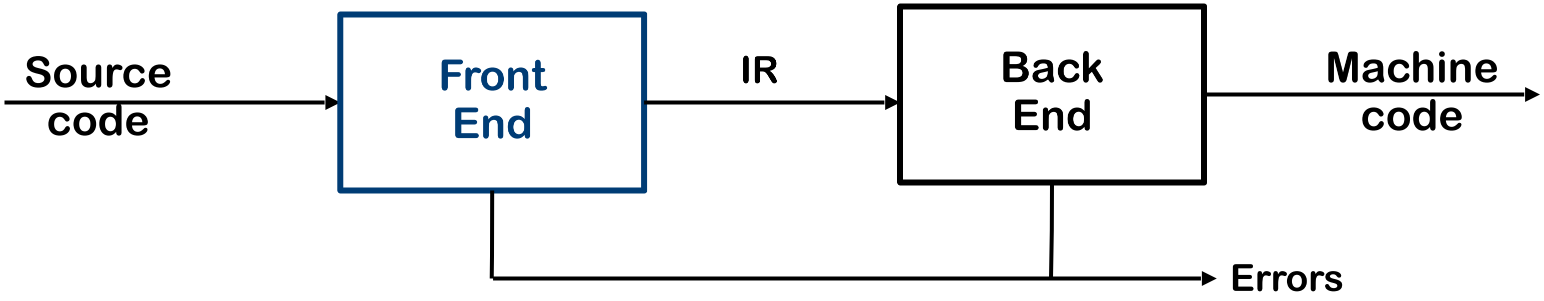
Lexical Analysis

The Front End

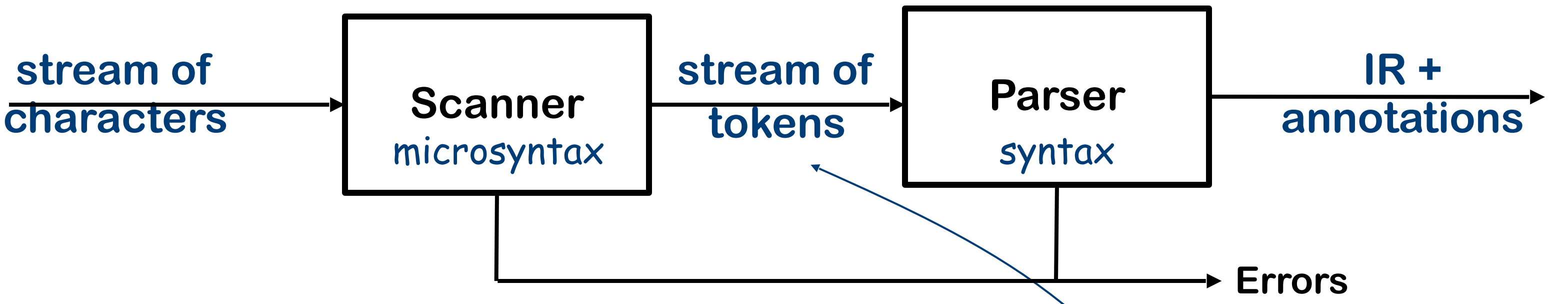


The purpose of the front end is to deal with the input language

- Perform a membership test: code $\in$ 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



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

Why separate the scanner and the parser?

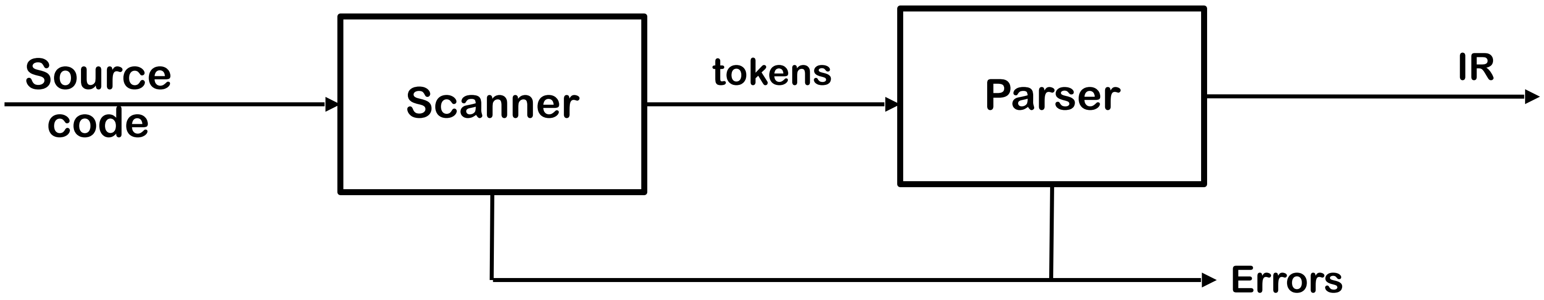
- Scanner classifies words
- Parser constructs grammatical derivations
- Parsing is harder and slower

token is a pair
<part of speech, lexeme>

Separation simplifies the implementation

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

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>

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

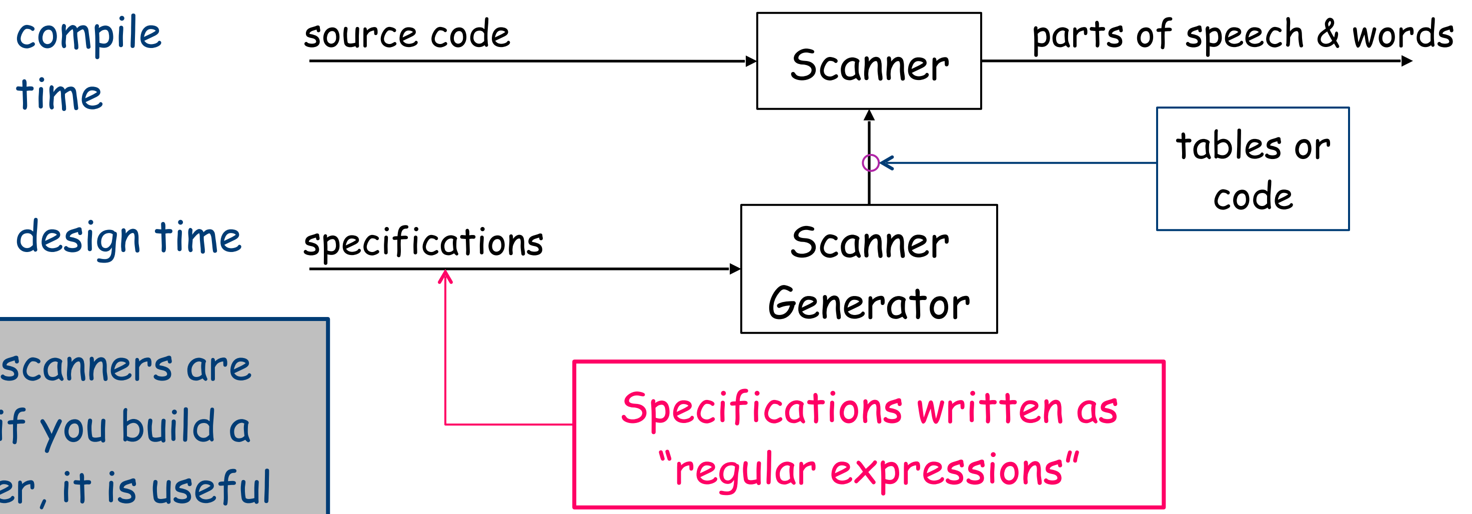
that specify the lexemes into a code (the lexical analyser).

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



In practice, many scanners are hand coded. Even if you build a hand-coded scanner, it is useful to write down the specification and the automaton.

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-> aT|…|zT|AT|…|ZT

T-> ε|0T|…|9T|S

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

(a|…|z|A|…|Z) (a|…|z|A|…|Z|0|….|9) *

Examples of Regular Expressions

Identifiers:

Letter → (a|b|c| … |z|A|B|C| … |Z)

Digit → (0|1|2| … |9)

Identifier → Letter (Letter | Digit)*

shorthand for

(a|b|c| … |z|A|B|C| … |Z) ((a|b|c| … |z|A|B|C| … |Z) | (0|1|2| … |9))*

Numbers:

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

Decimal → Integer . Digit *

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

Complex → (Real , Real)

underlining indicates a letter in the input stream

In reality they can get much more complicated!

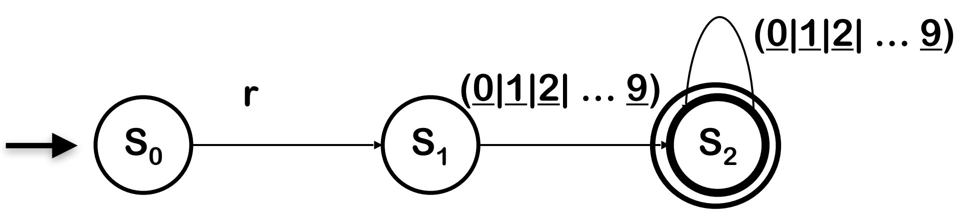
Example

Consider the problem of recognizing ILOC register names

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

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

RE corresponds to a recognizer (or DFA)



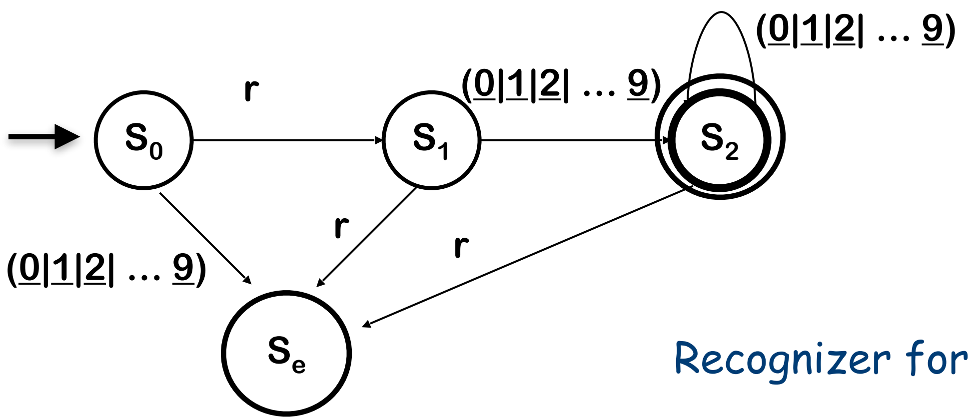
Recognizer for Register

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

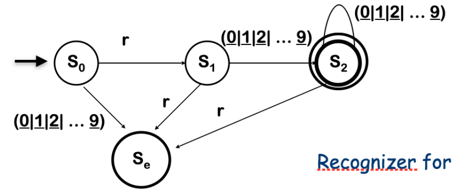


Recognizer for Register

So,

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

Example



Recognizer for Register

To be useful, the DFA must be converted 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
```

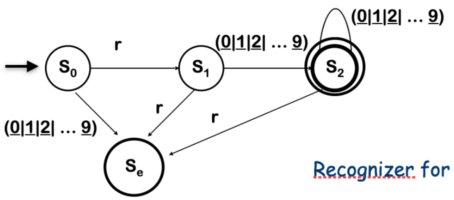
Skeleton recognizer

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 the RE

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

Example



We can add "actions" to each transition

```
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

Table encoding RE

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?

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))

Produces a more complex DFA

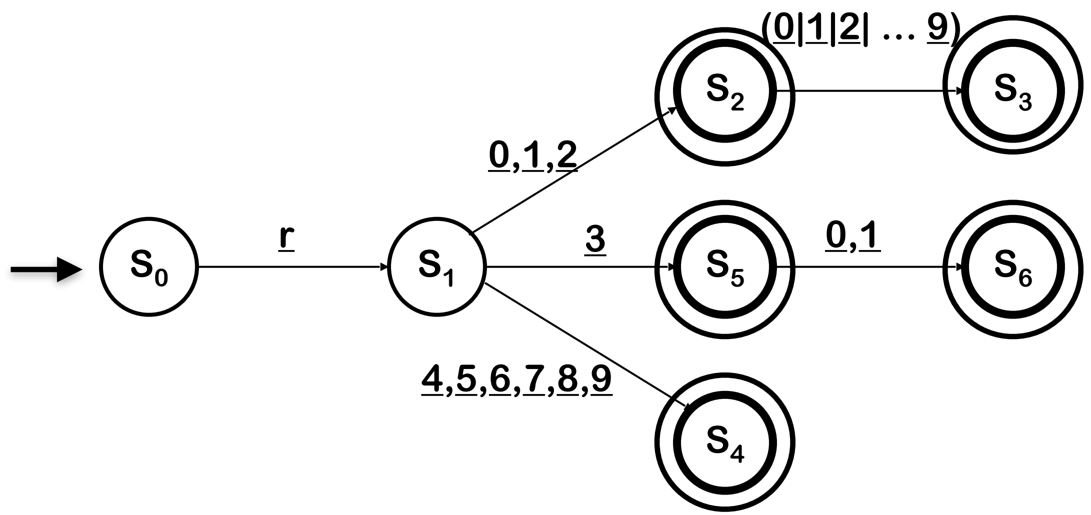
- DFA has more states
- DFA has same cost per transition
- DFA has same basic implementation

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)

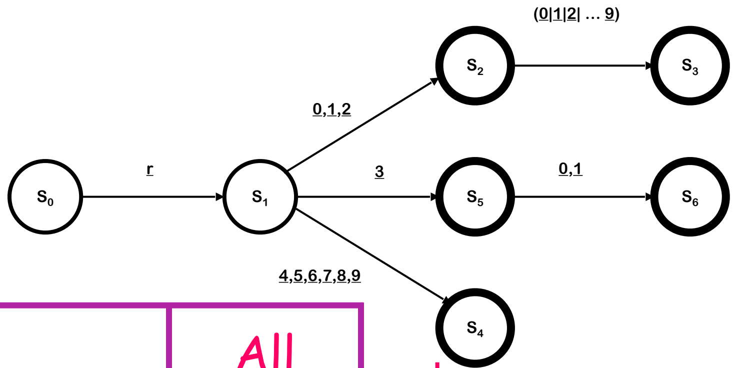
The DFA for

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



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

Tighter register specification

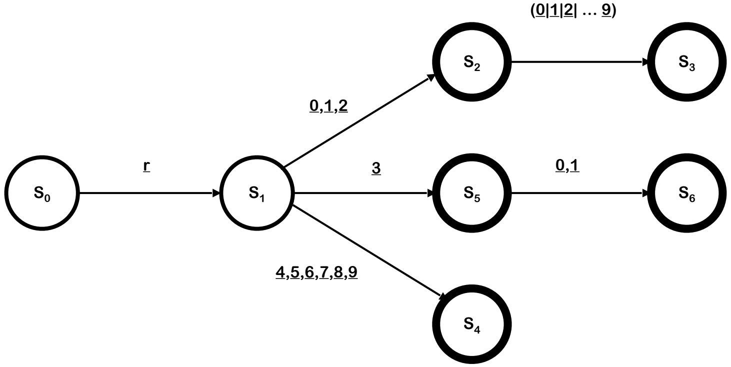


δ	r	0,1	2	3	4-9	All others
s_0	s_1	s_e	s_e	s_e	s_e	s_e
s_1	s_e	s_2	s_2	s_5	s_4	s_e
s_2	s_e	s_3	s_3	s_3	s_3	s_e
s_3	s_e	s_e	s_e	s_e	s_e	s_e
s_4	s_e	s_e	s_e	s_e	s_e	s_e
s_5	s_e	s_6	s_e	s_e	s_e	s_e
s_6	s_e	s_e	s_e	s_e	s_e	s_e
s_e	s_e	s_e	s_e	s_e	s_e	s_e

This table runs in the same skeleton recognizer

Table encoding RE for the tighter register specification

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-> ε-NFA->NFA->DFA->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 ← s0 ;
while (state ≠ Serror ) do
    char ← NextChar( )          // read next character
    state ← δ(state,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

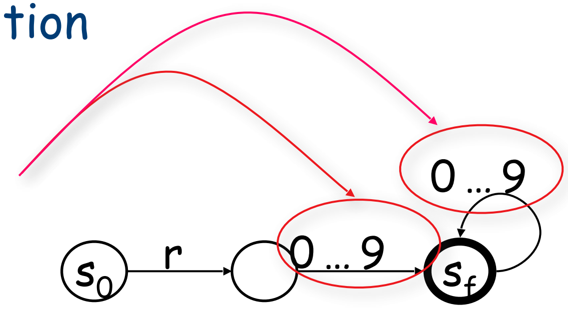


Table-Driven Scanners

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 ← s0 ;
while (state ≠ serror) do
   char ← NextChar( )          // read next character
   cat ← CharCat(char)         // classify character
   state ← δ(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 ≠ s_error) 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 ≠s_error) 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 ≠s_A ) do                //RollBack
   state ← pop();
   truncate lexeme;                  //s_A  final state
   Rollback();
  end
```

Table-Driven Scanners

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 1st)

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 ← s0 ;
  lexeme ← “ ”;
  clear stack;
  push(bad);
```

scanning loop

```
  while (state≠se) do
    NextChar(char);
    lexeme ← lexeme + char;
    if state ∈ SA
        then clear stack;
    push(state);
    cat ← CharCat[char];
    state ← δ[state,cat];
  end;
```

roll-back

```
  while(state ∉ SA and
        state≠bad) do
    state ← pop();
    truncate lexeme;
    RollBack();
  end;
```

final-section

```
  if state ∈ SA
    then return Type[state];
    else return invalid;
```

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

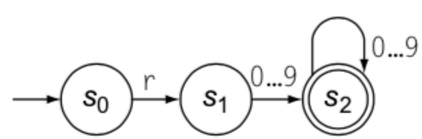
The Classifier Table, CharCat

	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, δ

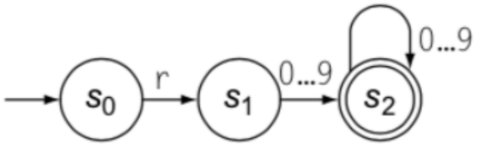
s_0	s_1	s_2	s_e
invalid	*invalid*	*register*	*invalid*

The Token Type Table, Type



The Underlying DFA

Direct-Coded scanners



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

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

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

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

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

s_out :  while (state ∉ S_A and
                state ≠ bad) do
             state ← pop();
             truncate lexeme;
             RollBack();
         end;
```

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

- Binary search

Building Scanners

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

Of course, not everything fits into a regular language …

What About Hand-Coded Scanners?

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

Exercise

Write a hand-coded scanner to recognise comments in the language C