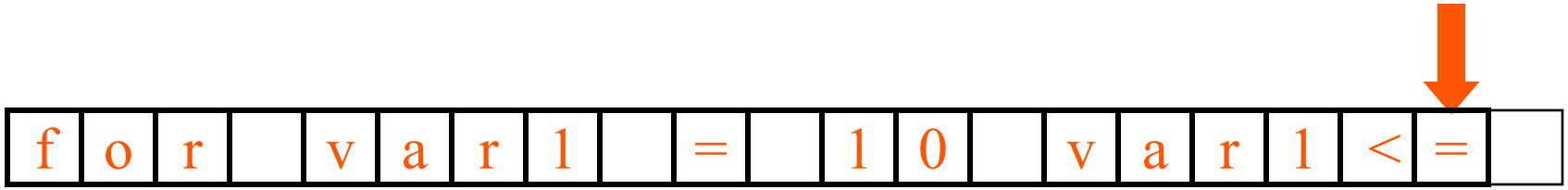

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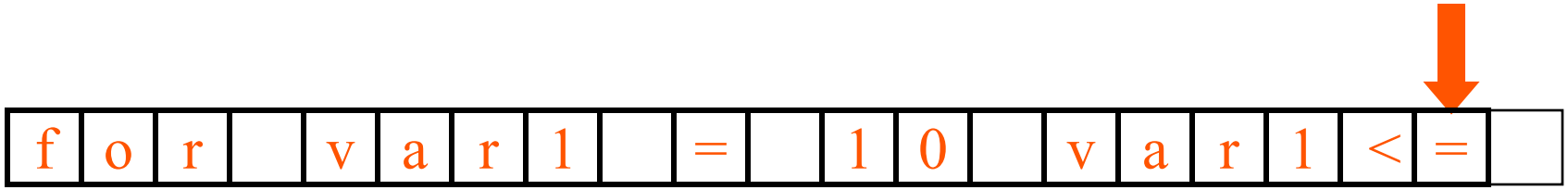

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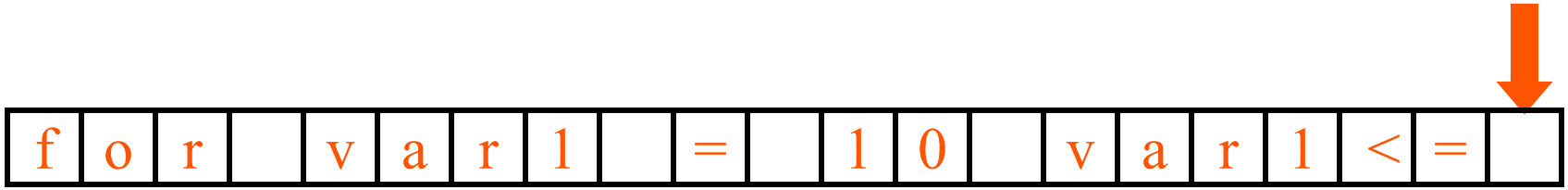

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Lexical Analyzer needs to…

- Partition Input Program Text into Subsequence of Characters Corresponding to Tokens
- Attach the Corresponding Attributes to the Tokens
- Eliminate White Space and Comments

Lexical Analysis: Basic Issues

- How to Precisely Match Strings to Tokens
- How to Implement a Lexical Analyzer

Regular Expressions

Lexical patterns form a *regular language*

*** *any finite language is regular* ***

Regular expressions (REs) describe regular languages

Regular Expression (over alphabet Σ)

- ε is a RE denoting the set {ε}
- If a is in Σ then a is a RE denoting {a}
- If x and y are REs denoting $L(x)$ and $L(y)$ then
  - $x \mid y$ is an RE denoting $L(x) \cup L(y)$
  - xy is an RE denoting $L(x)L(y)$
  - x^* is an RE denoting $L(x)^*$

Precedence : *closure*, then *concatenation*, then *alternation*

Set Operations (review)

Operation	Definition
Union of L and M Written L ∪ M	$L \cup M = \{s \mid s \in L \text{ or } s \in M\}$
Concatenation of L and M Written LM	$LM = \{st \mid s \in L \text{ and } t \in M\}$
Kleene closure of L Written L^*	$L^* = \bigcup_{0 \le i \le \infty} L^i$
Positive Closure of L Written L^+	$L^+ = \bigcup_{1 \le i \le \infty} L^i$

These definitions should be well known

Examples of Regular Expressions

Identifiers:

Letter → (a|b|c| … |z|A|B|C| … |Z)

Digit → (0|1|2| … |9)

Identifier → *Letter* (*Letter* | *Digit*)*

Numbers:

Integer → (+|-| ε) (0| (1|2|3| … |9)(*Digit* *))

Decimal → *Integer* . *Digit* *

Real → (*Integer* | *Decimal*) E (+|-| ε) *Digit* *

Complex → (*Real* , *Real*)

Numbers can get much more complicated!

Regular Expressions (the point)

Regular expressions can be used to specify the words to be translated to parts of speech by a lexical analyzer

- Using results from automata theory and theory of algorithms, we can automatically build recognizers from regular expressions

- Some of you may have seen this construction for string pattern matching (*e.g.*, python)

⇒ We study REs and associated theory to automate scanner construction !

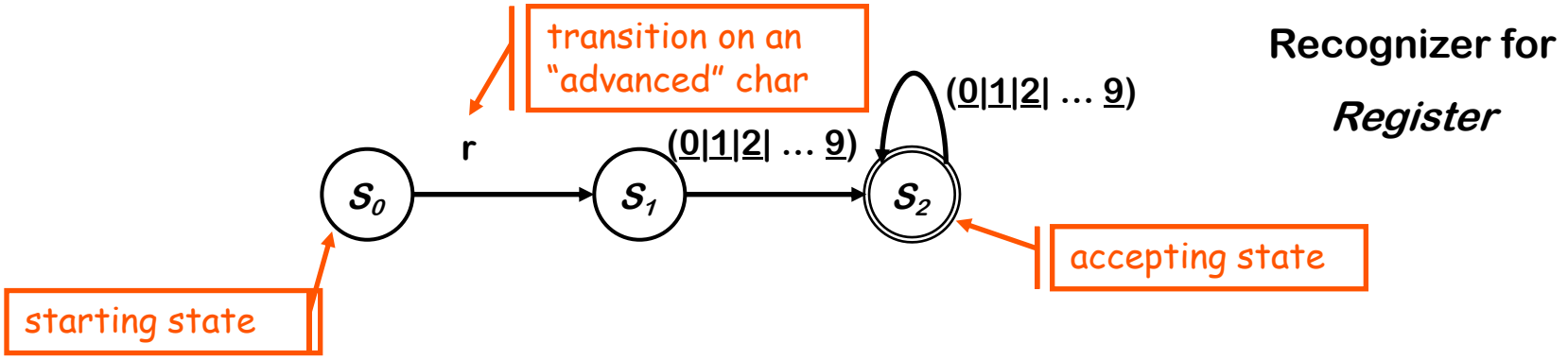
Example

Consider the problem of recognizing Register names

Register → r (0|1|2| … | 9) (0|1|2| … | 9)*

- Allows registers of arbitrary number
- Requires at least one digit

RE can be recognized by a "machine" (DFA)

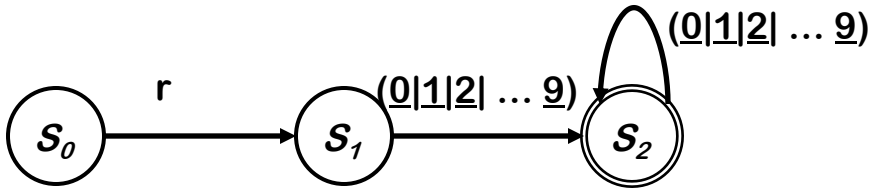


Transitions on other inputs go to an error state, s_e

Example (continued)

DFA operation

- Start in state S_0 & take transitions on each input character
- DFA accepts a word $\underline{x}$ *iff* $\underline{x}$ leaves it in a final state (S_2)



Recognizer for *Register*

So,

- r17 takes it through s_0, s_1, s_2 and accepts
- r takes it through s_0, s_1 and fails
- a takes it straight to s_e

Example (continued)

To be useful, recognizer must turn into code

```
Char ← next character
State ← s0
while (Char =/ EOF)
    State ← δ(State,Char)
     Char ← next character
if (State is a final state )
    then report success
    else  report failure
```

Skeleton recognizer

δ	r	0,1,2,3,4,5 ,6,7,8,9	*All others*
s_0	s_1	s_e	s_e
s_1	s_e	s_2	s_e
s_2	s_e	s_2	s_e
s_e	s_e	s_e	s_e

Table encoding RE

Example (continued)

To be useful, recognizer must turn into code

```
Char ← next character
State ← s0

while (Char =/ EOF)
    State ← δ(State,Char)
     perform specific action
     Char ← next character

if (State is a final state )
    then report success
    else  report failure
```

Skeleton recognizer

δ	r	0,1,2,3,4,5, 6,7,8,9	*All others*
s_0	s_1 *start*	s_e *error*	s_e *error*
s_1	s_e *error*	s_2 add	s_e *error*
s_2	s_e *error*	s_2 add	s_e *error*
s_e	s_e *error*	s_e *error*	s_e *error*

Table encoding RE

What about a Tighter Specification?

r *Digit Digit** allows arbitrary numbers

- Accepts r00000
- Accepts r99999
- What if we want to limit it to r0 through r31 ?

Write a tighter regular expression

- *Register* → r ((0|1|2) (*Digit* | ε) | (4|5|6|7|8|9) | (3|30|31))
- *Register* → r0|r1|r2| … |r31|r00|r01|r02| … |r09

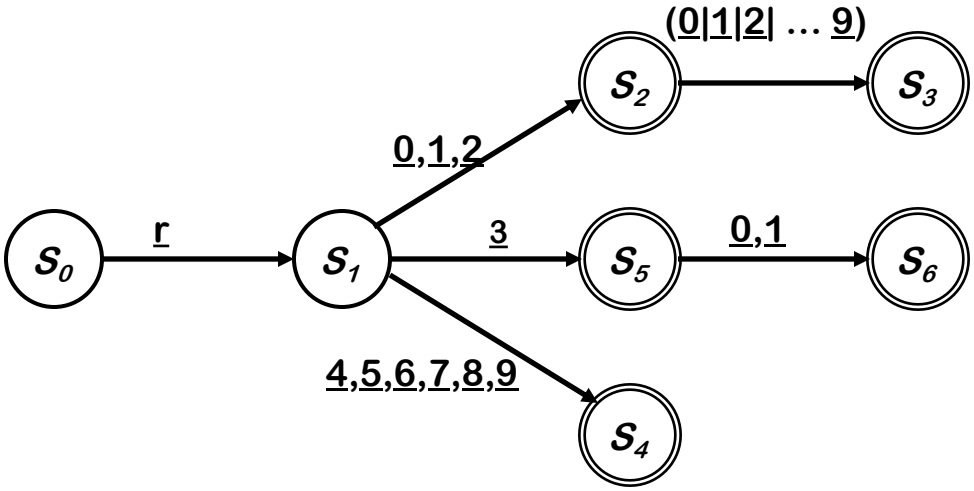
Produces a more complex DFA

- Has more states
- Same cost per transition
- Same basic implementation

Tighter Register Specification (cont'd)

The DFA for

Register → r ((0|1|2) (*Digit* | ε) | (4|5|6|7|8|9) | (3|30|31))



- Accepts a more constrained set of registers
- Same set of actions, more states

Tighter Register Specification (cont' d)

δ	r	0,1	2	3	4-9	All others
s_0	s_1	s_e	s_e	s_e	s_e	s_e
s_1	s_e	s_2	s_2	s_5	s_4	s_e
s_2	s_e	s_3	s_3	s_3	s_3	s_e
s_3	s_e	s_e	s_e	s_e	s_e	s_e
s_4	s_e	s_e	s_e	s_e	s_e	s_e
s_5	s_e	s_6	s_e	s_e	s_e	s_e
s_6	s_e	s_e	s_e	s_e	s_e	s_e
s_e	s_e	s_e	s_e	s_e	s_e	s_e

Runs in the same skeleton recognizer

Table encoding RE for the tighter register specification

Summary

- The Role of the Lexical Analyzer
  - Partition input stream into tokens
- Regular Expressions
  - Used to describe the structure of tokens
- DFA: Deterministic Finite Automata
  - Machinery to recognize Regular Languages