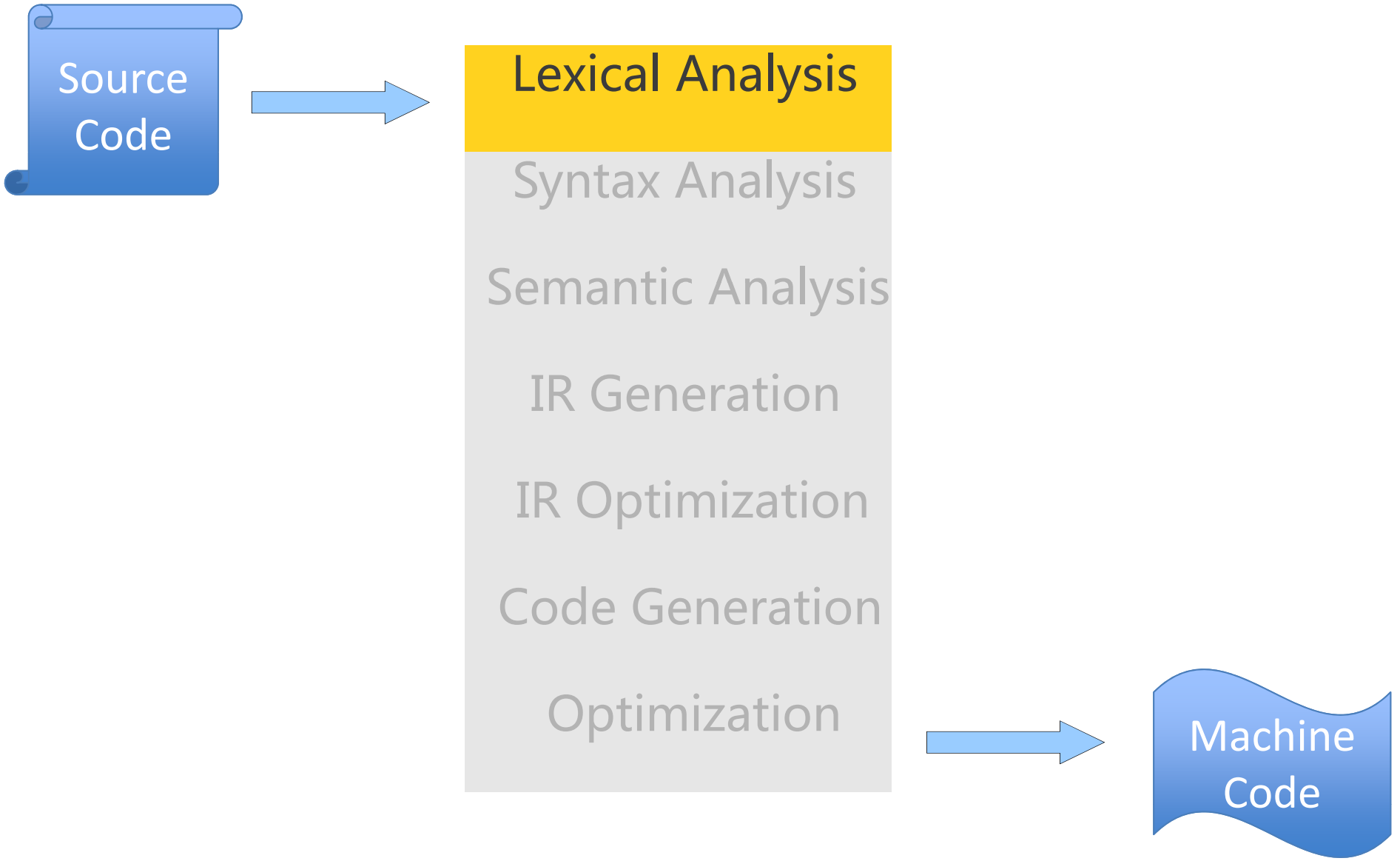
Compilers and Interpreters

Lexical Analysis

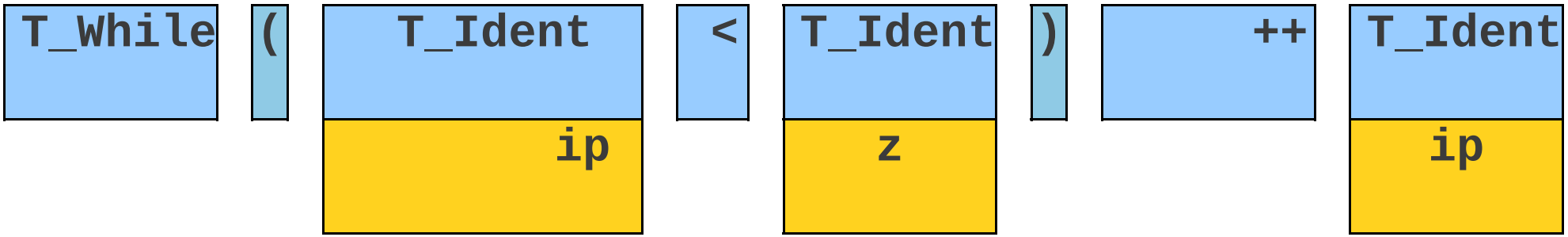
Where We Are


Source Code
Lexical Analysis
Syntax Analysis
Semantic Analysis
IR Generation
IR Optimization
Code Generation
Optimization
Machine Code

```
while (ip < z)
    ++ip;
```

w	h	i	l	e		(	i	p		<		z	)	\n	\t	+	+	i	p	;

```
while (ip < z)
    ++ip;
```



w	h	i	l	e		(	i	p		<		z	)	\n	\t	+	+	i	p	;

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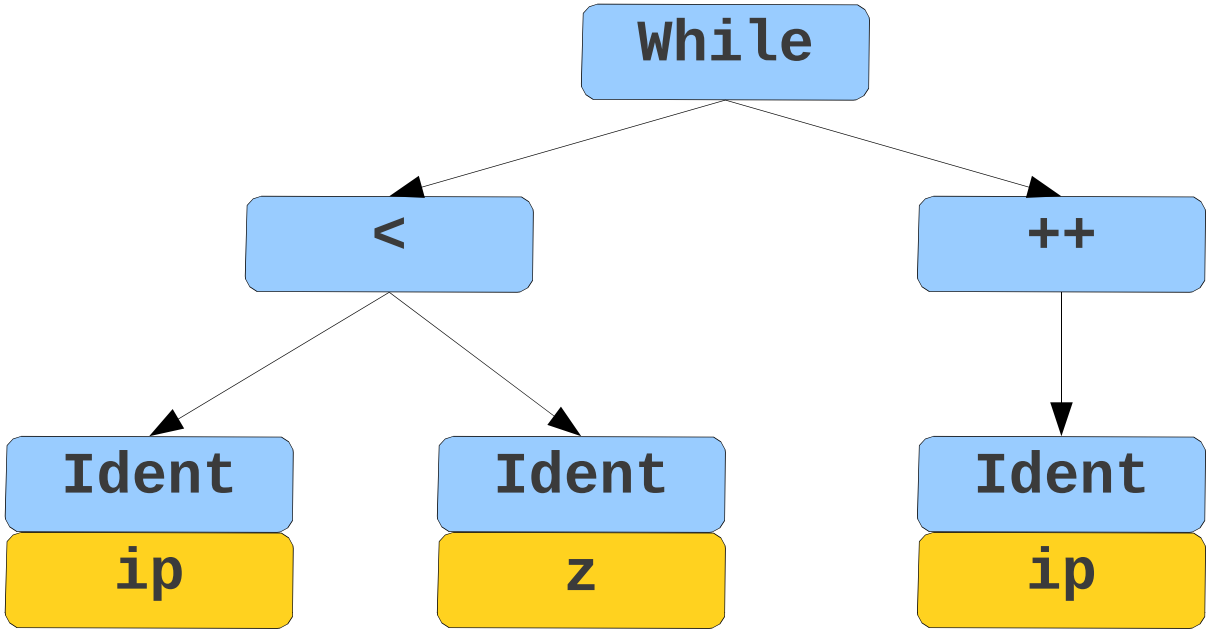
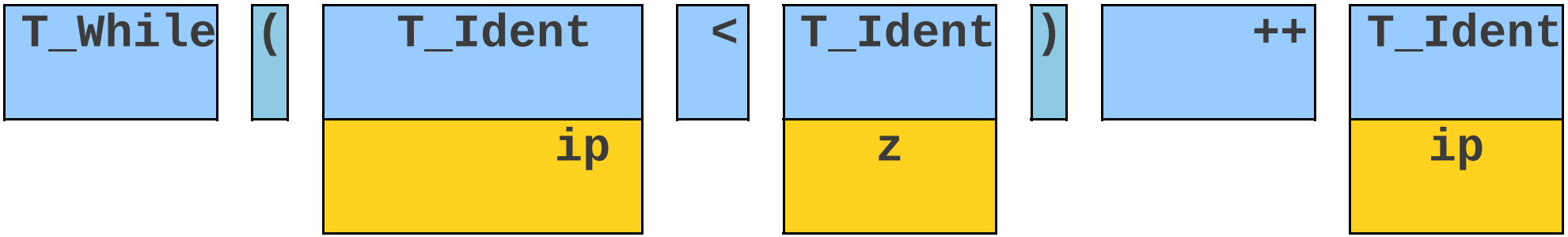


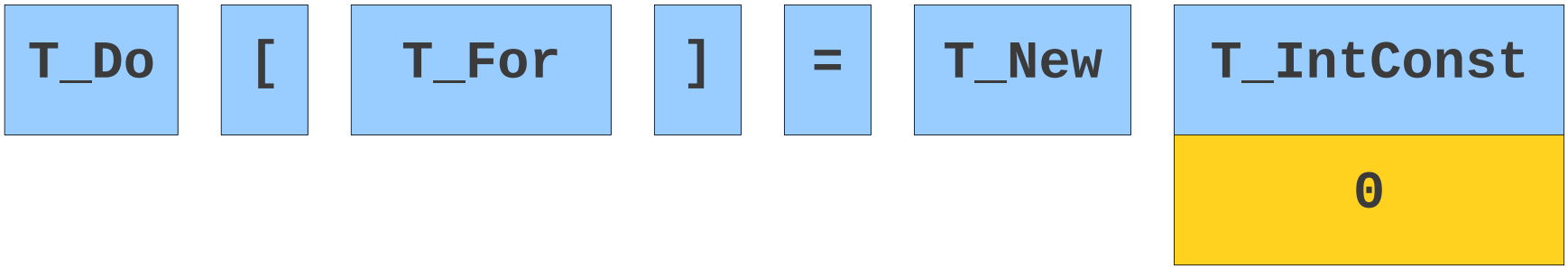


w	h	i	l	e		(	i	p		<		z	)	\n	\t	+	+	i	p	;

```
while (ip < z)
    ++ip;
```

d	o	[	f	o	r	]		=		n	e	w		0	;

do[for] = new 0;



d	o	[	f	o	r	]		=		n	e	w		0	;

do[for] = new 0;

Scanning a Source File

w	h	i	l	e		(	1	3	7		<		i	)	\n	\t	+	+	i	;

Scanning a Source File

w	h	i	l	e		(	1	3	7		<		i	)	\n	\t	+	+	i	;

Scanning a Source File

w	h	i	l	e		(	1	3	7		<		i	)	\n	\t	+	+	i	;

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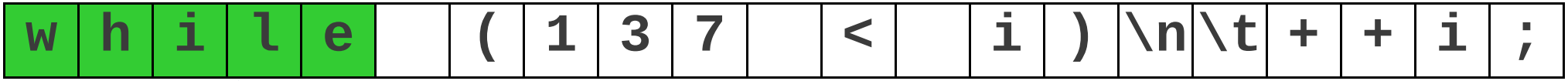
Scanning a Source File

w	h	i	l	e		(	1	3	7		<		i	)	\n	\t	+	+	i	;

T_While

Scanning a Source File



The piece of the original program from which we made the token is called a **lexeme**.

`T_While`

This is called a **token**. You can think of it as an enumerated type representing what logical entity we read out of the source code.

Scanning a Source File

w	h	i	l	e		(	1	3	7		<		i	)	\n	\t	+	+	i	;

T_While

Scanning a Source File

w	h	i	l	e		(	1	3	7		<		i	)	\n	\t	+	+	i	;

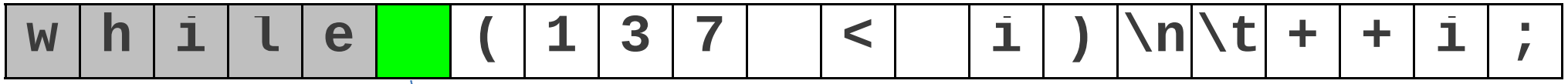
T_While

Scanning a Source File

w	h	i	l	e		(	1	3	7		<		i	)	\n	\t	+	+	i	;

T_While

Scanning a Source File



T_While

Sometimes we will discard a lexeme rather than storing it for later use. Here, we ignore whitespace, since it has no bearing on the meaning of the program.

Scanning a Source File

w	h	i	l	e		(	1	3	7		<		i	)	\n	\t	+	+	i	;

T_While

Scanning a Source File

w	h	i	l	e		(	1	3	7		<		i	)	\n	\t	+	+	i	;

T_While

Scanning a Source File

w	h	i	l	e		(	1	3	7		<		i	)	\n	\t	+	+	i	;

T_While

Scanning a Source File

w	h	i	l	e		(	1	3	7		<		i	)	\n	\t	+	+	i	;

T_While	(

Scanning a Source File

w	h	i	l	e		(	1	3	7		<		i	)	\n	\t	+	+	i	;

T_While	(

Scanning a Source File

w	h	i	l	e		(	1	3	7		<		i	)	\n	\t	+	+	i	;

T_While

(

Scanning a Source File

w	h	i	l	e		(	1	3	7		<		i	)	\n	\t	+	+	i	;

T_While

(

Scanning a Source File

w	h	i	l	e		(	1	3	7		<		i	)	\n	\t	+	+	i	;

T_While

(

Scanning a Source File

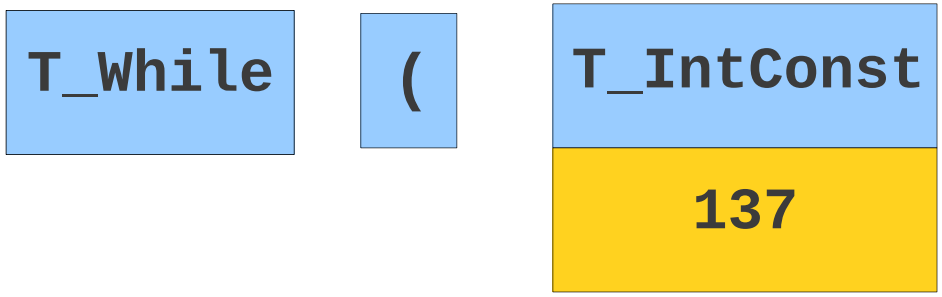
w	h	i	l	e		(	1	3	7		<		i	)	\n	\t	+	+	i	;

T_While

(

Scanning a Source File

w	h	i	l	e		(	1	3	7		<		i	)	\n	\t	+	+	i	;



Scanning a Source File

w	h	i	l	e		(	1	3	7		<		i	)	\n	\t	+	+	i	;

Goals of Lexical Analysis

- Convert from physical description of a program into sequence of of **tokens**.
  - Each token represents one logical piece of the source file – a keyword, the name of a variable, etc.
- Each token is associated with a **lexeme**.
  - The actual text of the token: "137," "int," etc.
- Each token may have optional **attributes**.
  - Extra information derived from the text – perhaps a numeric value.
- The token sequence will be used in the parser to recover the program structure.

Choosing Tokens

What Tokens are Useful Here?

```
for (int k = 0; k < myArray[5]; ++k) {
cout     << k << endl;
}
```

What Tokens are Useful Here?

```
for (int k = 0; k < myArray[5]; ++k) {
        cout << k << endl;
}
```

```
for     {
int     }
<<      ;
=       <
(       [
)       ]
++
```

```
Identifier
IntegerConstant
```

Choosing Good Tokens

- Very much dependent on the language.
- Typically:
  - Give keywords their own tokens.
  - Give different punctuation symbols their own tokens.
  - Group lexemes representing identifiers, numeric constants, strings, etc. into their own groups.
  - Discard irrelevant information (whitespace, comments)

Scanning is Hard

- FORTRAN: Whitespace is irrelevant

```
DO 5 I = 1,25
DO 5 I = 1.25
```

Scanning is Hard

- FORTRAN: Whitespace is irrelevant

```
DO 5 I = 1,25
DO 5 I = 1.25
```

Can be difficult to tell when to partition input.

Scanning is Hard

- C++: Nested template declarations

```
vector<vector<int>>myVector
```

Scanning is Hard

- C++: Nested template declarations

```
Vector < vector < int >> myVector
```

Scanning is Hard

- C++: Nested template declarations

```
( vector < ( vector < ( int >> myVector ) )
```

Can be difficult to determine where to split.

Scanning is Hard

- PL/1: Keywords can be used as identifiers.

```
IF THEN THEN THEN = ELSE; ELSE ELSE = IF
```

Can be difficult to determine how to label lexeme.

Challenges in Scanning

- How to determine which lexemes are associated with each token?
- When there are multiple ways we could scan the input, how to know which one to pick?
- How to address these concerns efficiently?

Challenges in Scanning

- The goal of lexical analysis is to
  - Partition the input string into lexemes
  - Identify the token of each lexeme

- Left-to-right scan
  - Lookahead sometimes required

Associating Lexemes with Tokens

Lexemes and Tokens

- Tokens give a way to categorize lexemes by what information they provide.
- Some tokens might be associated with only a single lexeme:
  - Tokens for keywords like `if` and `while` probably only match those lexemes exactly.
- Some tokens might be associated with lots of different lexemes
  - All variable names, all possible numbers, all possible strings, etc.

Sets of Lexemes

- Idea: Associate a set of lexemes with each token.
- We might associate the "number" token with the set { **`0`**, **`1`**, **`2`**, …, **`10`**, **`11`**, **`12`**, … }
- We might associate the "string" token with the set { **`""`**, **`"a"`**, **`"b"`**, **`"c"`**, … }
- We might associate the token for the keyword **`while`** with the set { **`while`** }.

How to describe which (potentially infinite) set of lexemes is associated with each token type?

Formal Languages

- A **formal language** is a set of strings.
- Many infinite languages have finite descriptions:
  - Define the language using an **automaton**.

    Define the language using a grammar.
  - Define the language using a **regular expression**.
- We can use these compact descriptions of the language to define sets of strings.
- Over the course of this class, we will use all of these approaches.

Regular Expressions

- **Regular expressions** are a family of descriptions that can be used to capture certain languages (the *regular languages*).
- Often provide a compact and human-readable description of the language.
- Used as the basis for numerous software systems, e.g. **`flex, antlr.`**

Atomic Regular Expressions

- The regular expressions we will use in this course begin with two simple building blocks.
- The symbol **ε** is a regular expression matches the empty string.
- For any symbol **a**, the symbol **a** is a regular expression that just matches **a**.

Compound Regular Expressions

1. If R_1 and R_2 are regular expressions, **R_1R_2** is a regular expression represents the **concatenation** of the languages of R_1 and R_2.
2. If R_1 and R_2 are regular expressions, **$R_1 \mid R_2$** is a regular expression representing the **union** of $R_1$and R_2 .
3. If R is a regular expression, **R*** is a regular expression for the **Kleene closure** of R.
4. If R is a regular expression, **(R)** is a regular expression with the same meaning as R.

Operator Precedence

- Regular expression operator precedence is

(R)

R*

R_1R_2

$R_1| R_2$

- So **ab*c|d** is parsed as **((a(b*))c)|d**

Algebraic Laws for Regular Expression

LAW	DESCRIPTION
r|s = s|r	| is commutative
r|(s|t) = (r|s)|t	| is associate
r(st) = (rs)t	Concatenation is associate
r(s|t) = rs|rt; (s|t)r = sr|tr	Concatenation distributes over |
εr = rε = r	ε is the identity for concatenation
r* = (r|ε)*	ε is guaranteed in a closure
r** = r*	ε is idempotent

Simple Regular Expressions

- Suppose the only characters are `0` and `1`.
- Here is a regular expression for strings containing `00` as a substring:

(0 | 1)*00(0 | 1)*

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(0 | 1)*00(0 | 1)*

11011100101
0000
1111101111001111
1

Simple Regular Expressions

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- Here is a regular expression for strings containing `00` as a substring:

(0 | 1)*00(0 | 1)*

11011100101
0000
1111101111001111
1

Simple Regular Expressions

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Simple Regular Expressions

- Suppose the only characters are `0` and `1`.
- Here is a regular expression for strings of length exactly four:

(0|1)(0|1)(0|1)(0|1)

0000
1010
1111
1000

Simple Regular Expressions

- Suppose the only characters are **`0`** and **`1`**.
- Here is a regular expression for strings of length exactly four:

(0|1)(0|1)(0|1)(0|1)

0000
1010
1111
1000

Simple Regular Expressions

- Suppose the only characters are `0` and `1`.
- Here is a regular expression for strings of length exactly four:

(0|1){4}

0000
1010
1111
1000

Simple Regular Expressions

- Suppose the only characters are `0` and `1`.
- Here is a regular expression for strings that contain at most one zero:

1*(0 | ε)1* **1*0?1***

11110111
111111
0111
0

Applied Regular Expressions

- Suppose our alphabet is **a**, **@**, and **.**, where **a** represents "some letter."
- A regular expression for email addresses is

aa* (.aa*)* @aa*.aa*(.aa*)*

a+ (. a+)* @ a+ .a+ (.a+) *

a+ (. a+)* @ a+ . (. a+)+

lli@whu.edu.cn

Applied Regular Expressions

- Suppose that our alphabet is all ASCII characters.
- A regular expression for even numbers is

(+|-)?(0|1|2|3|4|5|6|7|8|9)*(0|2|4|6|8)

(+|-)?[0123456789]*[02468]

(+|-)?[0-9]*[02468]

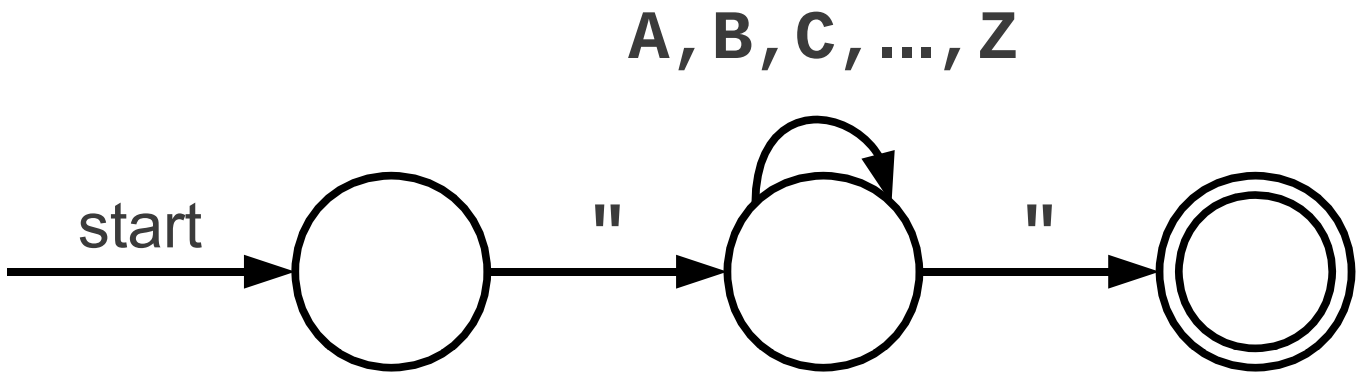
42
+1370
-3248
-9999912

Matching Regular Expressions

Implementing Regular Expressions

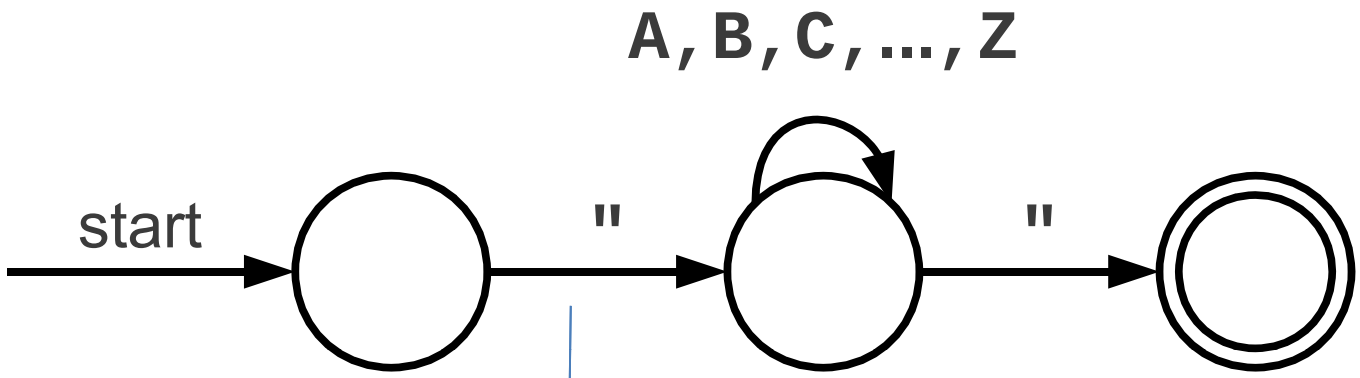
- Regular expressions can be implemented using **finite automata**.
- There are two main kinds of finite automata:
  - **NFA**s (**nondeterministic** finite automata), which we'll see in a second, and
  - **DFA**s (**deterministic** finite automata), which we'll see later.

A Simple Automaton



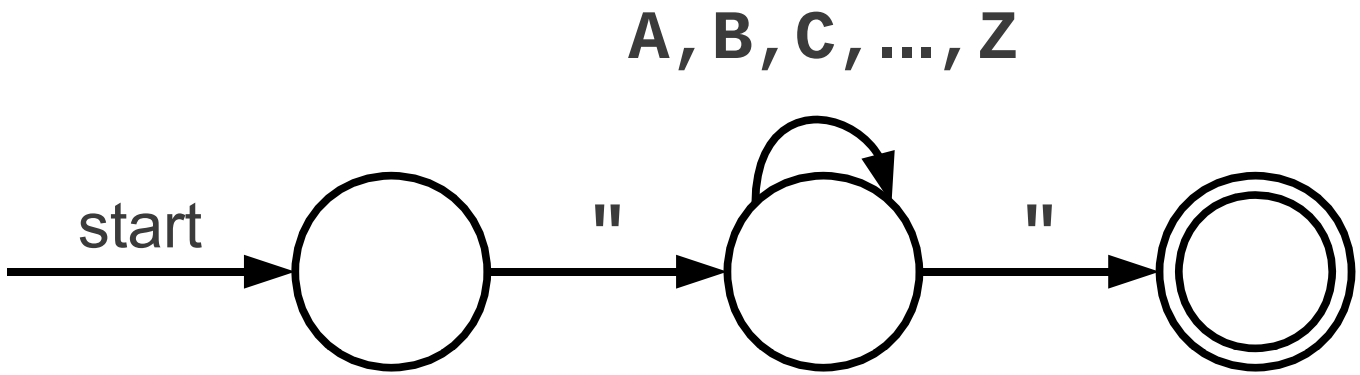
Transition diagrams have a collection of nodes or circles, called states. Each state represents a condition that could occur during the process of scanning the input looking for a lexeme that matches one of several patterns.

A Simple Automaton



Arrows are called transitions. The automaton changes which state(s) it is in by following transitions.

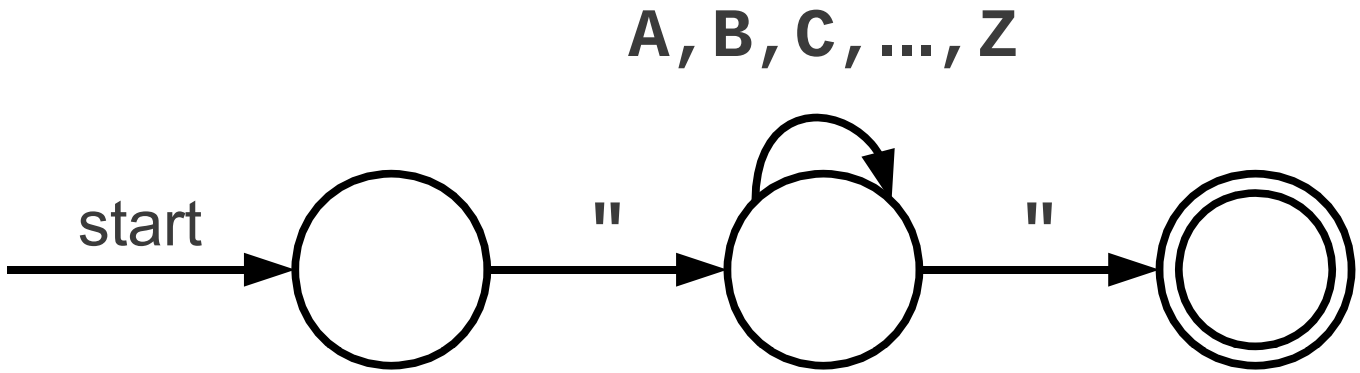
A Simple Automaton

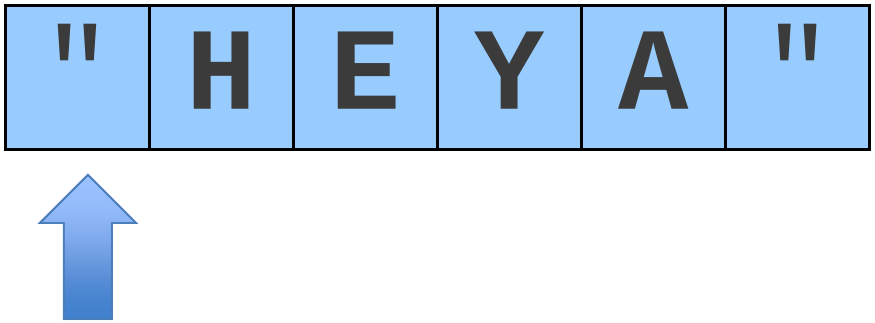


"	H	E	Y	A	"

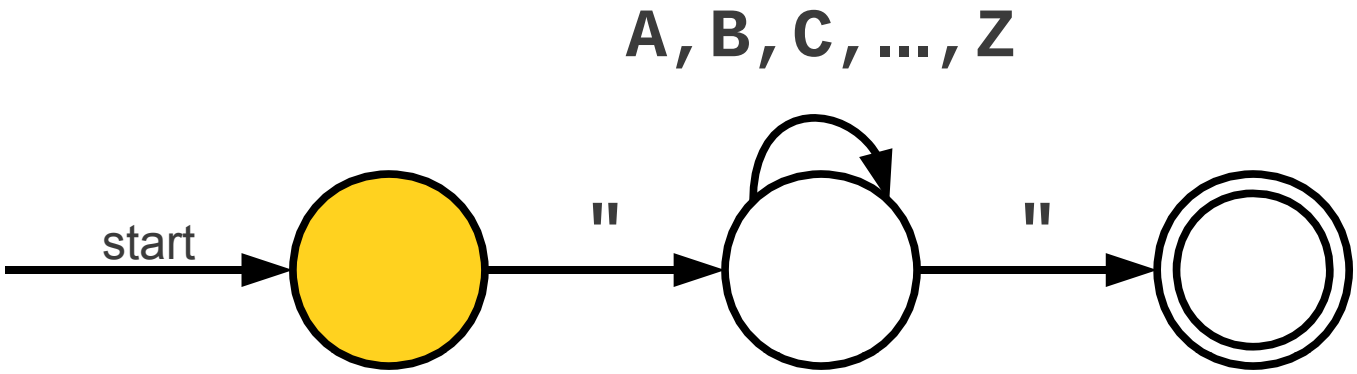
The automaton takes a string as input and decide whether to accept or reject the string.

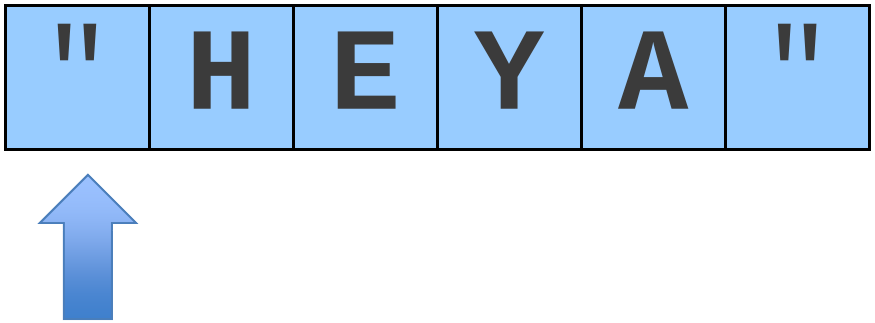
A Simple Automaton





A Simple Automaton





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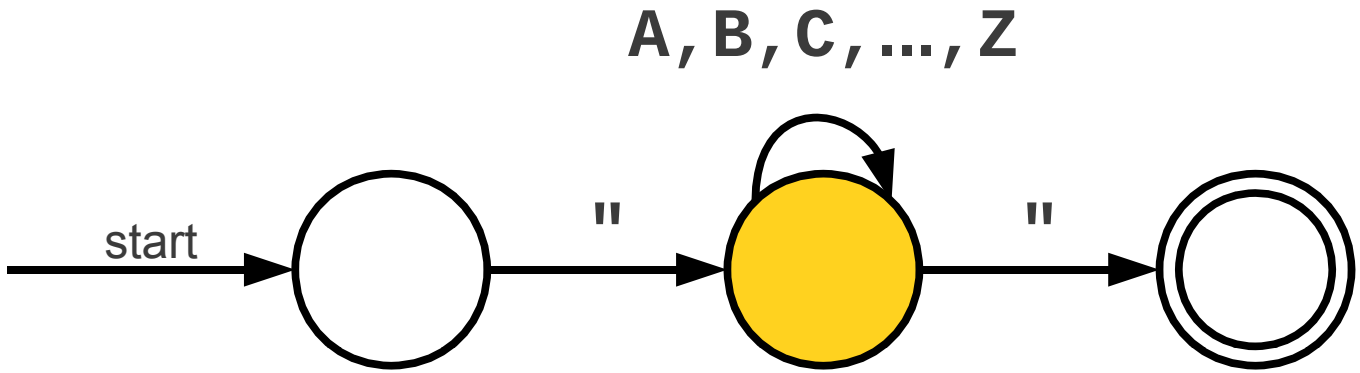

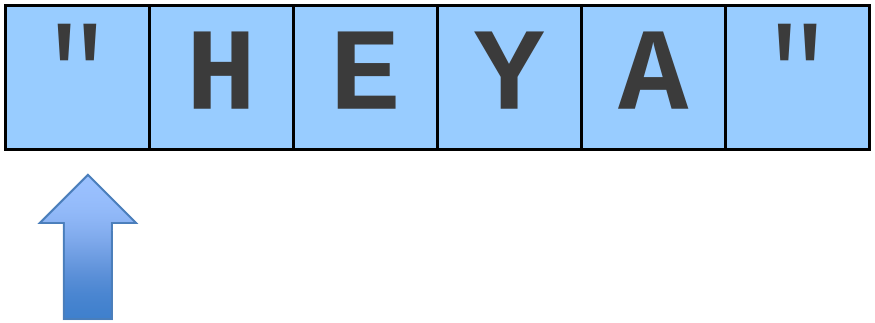

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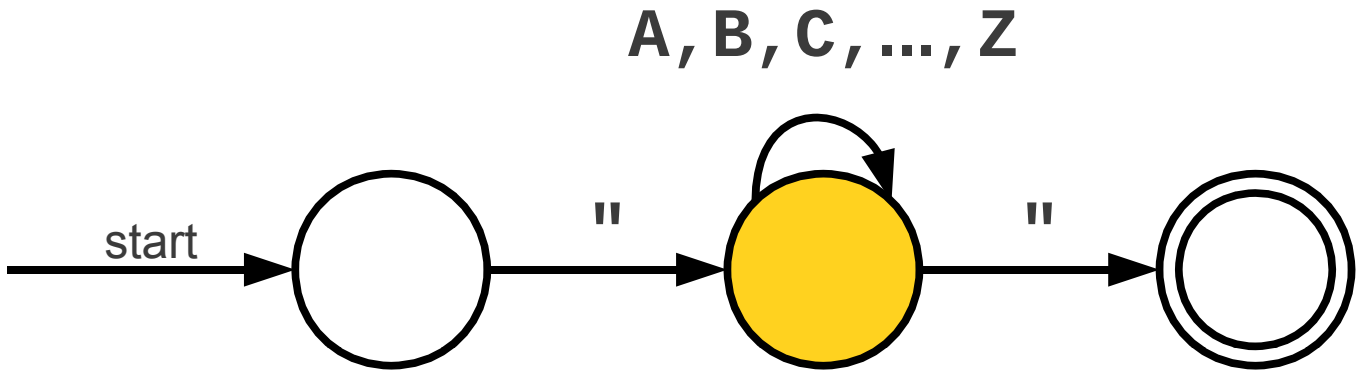

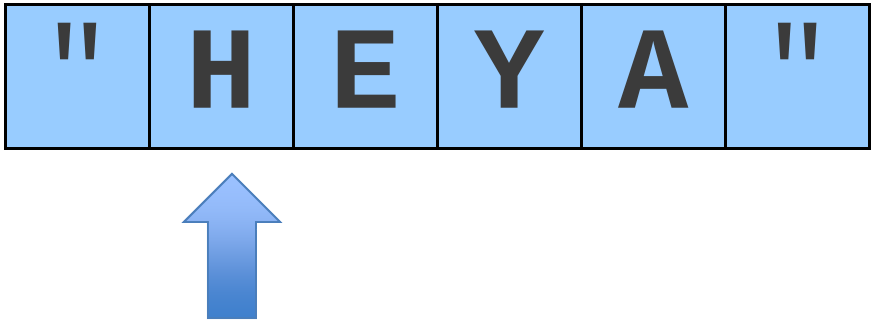

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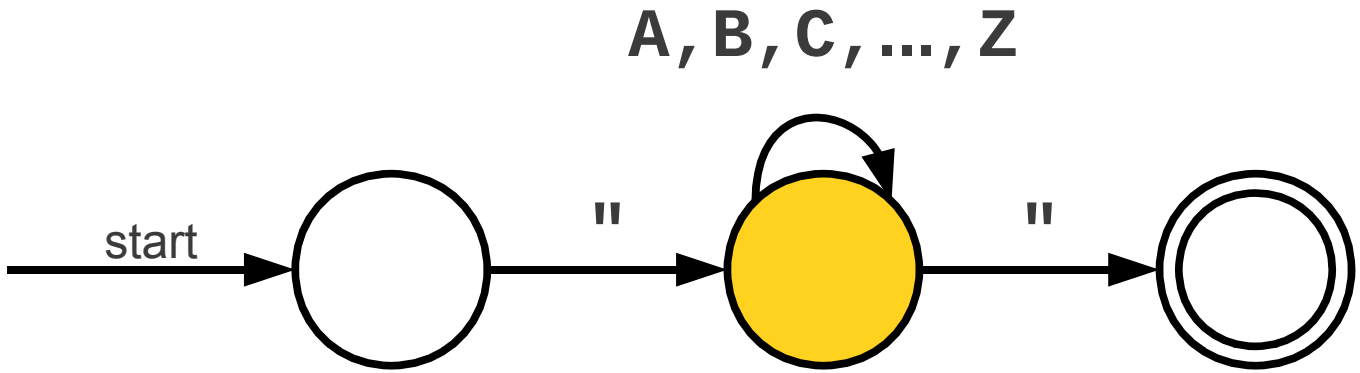

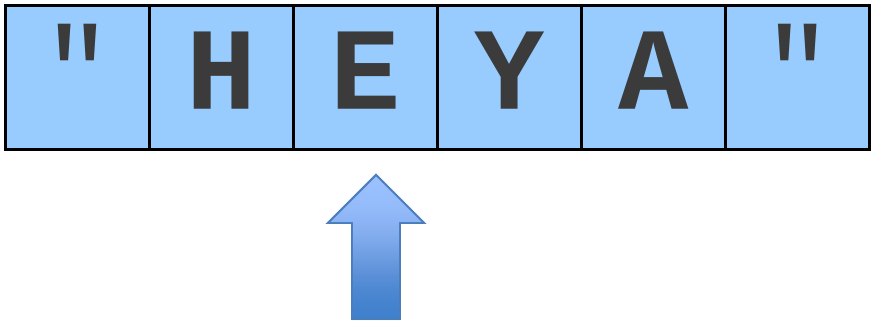

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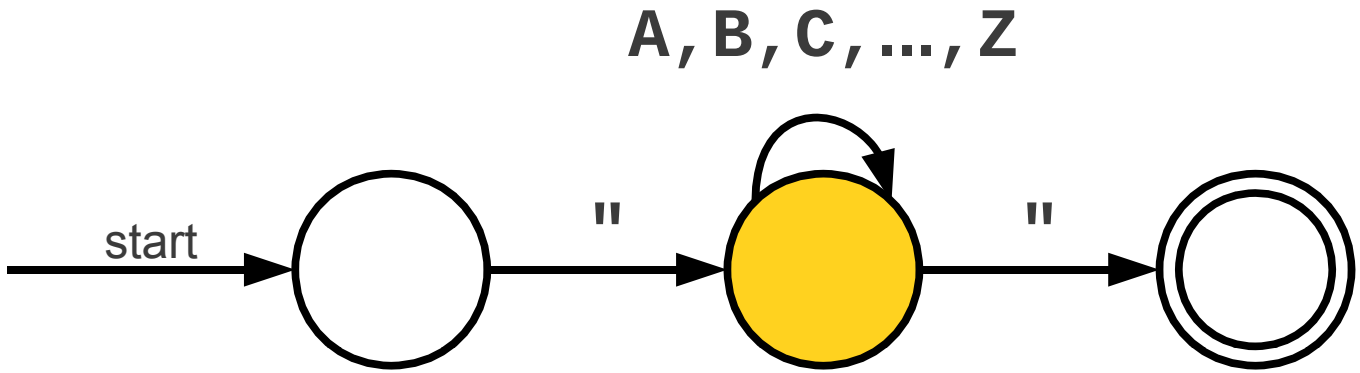

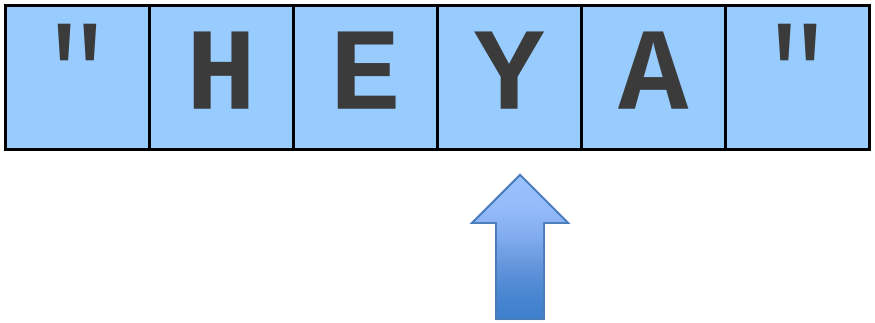

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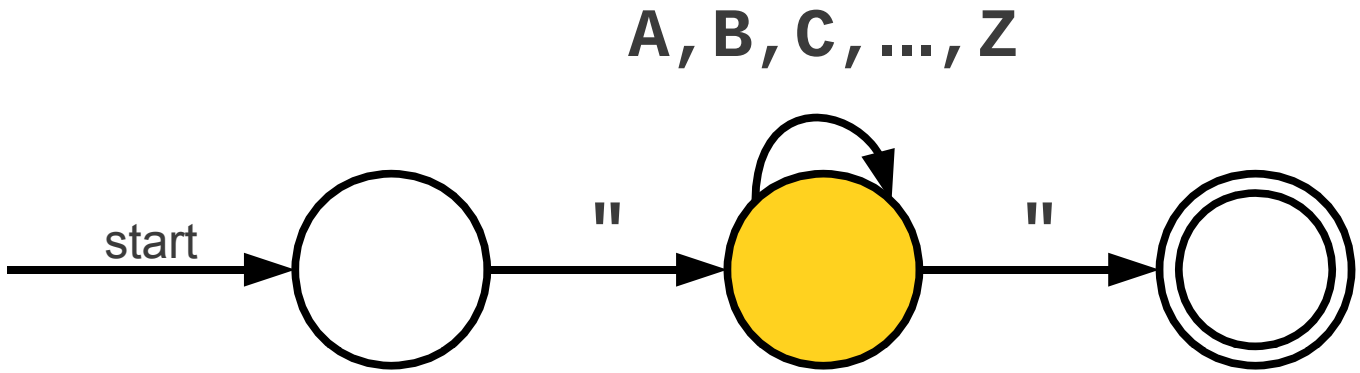

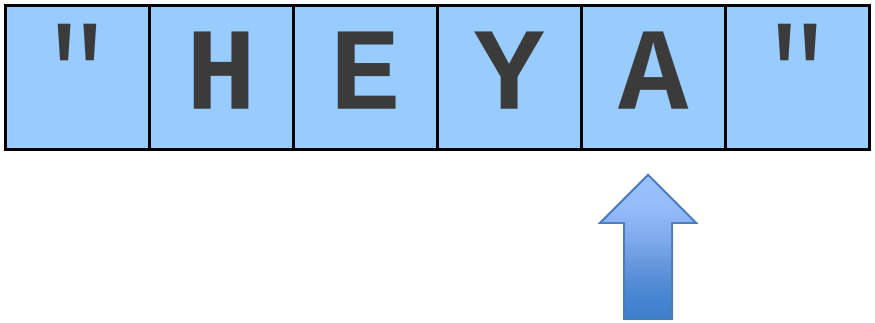

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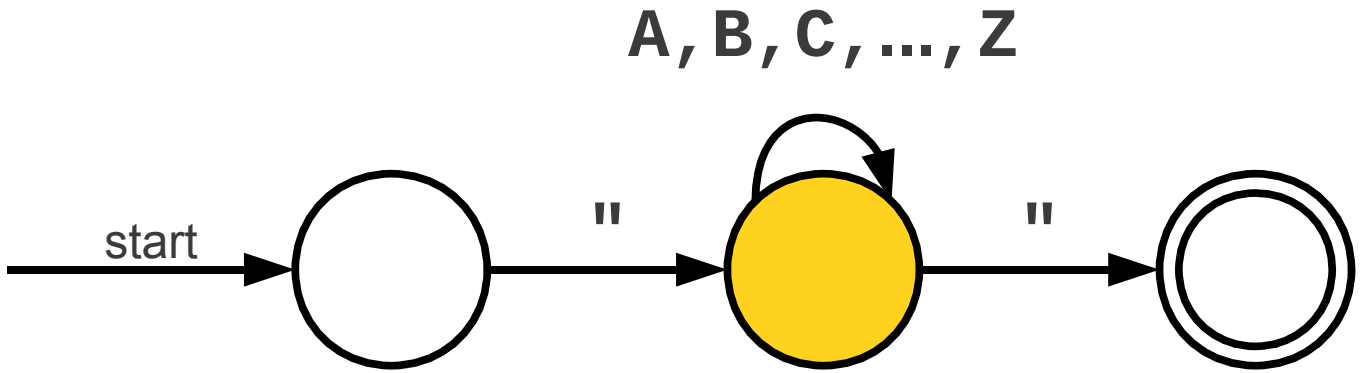
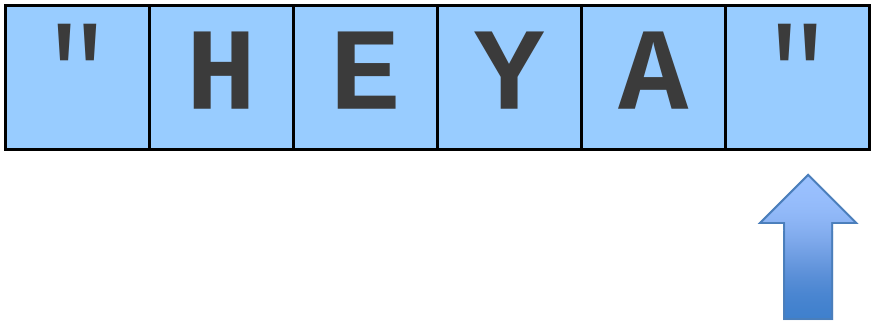
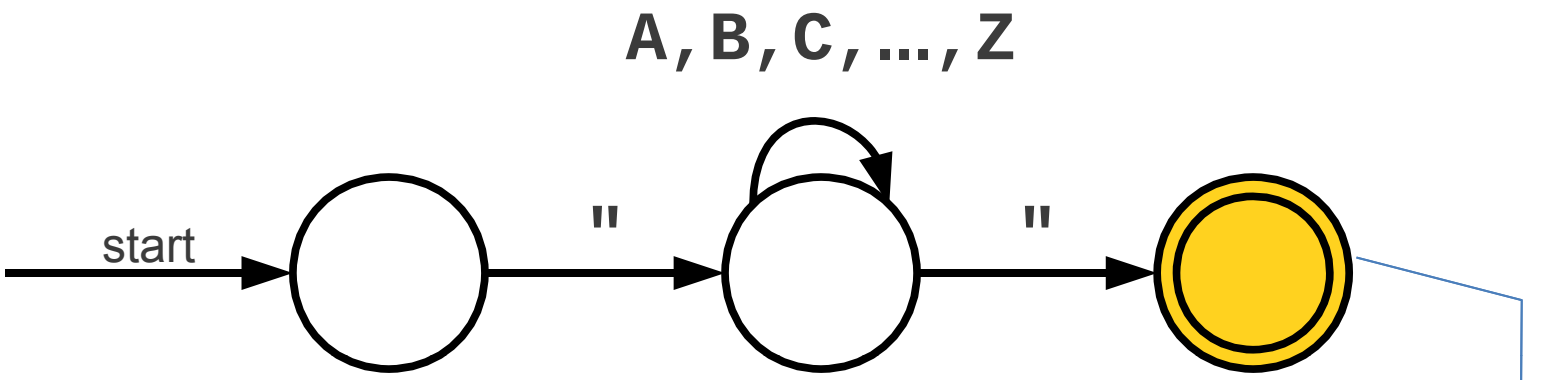




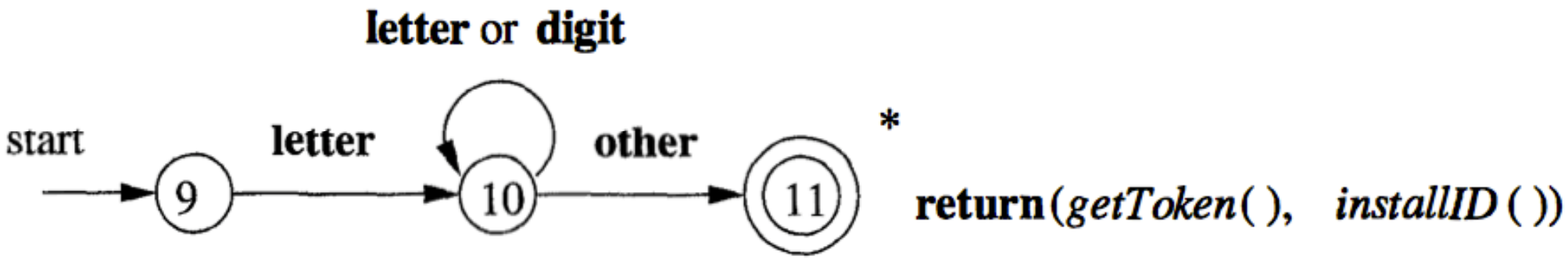
A Simple Automaton



"	H	E	Y	A	"

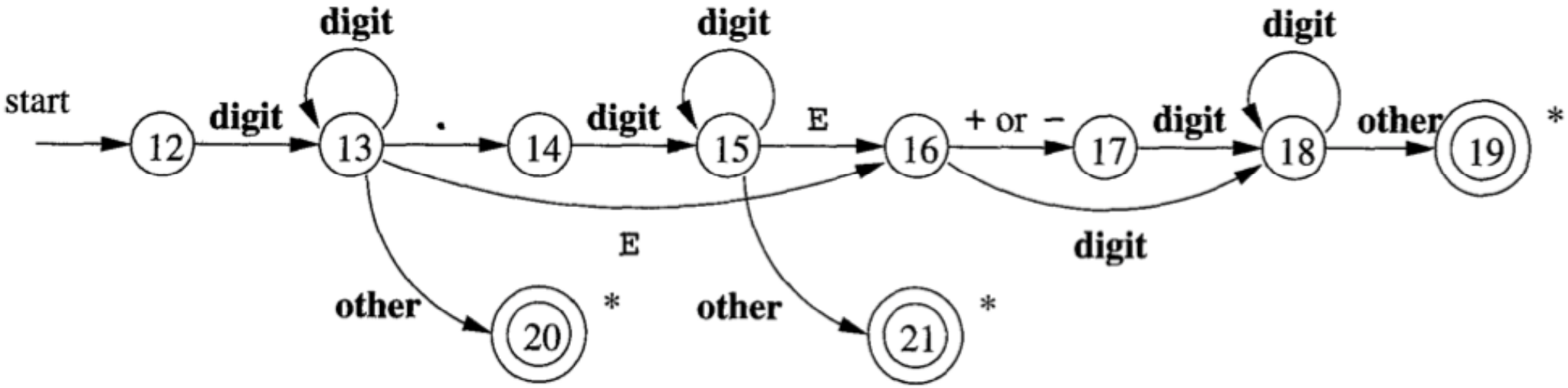
The double circle indicates that this state is an accepting state. The automaton accepts string if it ends in an accepting state.

A More Complex Automaton



h	i	1	2	3

A More Complex Automaton



1	2	.	3	7	5

Finite Automata

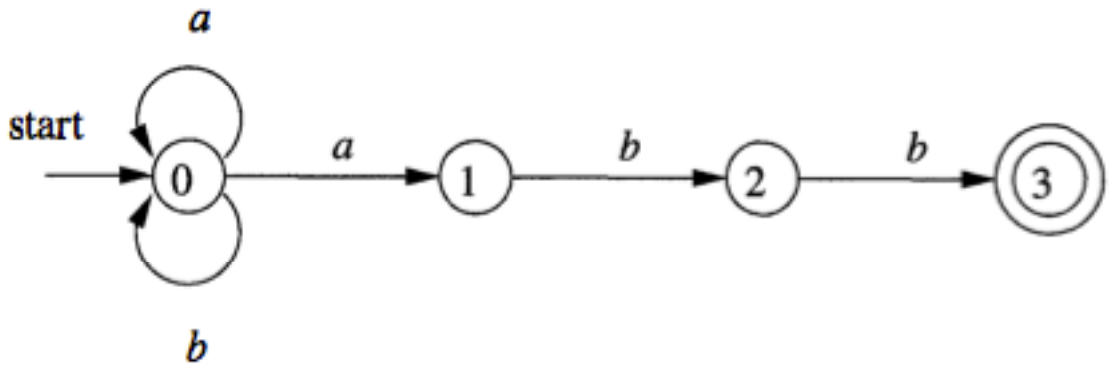
- Finite automata are recognizers; they simply say "yes" or "no" about each possible input string.
- Finite automata come in two flavors:
  - Nondeterministic finite automata (NFA) have no restrictions on the labels of their edges. A symbol can label several edges out of the same state, and E, the empty string, is a possible label.
  - Deterministic finite automata (DFA) have, for each state, and for each symbol of its input alphabet exactly one edge with that symbol leaving that state.

NFA

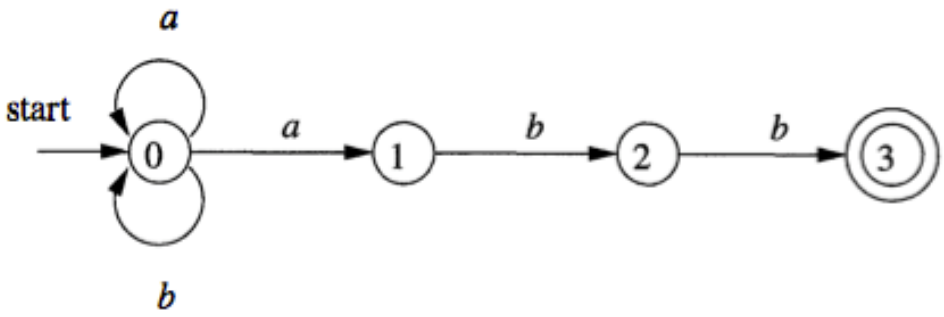
- A nondeterministic finite automaton (NFA) consists of:
  1. A finite set of states S.
  2. A set of input symbols Σ, the input alphabet. We assume that ε, which stands for the empty string, is never a member of Σ .
  3. A transition function that gives, for each state, and for each symbol in Σ U {ε} a set of next states.
  4. A state s_0 from S that is distinguished as the start state (or initial state) .
  5. A set of states F, a subset of S, that is distinguished as the accepting states (or final states).

NFA (cont.)

- The same symbol can label edges from one state to several different states, and
- An edge may be labeled by ε, the empty string, instead of, or in addition to, symbols from the input alphabet.



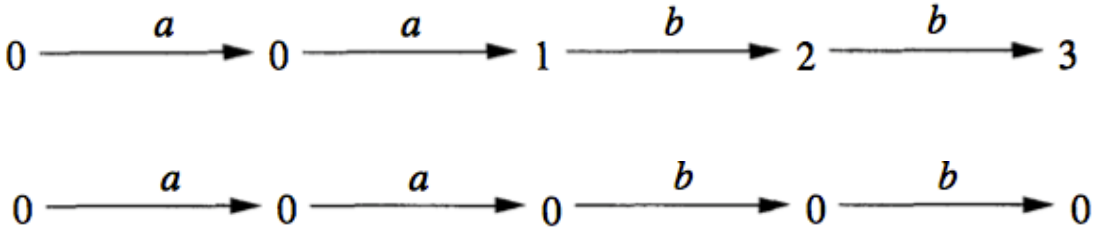
NFA (cont.)



Transition Table

STATE	a	b	ϵ
0	$\{0,1\}$	$\{0\}$	$\emptyset$
1	$\emptyset$	$\{2\}$	$\emptyset$
2	$\emptyset$	$\{3\}$	$\emptyset$
3	$\emptyset$	$\emptyset$	$\emptyset$

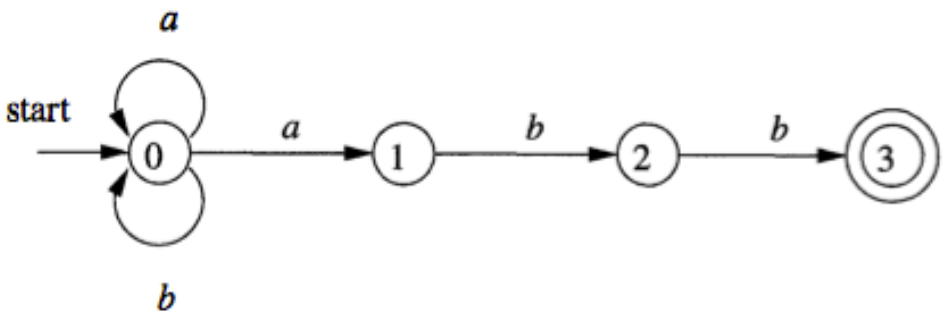
Acceptance of input strings



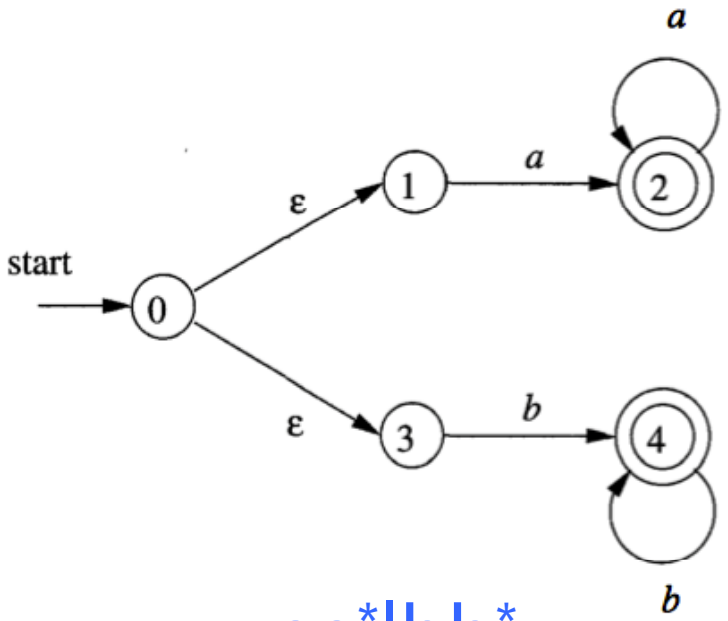
Complexity: O(mn^2) for strings of length m and automata with n states.

NFA (cont.)

- The language defined (or accepted) by an NFA is the set of strings labeling some path from the start to an accepting state.



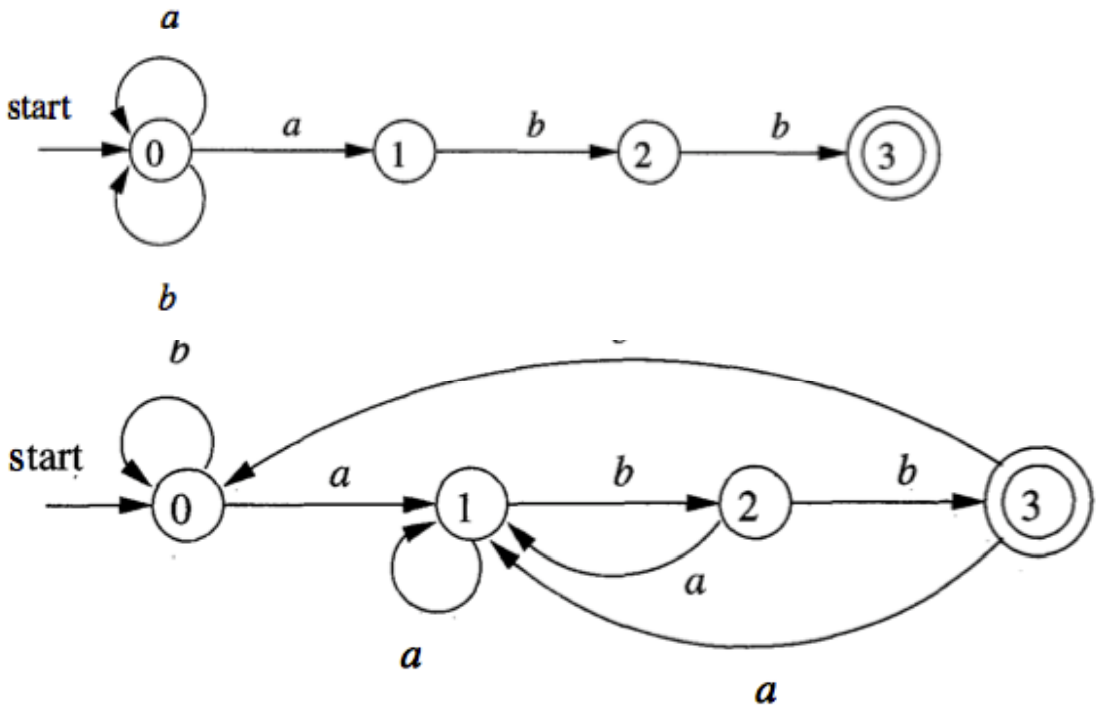
(a|b)*abb



aa*|bb*

DFA

- A deterministic finite automaton (DFA) is a special case of an NFA where:
  1. There are no moves on input ε, and
  2. For each state *s* and input symbol *a*, there is **exactly one** edge out of *s* labeled *a*.

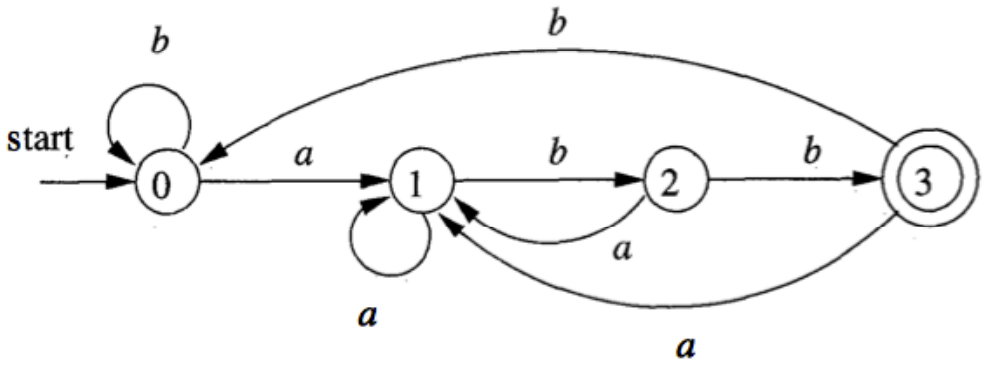


(a|b)*abb

Simulating DFA

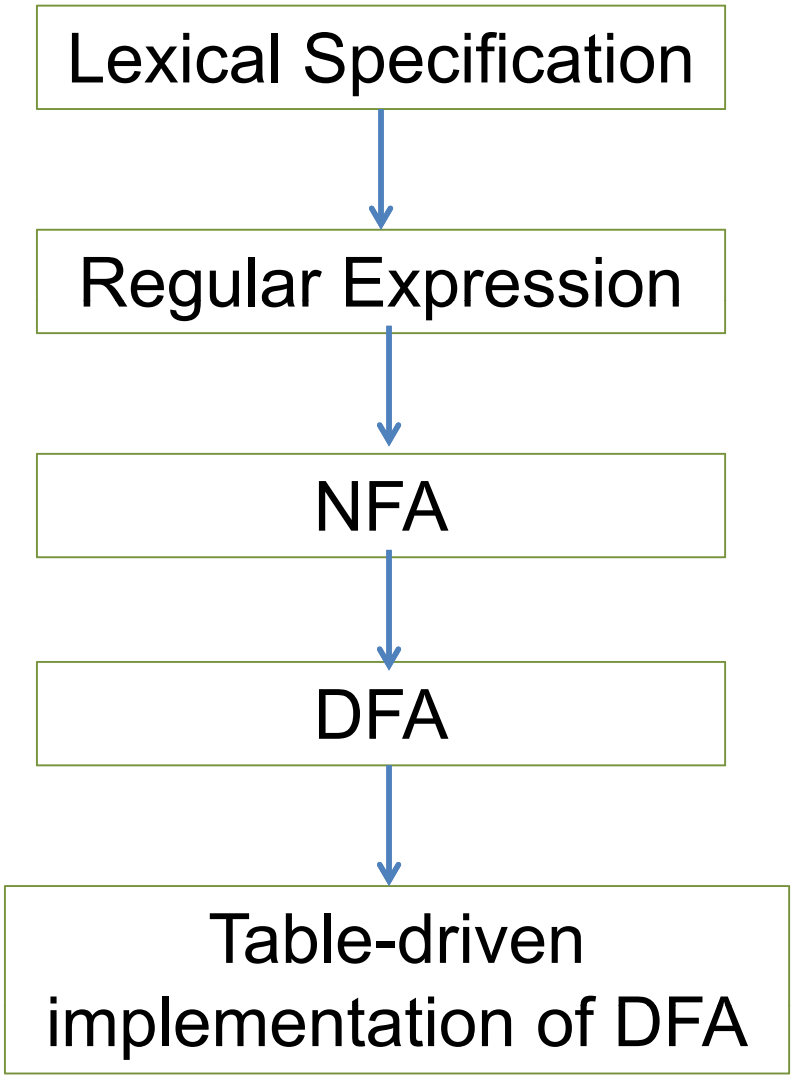
- **INPUT**: An input string *x* terminated by an end-of-file character eof. A DFA D with start state s_0, accepting states F, and transition function move.
- **OUTPUT**: Answer "yes" if D accepts *x*; "no" otherwise.

```
s = s0;
c = nextChar();
while ( c != eof ) {
        s = move(s, c);
        c = nextChar();
}
if ( s is in F ) return "yes";
else return "no";
```



(a|b)*abb

Get a lexical analyzer



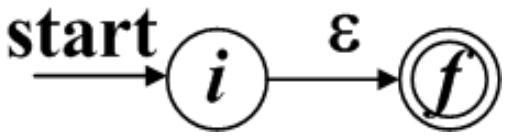
From Regular Expressions to NFA

- The **McNaughton-Yamada-Thompson** algorithm converts a regular expression to an NFA.
  - **INPUT**: A regular expression *r* over alphabet Σ.
  - **OUTPUT**: An NFA *N* accepting L(*r*).

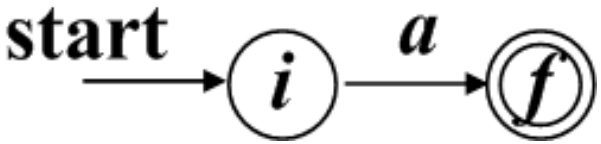
- Begin by parsing *r* into its constituent subexpressions. The rules for constructing an NFA consist of basis rules for handling subexpressiolls with no operators, and inductive rules for constructing larger NFA's from the NFA's
  - for the immediate subexpressions of a given expression.

From Regular Expressions to NFA(cont.)

- **Basic Rules**:



$r = \varepsilon$

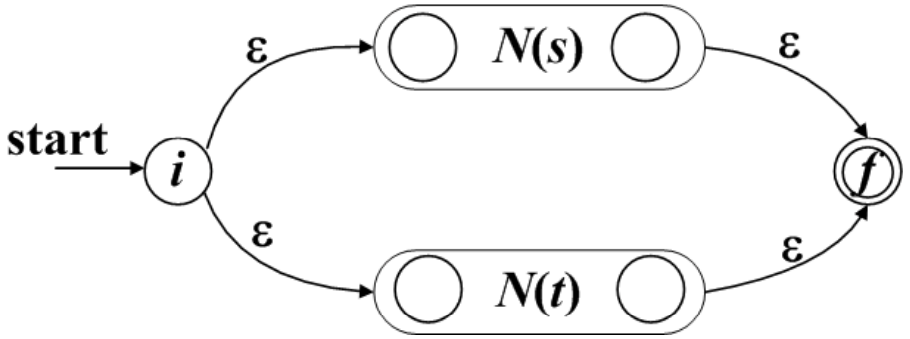


$r = a,\ a \in \Sigma$

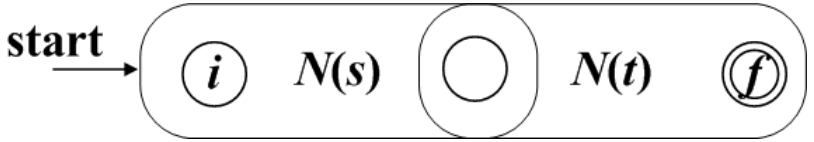
From Regular Expressions to NFA(cont.)

- **Inductive Rules**: Suppose N(s) and N(t) are NFA's for regular expressions *s* and *t*, respectively

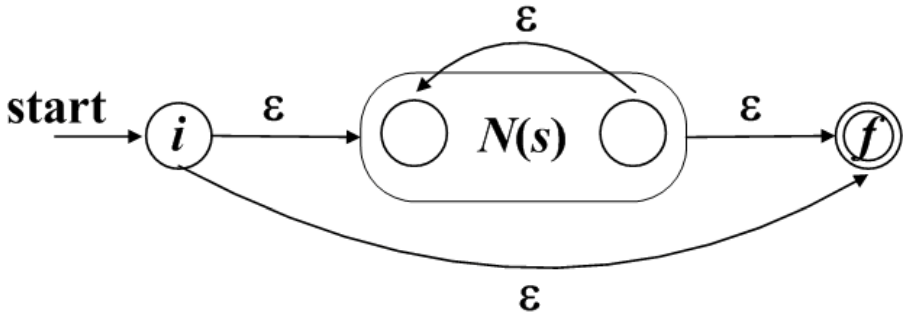
$r = s|t$ $N(r)$:



$r = st$ $N(r)$:



$r = s*$ $N(r)$:



From Regular Expressions to NFA(cont.)

- Any regular expression r of length $|r|$ can be converted into an NFA with $O(|r|)$ states.
- Can determine whether a string x of length $|x|$ matches a regular expression r of length $|r|$ in time $O(|r| \times |x|)$.

Challenges in Scanning

- How do we determine which lexemes are associated with each token?
- When there are multiple ways we could scan the input, how do we know which one to pick?
- How do we address these concerns efficiently?

Lexing Ambiguities

```
T_For           for
T_Identifier    [A-Za-z_][A-Za-z0-9_]*
```

Lexing Ambiguities

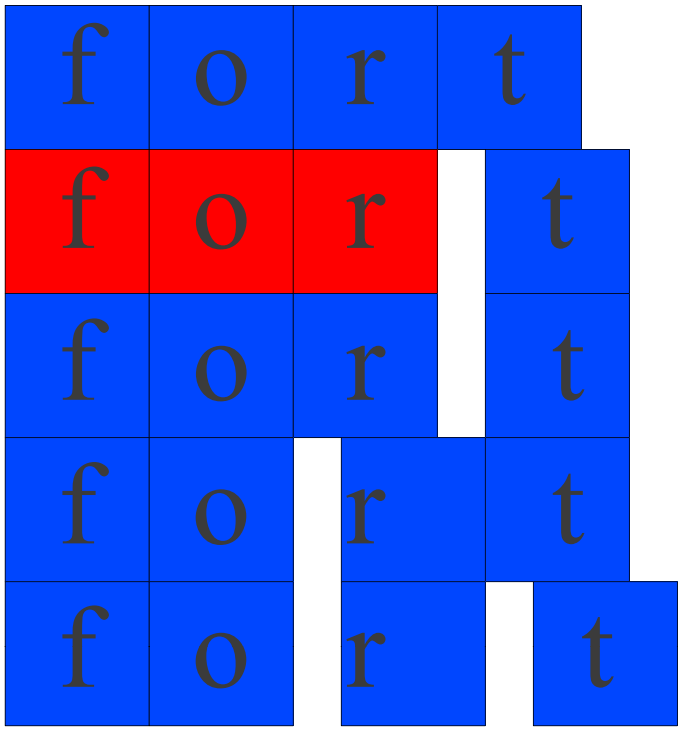
```
T_For           for
T_Identifier    [A-Za-z_][A-Za-z0-9_]*
```

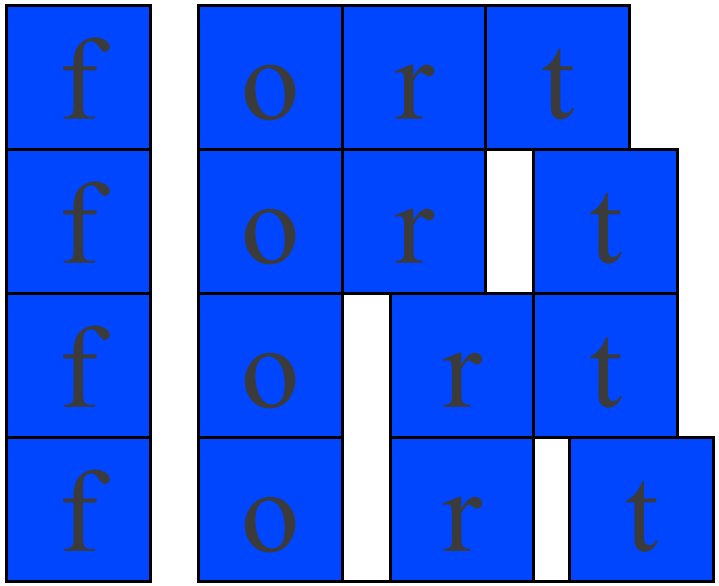
f o r t

Lexing Ambiguities

```
T_For              for
T_Identifier       [A-Za-z_][A-Za-z0-9_]*
```

f o r t





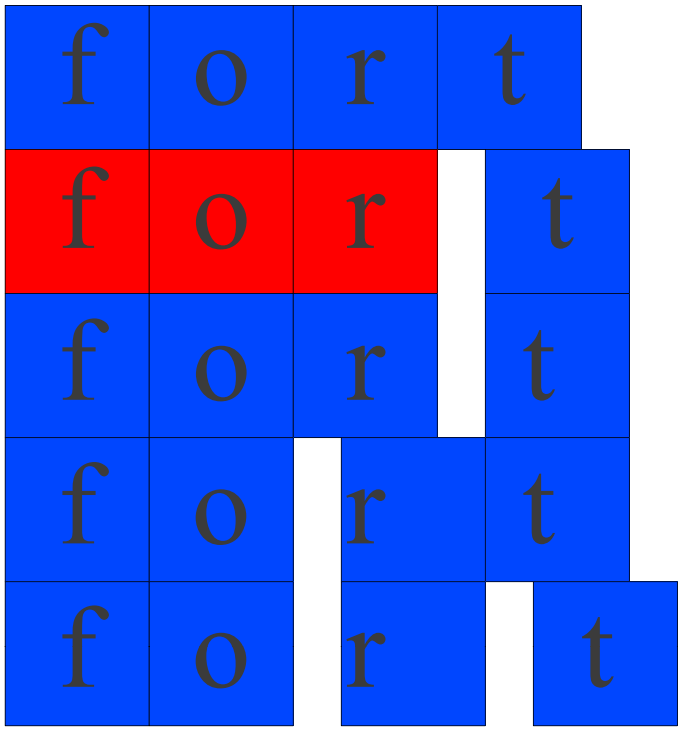
Conflict Resolution

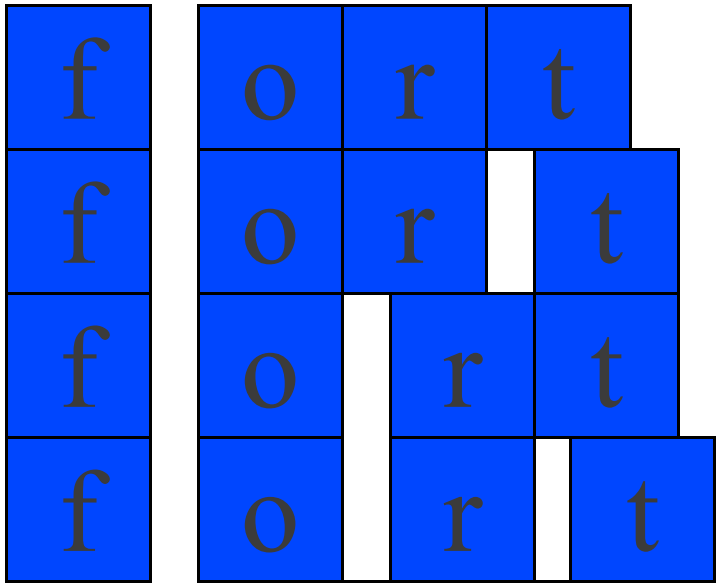
- Assume all tokens are specified as regular expressions.
- Algorithm: **Left-to-right scan**.
- Tiebreaking rule one: **Maximal munch**
  - Always match the longest possible prefix of the remaining text.

Lexing Ambiguities

```
T_For          for
T_Identifier   [A-Za-z_][A-Za-z0-9_]*
```

f o r t

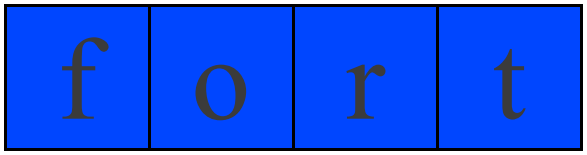




Lexing Ambiguities

```
T_For          for
T_Identifier   [A-Za-z_][A-Za-z0-9_]*
```

f o r t



Challenges in Scanning

- How do we determine which lexemes are associated with each token?
- When there are multiple ways we could scan the input, how do we know which one to pick?
- How do we address these concerns efficiently?

Implementing Maximal Munch

- Given a set of regular expressions, how to use them to implement maximum munch?
- Idea:
  - Convert expressions to NFAs.
  - Run all NFAs in parallel, keeping track of the last match.
  - When all automata get stuck, report the last match and restart the search at that point.

Java Patterns

- Greedy, Reluctant, and Possessive quantifiers in Java patterns

Quantifiers			Meaning
Greedy	**Reluctant**	**Possessive**	
X?	X??	X?+	X, once or not at all
X*	X*?	X*+	X, zero or more times
X+	X+?	X++	X, one or more times
X{n}	X{n}?	X{n}+	X, exactly n times
X{n,}	X{n,}?	X{n,}+	X, at least n times
X{n,m}	X{n,m}?	X{n,m}+	X, at least n but not more than m times

- https://docs.oracle.com/javase/tutorial/essential/regex/quant.html

Other Conflicts

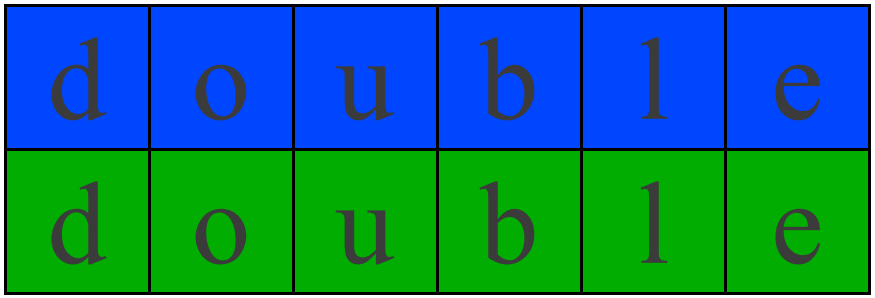
```
T_Do          do
T_Double      double
T_Identifier  [A-Za-z_][A-Za-z0-9_]*
```

d o u b l e

Other Conflicts

```
T_Do            do
T_Double        double
T_Identifier [A-Za-z_][A-Za-z0-9_]*
```

d o u b l e



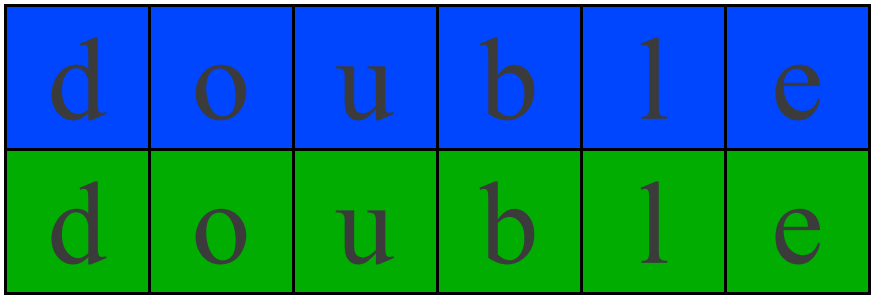
More Tiebreaking

- When two regular expressions apply, choose the one with the greater “priority.”
- Simple priority system: **pick the rule that was defined first.**

Other Conflicts

```
T_Do           do
T_Double       double
T_Identifier [A-Za-z_][A-Za-z0-9_]*
```

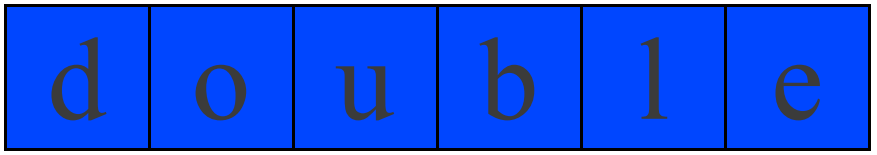
d o u b l e



Other Conflicts

```
T_Do          do
T_Double      double
T_Identifier  [A-Za-z_][A-Za-z0-9_]*
```

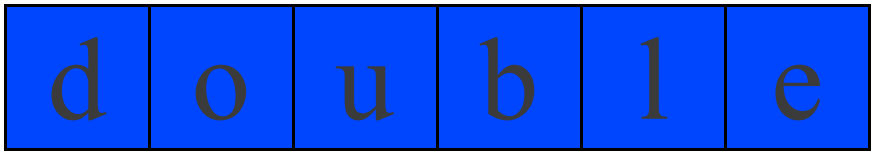
d o u b l e



Other Conflicts

```
T_Do          do
T_Double      double
T_Identifier [A-Za-z_][A-Za-z0-9_]*
```

d o u b l e



Summary of Conflict Resolution

- Construct an automaton for each regular expression.
- Merge them into one automaton by adding a new start state.
- Scan the input, keeping track of the last known match.
- Break ties by choosing higher- precedence matches.
- Have a catch-all rule to handle errors.

One Last Detail...

- We know what to do if *multiple* rules match
- What if *nothing* matches?
- Trick: Add a “catch-all” rule that matches any character and reports an error.

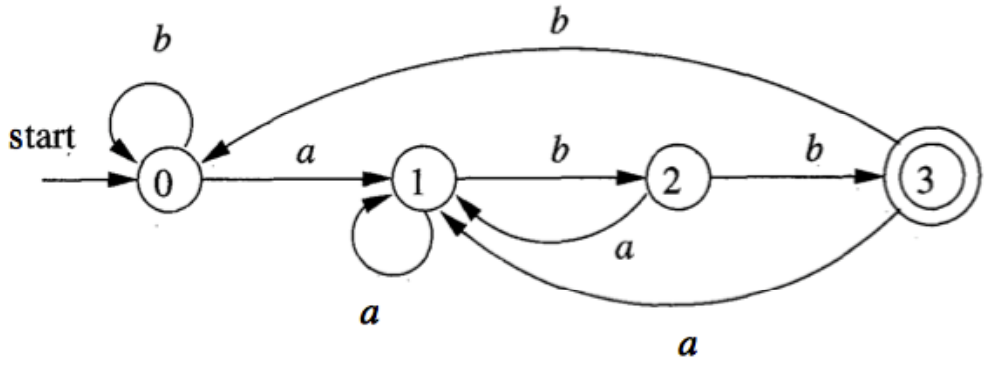
DFAs

- A **DFA** is like an NFA, but with tighter restrictions:
  - Every state must have exactly one transition defined for every letter.
  - ε-moves are not allowed.

Simulating DFA

- **INPUT**: An input string *x* terminated by an end-of-file character eof. A DFA D with start state s_0, accepting states F, and transition function move.
- **OUTPUT**: Answer "yes" if D accepts *x*; "no" otherwise.

```
s = s0;
c = nextChar();
while ( c != eof ) {
        s = move(s, c);
        c = nextChar();
}
if ( s is in F ) return "yes";
else return "no";
```



(a|b)*abb

DFA runs in time O(|*x*|) on an input string *x*.

Speeding up Matching

- In the worst-case, an NFA with n states takes time $O(|r||x|)$ to match a string x.
- DFAs, on the other hand, take only $O(|x|)$.
- There is an algorithm to convert NFAs to DFAs.

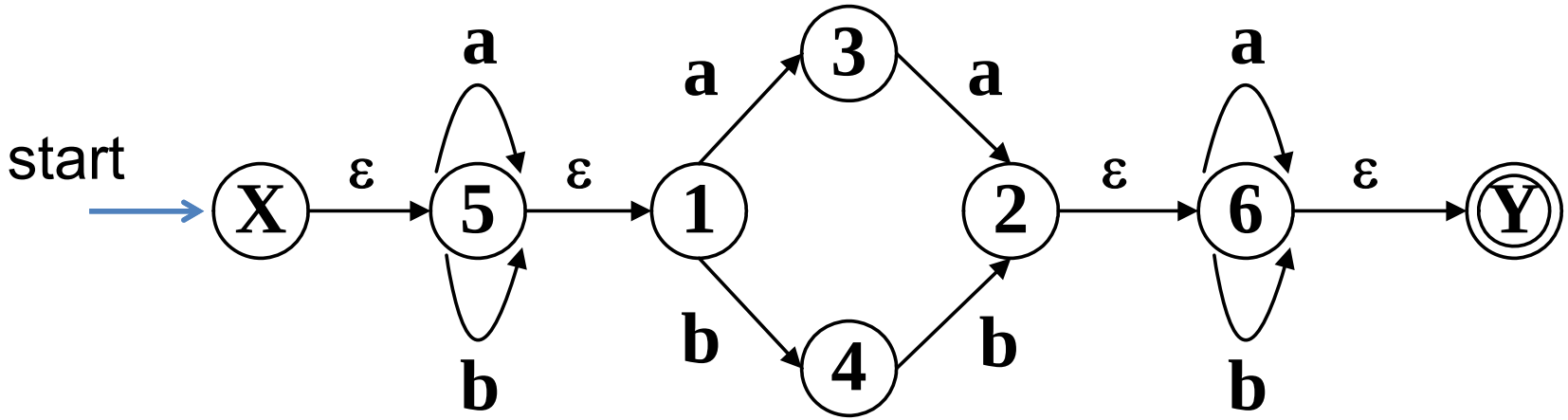
Subset Construction

- NFAs can be in many states at once, while DFAs can only be in a single state at a time.
- Key idea: **Make the DFA simulate the NFA**.
- Have the states of the DFA correspond to the *sets of states* of the NFA.
- Transitions between states of DFA correspond to transitions between *sets of states* in the NFA.

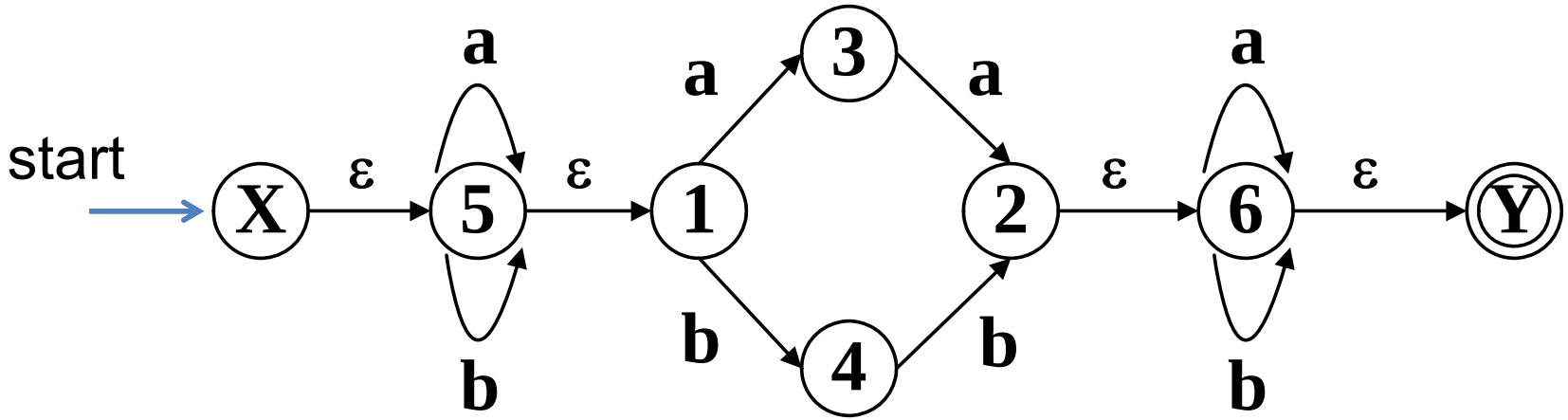
Conversion of an NFA to a DFA

- **INPUT**: An NFA N.
- **OUTPUT**: A DFA D accepting the same language as N.
- **METHOD**: The algorithm constructs a transition table Dtran for D. Each state of D is a set of NFA states, and we construct Dtran so D will simulate "in parallel" all possible moves N can make on a given input string.

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 set T on ϵ-transitions alone; $= \cup_{s \text{ in } T}$ ϵ-*closure*(s).
move(T, a)	Set of NFA states to which there is a transition on input symbol a from some state s in T.

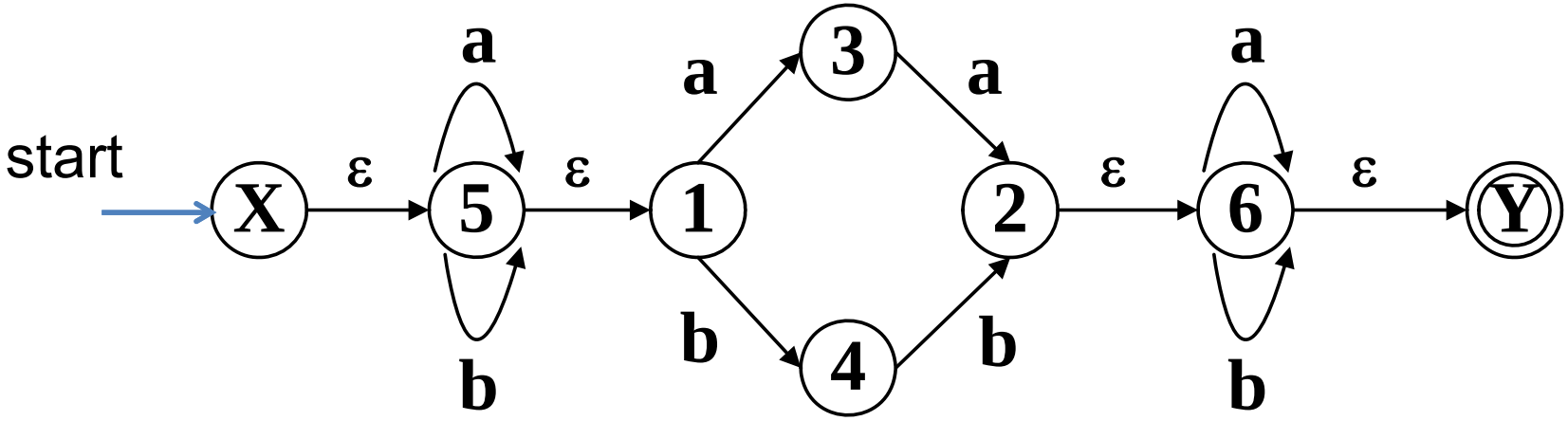


I	I_a	I_b
{X, 5, 1}	{5, 3, 1}	{5, 4, 1}
{5, 3, 1}	{5, 3, 1, 2, 6, Y}	{5, 4, 1}
{5, 4, 1}	{5, 3, 1}	{5, 4, 1, 2, 6, Y}
{5, 3, 1, 2, 6, Y}	{5, 3, 1, 2, 6, Y}	{5, 4, 1, 6, Y}
{5, 4, 1, 6, Y}	{5, 3, 1, 6, Y}	{5, 4, 1, 2, 6, Y}
{5, 4, 1, 2, 6, Y}	{5, 3, 1, 6, Y}	{5, 4, 1, 2, 6, Y}
{5, 3, 1, 6, Y}	{5, 3, 1, 2, 6, Y}	{5, 4, 1, 6, Y}

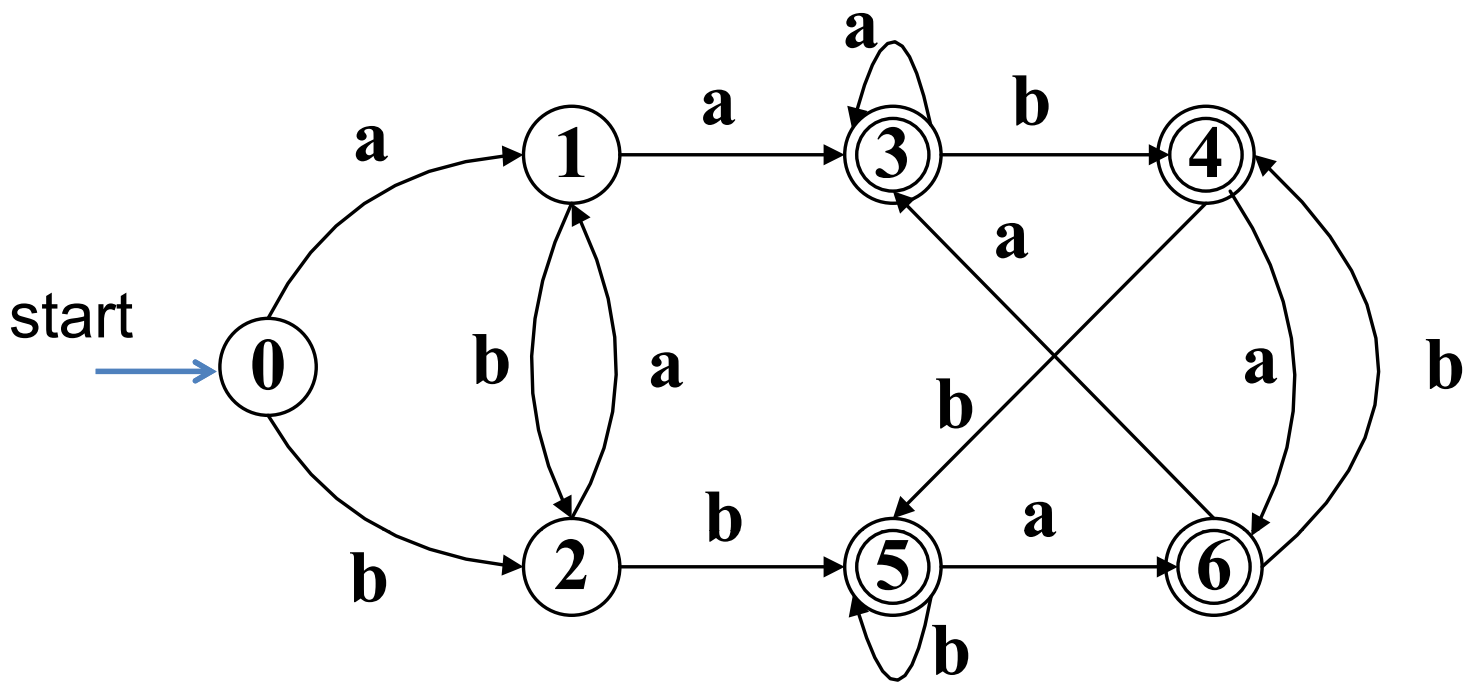


I	s	I_a	a	I_b	b
{X, 5, 1}	0	{5, 3, 1}	1	{5, 4, 1}	2
{5, 3, 1}	1	{5, 3, 1, 2, 6, Y}	3	{5, 4, 1}	2
{5, 4, 1}	2	{5, 3, 1}	1	{5, 4, 1, 2, 6, Y}	5
{5, 3, 1, 2, 6, Y}	3	{5, 3, 1, 2, 6, Y}	3	{5, 4, 1, 6, Y}	4
{5, 4, 1, 6, Y}	4	{5, 3, 1, 6, Y}	6	{5, 4, 1, 2, 6, Y}	5
{5, 4, 1, 2, 6, Y}	5	{5, 3, 1, 6, Y}	6	{5, 4, 1, 2, 6, Y}	5
{5, 3, 1, 6, Y}	6	{5, 3, 1, 2, 6, Y}	3	{5, 4, 1, 6, Y}	4

NFA



DFA

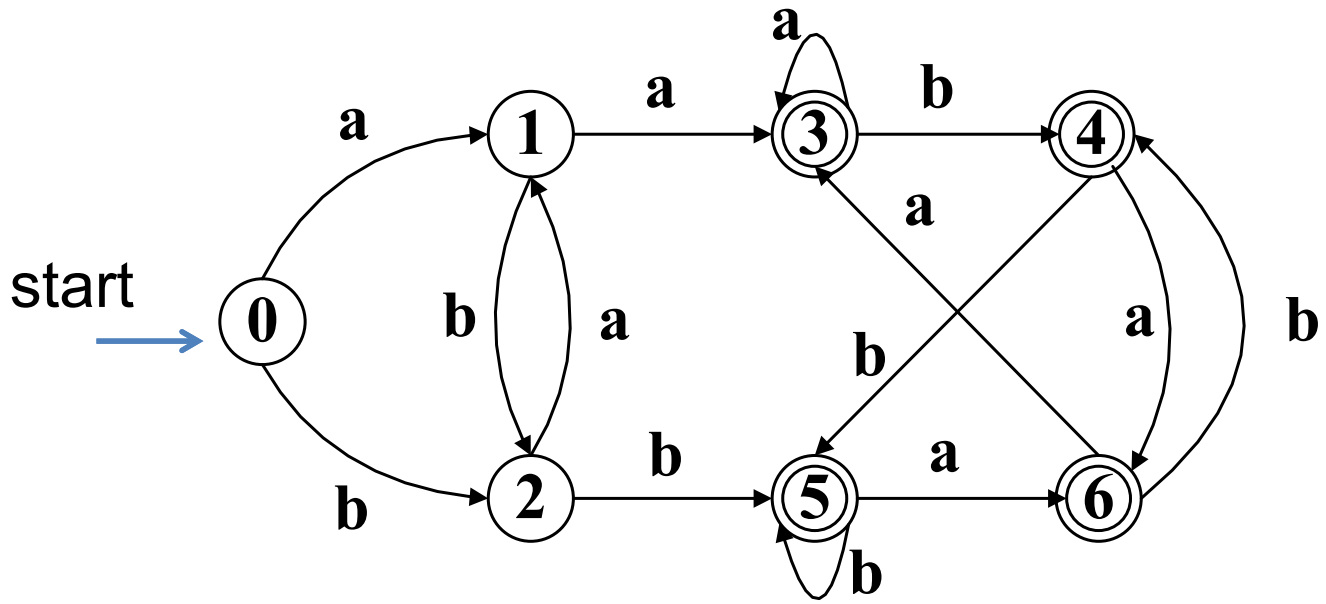


Minimizing the number of states of a DFA

- **INPUT**: An DFA *D*
- **OUTPUT**: A DFA *D'* accepting the same language as *D* and having as few states as possible.
- **METHOD**:

1. Construct initial partition Π of S with two groups: accepting/ non-accepting.
2. (Construct Π_{new})For each group *G* of Π do begin
   a) Partition *G* into subgroups such that two states s,t of *G* are in the same subgroup if for all symbols a states s,t have transitions on a to states of the same group of Π.
   b) Replace *G* in Π_{new} by the set of all these subgroups.
3. Compare Π_{new} and Π. If equal, Π_{final}:= Π then proceed to 4, otherwise, set Π := Π_{new} and goto 2.
4. Choose one state in each group of Πfinal as the representative for that group.

DFA



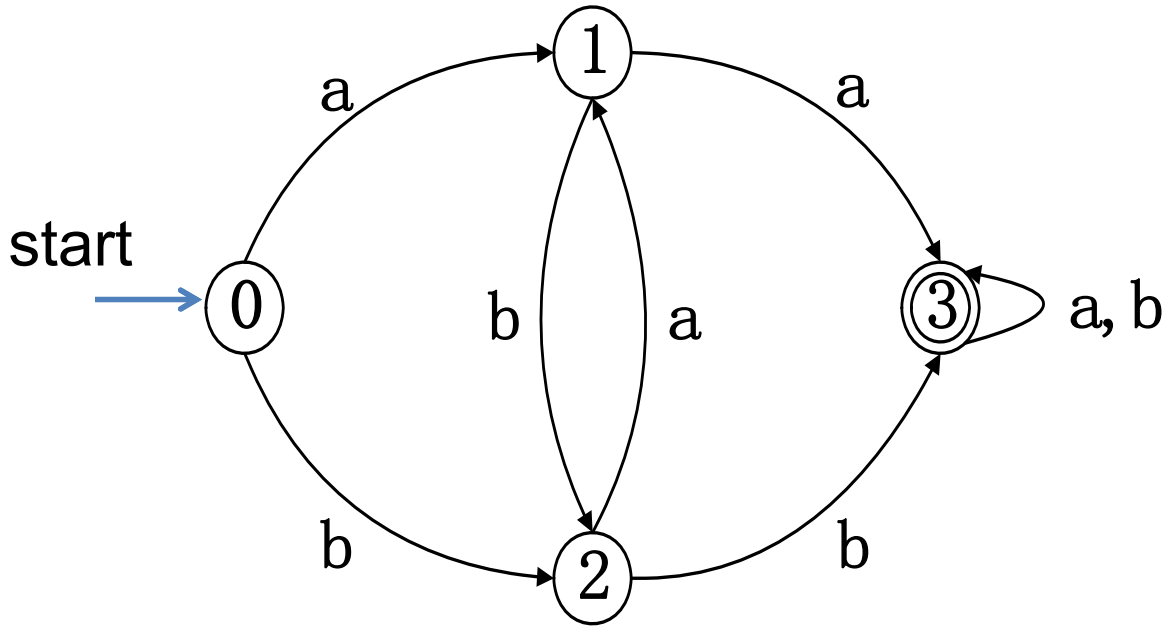
- (1) Initial partition: Π＝{{3,4,5,6}, {0,1,2}}.
- (2) Consider {3,4,5,6}: since $\{3,4,5,6\}_a \subset \{3,4,5,6\}$, $\{3,4,5,6\}_b \subset \{3,4,5,6\}$, so, {3,4,5,6} cannot be partitioned
- (3) Consider {0,1,2} : $\{0,1,2\}_a = \{1,3\}$

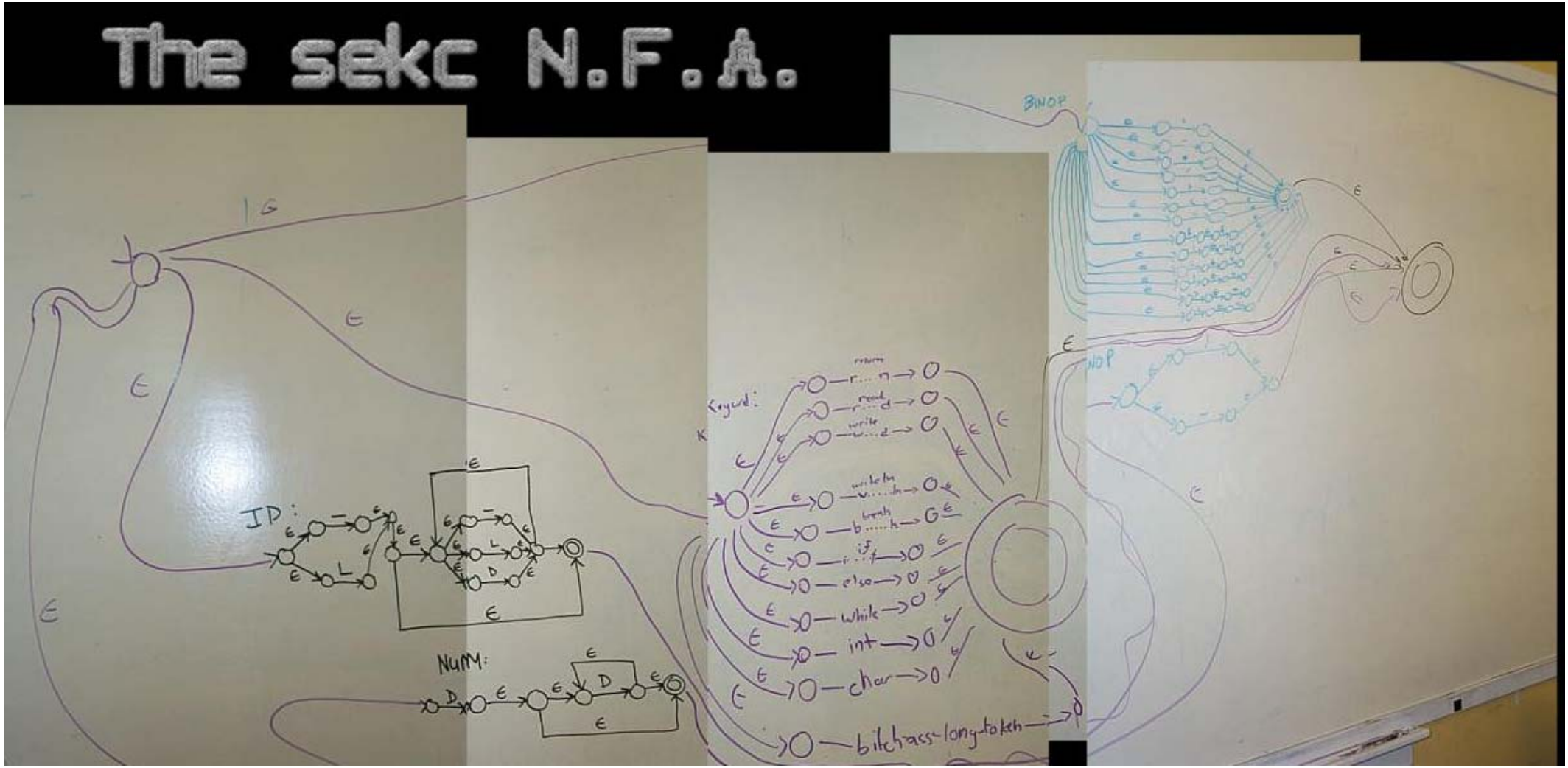
  since $\{0,2\}_a = \{1\}$, $\{1\}_a = \{3\}$, we can get new partition Π＝{{3,4,5,6}, {1}, {0, 2}}
- (4) Consider {0, 2} : $\{0, 2\}_b = \{2,5\}$

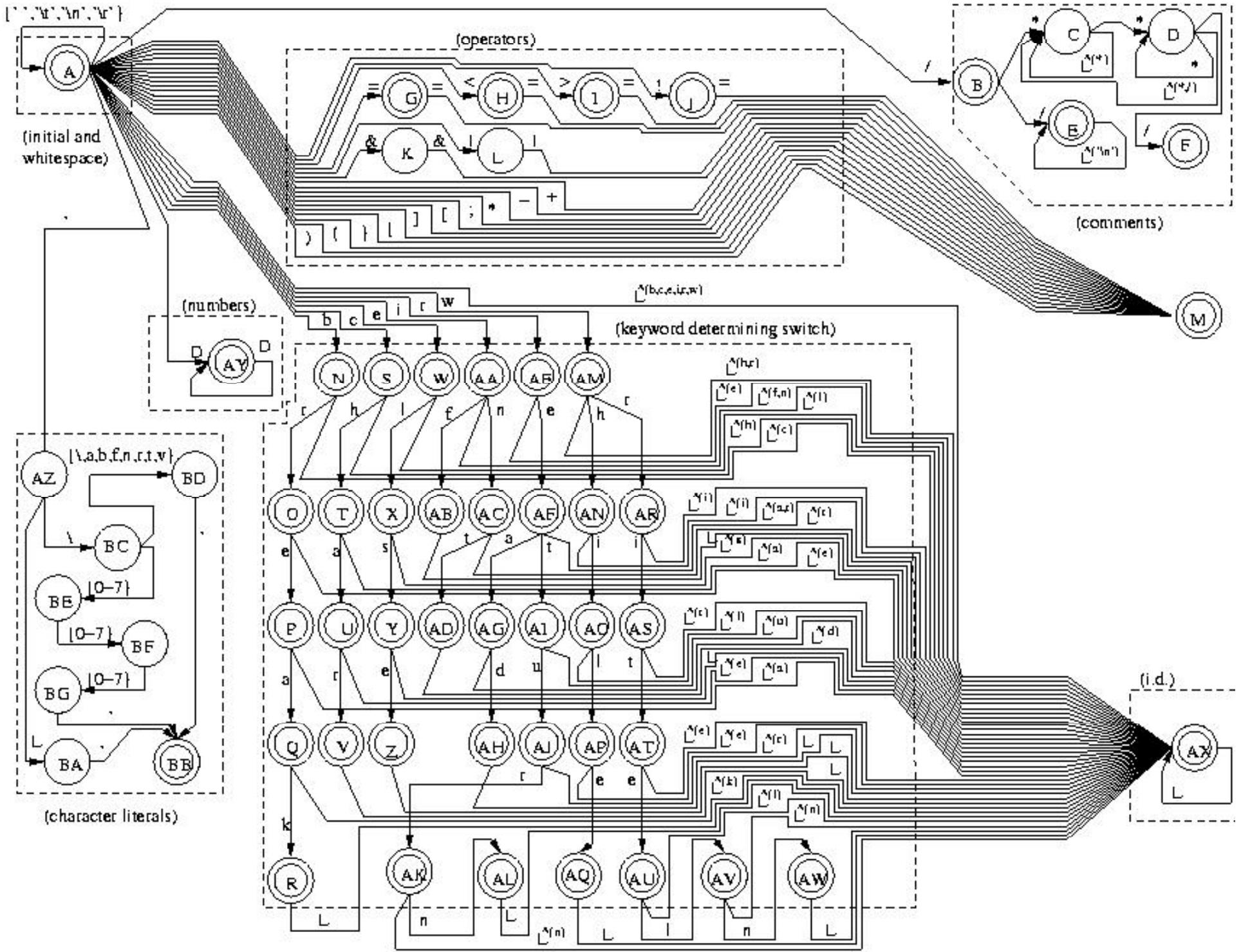
  since $\{0\}_b = \{2\}$, $\{2\}_b = \{5\}$, we can get new partition Π＝{{3,4,5,6}, {1}, {0}, {2}}

DFA with minimal states

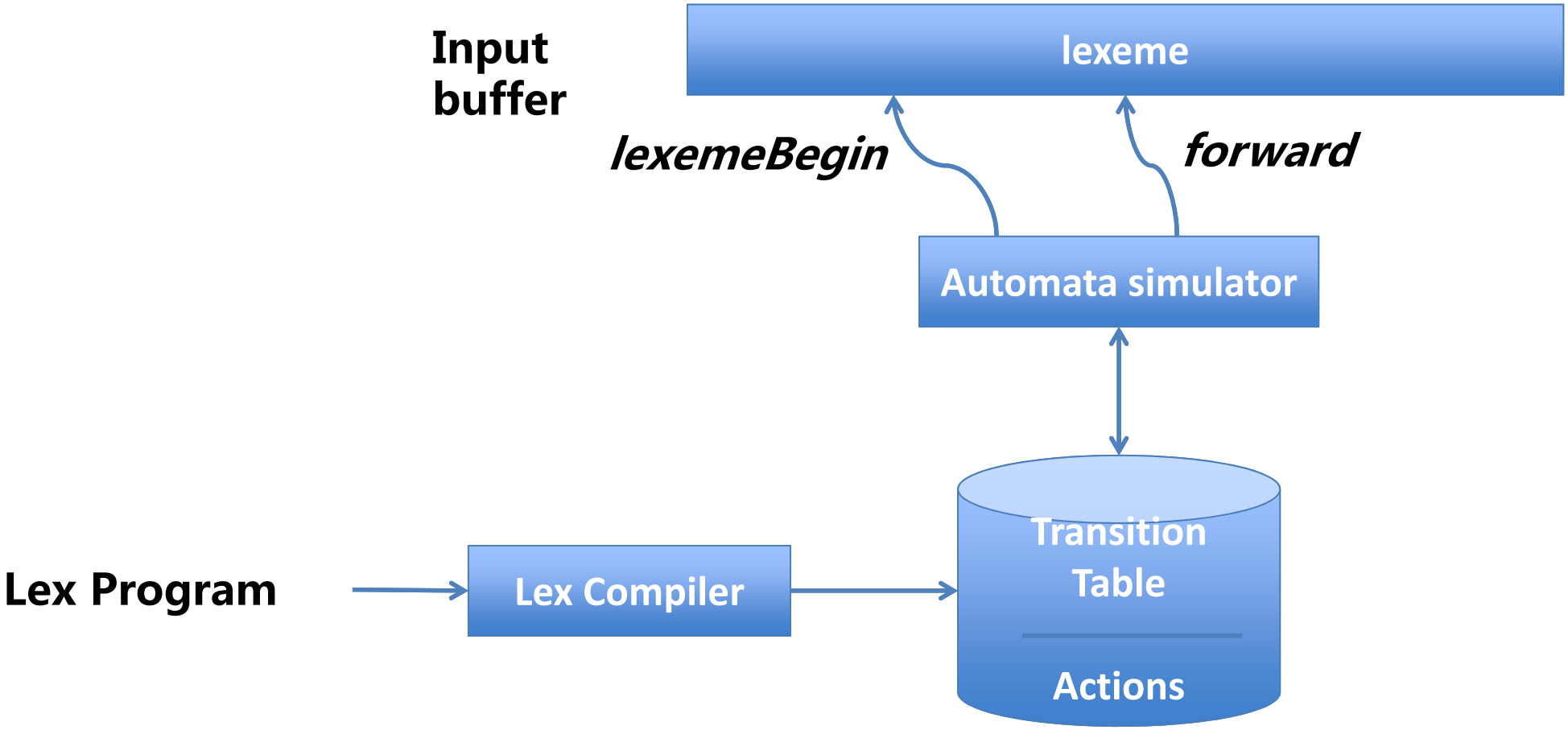
$\Pi = \{\{3,4,5,6\}, \{1\}, \{0\}, \{2\}\}$




The sekc N.F.A.
BINOP
NOP
ID:
NUM:
int
char
while
else
bitchass-long-token


(initial and whitespace)
(operators)
(comments)
(numbers)
(keyword determining switch)
(character literals)
(i.d.)

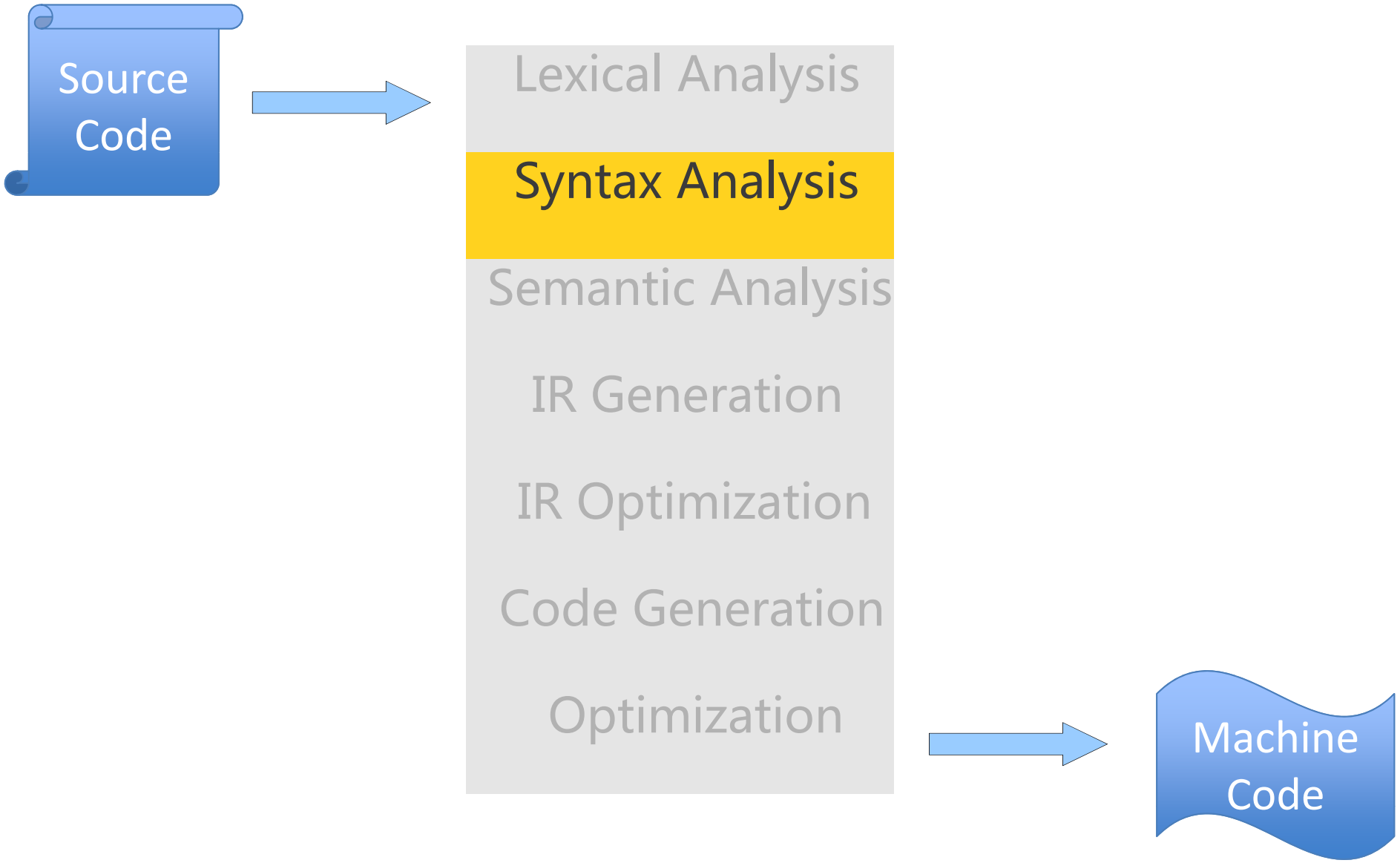
A Lexical Analyzer Generated by Lex



Lexical Analysis Summary

- Problems and challenges in Lexical Analysis
  - 3.1, 3.2
- Describe problems and Lexical rules
  - 3.3
  - Lexical Specification
  - Regular Expressions
- Recognition of Tokens
  - 3.4
  - NFA (3.6.1, 3.6.2, 3.6.3)
  - DFA (3.6.4)
  - From RE to automata (3.7)
- Lexical-Analyzer Generator
  - 3.5, 3.8

Next Time


Source Code
Lexical Analysis
Syntax Analysis
Semantic Analysis
IR Generation
IR Optimization
Code Generation
Optimization
Machine Code

Reference

- Compilers Principles, Techniques & Tools (Second Edition) Alfred Aho., Monica S. Lam, Ravi Sethi, Jeffrey D. Ullman, Addison-Wesley, 2007
- Coursera Course – Compiler, http://www. Coursera.org
- Stanford Course CS143 by Keith Schwarz, http://cs143.stanford.edu