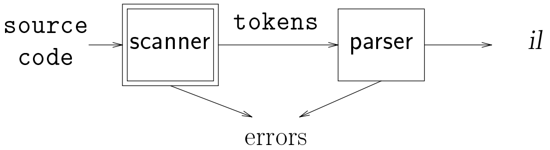
Scanner



A scanner must recognize various parts of the language's syntax.

Input is separated into *tokens* based on lexical analysis.

```
x = x + y;
```

becomes

<id, `x`> `=` <id, `x`> `+` <id, `y`> `;`

Specifying patterns

A scanner must recognize various parts of the language's syntax.

Some parts are easy:

white space
some combination of $< \not{b} >$ and `tab`

keywords and operators
specified as literal patterns — `do`, `end`

comments
opening and closing delimiters — `/* ··· */`

Specifying patterns

Other parts are much harder:

identifiers
alphabetic followed by k alphanumerics
(_, $, &, . . .)

numbers
integers — 0 or digit from 1-9 followed by digits from 0-9
decimals — integer "." digits from 0-9

We need a powerful notation to specify these patterns.

Regular expressions

Regular expressions represent languages.

Languages are sets of strings.

Operations include *Kleene closure*, *concatenation*, and *union*.

Regular expression	Language
(a)	$\{$ "a" $\}$
$(a) \mid (b)$	$\{$ "a", "b" $\}$
$(a)(b)$	$\{$ "ab" $\}$
$(a)^*$	$\{$ "", "a", "aa", ... $\}$
$(a)^+$	$\{$ "a", "aa", ... $\}$

We assume *closure*, *concatenation*, *union* as the order of precedence.

$ab \mid cd^* = (ab) \mid (c(d^*))$

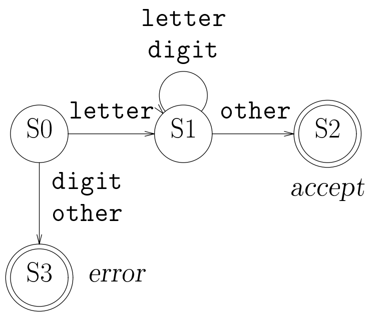
$= \{$ "ab", "c", "cd", "cdd", ... $\}$

$a(bc)^* = \{$ "a", "abc", "$abcbc$", ... $\}$

Recognizers

From a regular expression, we can construct a *deterministic finite automaton* (*dfa*).

Recognizer for *identifier*:



identifier

$letter \rightarrow (a \mid b \mid c \mid ... \mid z \mid A \mid B \mid C \mid ... \mid Z)$

$digit \rightarrow (0 \mid 1 \mid 2 \mid 3 \mid 4 \mid 5 \mid 6 \mid 7 \mid 8 \mid 9)$

$id \rightarrow letter\ (letter \mid digit)^*$

Code for the recognizer

```
char ← next_char(); done ← false;
state ← S0;         /* code for S0 */
token_value ← ""    /* empty string */
while( not done ) {
   class ← char_class[char];
   state ← next_state[class,state];
   switch(state) {
      case S1:     /* building an id */
         token_value ← token_value + char;
         char ← next_char(); break;
      case S2:     /* accept state */
         token_type ← identifier;
         done ← true; break;
      case S3:     /* error */
         token_type ← error;
         done ← true; break;
}  }
return token_type;
```


Tables for the recognizer

Two tables control the recognizer.

`char_class`:

	$a-z$	$A-Z$	$0-9$	other
value	letter	letter	digit	other

`next_state`:

class	S0	S1	S2	S3
letter	S1	S1	—	—
digit	S3	S1	—	—
other	S3	S2	—	—

To change languages, we can just change tables.

Improved efficiency

Table driven implementation is slow relative to direct code. Each state transition involves:

1. classifying the input character
2. finding the next state
3. an assignment to the state variable
4. a branch
5. a trip through the case statement logic

We can do better by "encoding" the state table in the scanner code.

1. classify the input character
2. test character class locally
3. branch directly to next state

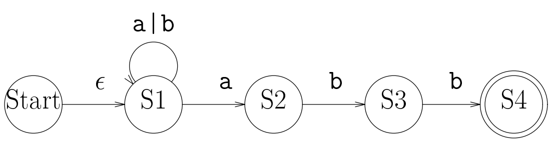
This takes many fewer instructions per cycle.

Faster scanning

```
     token_type ← error;
     char ← next_char();
     class ← char_class[char];
     if (class != letter)
        return token_type;

S1:  token_value ← char;
     char ← next_char();
     class ← char_class[char];
     if (class == other) goto S3;

S2:  token_value ← token_value + char;
     char ← next_char();
     class ← char_class[char];
     if (class != other) goto S2;

S3:  token_type = identifier;
     return token_type;
```


Nondeterministic finite automata

What about the regular expression $(a \mid b)^* abb$?



State Start has ϵ transition to S1.

State S1 has multiple transitions on `a` !

$\Rightarrow$ *nondeterministic finite automaton* (*nfa*)

Different definition for *accept*

A *nfa accepts x* if and only if there is some path through the transition graph from the start state to an accepting state such that the labels along the edges spell *x*.

*nfa*s versus *dfa*s

What is the relationship between a nfa *and a* dfa*?*

dfa is special case of *nfa*

1. no ϵ transitions
2. single-valued transition function

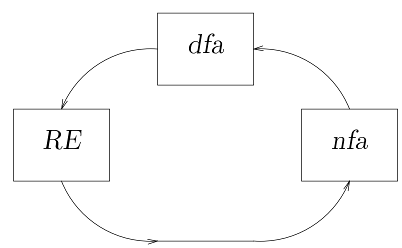
dfa can be simulated on a *nfa*

- obviously

nfa can be simulated on a *dfa*

- simulate sets of simultaneous states
- possible exponential blowup

Constructing a *dfa* from a regular expression



regular expression (RE) →*nfa*

build *nfa* for each term, connect them with ϵ moves

nfa→*dfa*

construct the simulation, using the "subset" construction

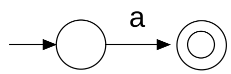
dfa→ regular expression

construct $R_{ij}^k = R_{ik}^{k-1}(R_{kk}^{k-1})^* R_{kj}^{k-1} \cup R_{ij}^{k-1}$

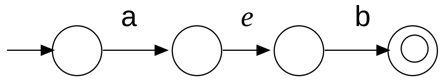
Converting regular expressions to *nfa*s

Build two-state automaton for atomic regular expression `a`, with `a` as the edge.

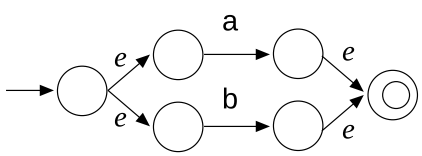
Compose automata as follows:



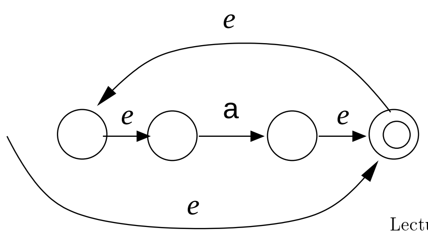
- concatenate



- union



- Kleene closure



Subset construction algorithm

Input:	*nfa* N
Output:	*dfa* D with *Dstates* and *Dtran* that accepts same language
Method:	let s be a state in *nfa* and T a set of states, using the following definitions

Operation	Description
ϵ-*closure*(s)	Set of *nfa* states reachable from *nfa* state s on ϵ-transitions alone.
ϵ-*closure*(T)	Set of *nfa* states reachable from some *nfa* state s in T on ϵ-transitions alone.
move(T,a)	Set of *nfa* states to which there is a transition on input symbol a from some *nfa* state s in T.

Subset construction (cont)

state *Start* = ϵ-*closure*(s_0)
add *Start* unmarked to *Dstates*
while $\exists$ an unmarked state T in *Dstates*
    mark T
    for each input symbol a **do**
        U = ϵ-*closure*(*move*(T,a))
        if U is not in *Dstates* **then**
            add U to *Dstates* unmarked
        Dtran[T,a] = U
    endfor
endwhile

Each state in D corresponds to a *set* of states in N.

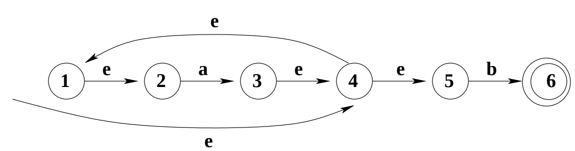
Up to $2^{|N|}$ possible states in D.

ϵ-*closure*(s_0) is the start state of D.

A state is an accepting state in D, if one or more of the states it represents in N is accepting.

Example subset construction

nfa for a*b



		ϵ-closure( ) = { } =
MOVE(,) = { }		ϵ-closure( ) = { } =
MOVE(,) = { }		ϵ-closure( ) = { } =
MOVE(,) = { }		ϵ-closure( ) = { } =
MOVE(,) = { }		ϵ-closure( ) = { } =

Building minimum-state *dfa*s

Important theoretical result

> *Every regular language is recognized by a minimum-state* dfa *that is unique up to state names.*

Look for states that can be *distinguished* from each other (i.e., end up in accepting/nonaccepting state for identical input).

dfa state minimization algorithm

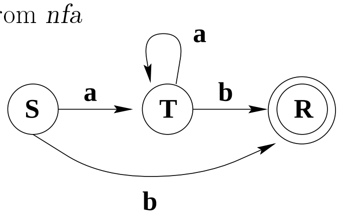
- construct initial partition of states into accepting and non-accepting states
- successively refine partition by splitting a group G into smaller groups if states in G have transitions to different groups

  (two states *x, y* are in same group *iff* for all input symbols *a x* and *y* have transitions to same group)
- update transition edges, remove dead states

Theorem 3.10, pages 67–71 in Hopcroft and Ullman's book *Introduction to Automata Theory, Languages, and Computation*

Example minimal *dfa* construction

dfa for a*b from *nfa*



Initial partition

accepting = { } =

non-accepting = { } =

Split groups

(state, input)	=	group
(S, a)	=	
(T, a)	=	
(S, b)	=	
(T, b)	=	

Minimal *dfa*

Issues

Complexity Tradeoffs

For regular expression r and input x

	Space	Time
nfa	$O(\|r\|)$	$O(\|r\| * \|x\|)$
dfa	$O(2^{\|r\|})$	$O(\|x\|)$

Other approaches

- generate *dfa* directly from regular expression
- two stack simulation of *nfa*
- "lazy" construction of *dfa*

So what is hard?

Language features that can cause problems:

reserved words

PL/I had no reserved words

```
if then then then = else;
else else = then;
```

significant blanks

FORTRAN and Algol68 ignore blanks

```
do 10 i = 1,25
do 10 i = 1.25
```

string constants

special characters in strings

`newline`, `tab`, `quote`, `comment delimiter`

These problems can be swept under the rug (avoided) by intelligent language design.

Lexical errors

What is a lexical error?

- 1234G6
- illegal character

What should the scanner do?

- report the error
- try to correct it?

Error correction techniques

- minimum distance corrections
- hard token recovery
- skip until match

How bad can it get?

```
           INTEGERFUNCTIONA
           PARAMETER(A=6,B=2)
           IMPLICIT CHARACTER*(A-B)(A-B)
           INTEGER FORMAT(10),IF(10),DO9E1
     100   FORMAT(4H)=(3)
     200   FORMAT(4 )=(3)
           DO9E1=1
           DO9E1=1,2
              IF(X)=1
              IF(X)H=1
              IF(X)300,200
     300      CONTINUE
           END
     C     this is a comment
         $ FILE(1)
     14    END
```


Summary

Scanners

- break up input into tokens
- catch lexical errors
- difficulty affected by language design

Issues

- input buffering
- lookahead
- error recovery

Scanner generators

- tokens specified by regular expressions
- construct *dfa* to recognize language
- highly efficient in practice