

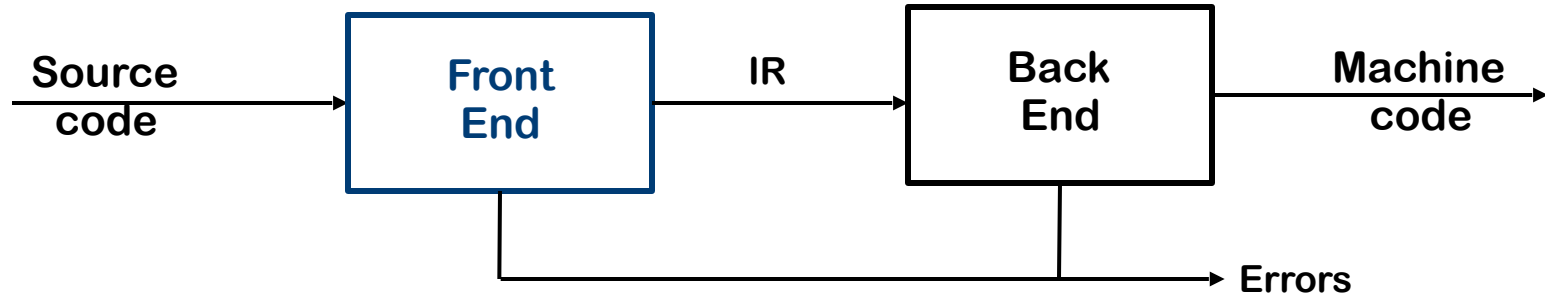
Lexical Analysis

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The Front End

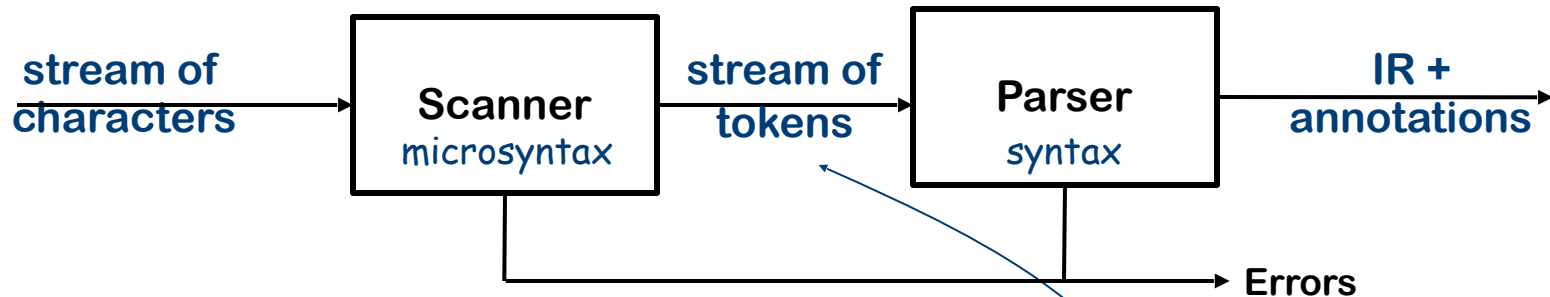


The purpose of the front end is to deal with the input language

- Perform a membership test: $\text{code} \in \text{source language?}$
- Is the program well-formed (semantically) ?
- Build an IR version of the code for the rest of the compiler

The front end deals with form (syntax) & meaning (semantics)

The Front End



Why separate the scanner and the parser?

- Scanner classifies words
- Parser constructs grammatical derivations
- Parsing is harder and slower

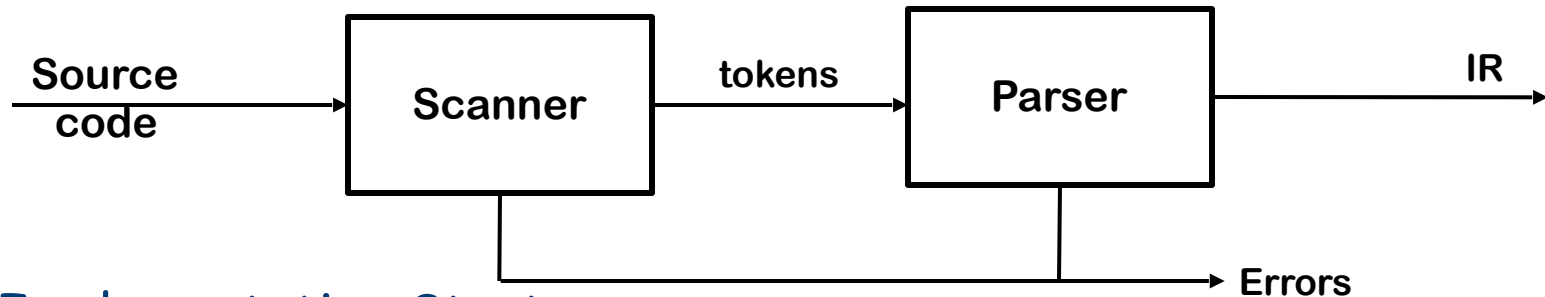
Separation simplifies the implementation

- Scanners are simple
- Scanner leads to a faster, smaller parser

Scanner is only pass that touches every character of the input.

token is a pair
<part of speech, lexeme>

Our setting: the Front End



Implementation Strategy

	Scanning	Parsing
Specify Syntax	regular expressions	context-free grammars
Implement Recognizer	deterministic finite automaton	push-down automaton
Perform Work	Actions on transitions in automaton	

Lexical Analysis

Relates to the words of the vocabulary of a language, (as opposed to grammar, i.e., correct construction of sentences).

Lexical Analyzer, a.k.a. lexer, scanner or tokenizer, splits the input program, seen as a stream of characters, into a sequence of tokens.

Tokens are the words of the (programming) language, e.g., keywords, numbers, comments, parenthesis, semicolon.

Tokens are classes of concrete input (called **lexeme**).

Example

Token created

int	Keyword
maximum	Identifier
(Operator
int	Keyword
x	Identifier
,	Operator
int	Keyword
y	Identifier
(Operator
{	Operator
if	Keyword

```
#include <stdio.h>
int maximum(int x, int y) {
    // This will compare 2 numbers
    if (x > y)
        return x;
    else {
        return y;
    }
}
```

Non-Token

Comment	// This will compare 2 numbers
Pre-processor directive	#include <stdio.h>
Pre-processor directive	#define NUMS 8,9
Macro	NUMS

Lexical analysis

- Lexical analysis is the very **first phase** in the compiler designing, the only one that analyses the entire code
- A **lexeme** is a sequence of characters that are included in the source program according to the matching pattern of a **token**
- Lexical analyzer helps to **identify token** into the symbol table
- A character sequence which is not possible to scan into any valid token is a **lexical error**

Constructing a Lexical Analyser

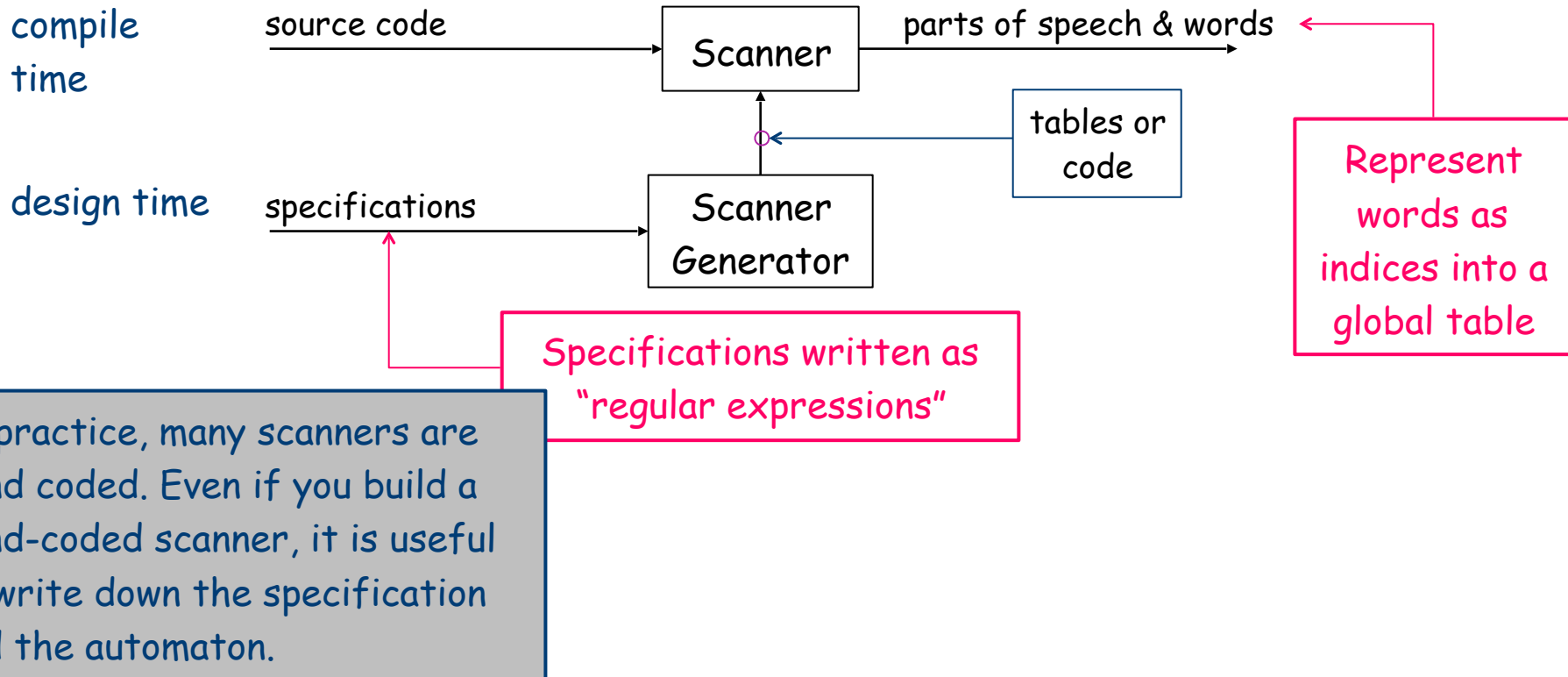
- By hand - Identify lexemes in input and return tokens
- Automatically - **Lexical-Analyser generator**: it compiles the patterns that specify the lexemes into a code (the lexical analyser).

Lexical analysis decides whether the individual tokens are well formed, this can be expressed by a **regular** language.

Automatic Scanner Construction

Why study automatic scanner construction?

- Avoid writing scanners by hand



The syntax can be expressed by a regular grammar

The **syntax** of a programming language can be expressed by a **regular grammar**

Example

The following grammar generates all the legal identifier

$$S \rightarrow aT \mid \dots \mid zT \mid AT \mid \dots \mid ZT$$
$$T \rightarrow \varepsilon \mid 0T \mid \dots \mid 9T \mid S$$

that can be more neatly be expressed using a **regular expressions** !

$$(a \mid \dots \mid z \mid A \mid \dots \mid Z) (a \mid \dots \mid z \mid A \mid \dots \mid Z \mid 0 \mid \dots \mid 9)^*$$

Examples of Regular Expressions

Identifiers:

Letter $\rightarrow (\underline{a}|\underline{b}|\underline{c} \dots |\underline{z}|\underline{A}|\underline{B}|\underline{C} \dots |\underline{Z})$

Digit $\rightarrow (\underline{0}|\underline{1}|\underline{2} \dots |9)$

Identifier $\rightarrow \text{Letter} (\text{Letter} | \text{Digit})^*$

$(\underline{a}|\underline{b}|\underline{c} \dots |\underline{z}|\underline{A}|\underline{B}|\underline{C} \dots |\underline{Z}) (\underline{a}|\underline{b}|\underline{c} \dots |\underline{z}|\underline{A}|\underline{B}|\underline{C} \dots |\underline{Z}) | (\underline{0}|\underline{1}|\underline{2} \dots |9)^*$

shorthand
for

Numbers:

Integer $\rightarrow (\underline{+}|\underline{-}|\underline{\epsilon}) (\underline{0} | (\underline{1}|\underline{2}|\underline{3} \dots |9)(\text{Digit}^*))$

Decimal $\rightarrow \text{Integer} \text{.} \text{Digit}^*$

Real $\rightarrow (\text{Integer} | \text{Decimal}) \underline{E} (\underline{+}|\underline{-}|\underline{\epsilon}) \text{Digit}^*$

Complex $\rightarrow (\text{Real} \text{,} \text{Real})$

underlining indicates a
letter in the input
stream

Numbers can get much more complicated!

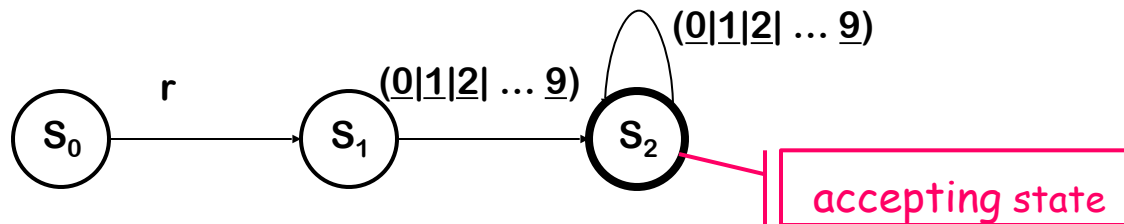
Example

Consider the problem of recognizing ILOC register names

Register $\rightarrow r (\underline{0}|\underline{1}|\underline{2}|\dots|\underline{9}) (\underline{0}|\underline{1}|\underline{2}|\dots|\underline{9})^*$

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

RE corresponds to a recognizer (or DFA)



Recognizer for Register

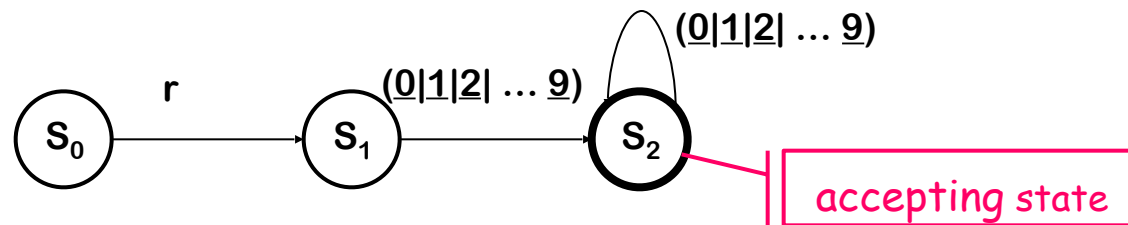
Transitions on other inputs go to an error state, s_e

Example

(continued)

DFA operation

- Start in state S_0 & make transitions on each input character

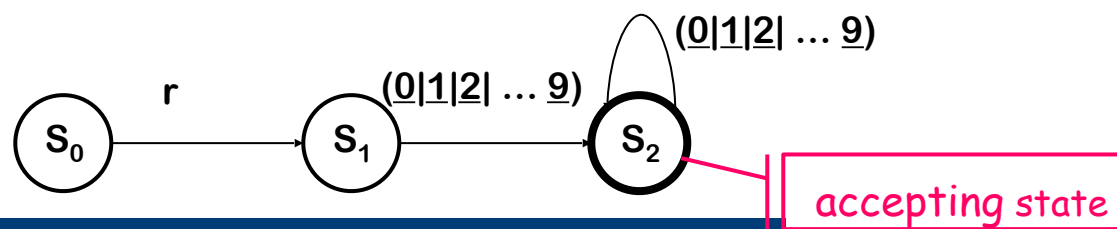


So,

Recognizer for Register

- 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



To be useful, the recognizer must be converted into code

Char \leftarrow next character

State $\leftarrow s_0$

while (Char \neq EOF)

 State $\leftarrow \delta(\text{State}, \text{Char})$

 Char \leftarrow next character

if (State is a final state)

 then report success

 else report failure

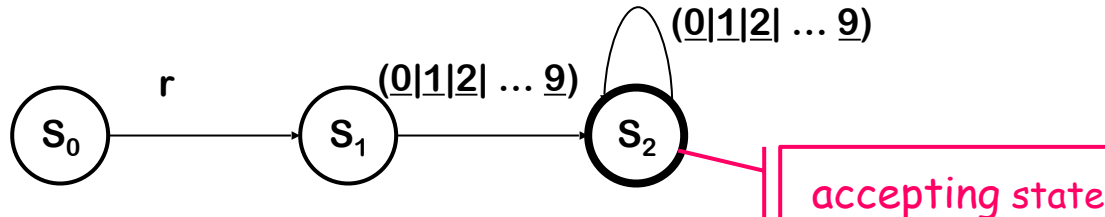
Skeleton recognizer

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 the RE

$O(1)$ cost per character (or per transition)

Example



We can add "actions" to each transition

Table encoding RE

```

Char ← next character
State ← s0

while (Char ≠ EOF)
  Next ← δ(State,Char)
  Act ← α(State,Char)
  perform action Act
  State ← Next
  Char ← next character

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

Skeleton recognizer

δ α	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

Typical action is to capture the lexeme

What if we need a tighter specification?

\underline{r} Digit Digit* allows arbitrary numbers

- Accepts r00000
- Accepts r99999

What if we want to limit it to r0 through r31 ?

We need a tighter regular expression

Register $\rightarrow \underline{r} ((\underline{0}|\underline{1}|\underline{2}) (\text{Digit} | \epsilon) | (\underline{4}|\underline{5}|\underline{6}|\underline{7}|\underline{8}|\underline{9}) | (\underline{3}|\underline{30}|\underline{31}))$

Produces a more complex DFA

- DFA has more states
- DFA has same cost per transition
- DFA has same basic implementation

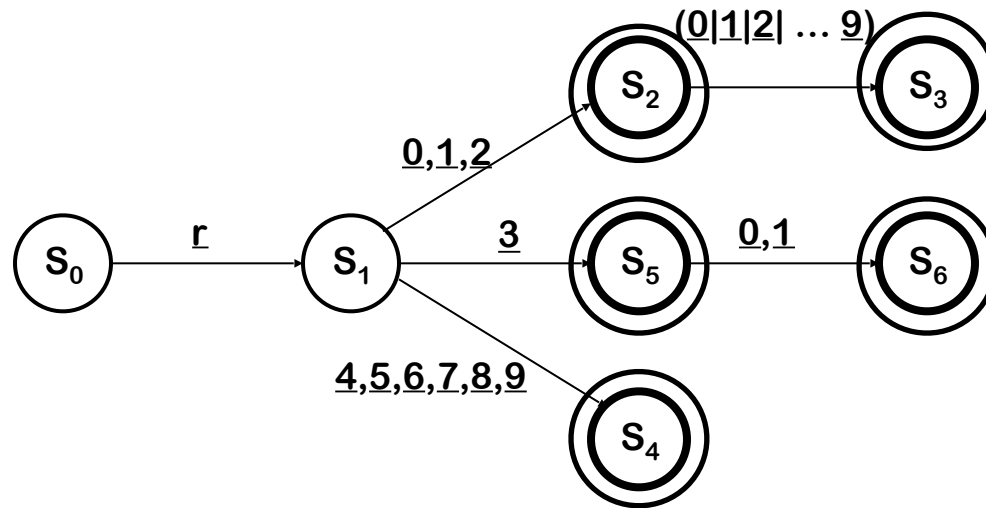
More states implies a larger table. The larger table might have mattered when computers had 128 KB or 640 KB of RAM. Today, when a cell phone has megabytes and a laptop has gigabytes, the concern seems outdated.

Tighter register specification

(continued)

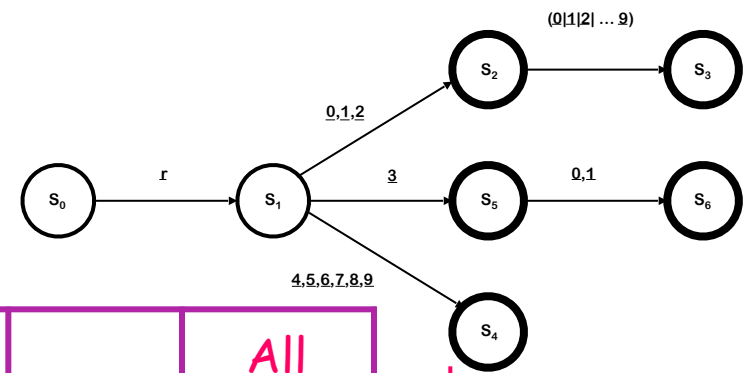
The DFA for

Register $\rightarrow \underline{r} ((\underline{0}|\underline{1}|\underline{2}) (\text{Digit} \mid \varepsilon) \mid (\underline{4}|\underline{5}|\underline{6}|\underline{7}|\underline{8}|\underline{9}) \mid (\underline{3}|\underline{30}|\underline{31}))$



- Accepts a more constrained set of register names
- Same set of actions, more states

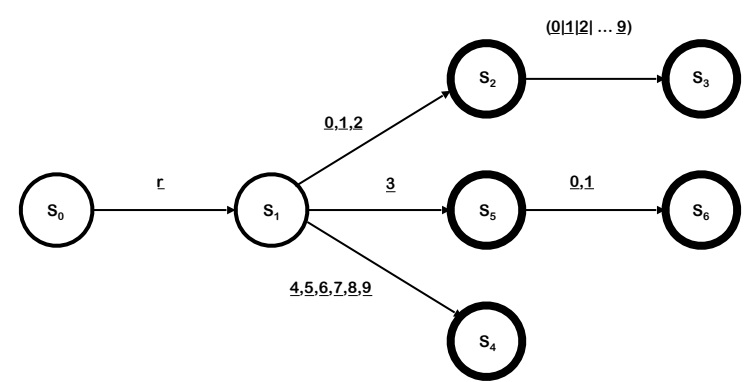
Tighter register specification



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

This table runs in the same skeleton recognizer

Tighter register specification



State Action	r	0,1	2	3	4,5,6 7,8,9	other
0	1 start	e	e	e	e	e
1	e	2 add	2 add	5 add	4 add	e
2	e	3 add	3 add	3 add	3 add	e exit
3,4,6	e	e	e	e	e	e exit
5	e	6 add	e	e	e	e exit
e	e	e	e	e	e	e

Automating Scanner Construction

To convert a specification into code:

- 1 Write down the RE for the input language
- 1 Build a ϵ -NFA collecting all the NFA for the RE
- 2 Build a NFA corresponding to the ϵ -NFA
- 3 Build the DFA that simulates the NFA
- 4 Systematically minimise the DFA
- 5 Turn it into code

Scanner generators

- Lex and Flex work along these lines
- Algorithms are well-known and well-understood
- Key issue is interface to parser
- You could build one in a weekend!

Implementing Scanners

The overall construction: RE \rightarrow ϵ -NFA \rightarrow NFA \rightarrow DFA \rightarrow minimized DFA

How we transform a DFA into code?

- Table driven scanners
- Direct code scanners
- Hand-coded scanners

all will simulate the DFA!

The actions that the different implementations have in common

- They repeatedly read the next character in the input and simulate the corresponding DFA transition
- This process stops when there are not outgoing transition from the state s with the input character
 - If s is an accepting state the scanner recognises the word and its syntactic category
 - If s is a nonaccepting state the scanner must determine whether or not it passes a final state at some point,
 - If yes it should **roll back** its internal state and its input stream and report **success**
 - If not it should report the **failure**

The differences between the different approaches

- Table driven scanners
- Direct code scanners
- Hand-coded scanners

All constant cost per character (with different constants) plus the cost of rollback

Differs from the way they implement the transition table and simulate the operations of the DFA

Table-Driven Scanners

- Table(s) + Skeleton Scanner
 - So far, we have used a simplified skeleton

state $\leftarrow s_0$;

while (state $\neq s_{\text{error}}$) do

 char $\leftarrow \text{NextChar}()$ // read next character

 state $\leftarrow \delta(\text{state}, \text{char})$; // take the transition

- In practice, the skeleton is more complex
 - Character classification for table compression
 - Building the lexeme
 - Recognizing subexpressions
 - Practice is to combine all the REs into one DFA
 - Must recognize individual words without hitting EOF

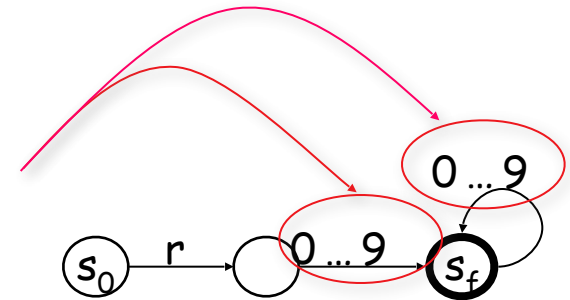


Table-Driven Scanners

Character Classification

- Group together characters by their actions in the DFA
 - Combine identical columns in the transition table, δ
 - Indexing δ by class shrinks the table

$state \leftarrow s_0;$

while ($state \neq s_{error}$) **do**

$char \leftarrow \text{NextChar}()$ // read next character

$cat \leftarrow \text{CharCat}(char)$ // classify character

$state \leftarrow \delta(state, cat)$ // take the transition

r	0, 1, 2, ..., 9	EOF	Other
Register	Digit	Other	Other

The Classifier Table, *CharCat*

	Register	Digit	Other
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

The Transition Table, δ

Table-Driven Scanners

Building the Lexeme

- Scanner produces syntactic category (part of speech)
 - Most applications want the lexeme (word), too
- ```
state ← s0
lexeme ← empty string
while (state ≠ serror) do
 char ← NextChar() // read next character
 lexeme ← lexeme + char // concatenate onto lexeme
 cat ← CharCat(char) // classify character
 state ← δ(state, cat) // take the transition
```
- This problem is trivial
    - Save the characters

# Recognising subexpressions : RollBack

- A stack is used to track all the traversed states

```
lexeme ← empty string
while (state ≠ serror) do
 char ← NextChar() // read next character
 lexeme ← lexeme + char // concatenate onto lexeme
 push (state); //remember all traversed states
 cat ← CharCat(char) // classify character
 state ← δ(state,cat)
while (state ≠ sA) do //RollBack
 state ← pop();
 truncate lexeme;
 Rollback();
end
```

# Table-Driven Scanners

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## Choosing a Category from an Ambiguous RE

- We want a DFA, so we combine all the REs into one
  - Some strings may fit RE for more than 1 syntactic category
    - Keywords versus general identifiers
  - Scanner must choose a category for ambiguous final states
    - Classic answer: specify priority by order of REs (return 1<sup>st</sup>)

### Identifiers:

Letter → (a|b|c| ... |z|A|B|C| ... |Z)

Digit → (0|1|2| ... |9)

Identifier → Letter ( Letter | Digit )\*

### Keywords:

key → if | ...

example: ife

# A table driven scanner for register names

## initialization

```
NextWord()
 state $\leftarrow s_0$;
 lexeme \leftarrow "";
 clear stack;
 push(bad);
```

## scanning loop

```
while (state $\neq s_e$) do
 NextChar(char);
 lexeme \leftarrow lexeme + char;
 if state $\in S_A$ final states
 then clear stack;
 push(state);
 cat \leftarrow CharCat[char];
 state $\leftarrow \delta$ [state, cat];
end;
```

## roll-back

```
while (state $\notin S_A$ and
 state \neq bad) do
 state \leftarrow pop();
 truncate lexeme;
 RollBack();
end;
```

## final-section

```
if state $\in S_A$
 then return Type[state];
else return invalid;
```

| r        | 0, 1, 2, ..., 9 | EOF   | Other |
|----------|-----------------|-------|-------|
| Register | Digit           | Other | Other |

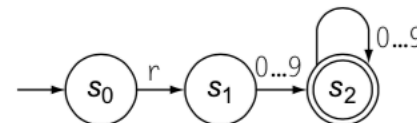
The Classifier Table, *CharCat*

|       | Register | Digit | Other |
|-------|----------|-------|-------|
| $s_0$ | $s_1$    | $s_e$ | $s_e$ |
| $s_1$ | $s_e$    | $s_2$ | $s_e$ |
| $s_2$ | $s_e$    | $s_2$ | $s_e$ |
| $s_e$ | $s_e$    | $s_e$ | $s_e$ |

The Transition Table,  $\delta$

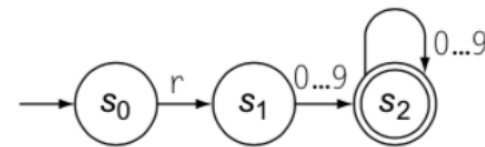
| $s_0$   | $s_1$   | $s_2$    | $s_e$   |
|---------|---------|----------|---------|
| invalid | invalid | register | invalid |

The Token Type Table, *Type*



The Underlying DFA

# Direct-Coded scanner



The Underlying DFA

For each character, the table driven scanner performs two table lookups, one in **CharCat** and the other in **δ**: to improve efficiency

```
sinit : lexeme ← " ";
 clear stack;
 push(bad);
 goto s0;

s0 : NextChar(char);
 lexeme ← lexeme + char;
 if state ∈ SA
 then clear stack;
 push(state);
 if (char='r')
 then goto s1;
 else goto sout;

s1 : NextChar(char);
 lexeme ← lexeme + char;
 if state ∈ SA
 then clear stack;
 push(state);
 if ('0' ≤ char ≤ '9')
 then goto s2;
 else goto sout;

s2 : NextChar(char);
 lexeme ← lexeme + char;
 if state ∈ SA
 then clear stack;
 push(state);
 if '0' ≤ char ≤ '9'
 then goto s2;
 else goto sout

sout : while (state ∉ SA and
 state ≠ bad) do
 state ← pop();
 truncate lexeme;
 RollBack();
 end;
 if state ∈ SA
 then return Type[state];
 else return invalid;
```

If end of state test is complex (e.g., many cases), scanner generator should consider other schemes

- Binary search

Of course, not  
everything fits  
into a regular  
language ...

# Building Scanners

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## The point

- All this technology lets us automate scanner construction
- Implementer writes down the regular expressions
- Scanner generator builds NFA, DFA, minimal DFA, and then writes out the (table-driven or direct-coded) code
- This reliably produces fast, robust scanners

## For most modern language features, this works

- You should think twice before introducing a feature that defeats a DFA-based scanner
- The ones we've seen (e.g., insignificant blanks, non-reserved keywords) have not proven particularly useful or long lasting

# What About Hand-Coded Scanners?

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Many (most?) modern compilers use hand-coded scanners

- Starting from a DFA simplifies design & understanding
  - Can use old assembly tricks
  - Combine similar states
- Scanners are fun to write
  - Compact, comprehensible, easy to debug