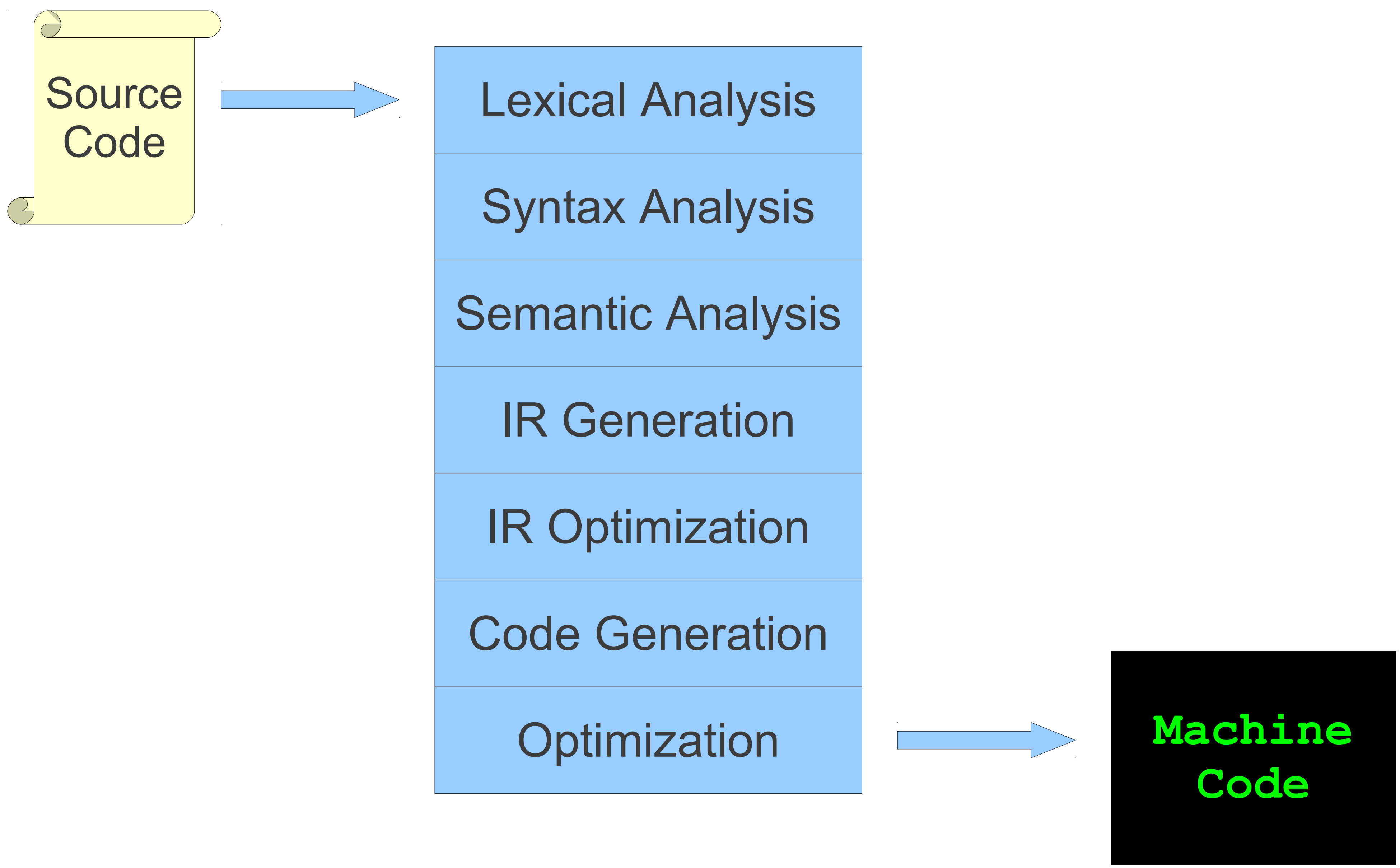
Lexical Analysis

Dec 6, 2021

Previously on EECS 483...

Structure of a modern compiler



```
while (y < z) {
    int x = a + b;
    y += x;
}
```

Lexical Analysis

Syntax Analysis

Semantic Analysis

IR Generation

IR Optimization

Code Generation

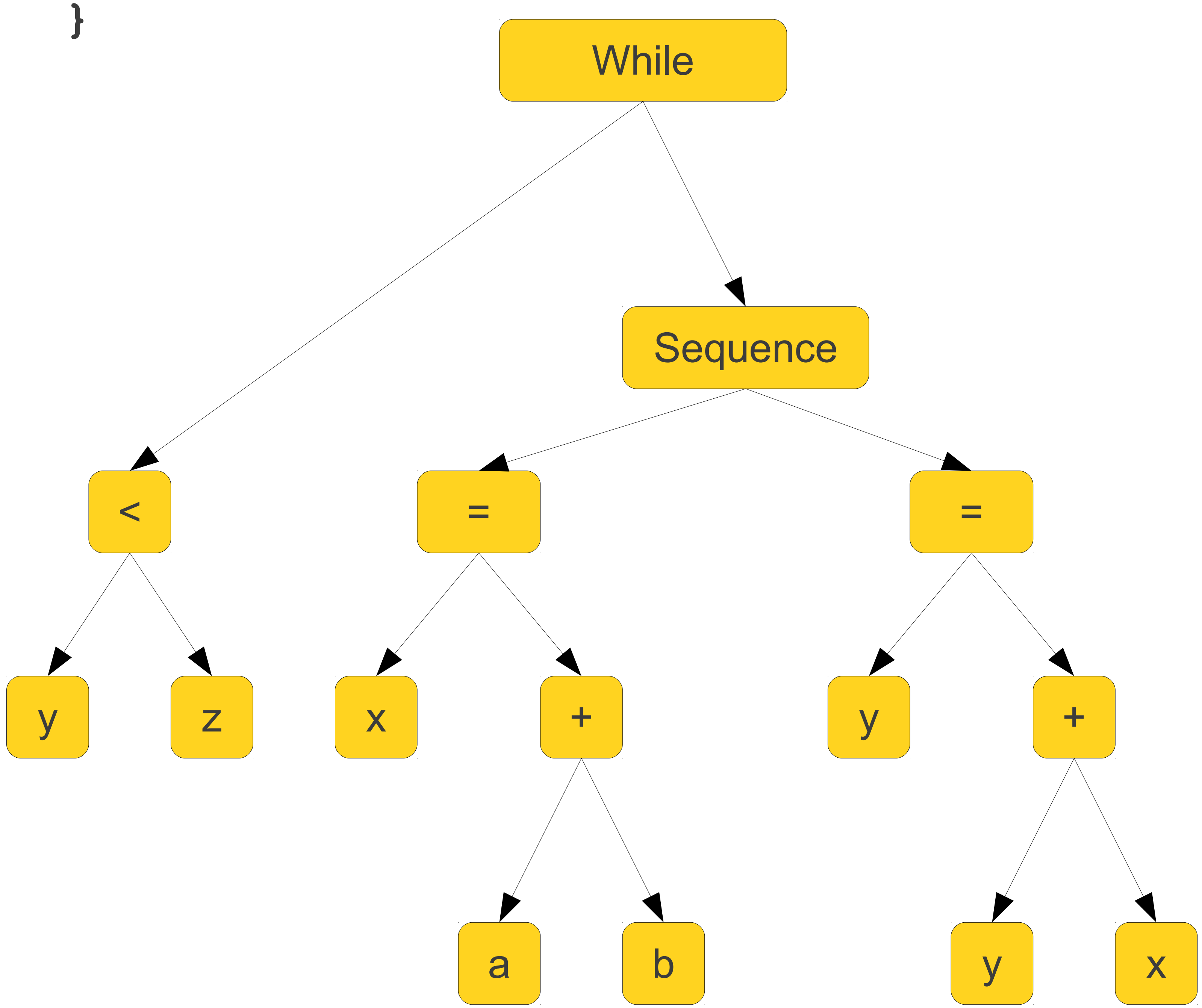
Optimization

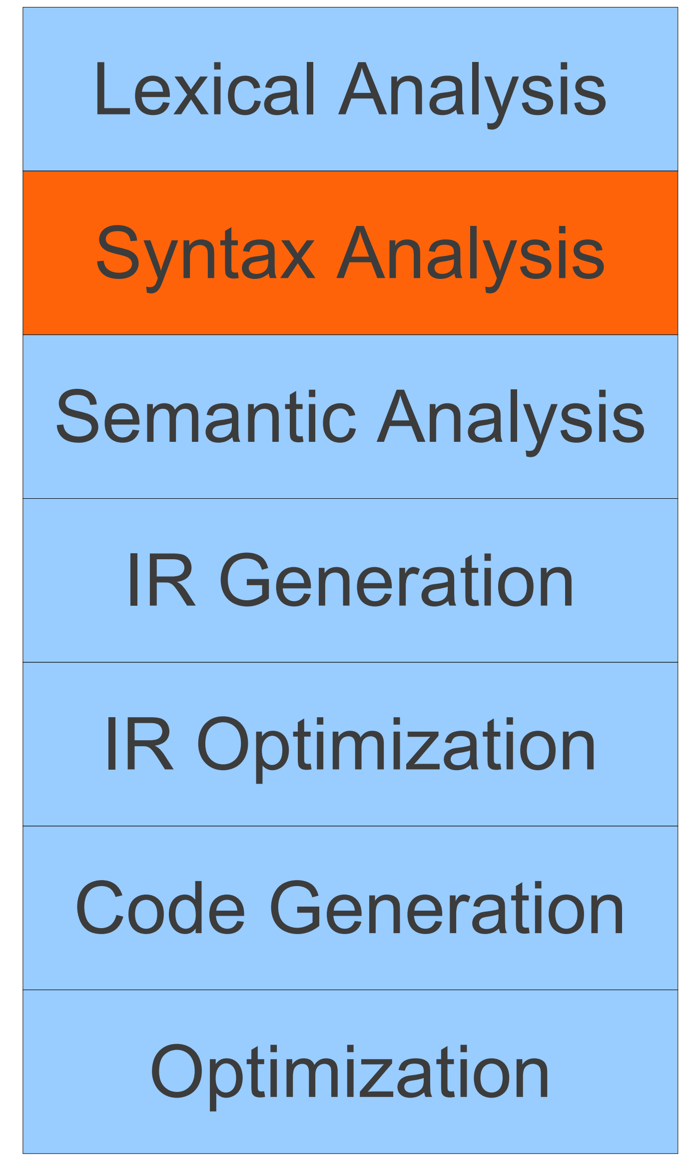
```
while (y < z) {
    int x = a + b;
    y += x;
}
```

```
T_While
T_LeftParen
T_Identifier y
T_Less
T_Identifier z
T_RightParen
T_OpenBrace
T_Int
T_Identifier x
T_Assign
T_Identifier a
T_Plus
T_Identifier b
T_Semicolon
T_Identifier y
T_PlusAssign
T_Identifier x
T_Semicolon
T_CloseBrace
```

Lexical analysis (Scanning): Group sequence of characters into lexemes – smallest meaningful entity in a language (keywords, identifiers, constants)

```
while (y < z) {
    int x = a + b;
    y += x;
}
```





Syntax analysis (Parsing): Convert a linear structure – sequence of tokens – to a hierarchical tree-like structure - abstract syntax tree (AST)

Goal of Lexical Analysis

Breaking the program down into words or “tokens”

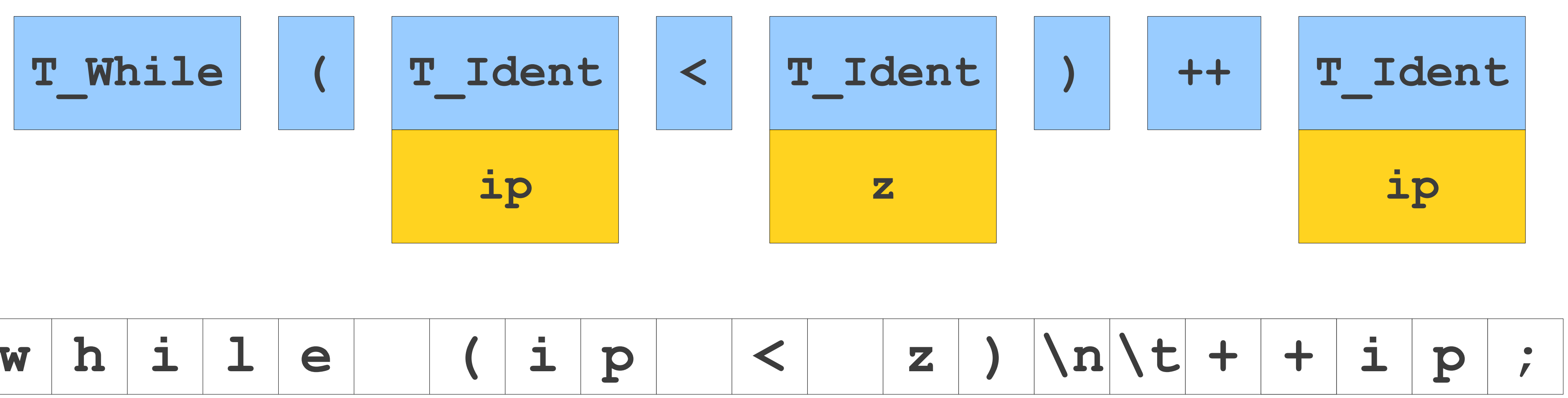
Input: code (character stream)

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

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

Goal of Lexical Analysis

Output: Token Stream




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

What's a token?

- What's a lexical unit of code?

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

What is my name ?

Token Type

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

- Keyword: for int if else while
- Punctuation: ( ) { } ;
- Operand: + - ++
- Relation: < > =
- Identifier: (variable name, function name) foo foo_2
- Integer, float point, string: 2345 2.0 “hello world”
- Whitespace, comment /* this code is awesome */

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	;

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**	**;**

Scanning a Source File

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

Scanning a Source File

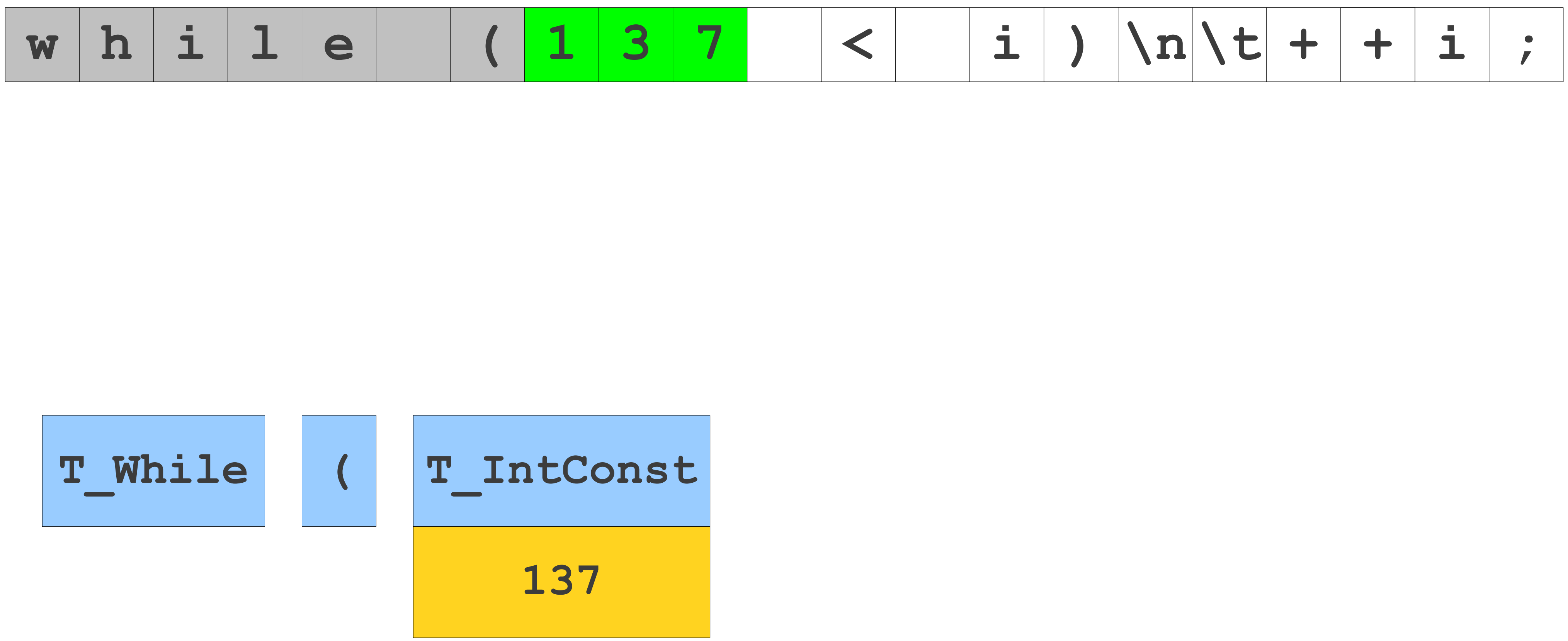
w	h	i	l	e		(	1	3	7		<		i	)	\n	\t	+	+	i	;

Lexeme: the piece of the original program from which we made the token

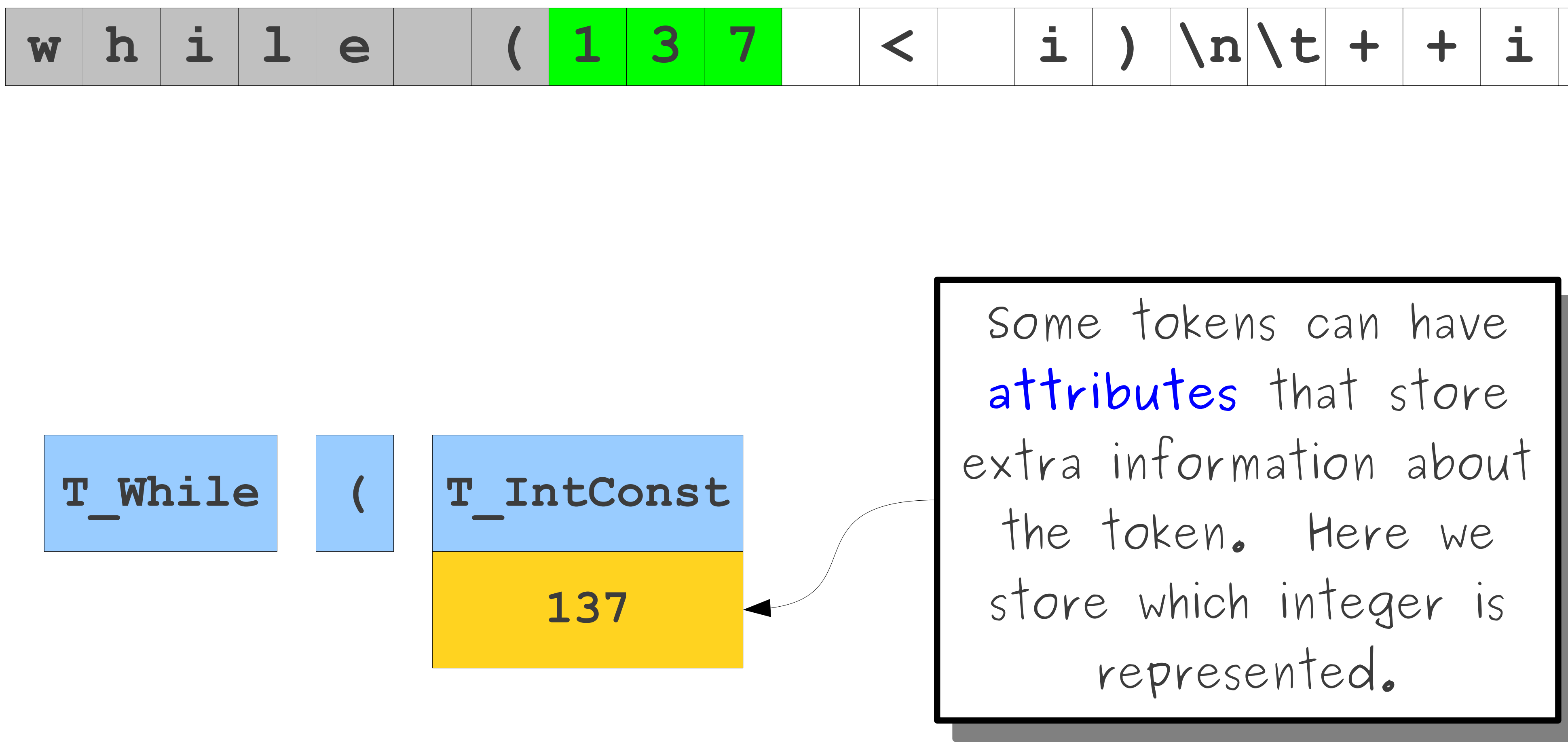
`T_While`

Token

Scanning a Source File



Scanning a Source File



Lexical Analyzer

- Recognize substrings that correspond to tokens: **lexemes**
  - **Lexeme:** actual text of the token
- For each lexeme, identify token type
  - < Token type, attribute>
  - attribute: optional, extra information, often numeric value

Challenges for Lexical Analyzer

- 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?
  - if
  - ifc
- How do we address these concerns efficiently?

Associate Lexemes to Tokens

- Tokens: categorize lexemes by what information they provide.
- Associate lexemes to token: Pattern matching
- How to describe patterns??

Token: Lexemes

- Keyword: for int if else while
- Punctuation: ( ) { } ;
- Operand: + - ++
- Relation: < > =
- Identifier: (variable name,function name) foo foo_2
- Integer, float point, string: 2345 2.0 “hello world”
- Whitespace, comment /* this code is awesome */

Finite possible lexemes

Infinite possible lexemes

- How do we 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.

- What type of formal language should we use to describe tokens?

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

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

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

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
11111011110011111

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)*

11011100101
0000
11111011110011111

Applied Regular Expressions

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

?

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)

42
+1370
-3248
-9999912

- More examples
  - Whitespace: [\t\n]+
  - Integers: [+\-]?[0-9]+
  - Hex numbers: 0x[0-9a-f]+
  - identifier
    - [A-Za-z]([A-Za-z]|[0-9])*

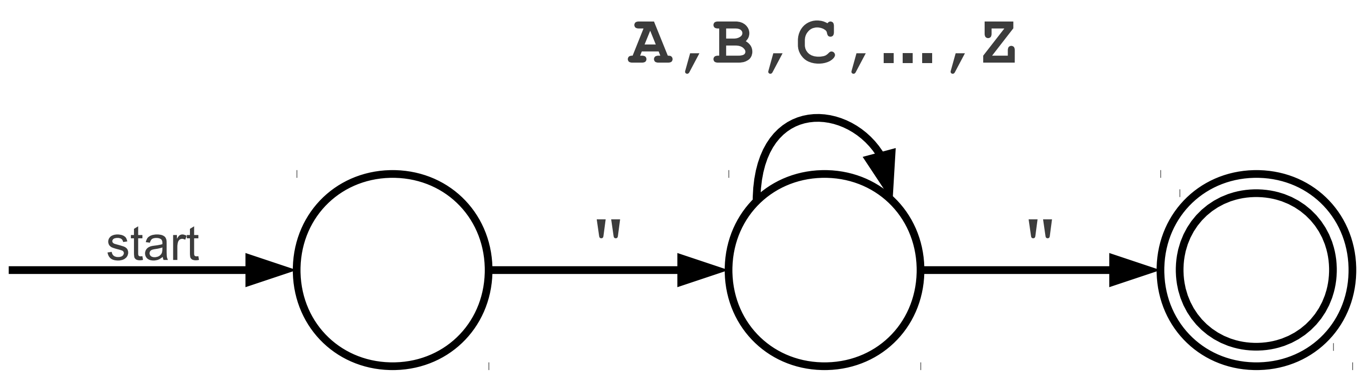
- Use regular expressions to describe token types
- How do we match regular expressions?

Recognizing Regular Language

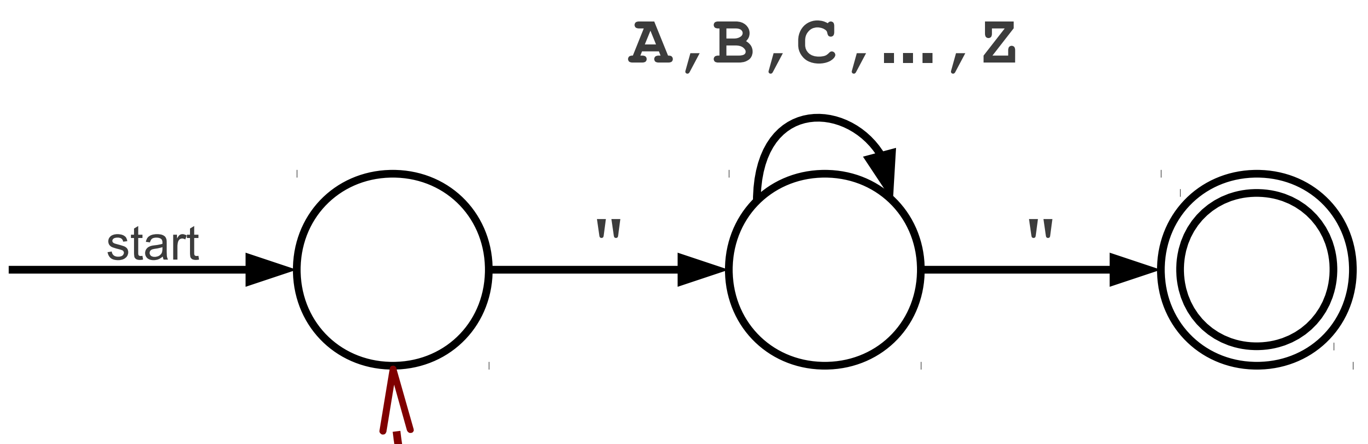
What is the machine that recognize regular language??

- Finite Automata
- DFA (Deterministic Finite Automata)
- NFA (Non-deterministic Finite Automata)

A Simple Automaton

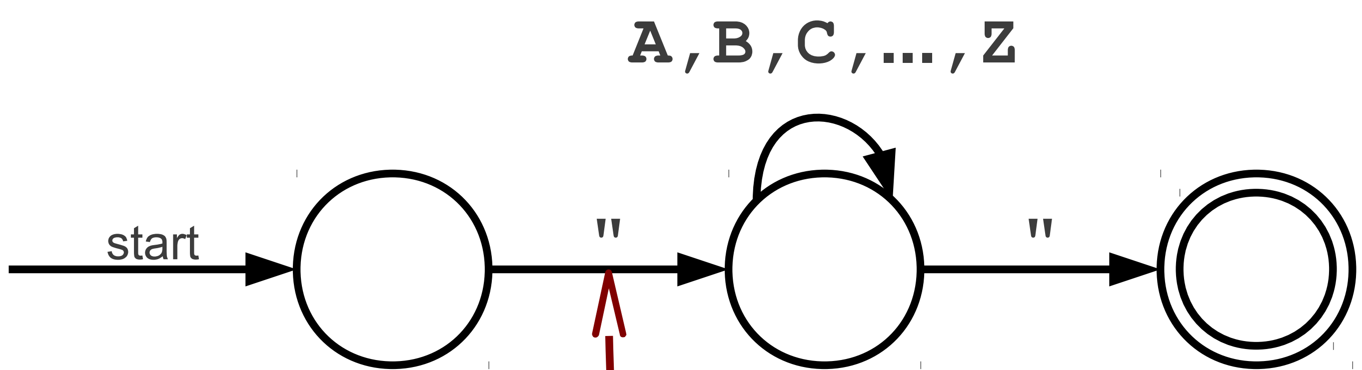


A Simple Automaton



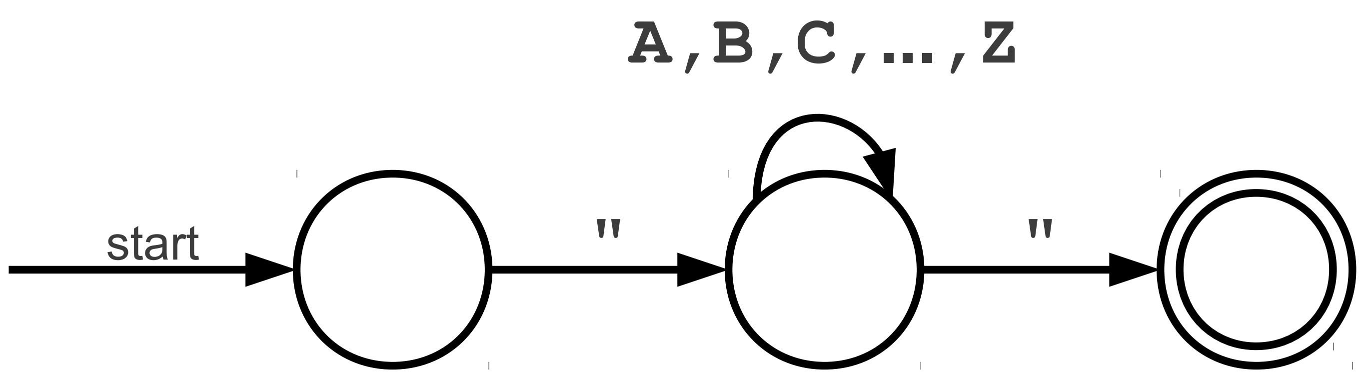
Each circle is a state of the automaton. The automaton's configuration is determined by what state(s) it is in.

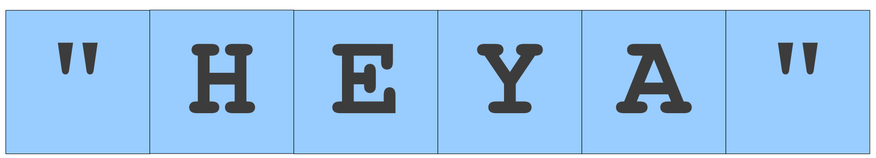
A Simple Automaton



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

A Simple Automaton

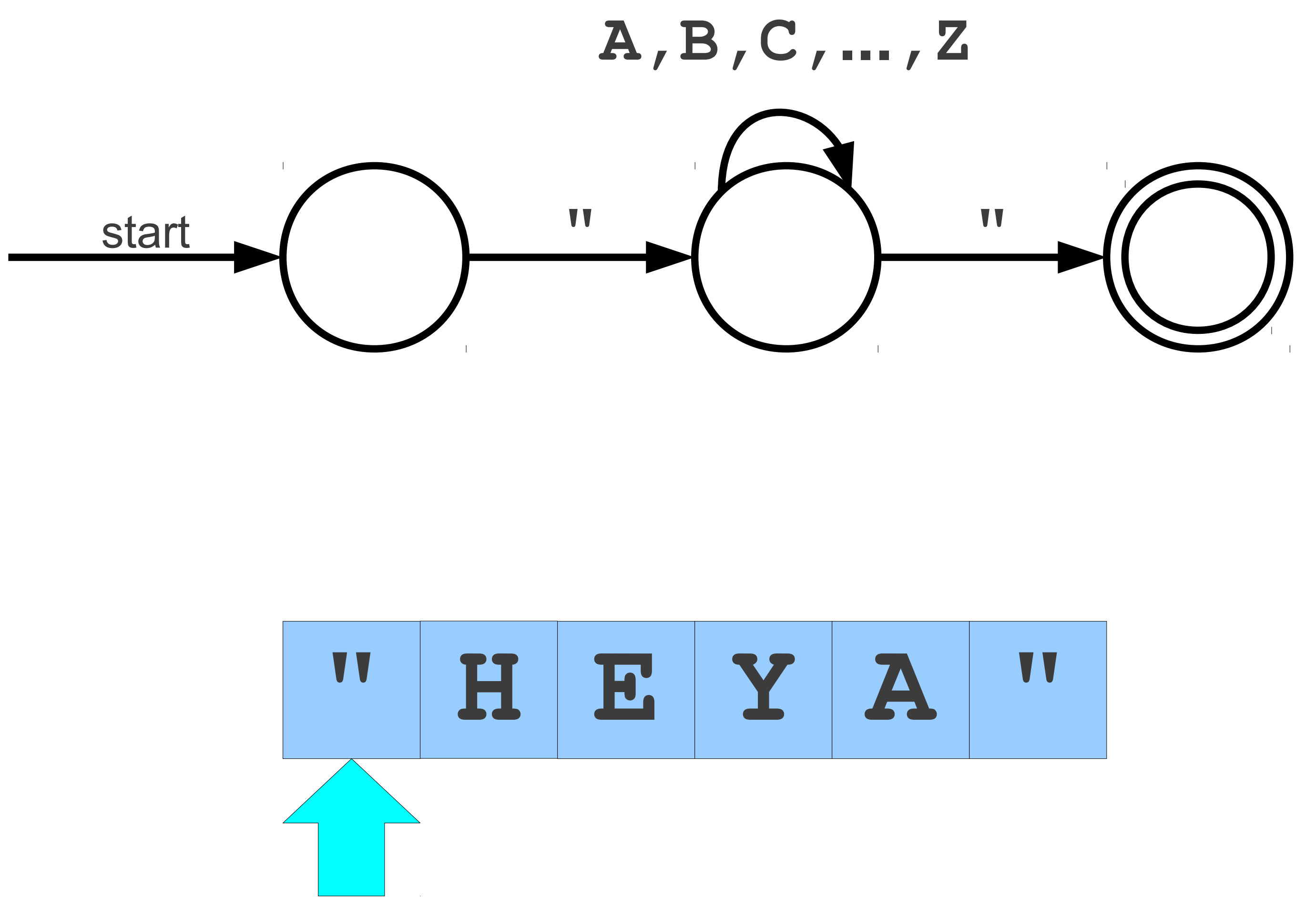




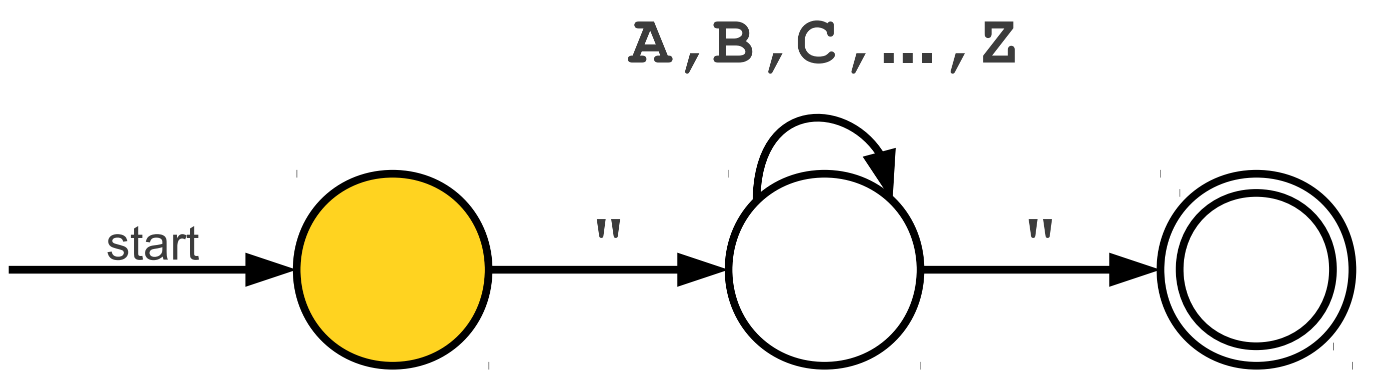
Finite Automata: Takes an input string and determines whether it's a valid sentence of a language

accept or reject

A Simple Automaton



A Simple Automaton



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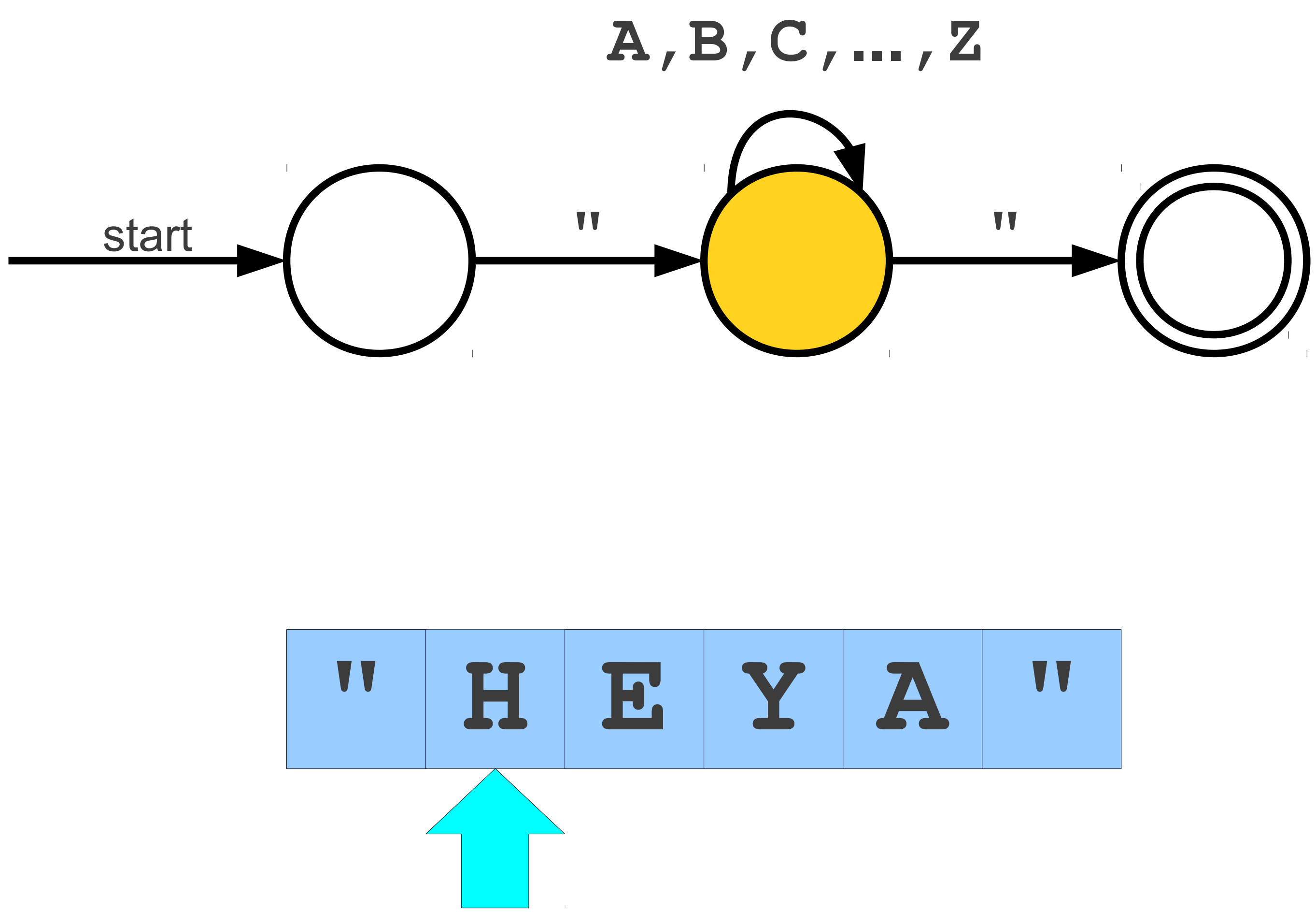

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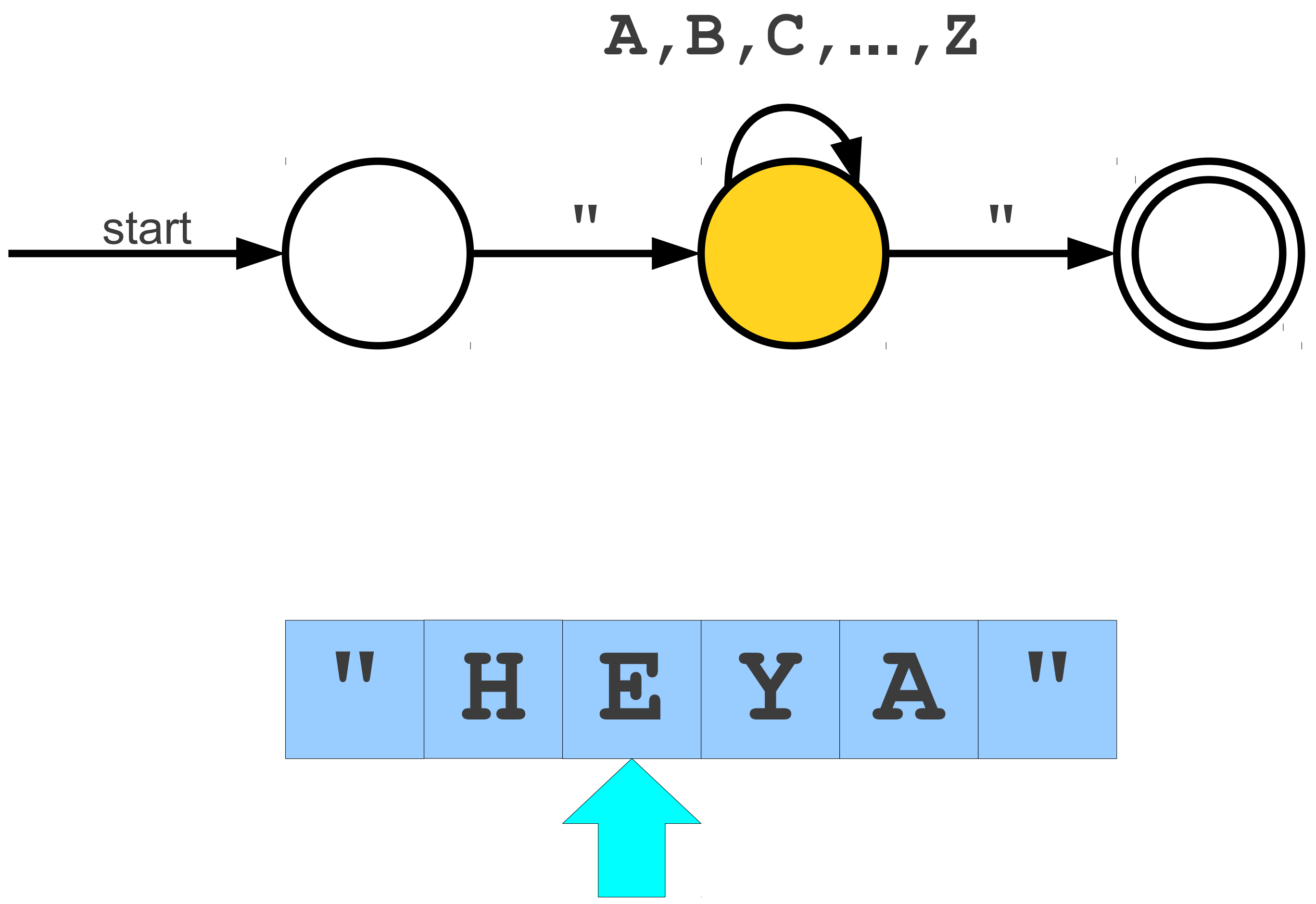

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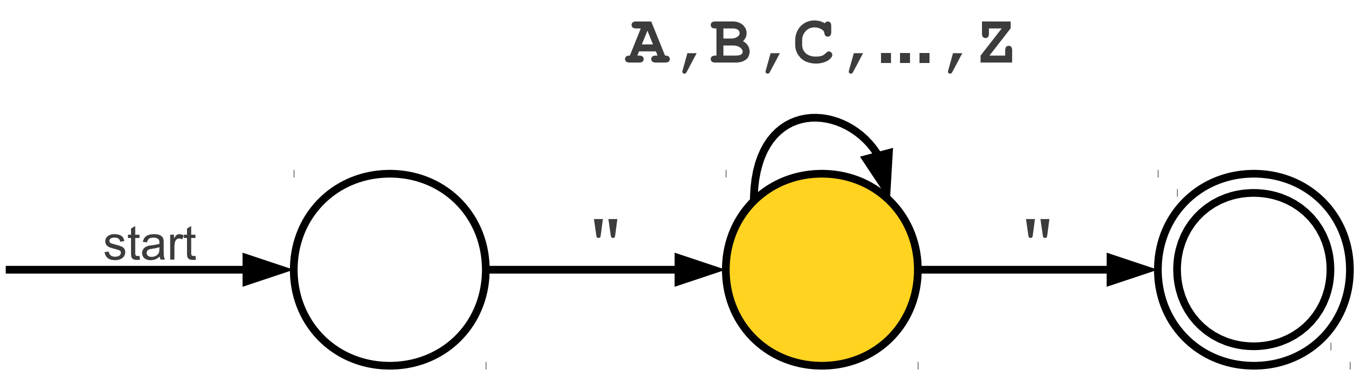

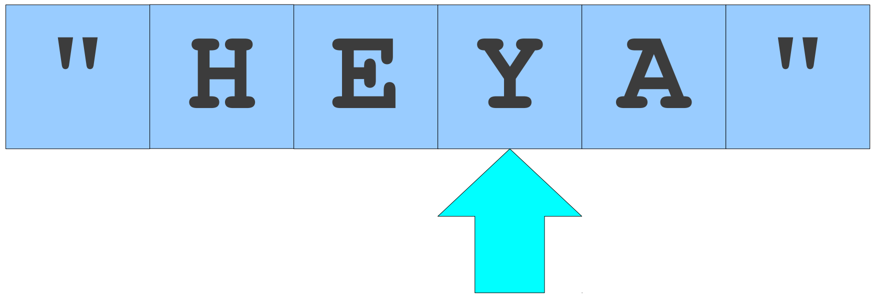

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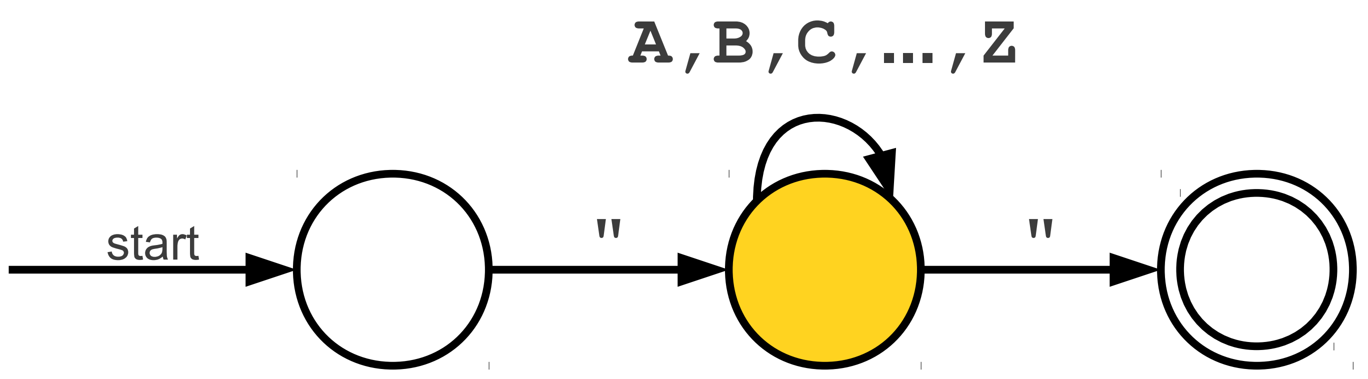
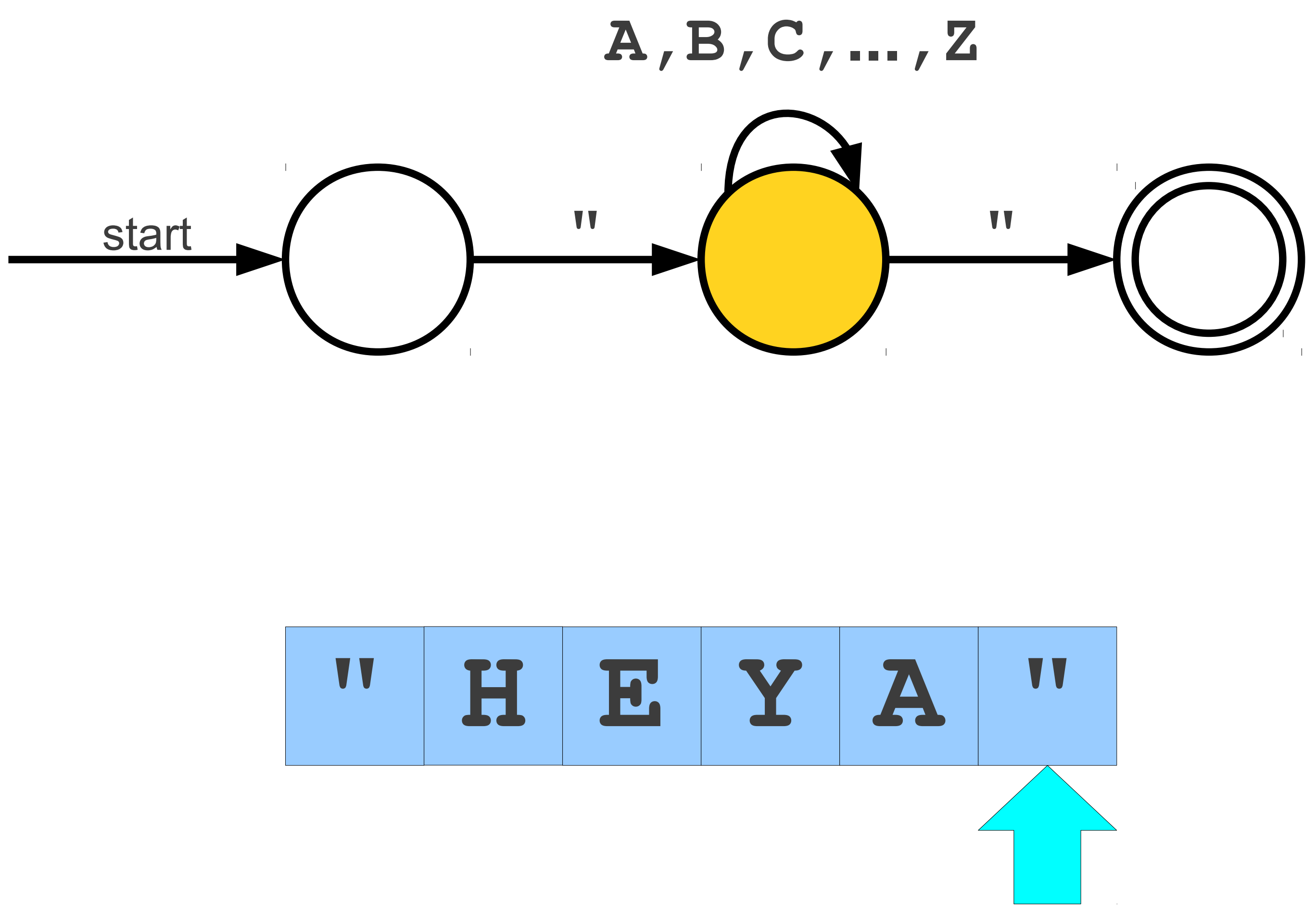
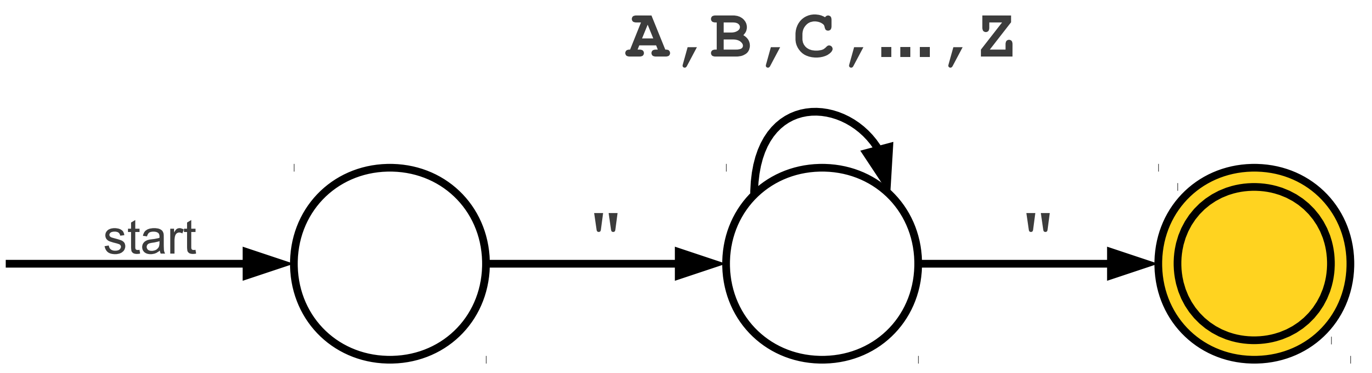


A Simple Automaton

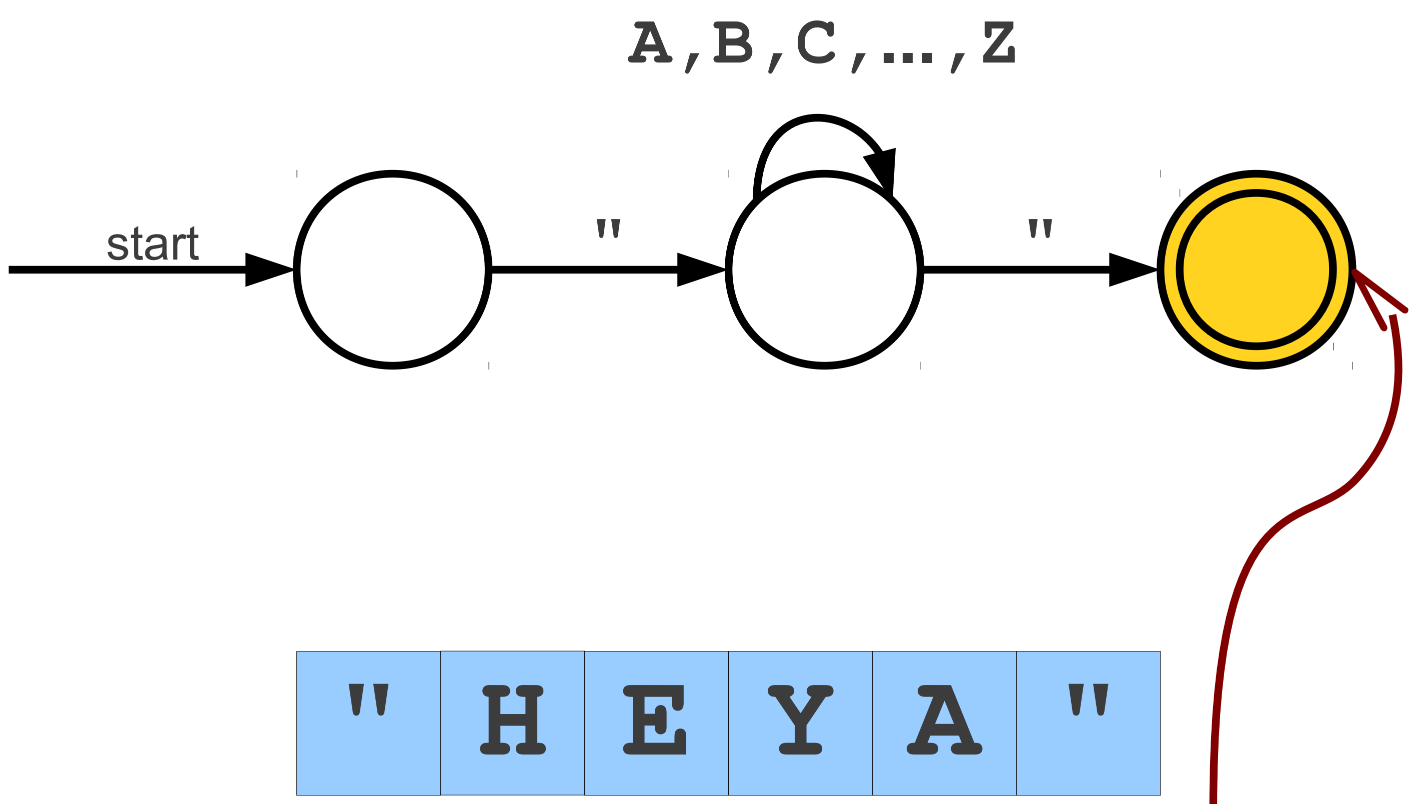


A Simple Automaton



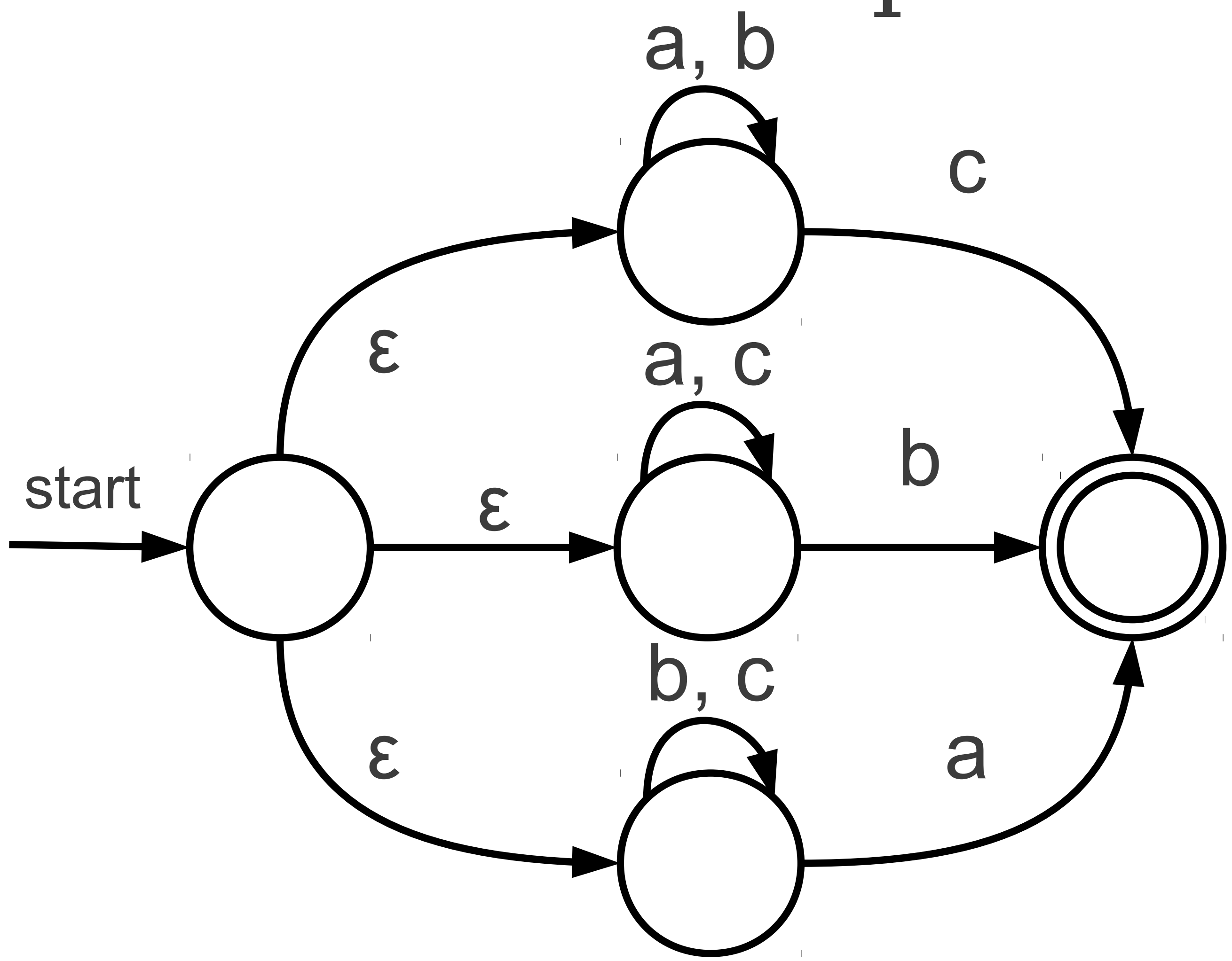
"	H	E	Y	A	"

A Simple Automaton



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

An Even More Complex Automaton



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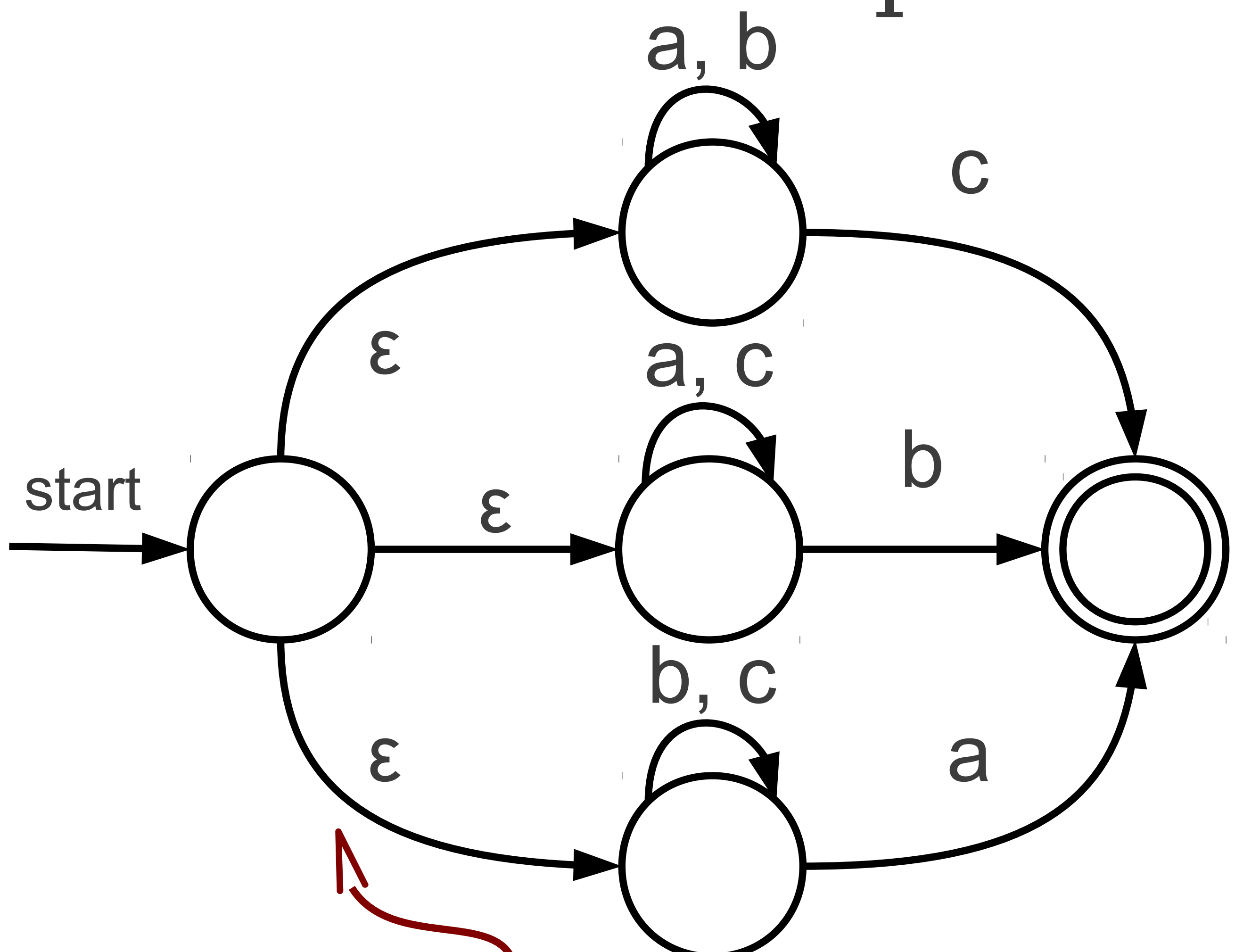
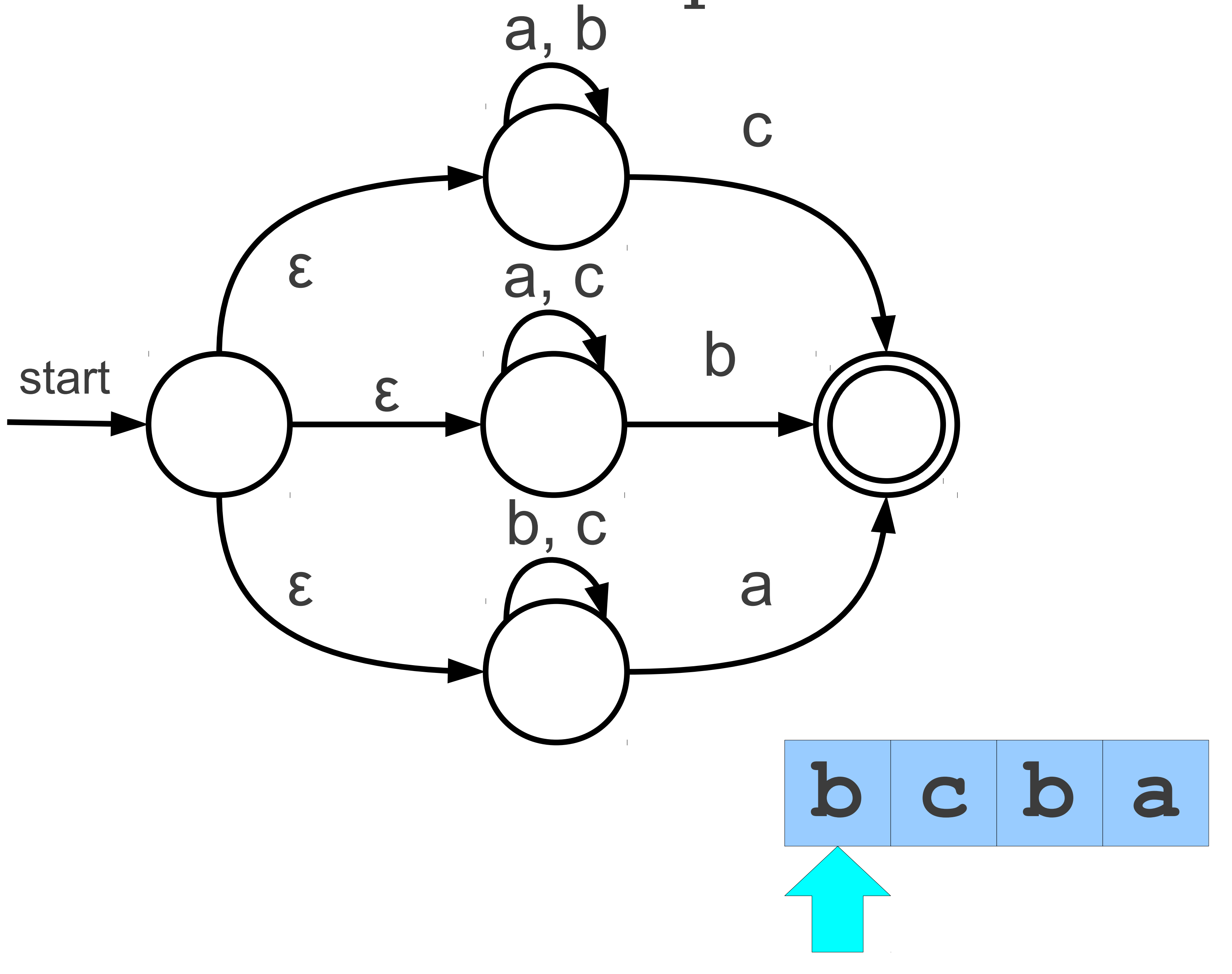


These are called **ε-transitions**. These transitions are followed automatically and without consuming any input.

An Even More Complex Automaton



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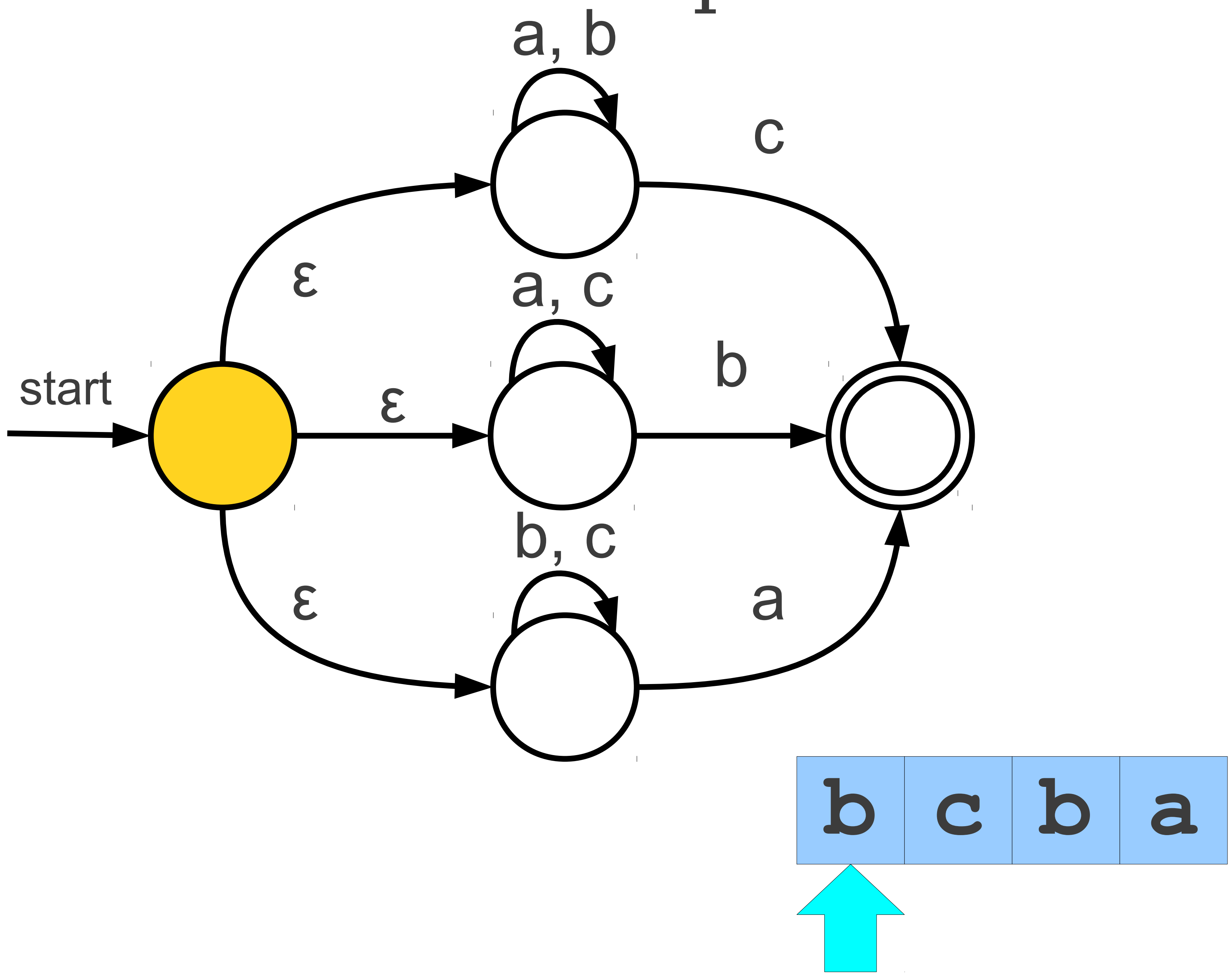

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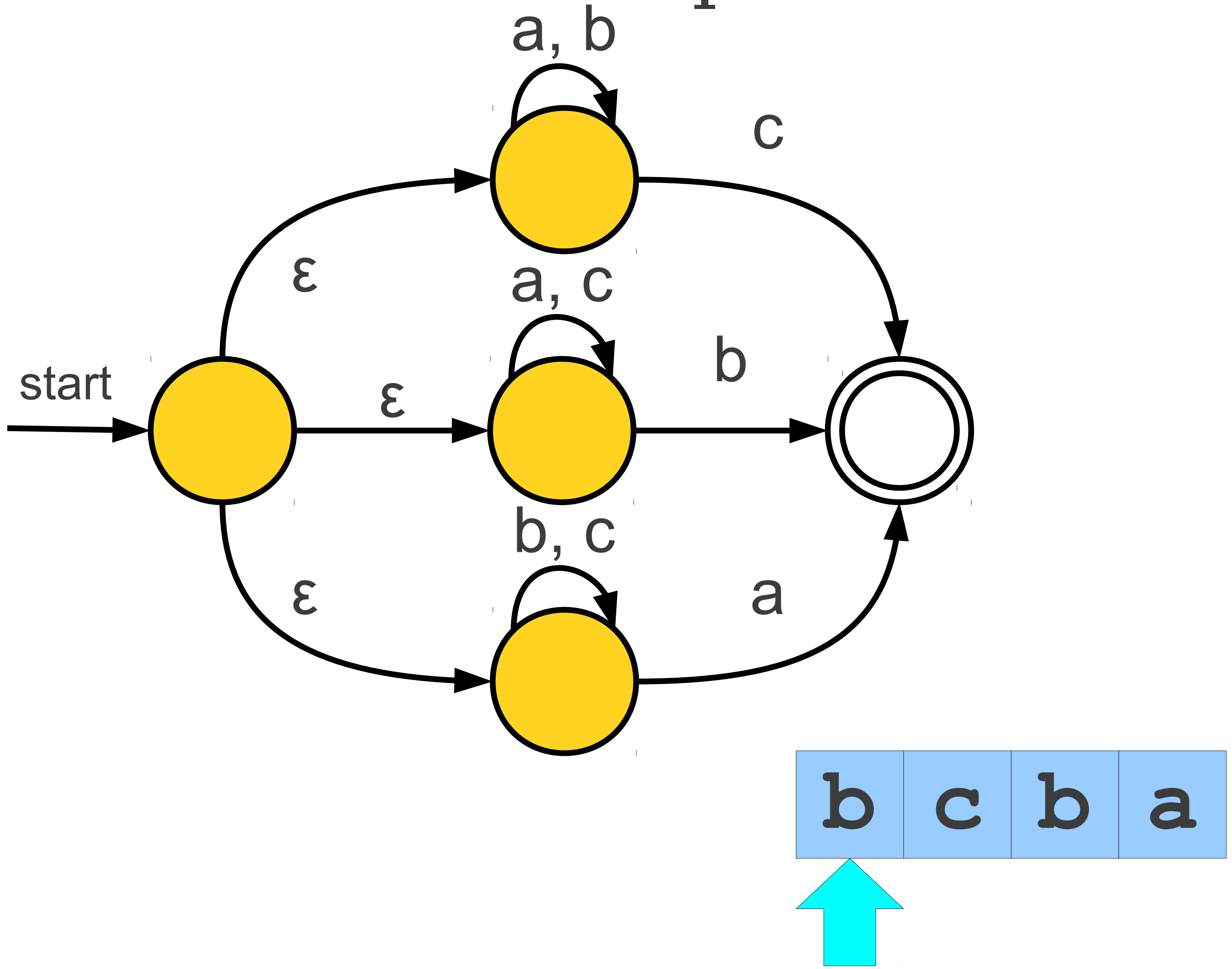

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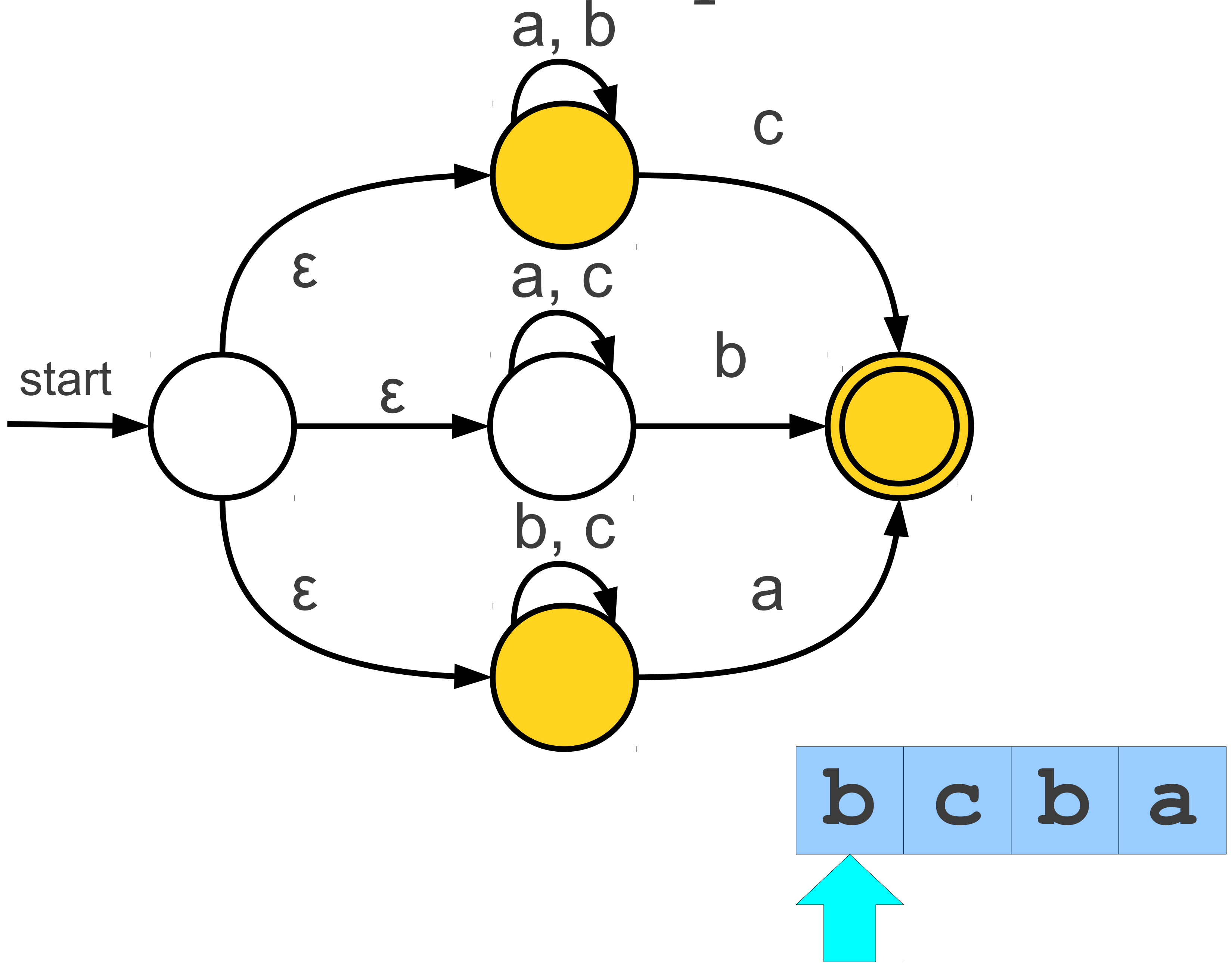

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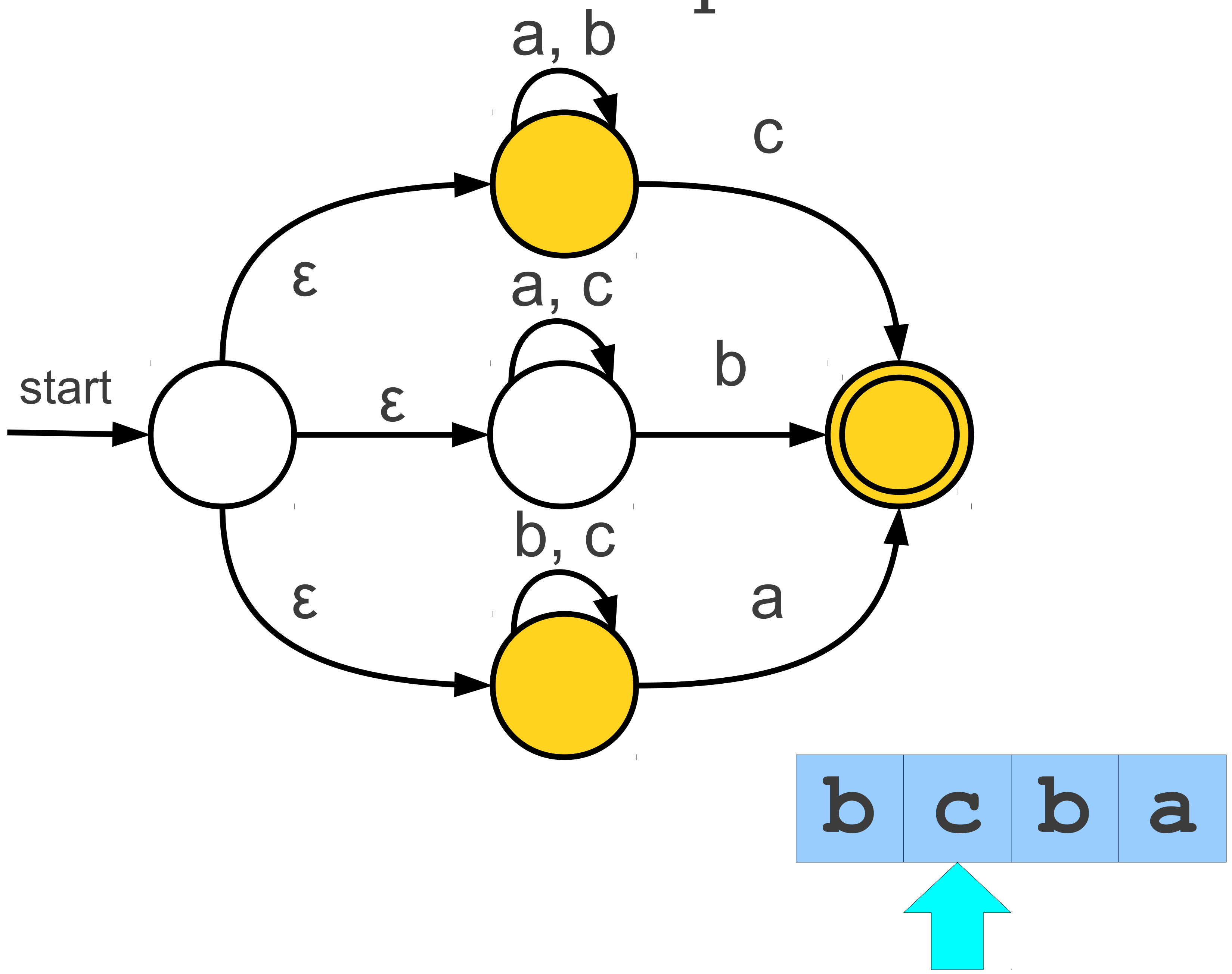

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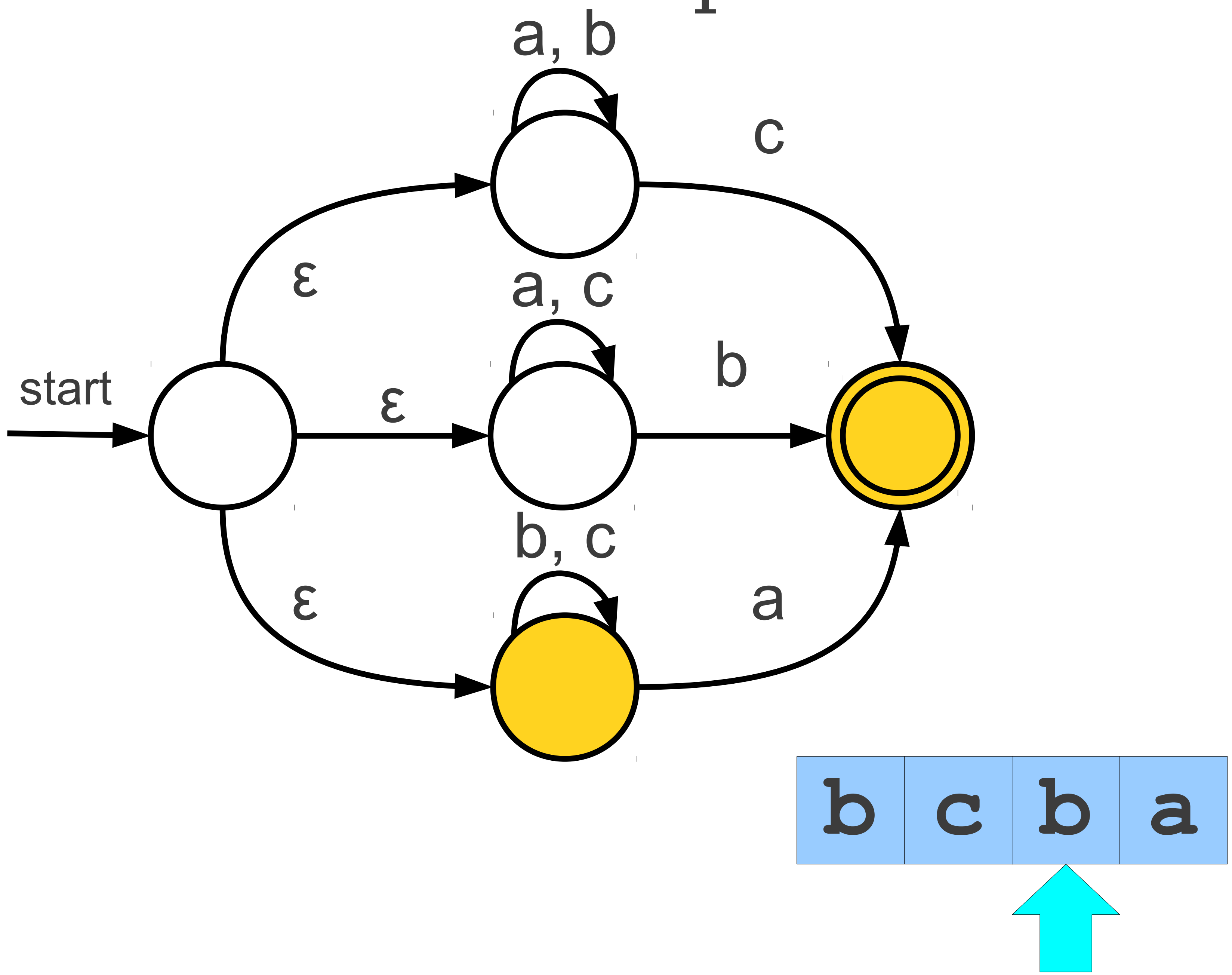

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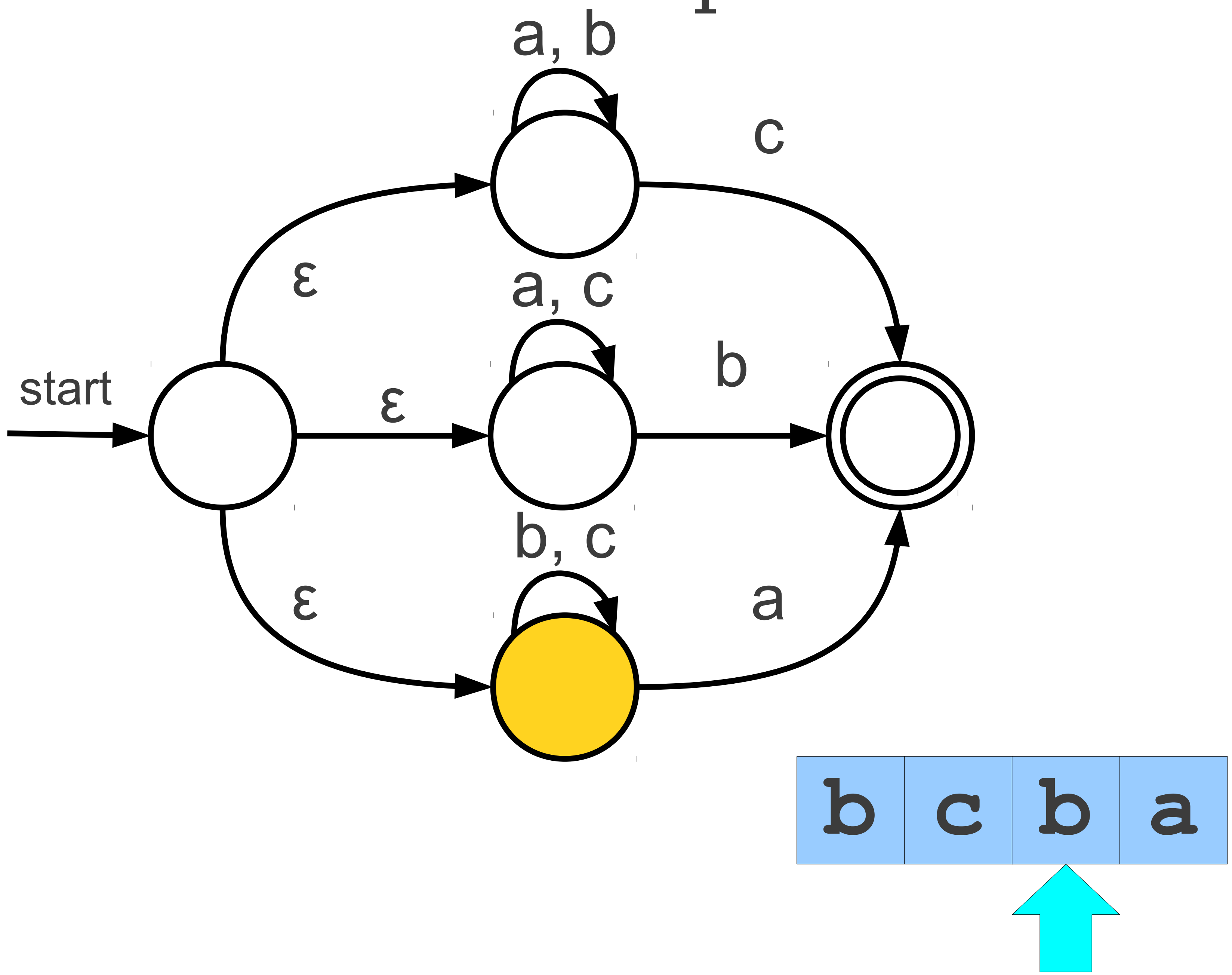

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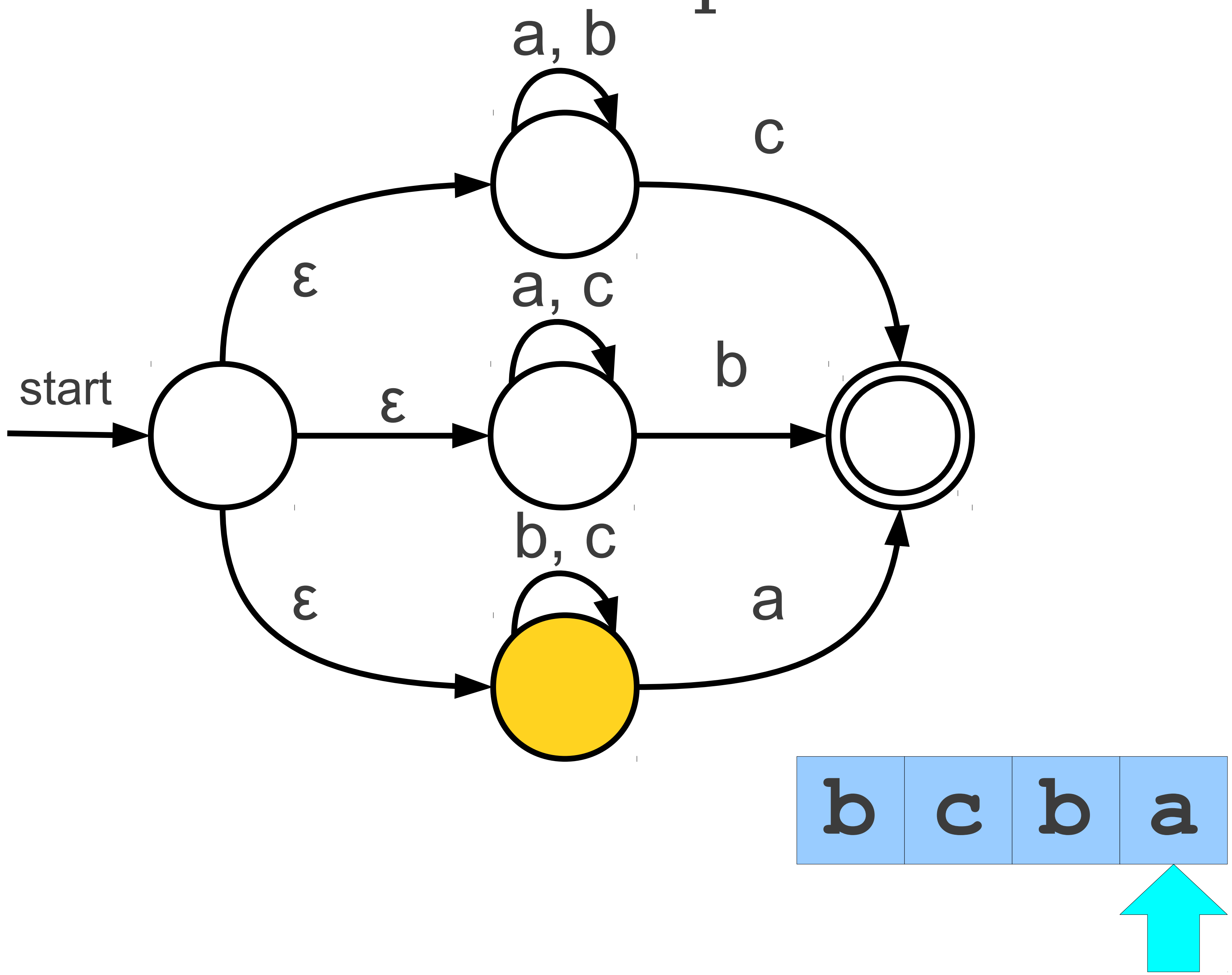

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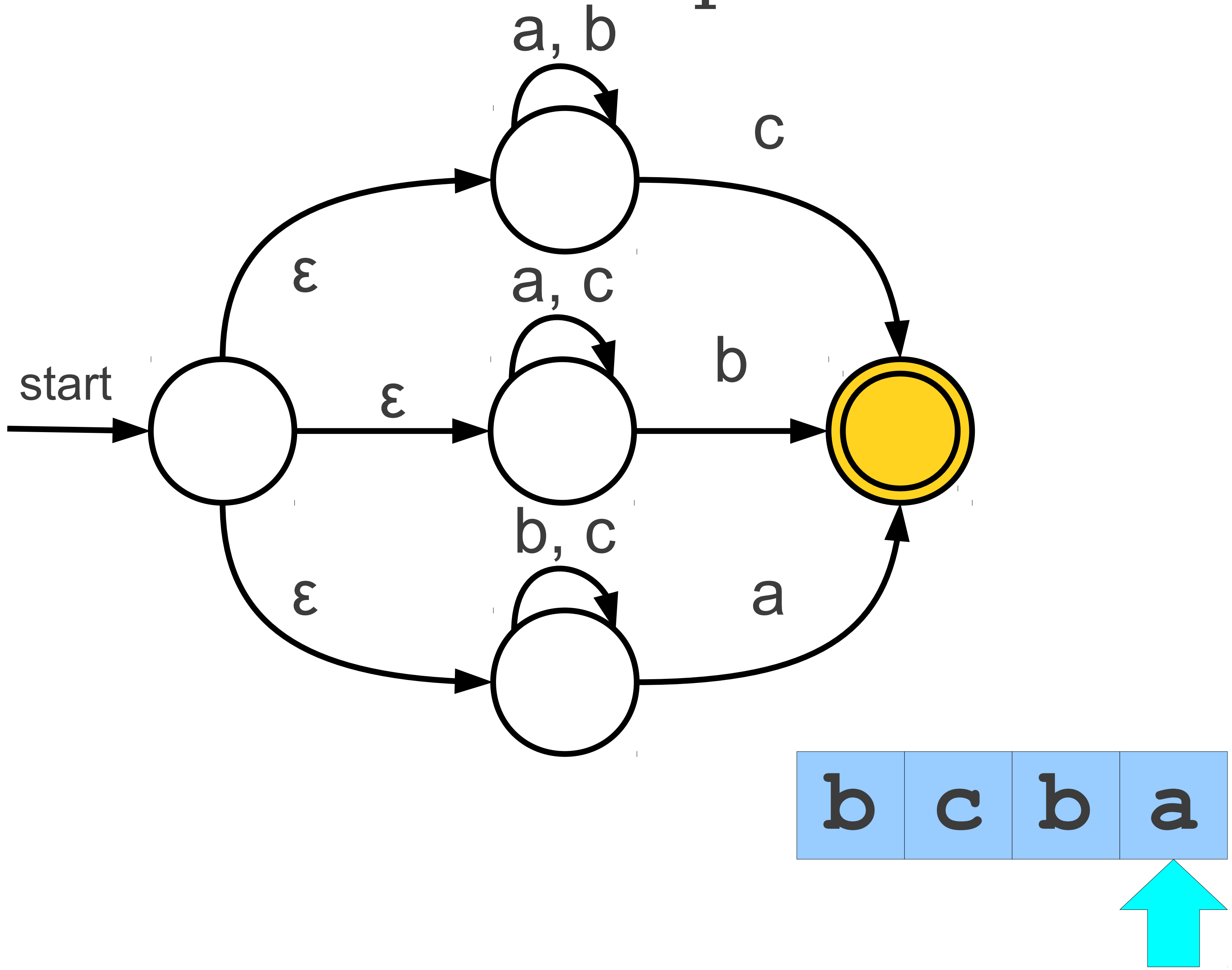

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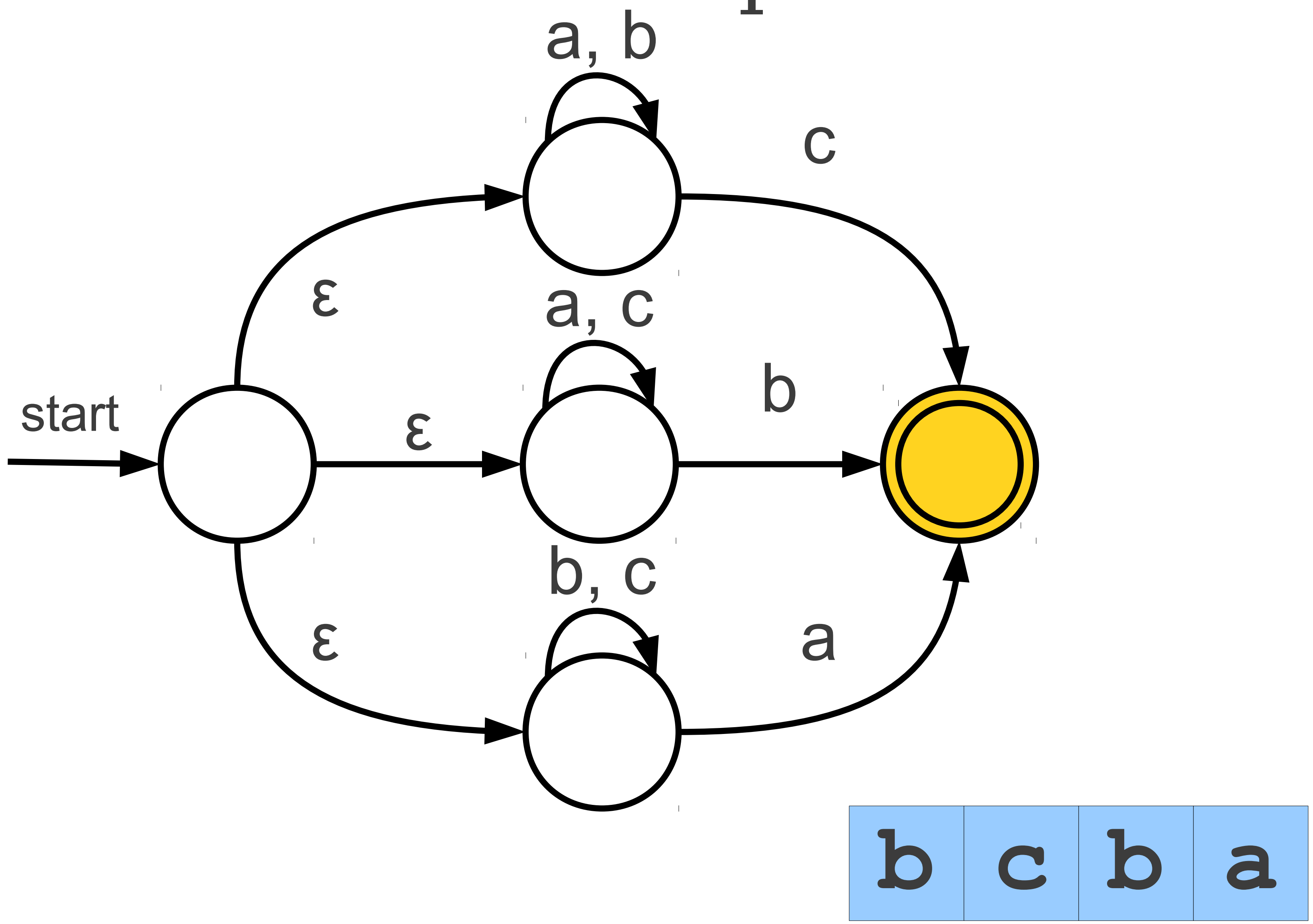

Lexer Generator

- Given regular expressions to describe the language (token types),
  - Step 1: Generates NFA that can recognize the regular language defined
    - existing algorithms
  - Step 2: Transforms NFA to DFA
    - existing algorithms
  - Tools: **lex, flex**

Challenges for Lexical Analyzer

- How do we determine which lexemes are associated with each token?
    - Regular expression to describe token type
- 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

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f	o	r	t

Lexing Ambiguities

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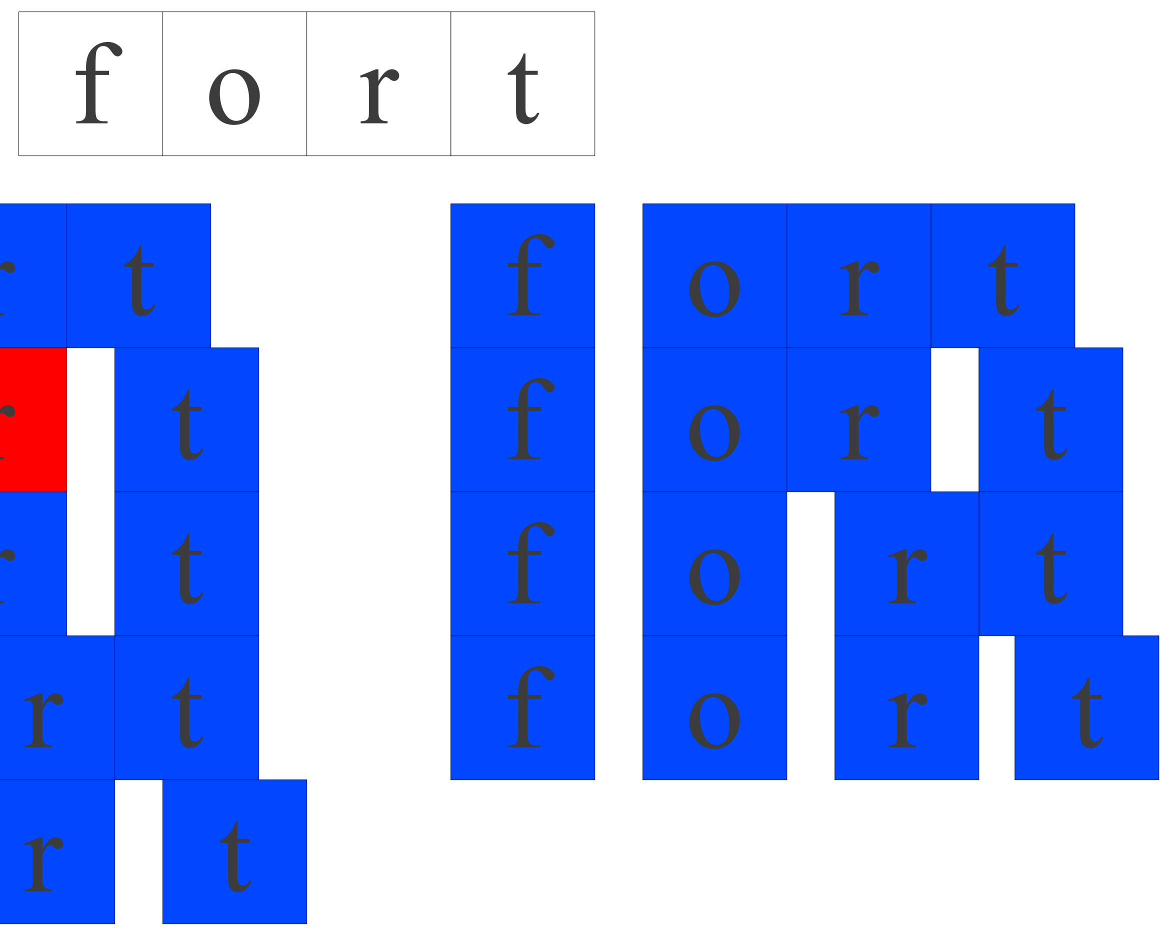

Conflict Resolution

- 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

f	o	r	t

Implementing Maximal Munch

- Given a set of regular expressions, how can we use them to implement maximum munch?

- Example

Implementing Maximal Munch

```
T_Do          do
T_Double      double
T_Mystery     [A-Za-z]
```

Implementing Maximal Munch

```
T_Do         do
T_Double     double
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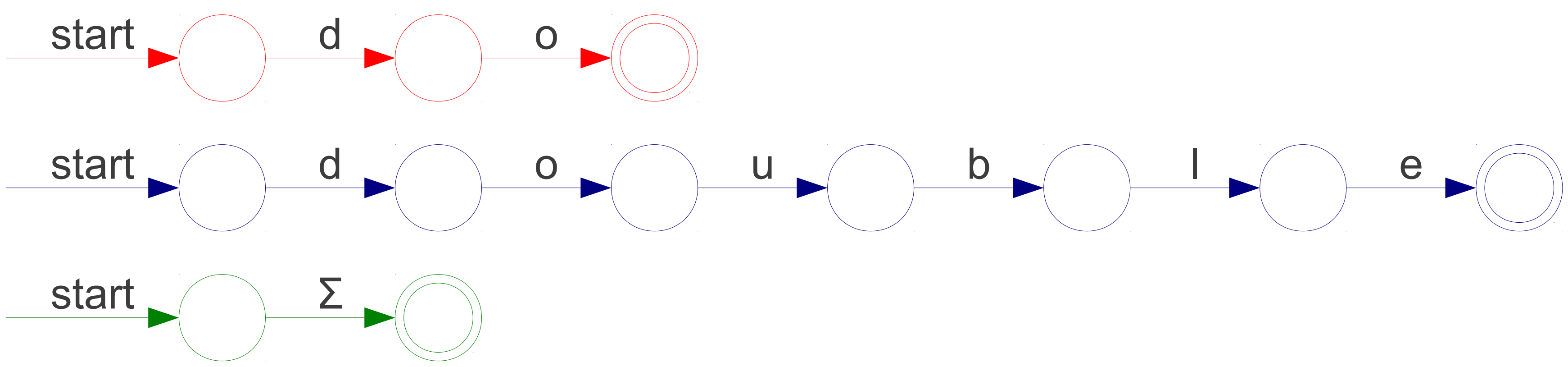
```



Implementing Maximal Munch

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T_Do          do
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T_Mystery     [A-Za-z]
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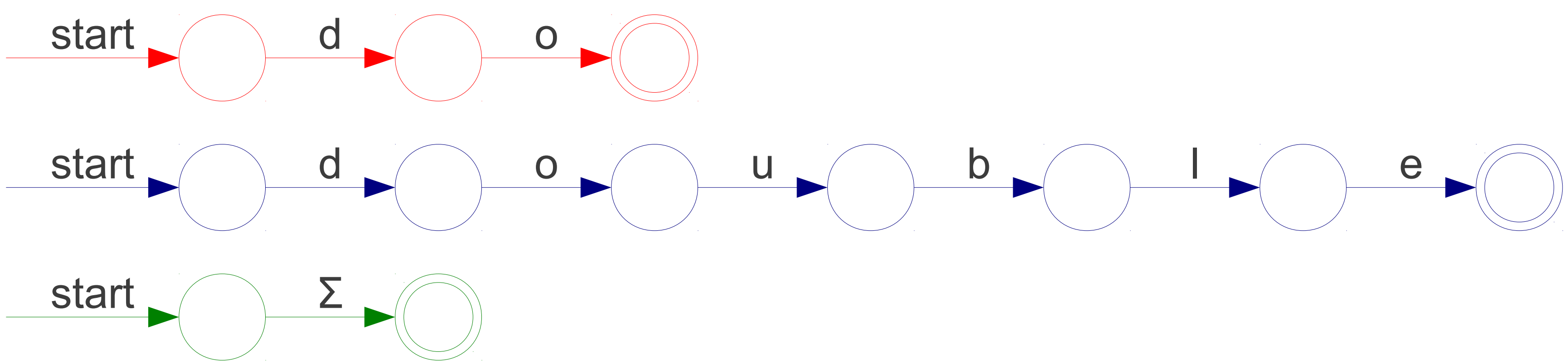
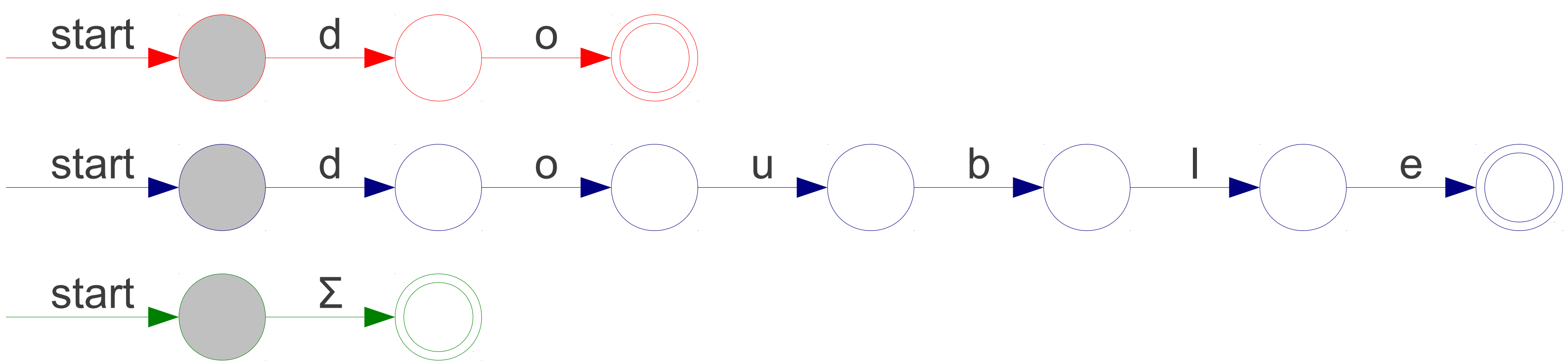


D	O	U	B	D	O	U	B	L	E

Implementing Maximal Munch

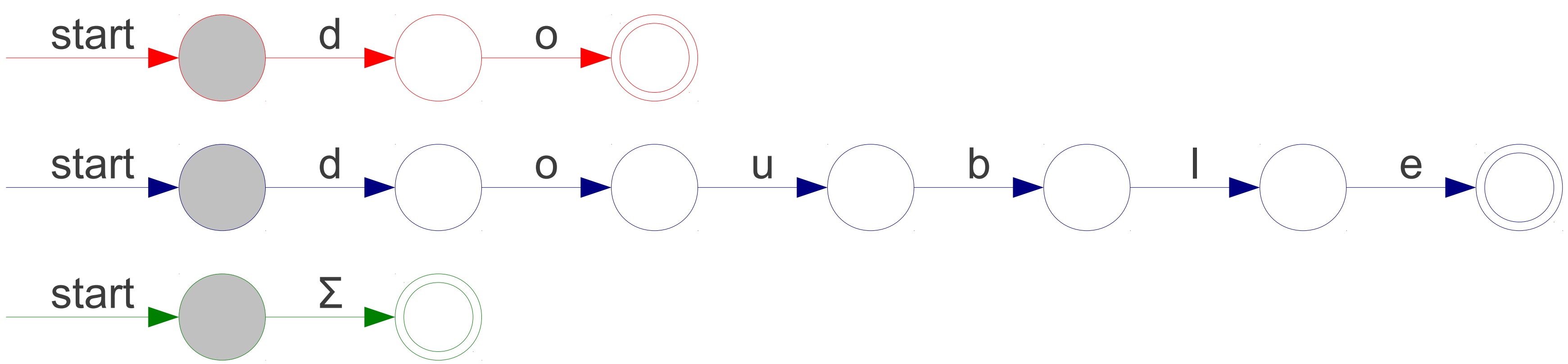
```
T_Do        do
T_Double    double
T_Mystery   [A-Za-z]
```

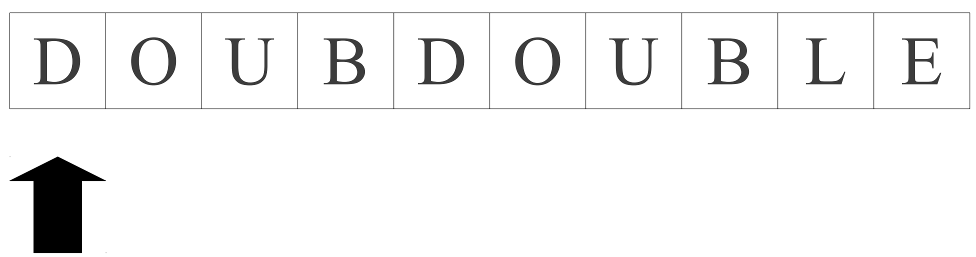


D	O	U	B	D	O	U	B	L	E

Implementing Maximal Munch

T_Do	do
T_Double	double
T_Mystery	[A-Za-z]





Implementing Maximal Munch

```
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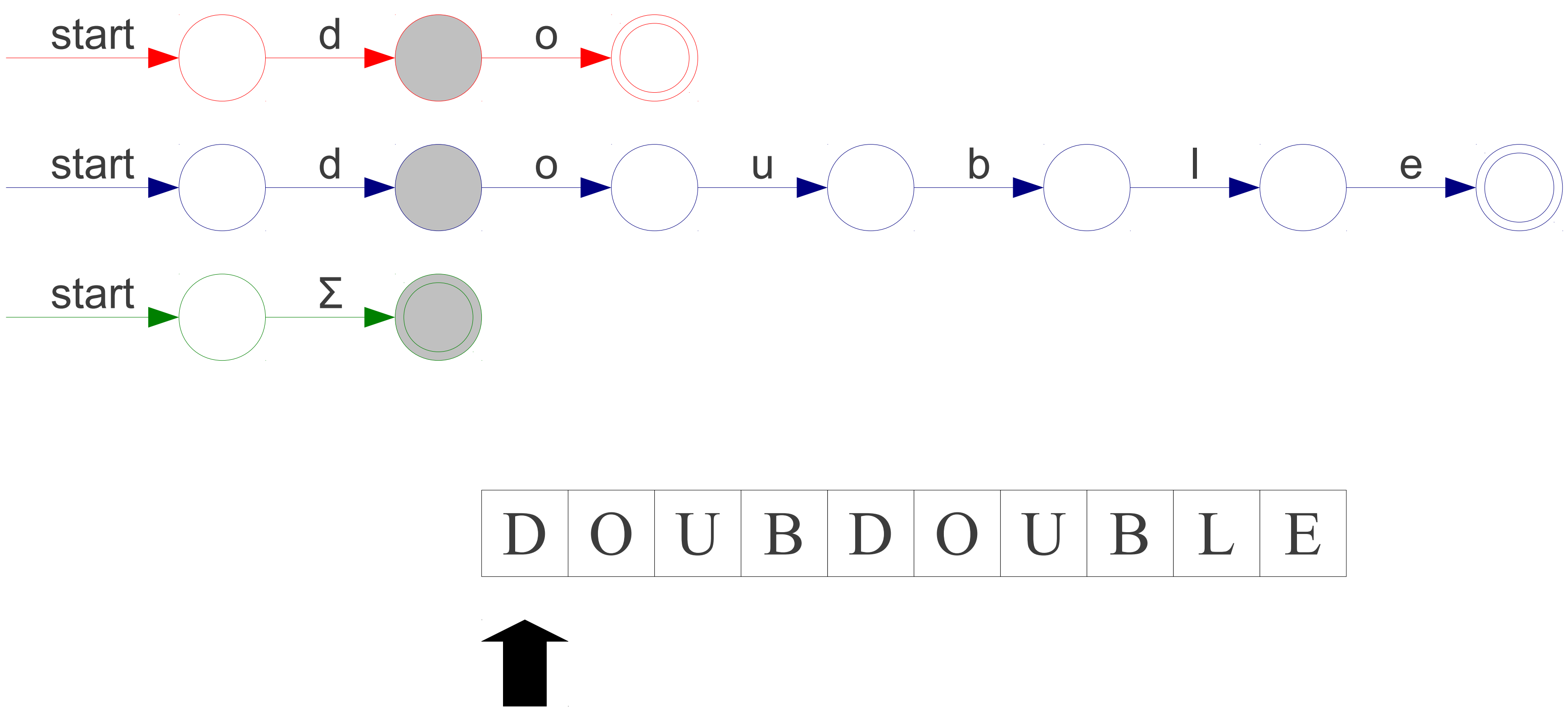

Implementing Maximal Munch

```
T_Do          do
T_Double      double
T_Mystery     [A-Za-z]
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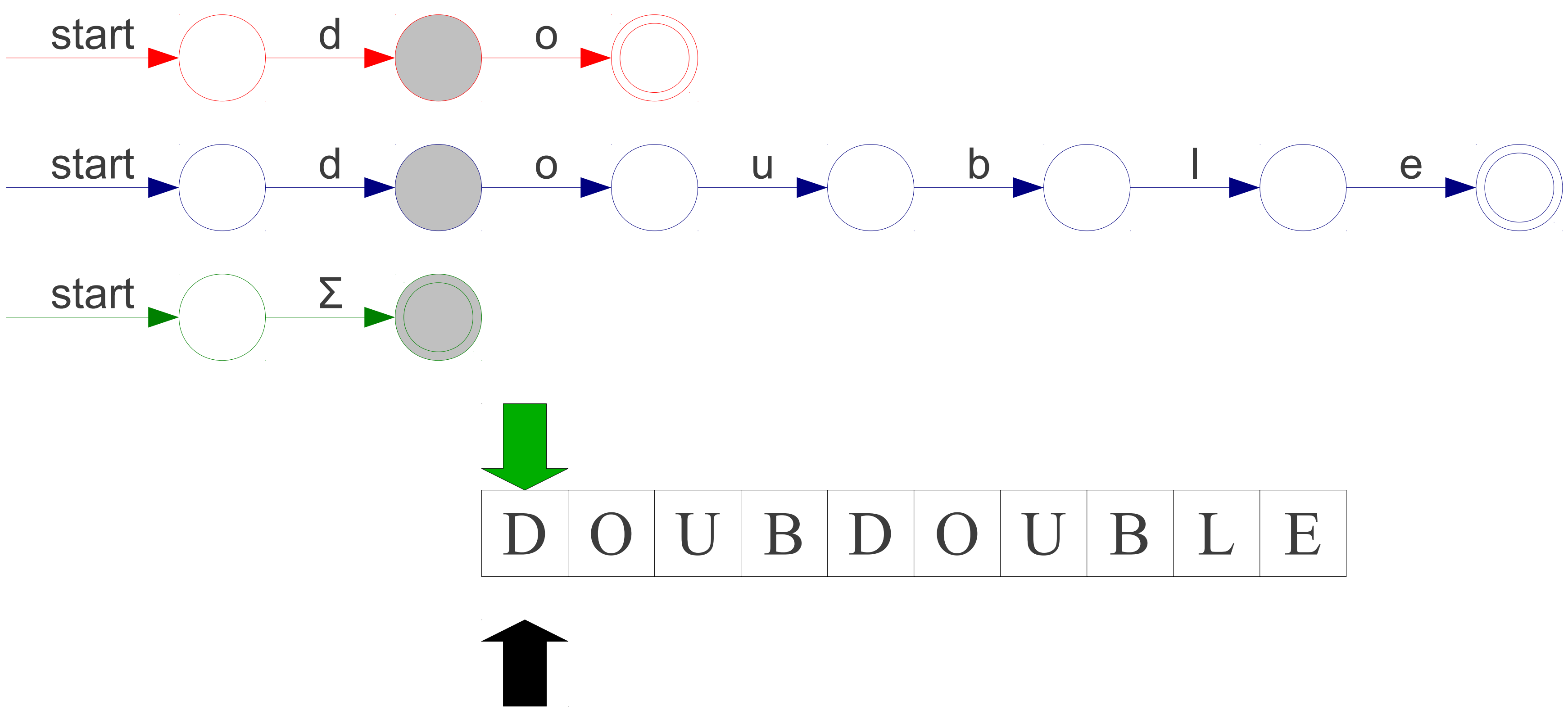
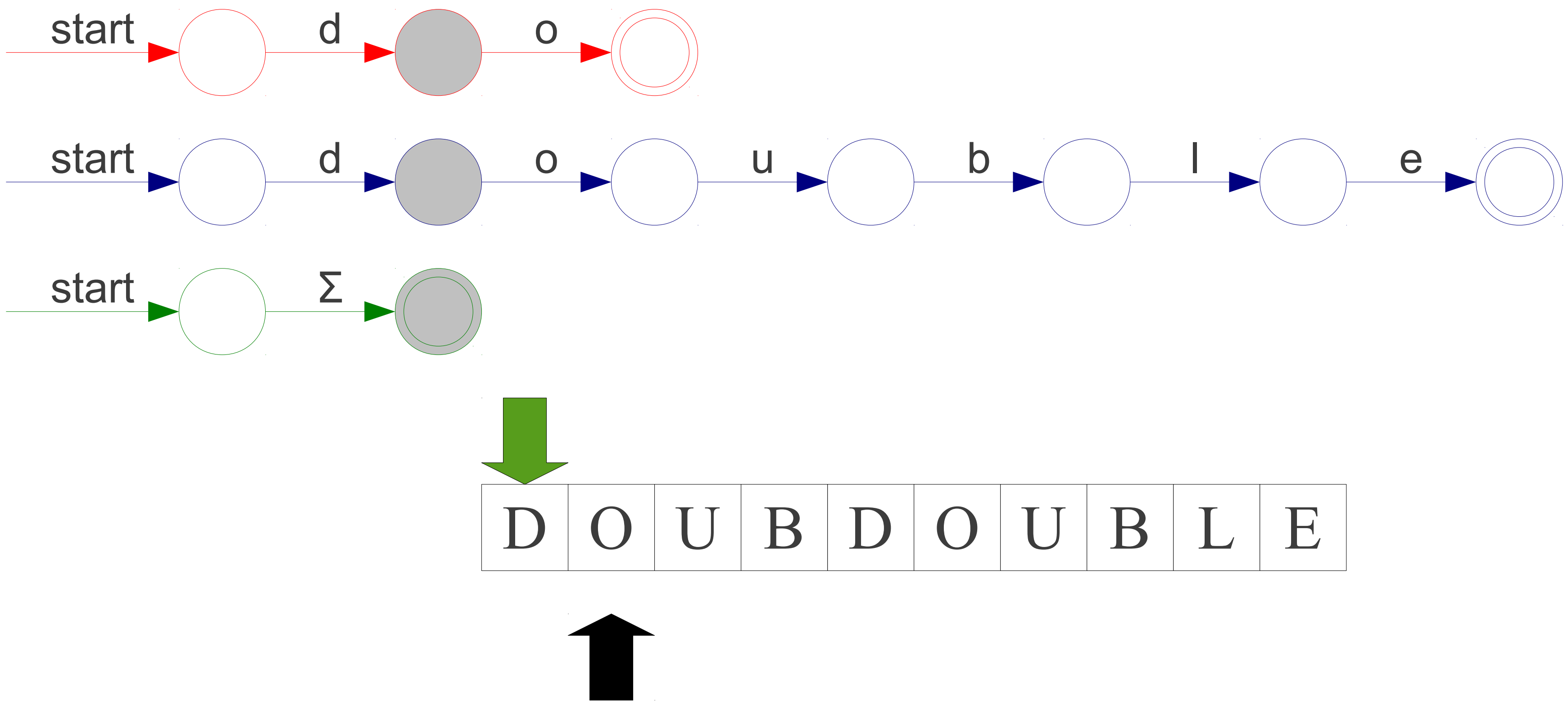


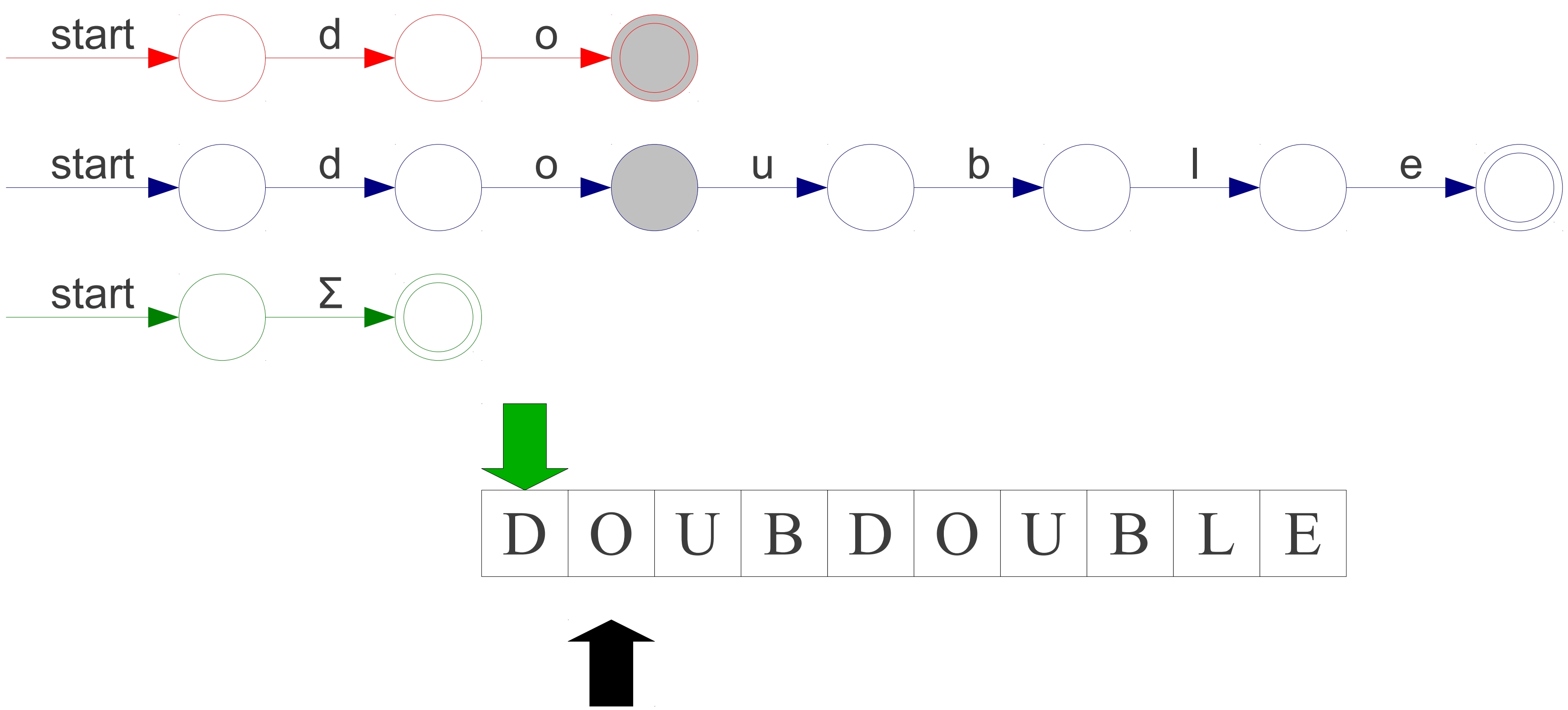
Implementing Maximal Munch

T_Do	do
T_Double	double
T_Mystery	[A-Za-z]



Implementing Maximal Munch

T_Do	do
T_Double	double
T_Mystery	[A-Za-z]



Implementing Maximal Munch

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T_Do          do
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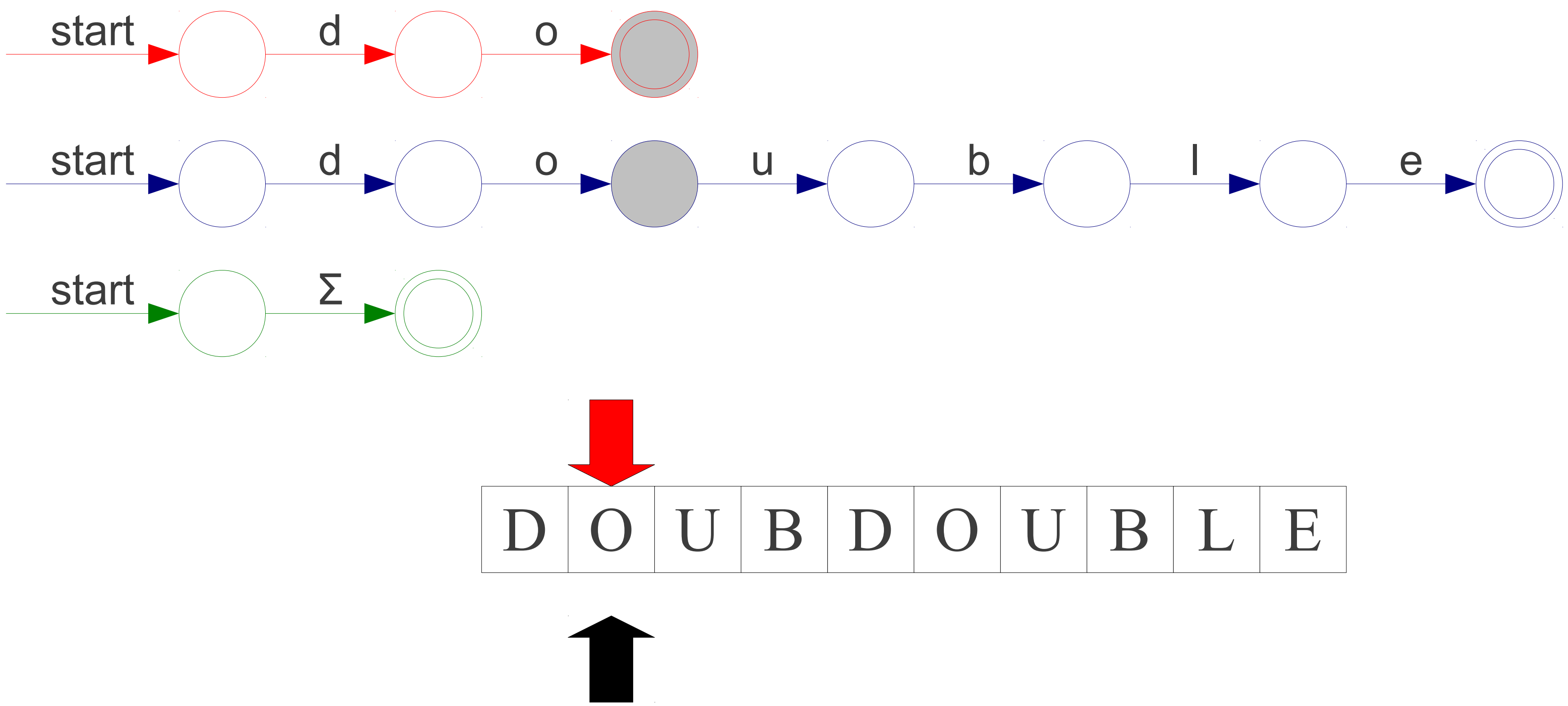
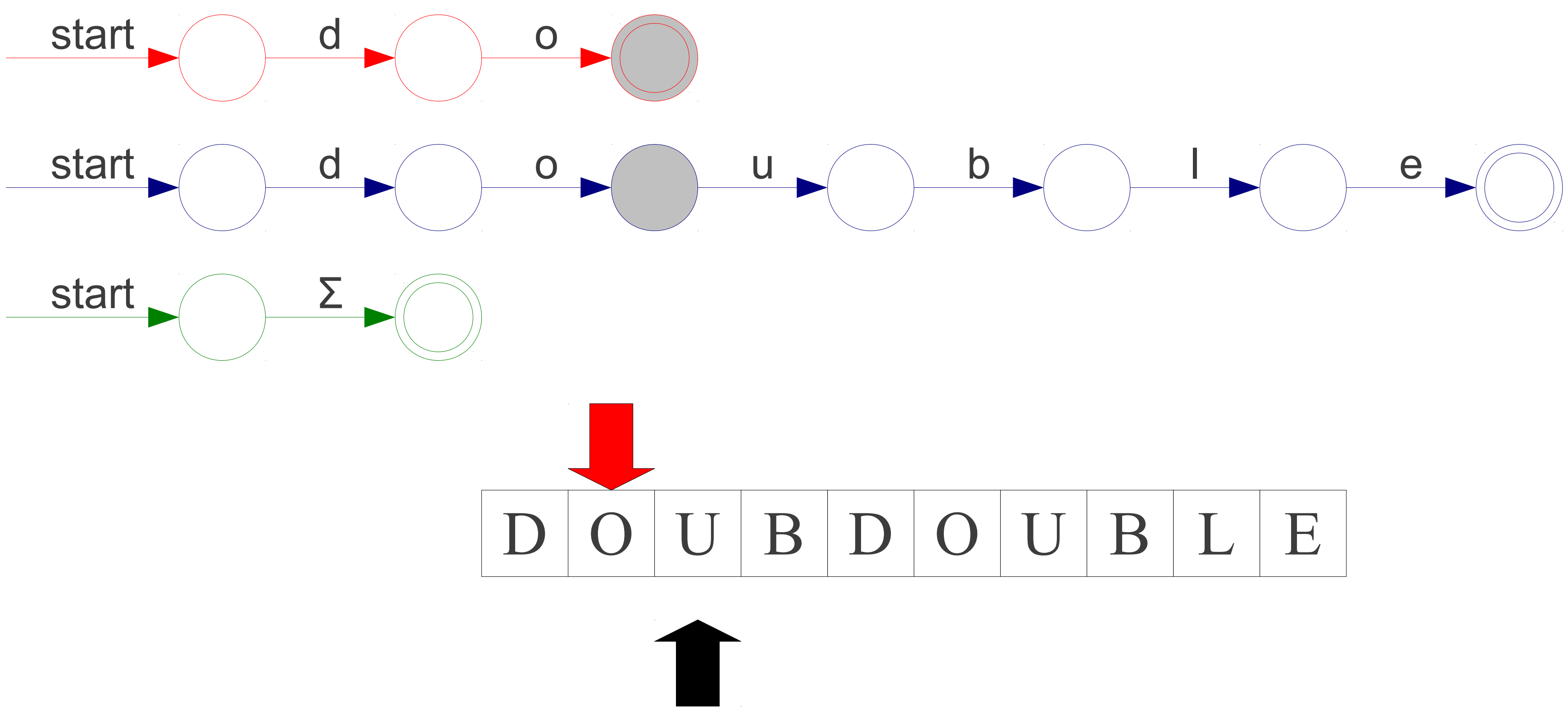
```



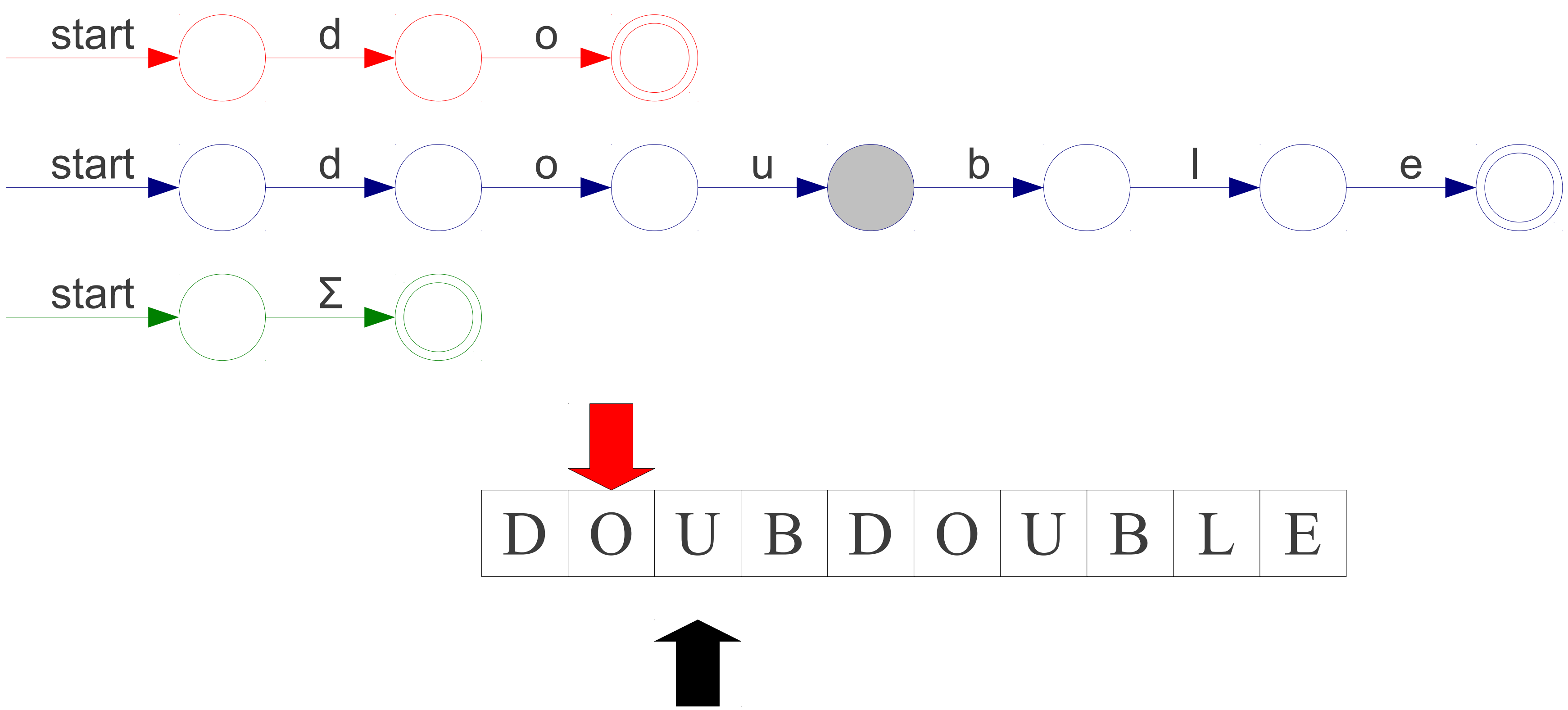
Implementing Maximal Munch

```
T_Do          do
T_Double      double
T_Mystery     [A-Za-z]
```



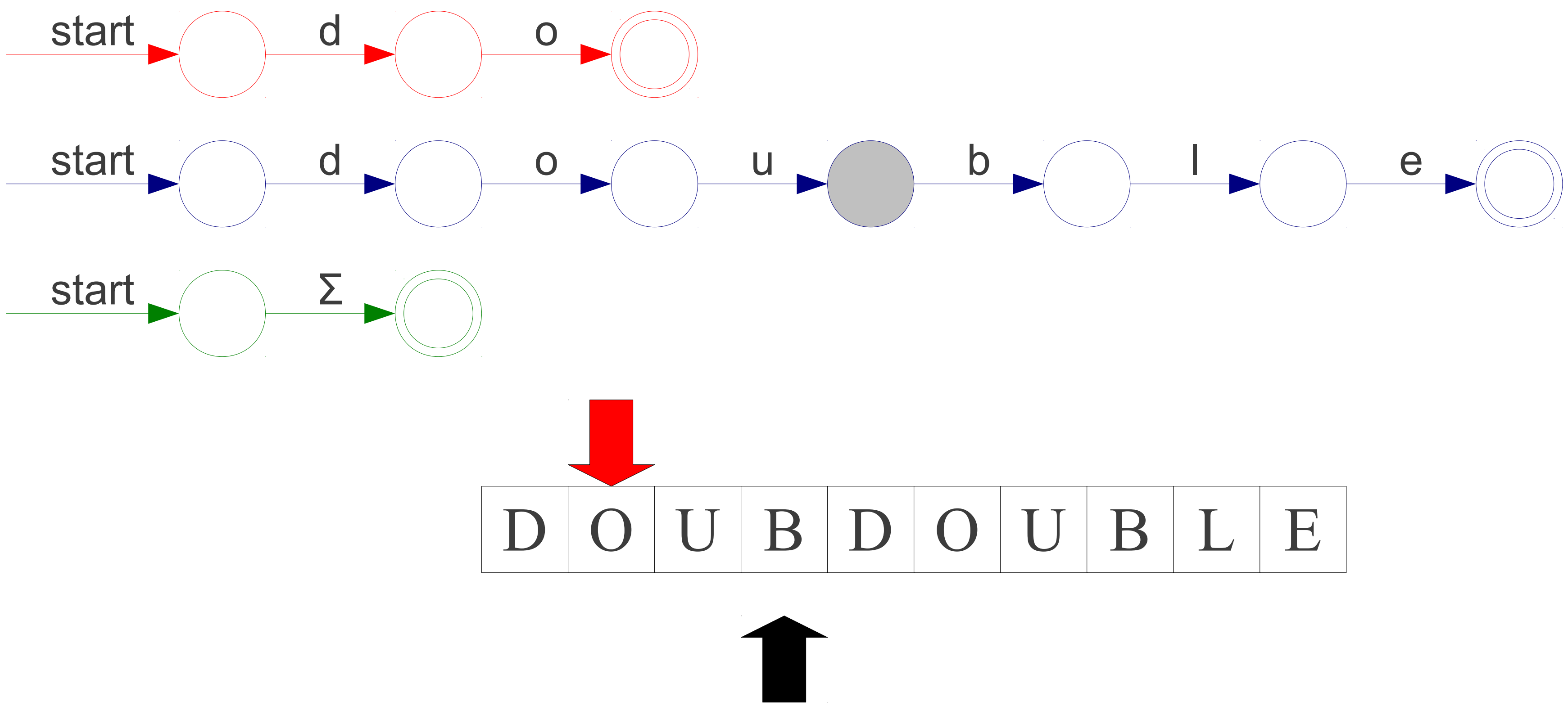
Implementing Maximal Munch

```
T_Do        do
T_Double    double
T_Mystery   [A-Za-z]
```



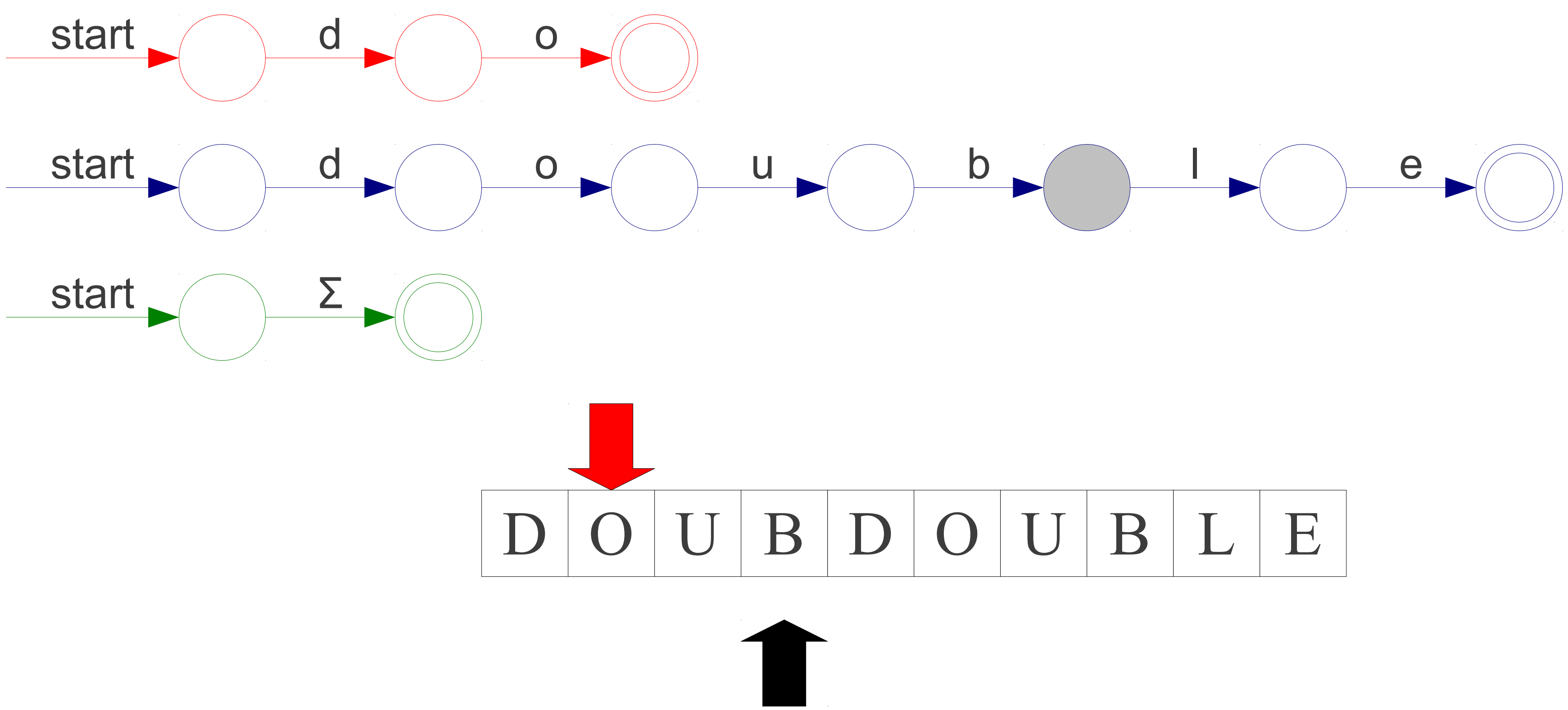
Implementing Maximal Munch

T_Do	do
T_Double	double
T_Mystery	[A-Za-z]



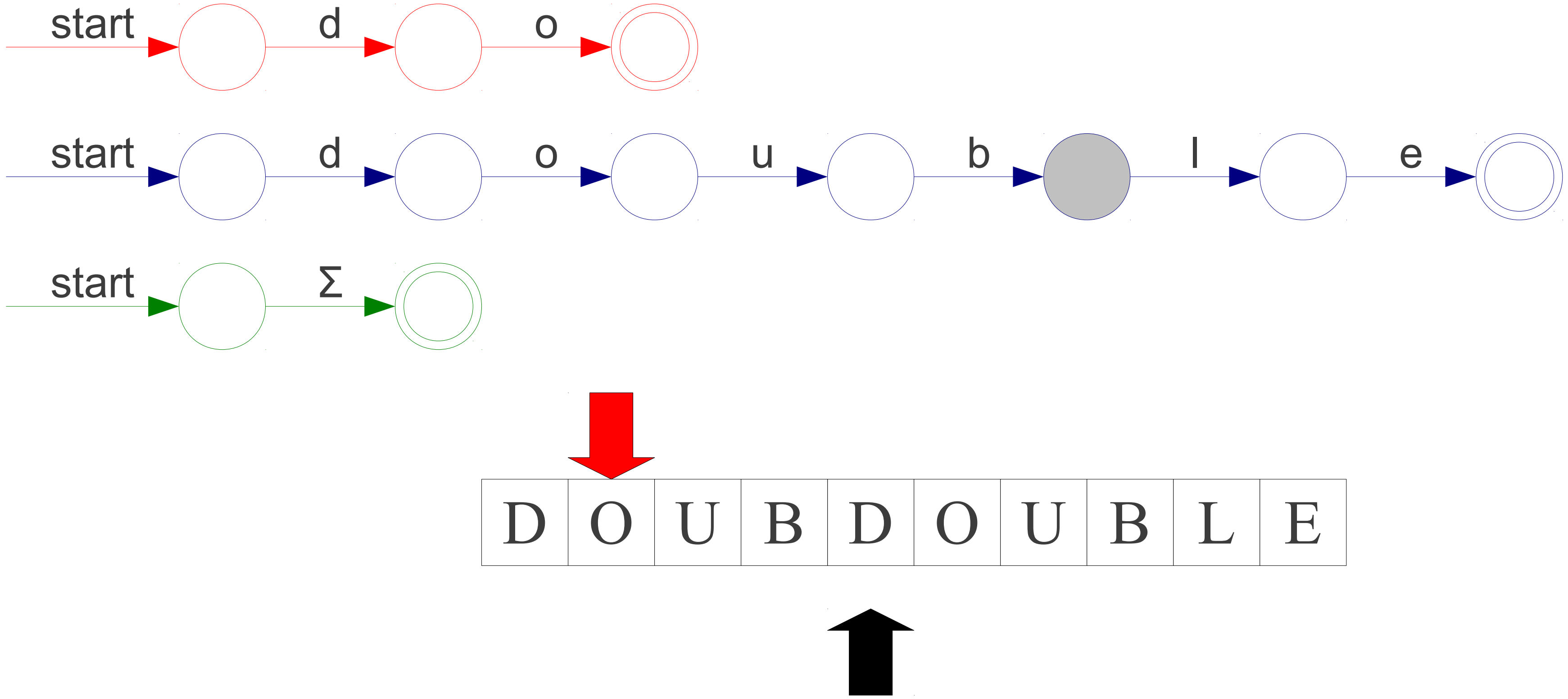
Implementing Maximal Munch

```
T_Do         do
T_Double     double
T_Mystery    [A-Za-z]
```



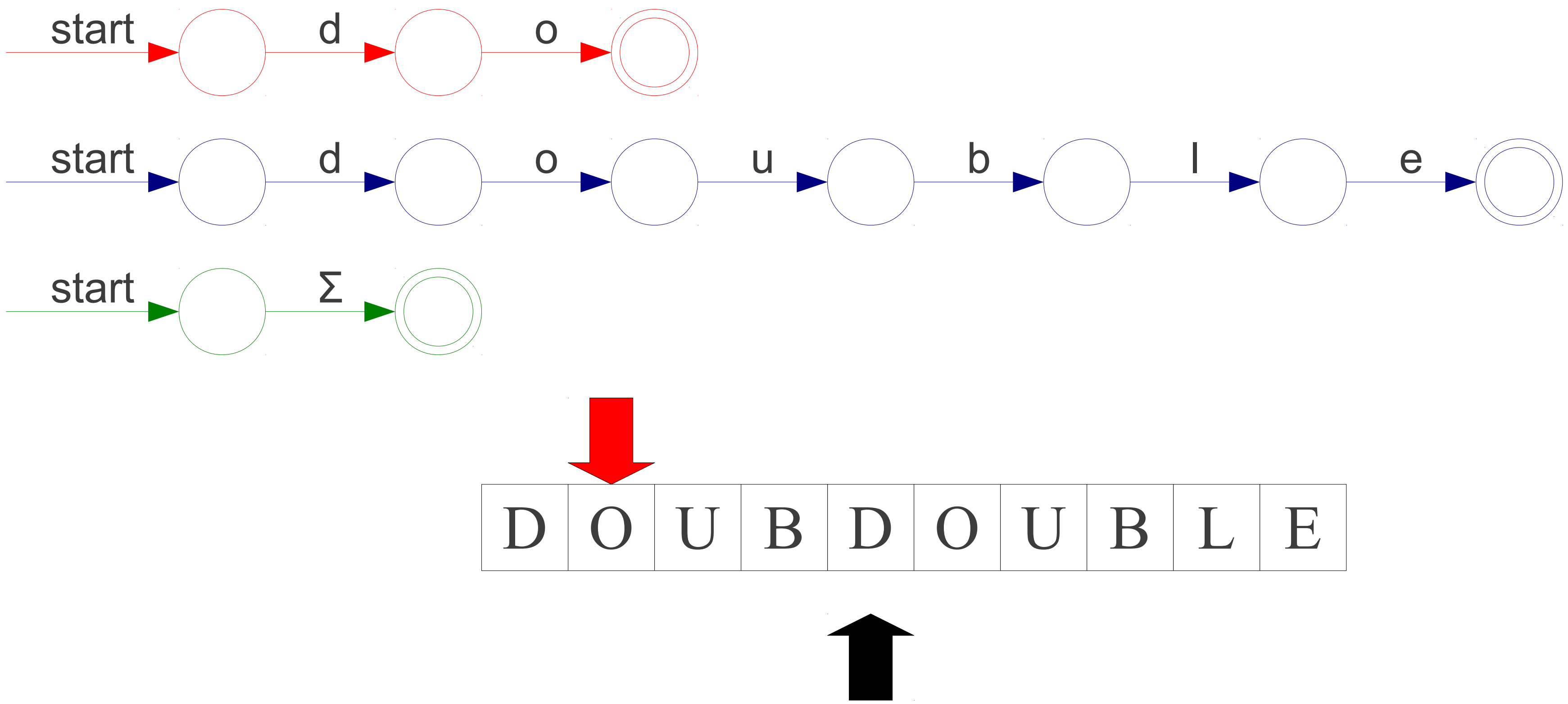
Implementing Maximal Munch

T_Do	do
T_Double	double
T_Mystery	[A-Za-z]



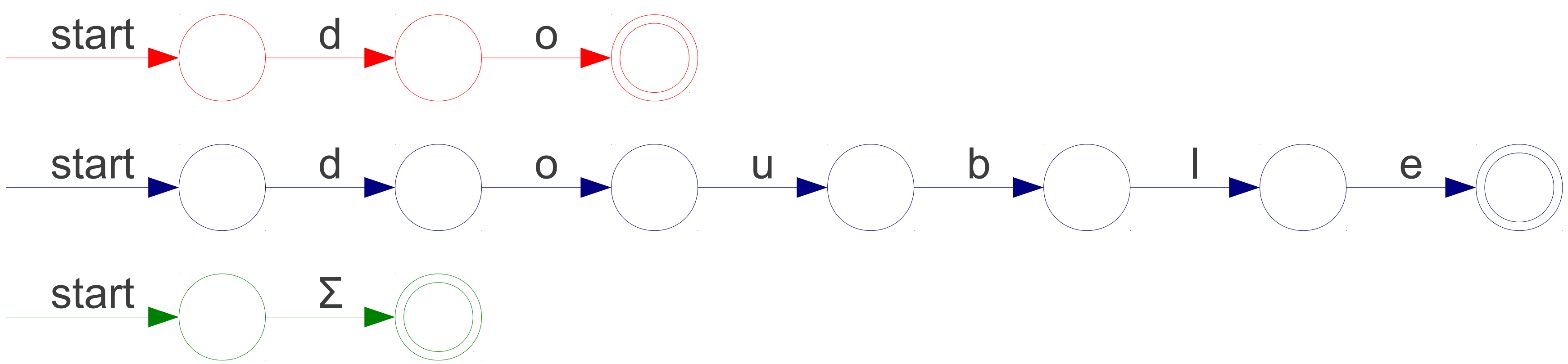
Implementing Maximal Munch

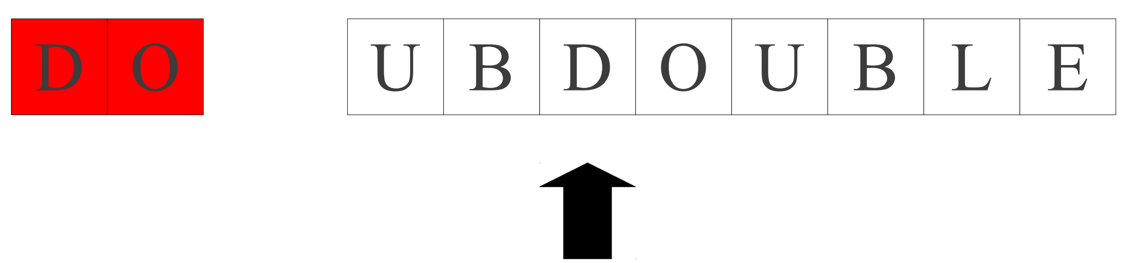
T_Do	do
T_Double	double
T_Mystery	[A-Za-z]



Implementing Maximal Munch

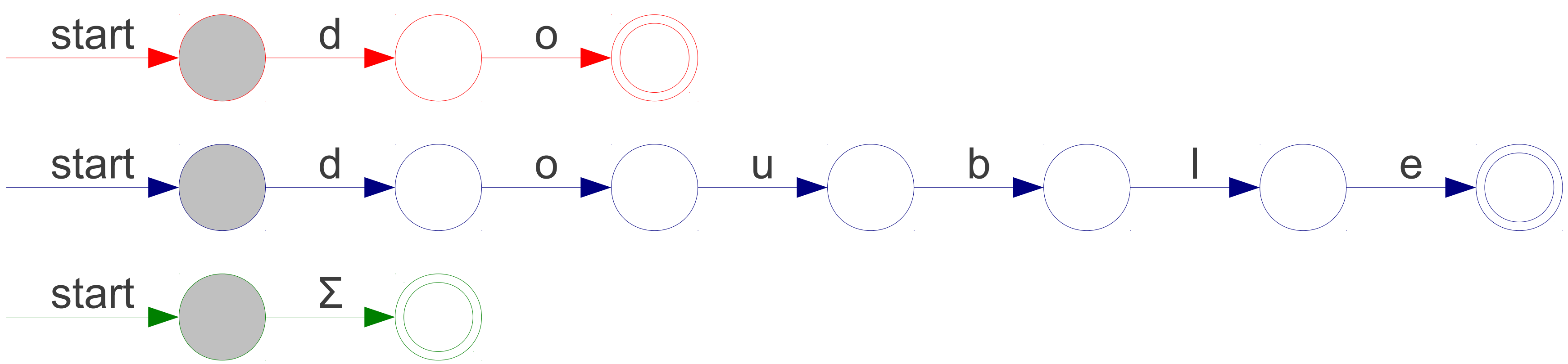
T_Do	do
T_Double	double
T_Mystery	[A-Za-z]

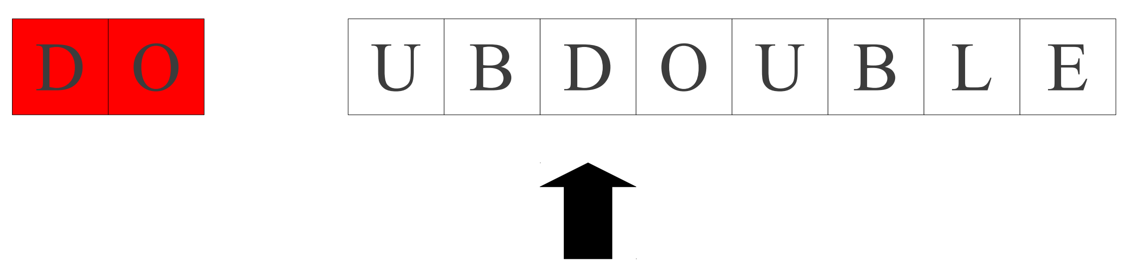




Implementing Maximal Munch

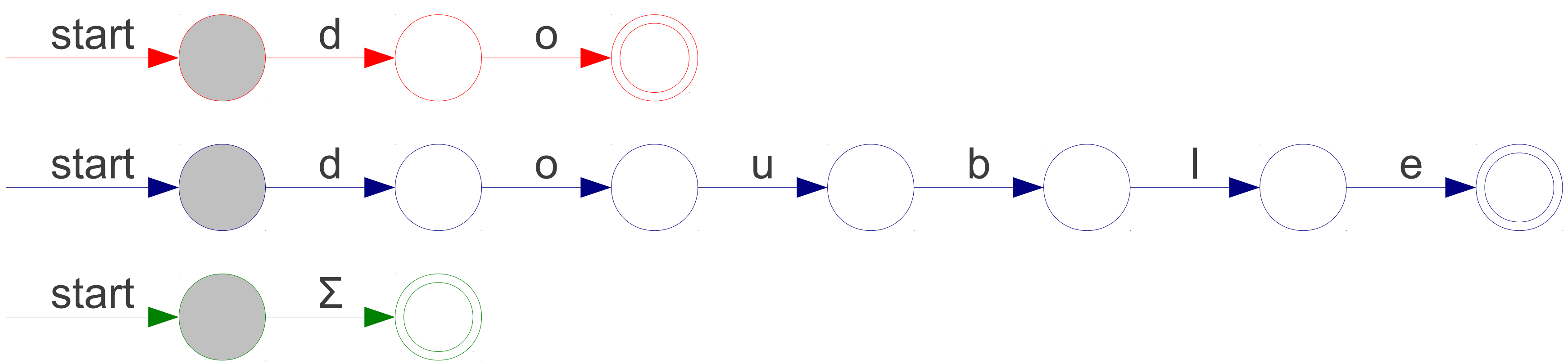
```
T_Do        do
T_Double    double
T_Mystery   [A-Za-z]
```

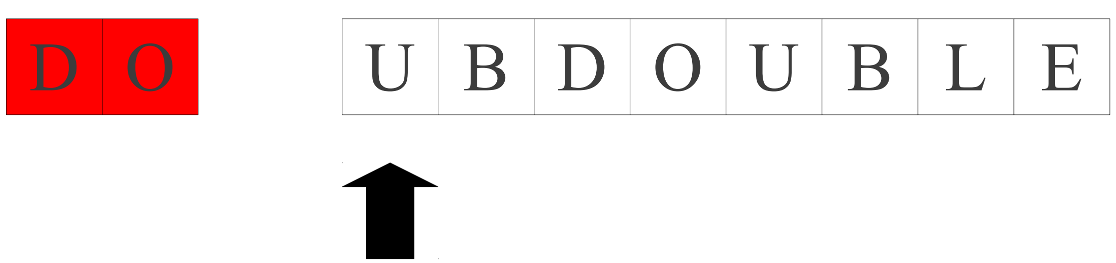




Implementing Maximal Munch

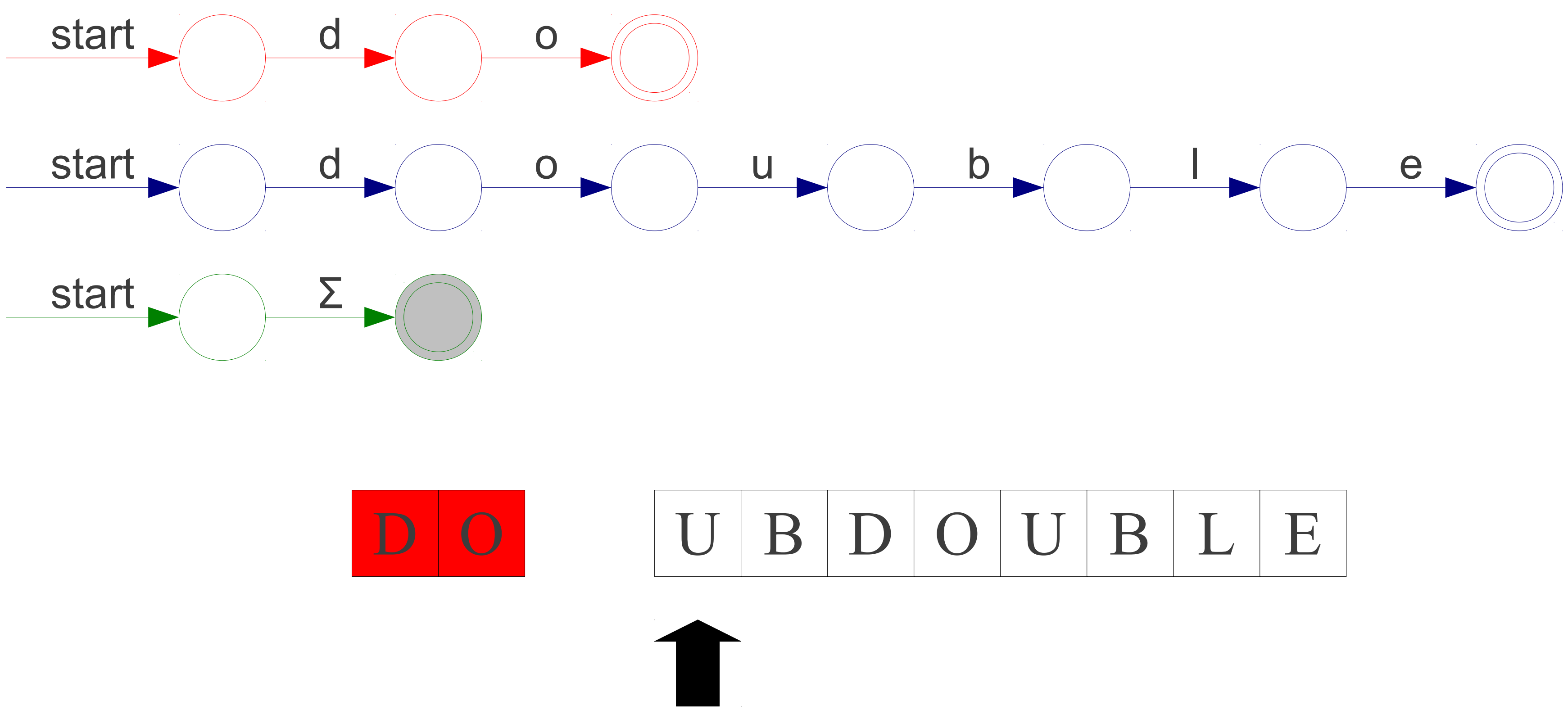
T_Do	do
T_Double	double
T_Mystery	[A-Za-z]





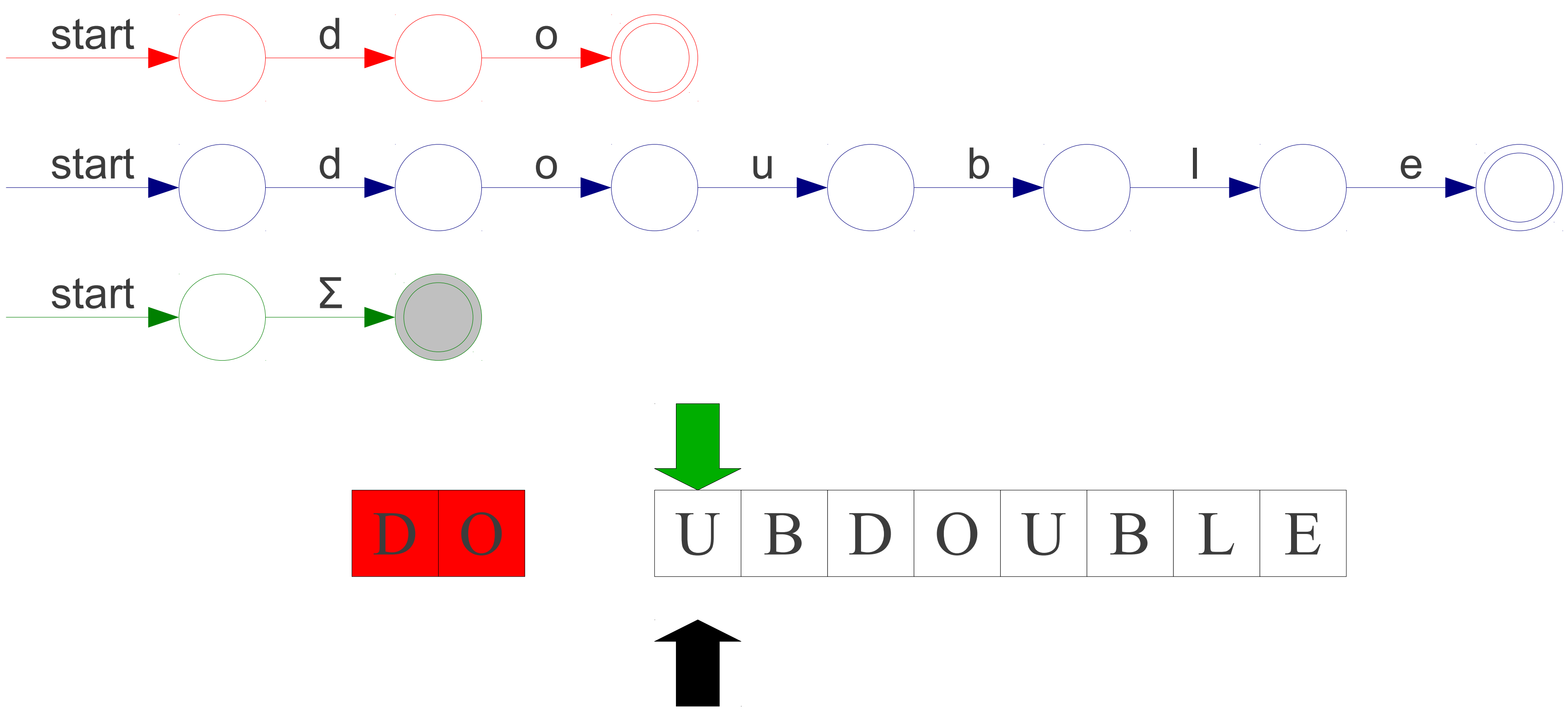
Implementing Maximal Munch

T_Do	do
T_Double	double
T_Mystery	[A-Za-z]



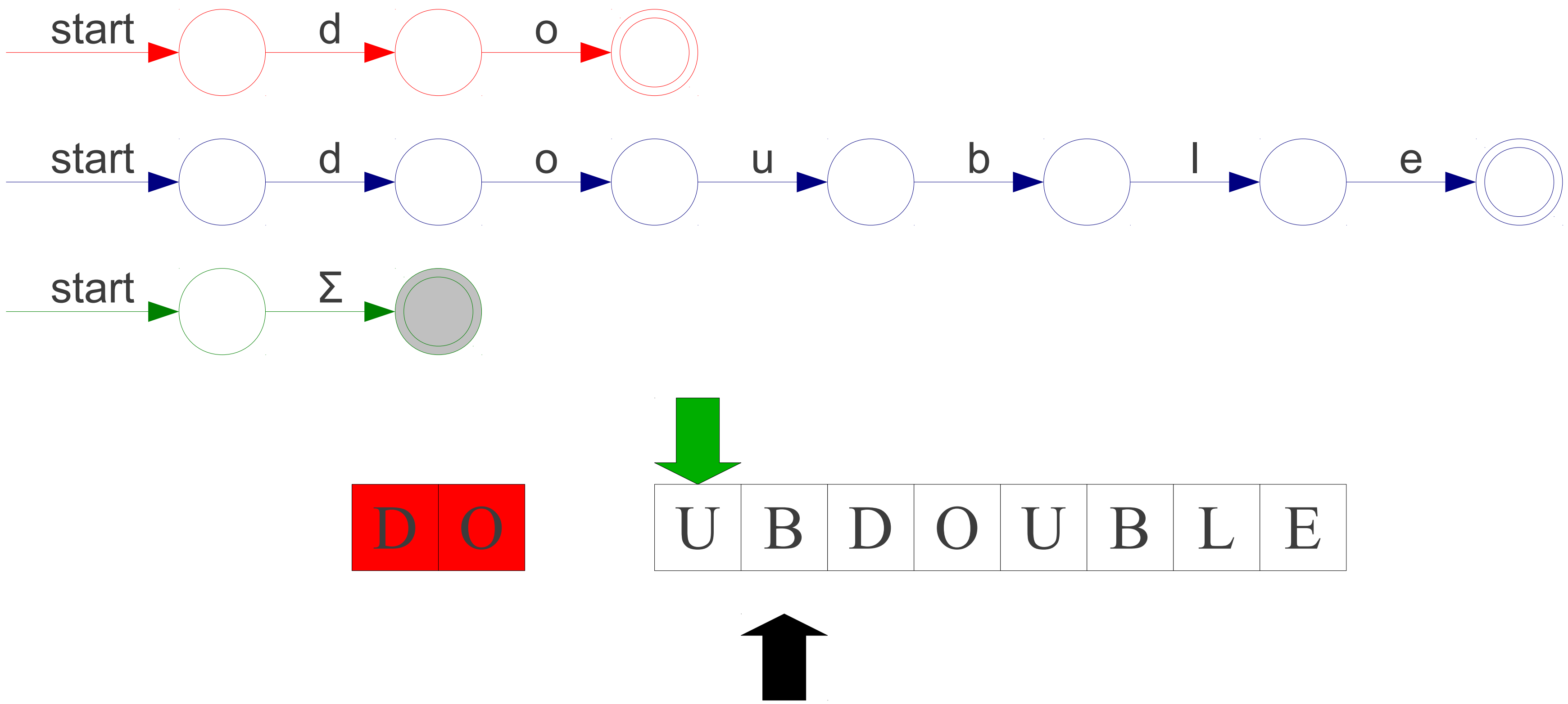
Implementing Maximal Munch

T_Do	do
T_Double	double
T_Mystery	[A-Za-z]



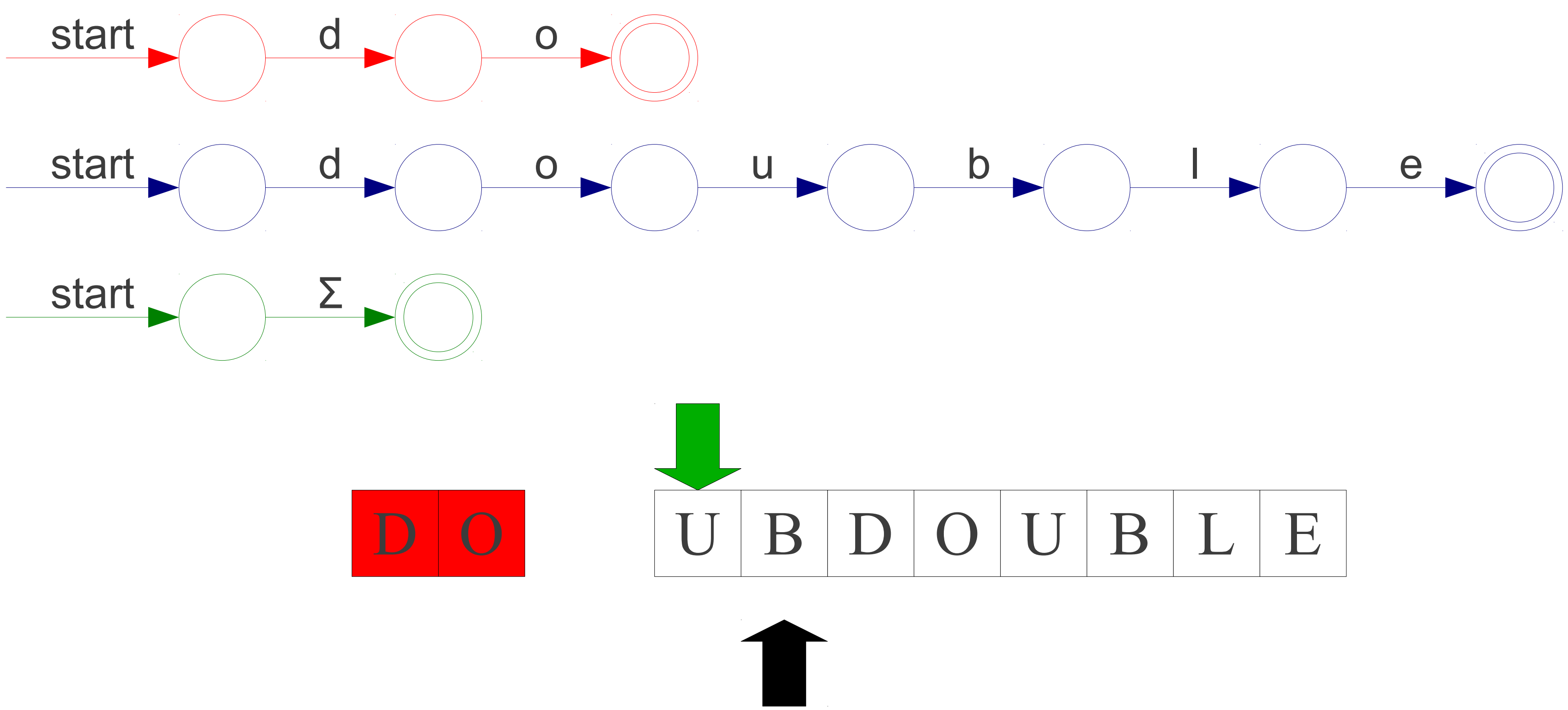
Implementing Maximal Munch

T_Do	do
T_Double	double
T_Mystery	[A-Za-z]



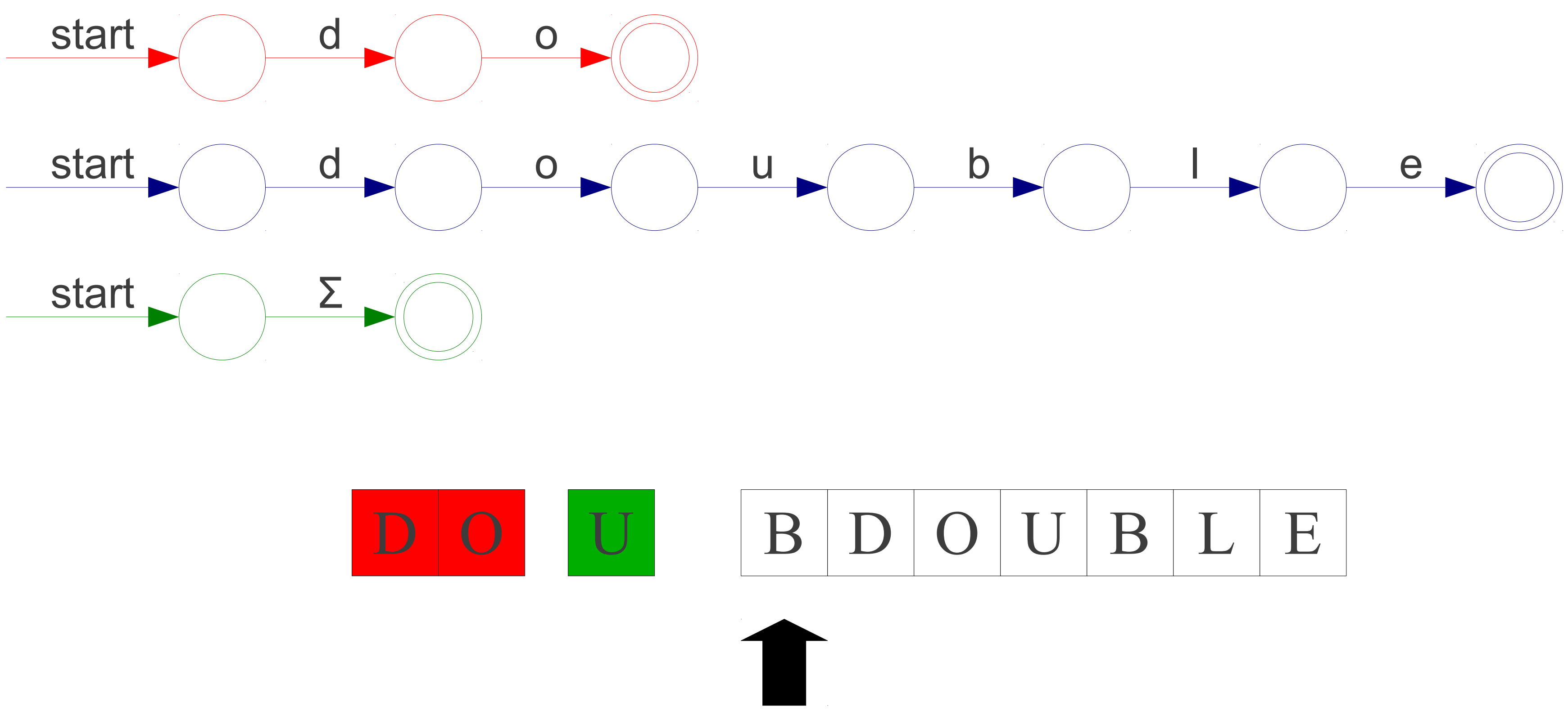
Implementing Maximal Munch

T_Do	do
T_Double	double
T_Mystery	[A-Za-z]



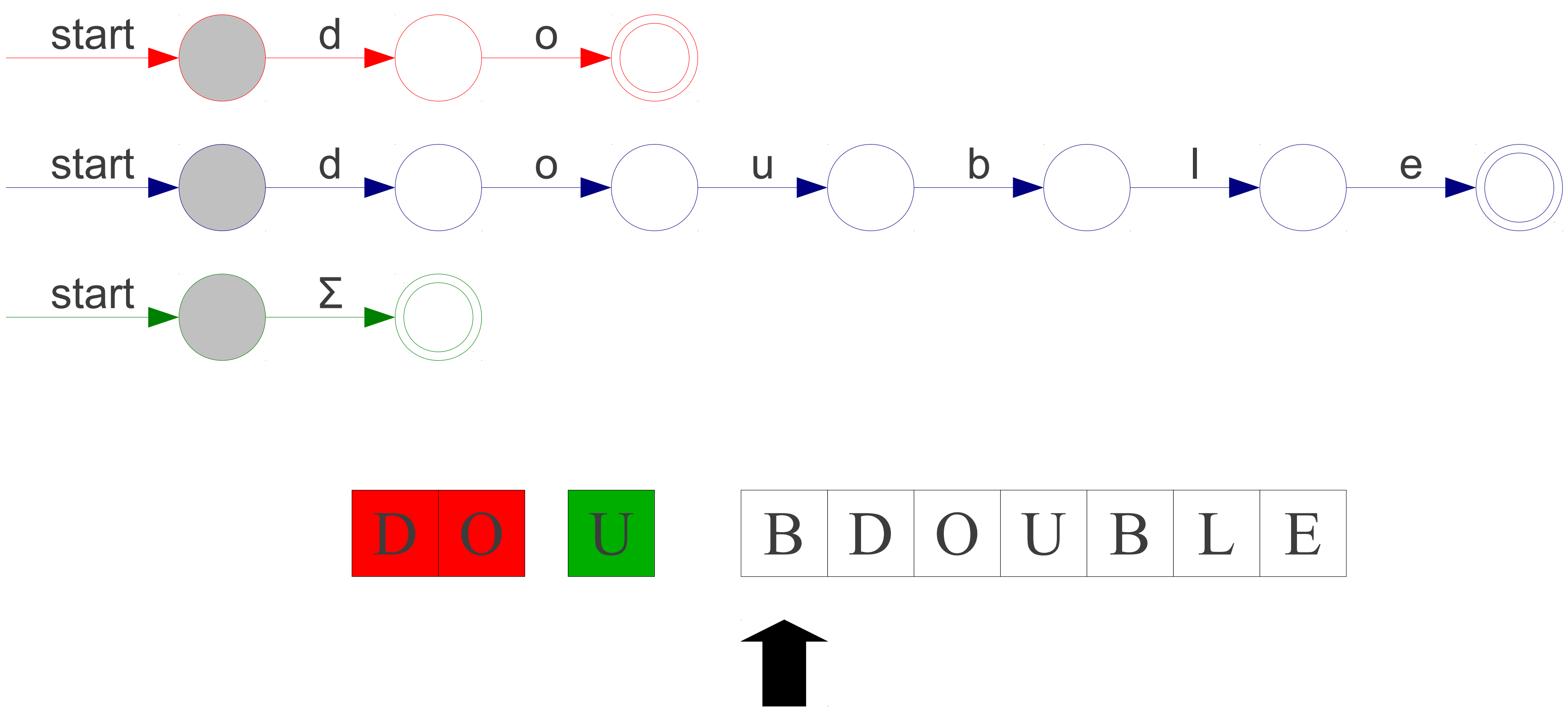
Implementing Maximal Munch

T_Do	do
T_Double	double
T_Mystery	[A-Za-z]



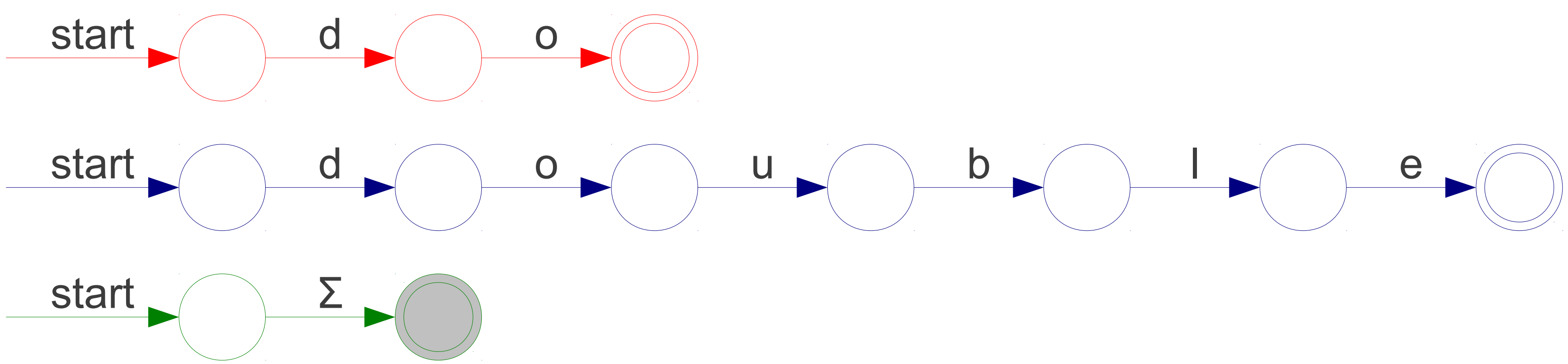
Implementing Maximal Munch

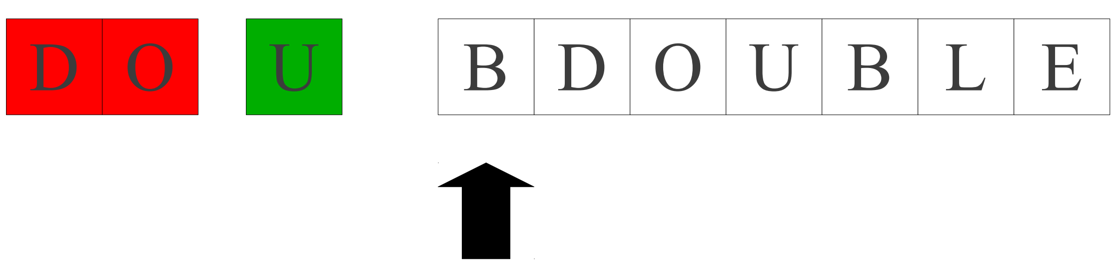
T_Do	do
T_Double	double
T_Mystery	[A-Za-z]



Implementing Maximal Munch

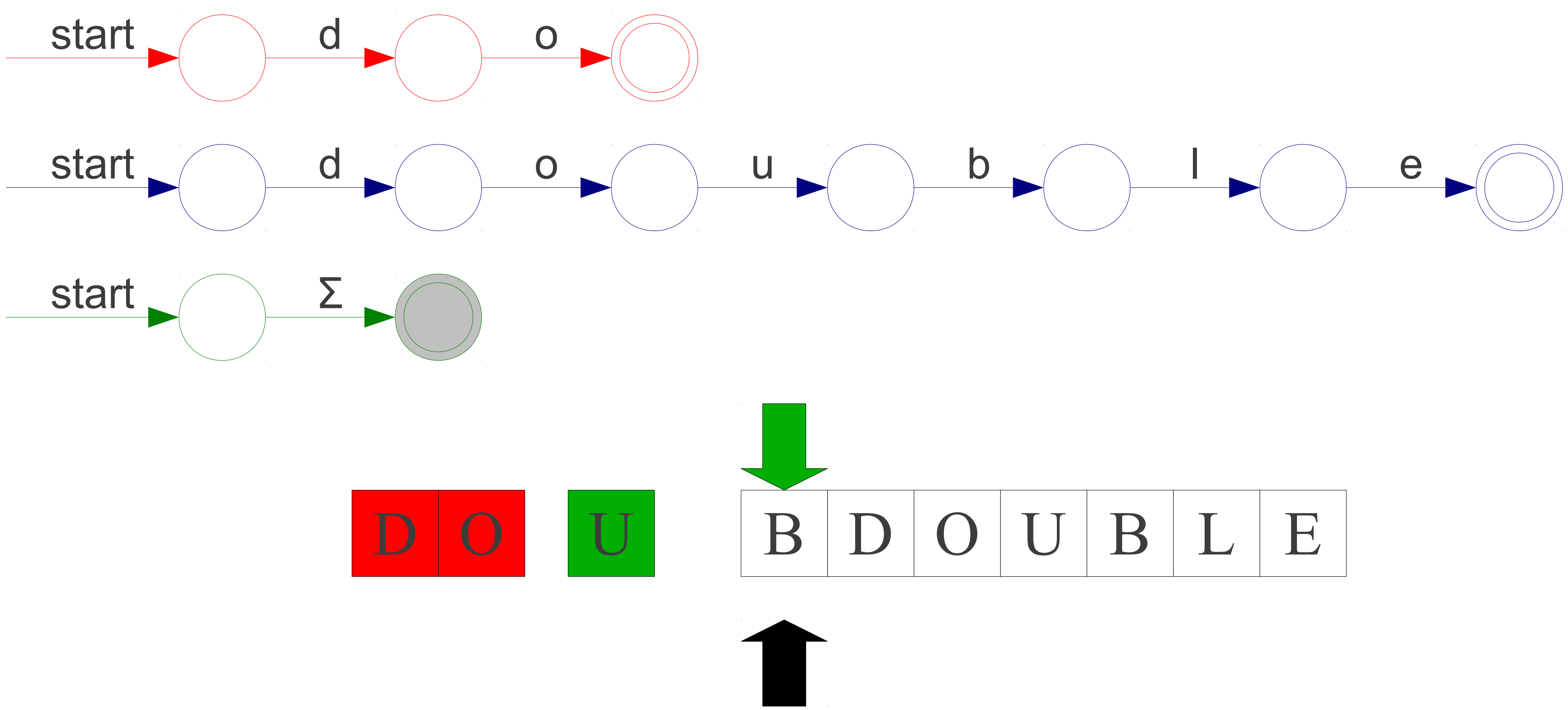
```
T_Do          do
T_Double      double
T_Mystery     [A-Za-z]
```





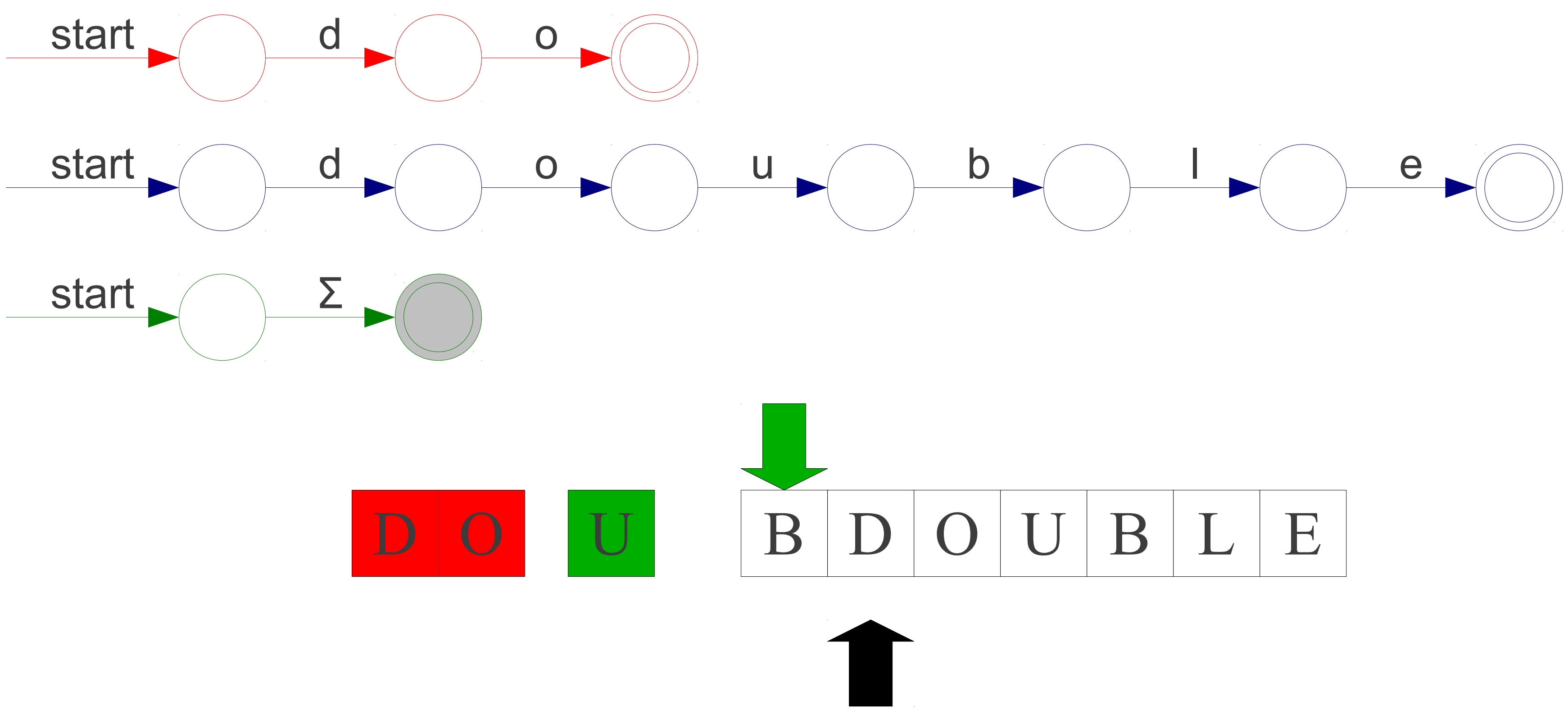
Implementing Maximal Munch

T_Do	do
T_Double	double
T_Mystery	[A-Za-z]



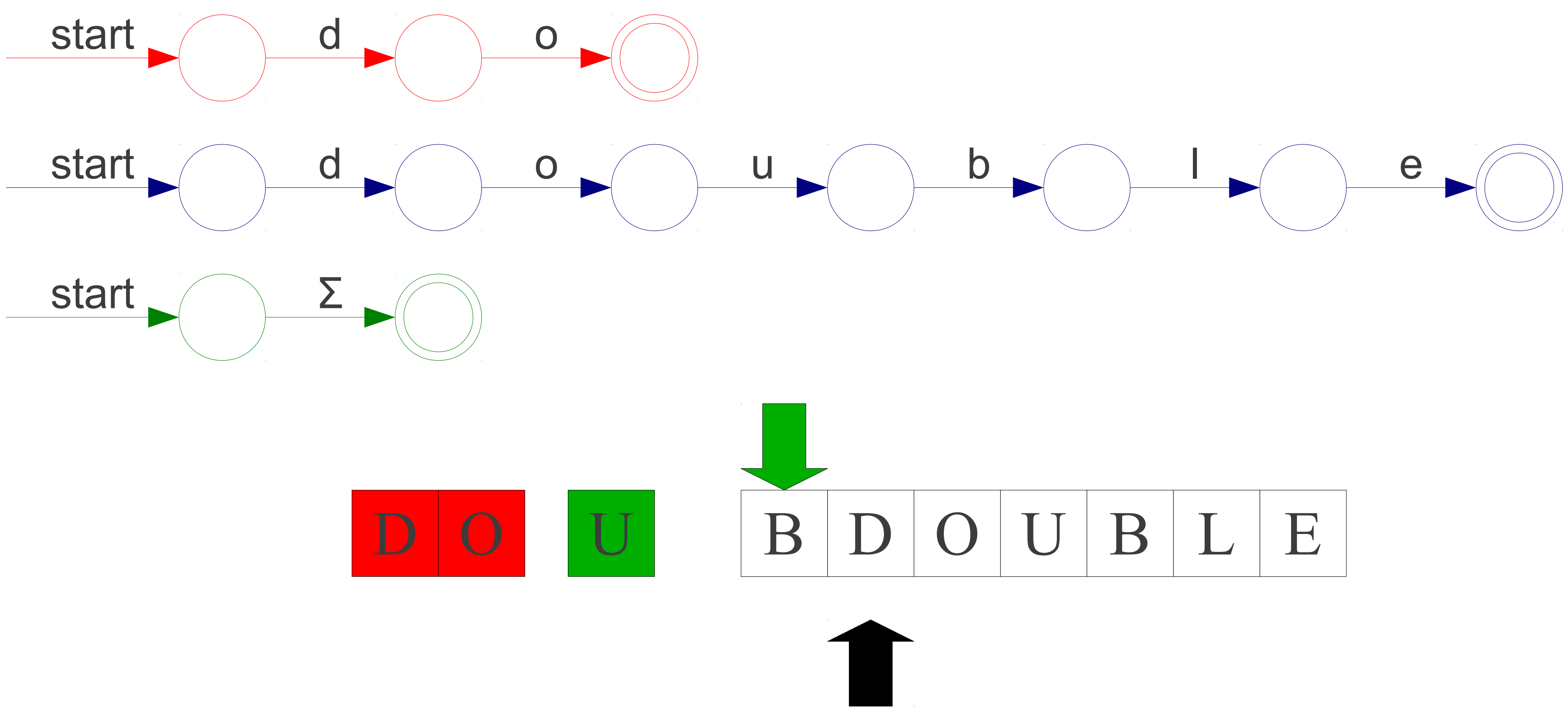
Implementing Maximal Munch

T_Do	do
T_Double	double
T_Mystery	[A-Za-z]



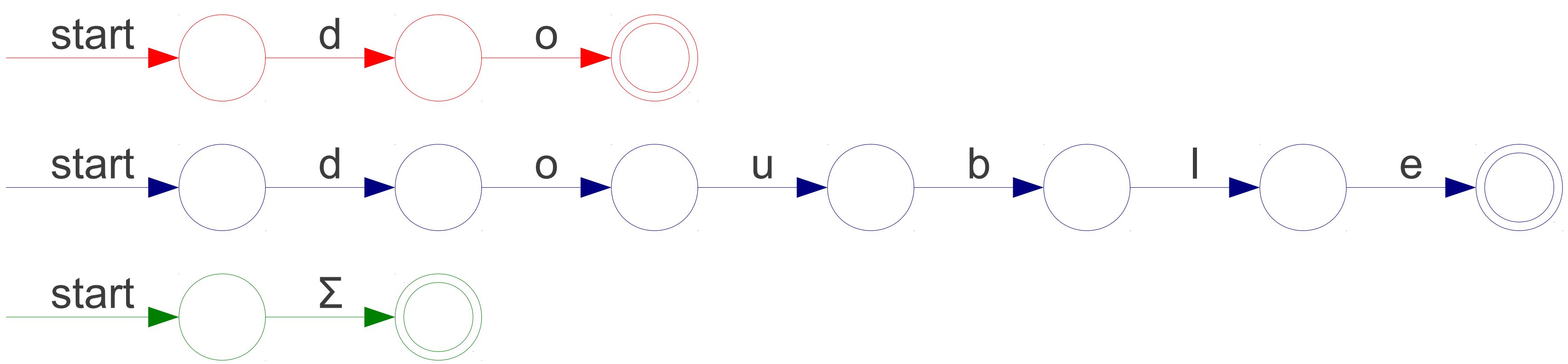
Implementing Maximal Munch

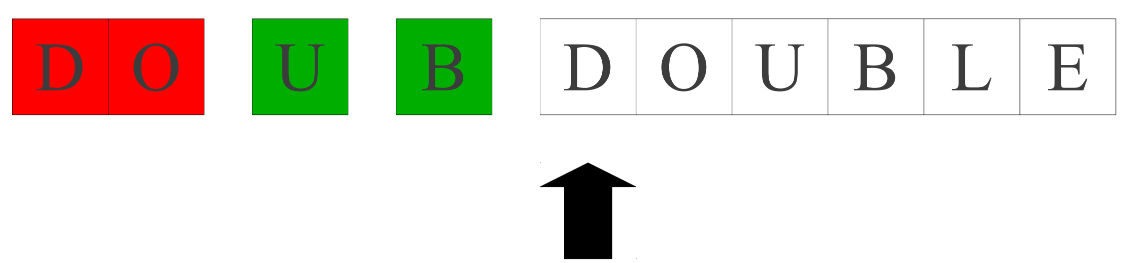
T_Do	do
T_Double	double
T_Mystery	[A-Za-z]



Implementing Maximal Munch

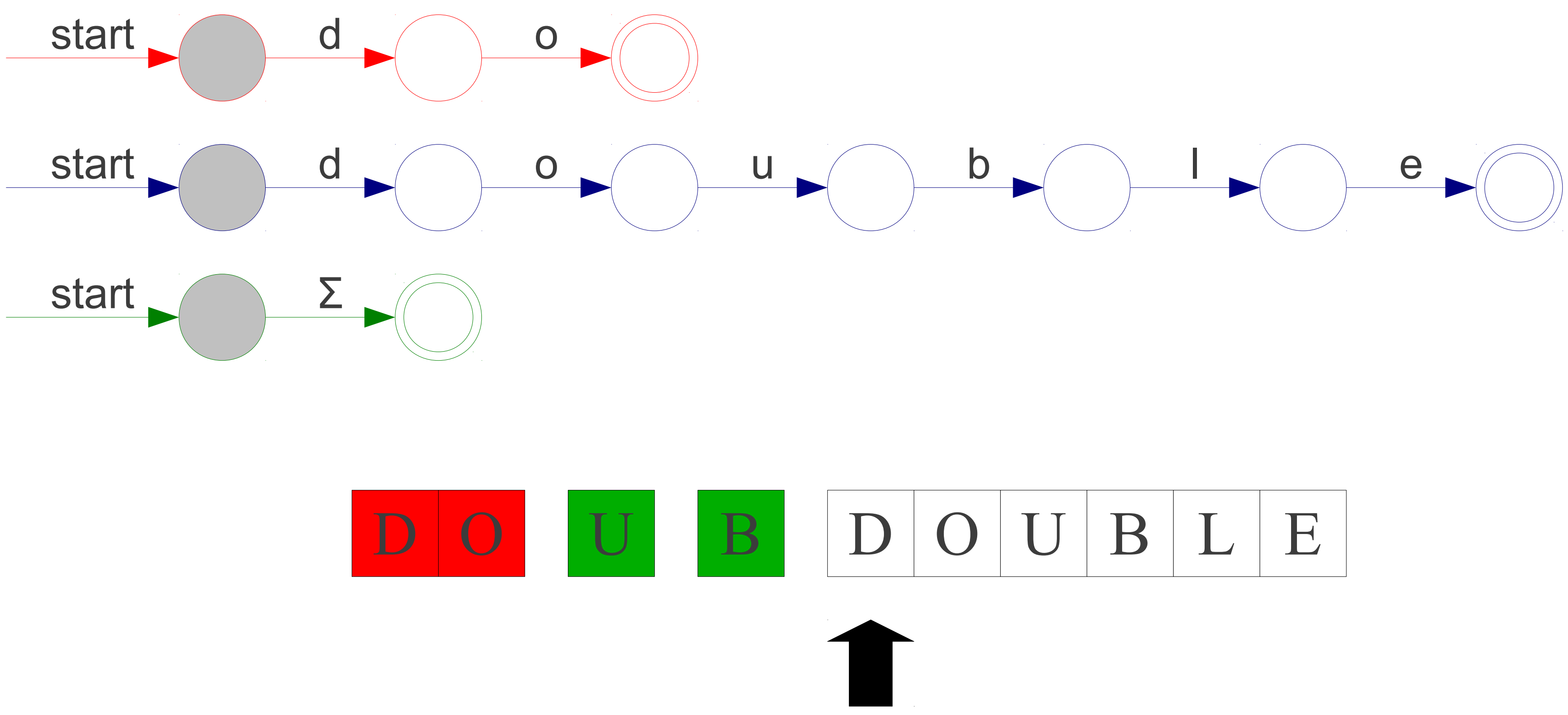
```
T_Do          do
T_Double      double
T_Mystery     [A-Za-z]
```





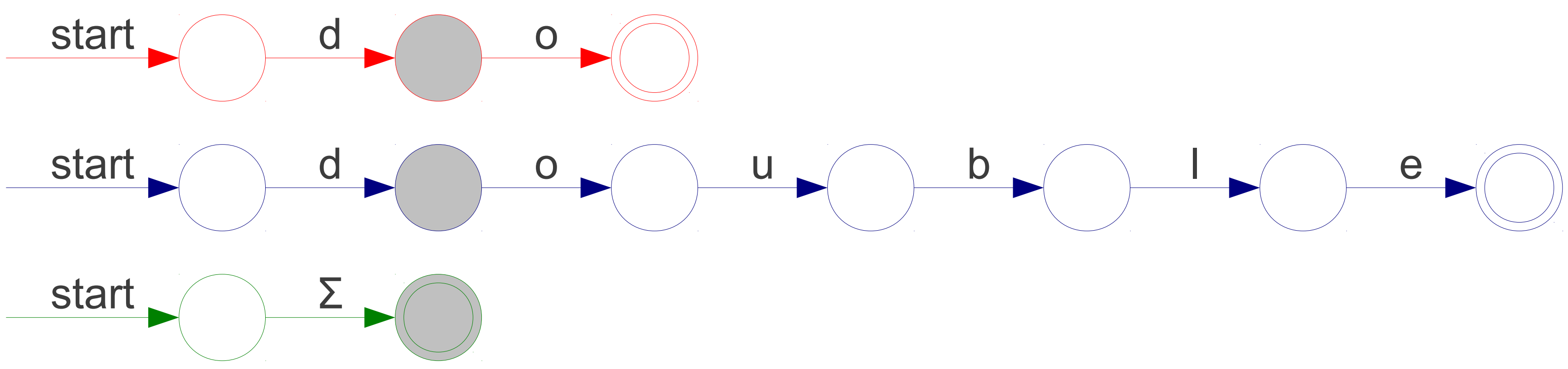
Implementing Maximal Munch

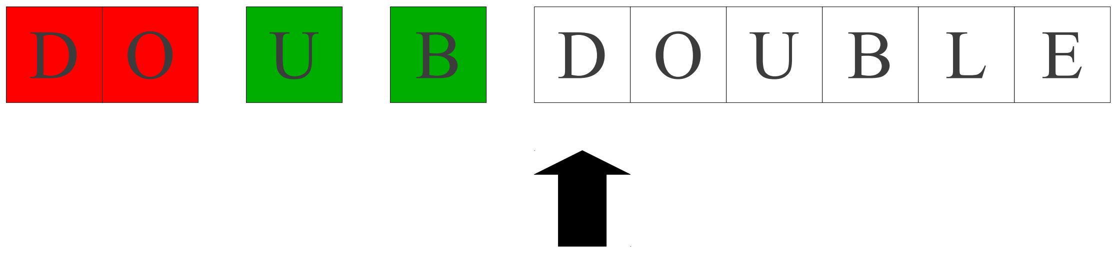
T_Do	do
T_Double	double
T_Mystery	[A-Za-z]



Implementing Maximal Munch

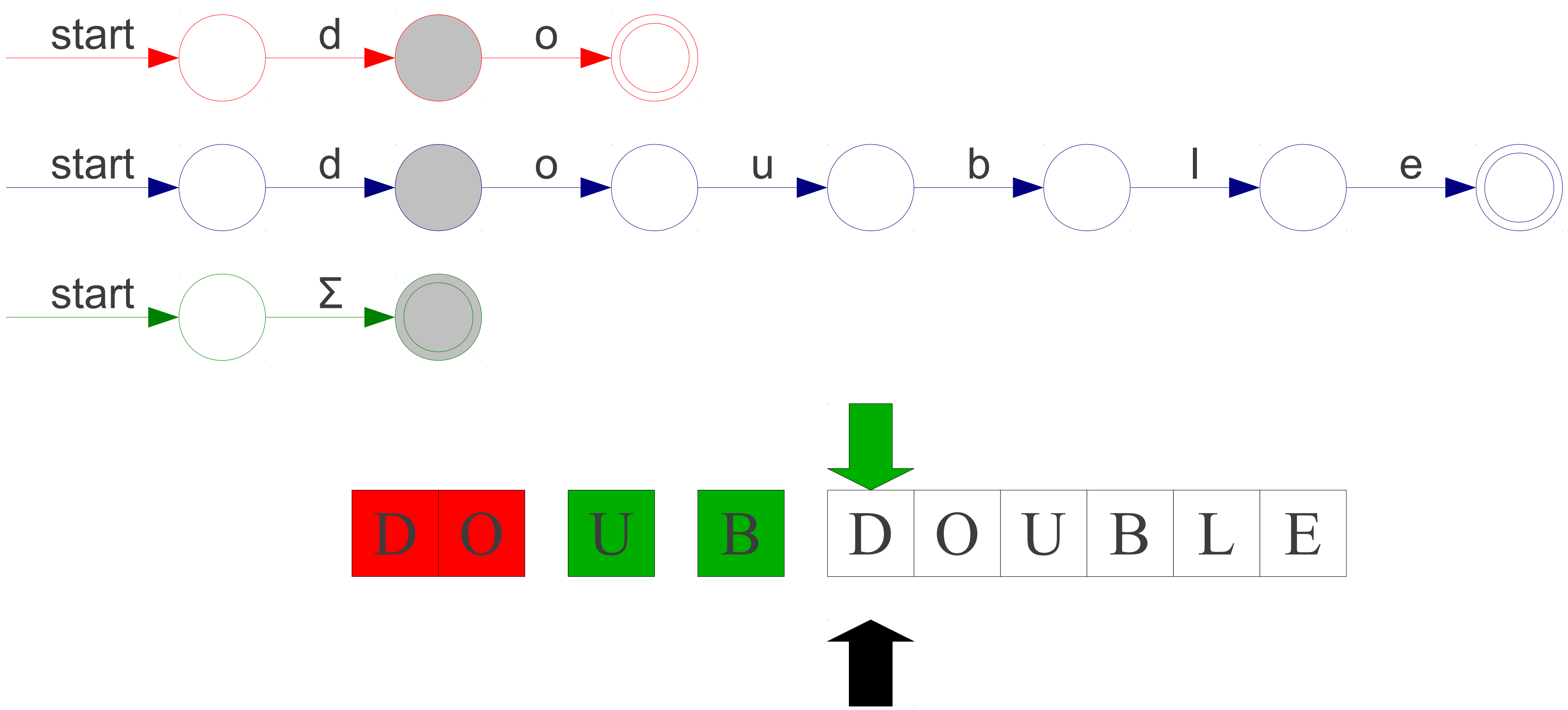
```
T_Do          do
T_Double      double
T_Mystery     [A-Za-z]
```





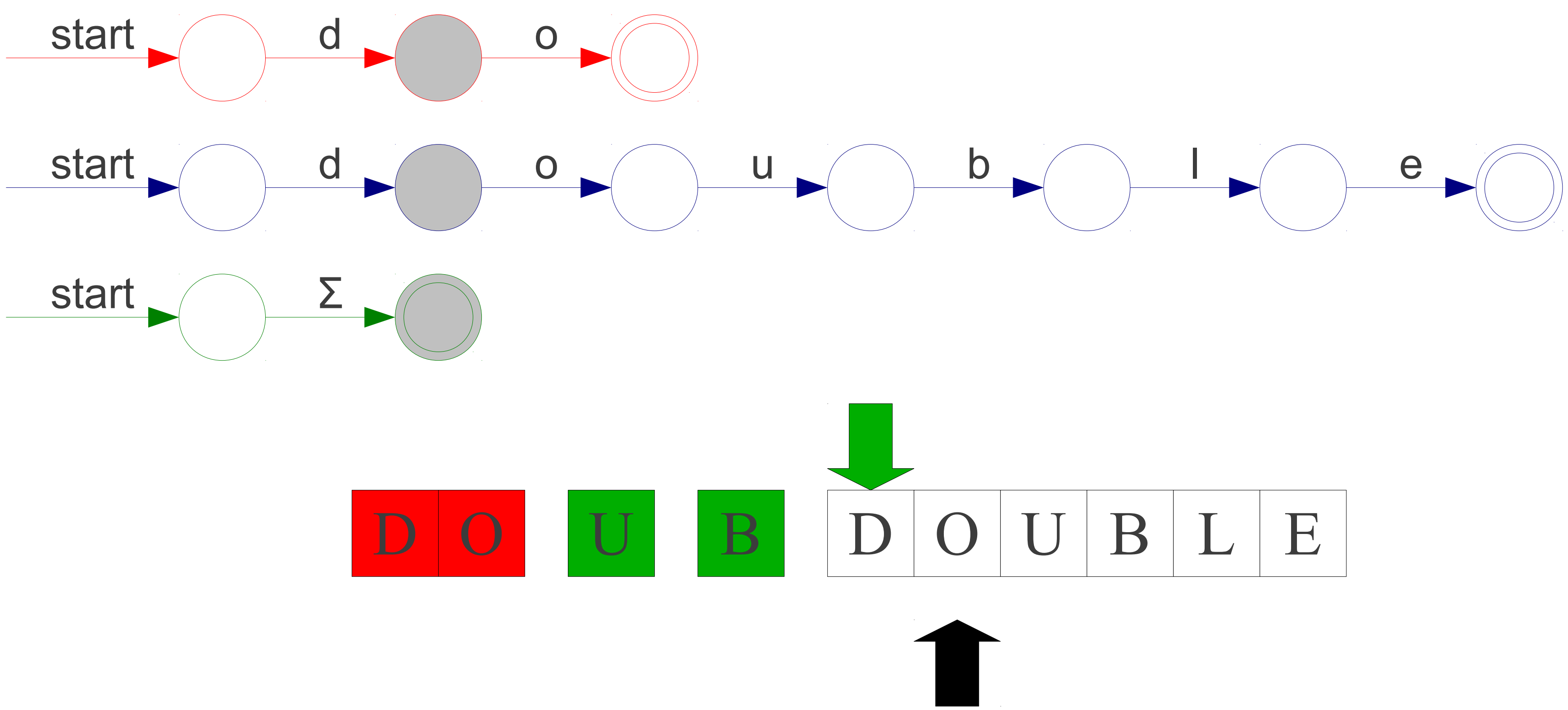
Implementing Maximal Munch

```
T_Do          do
T_Double      double
T_Mystery     [A-Za-z]
```



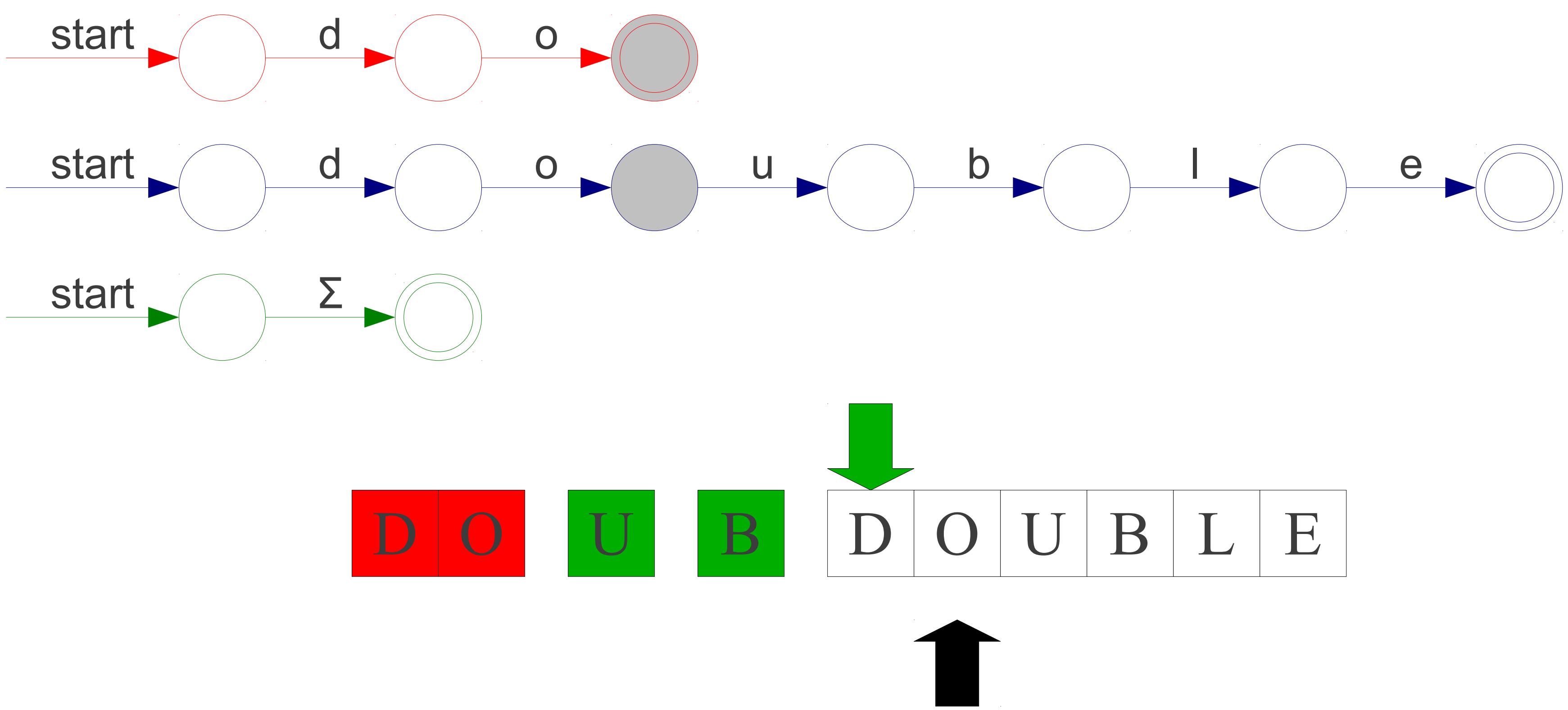
Implementing Maximal Munch

```
T_Do          do
T_Double      double
T_Mystery     [A-Za-z]
```



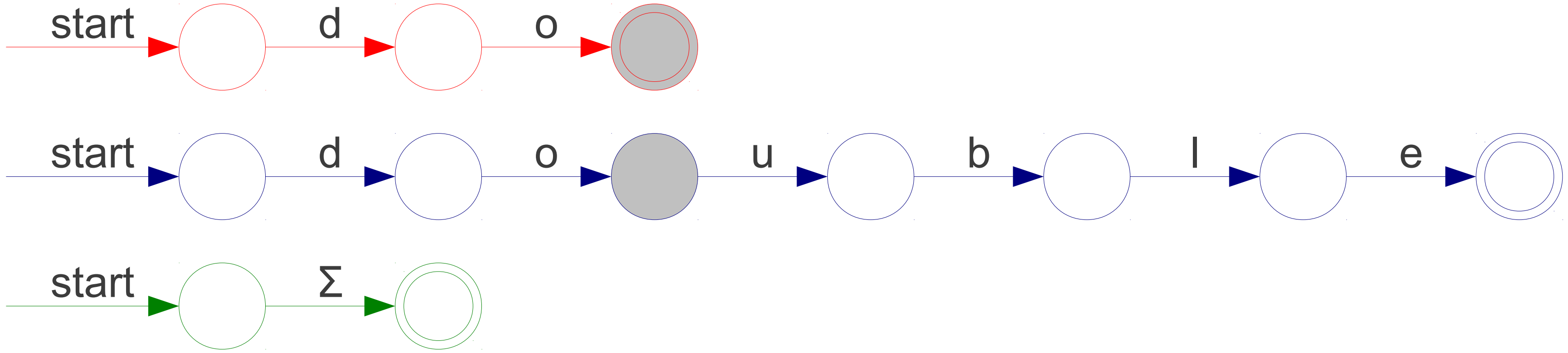
Implementing Maximal Munch

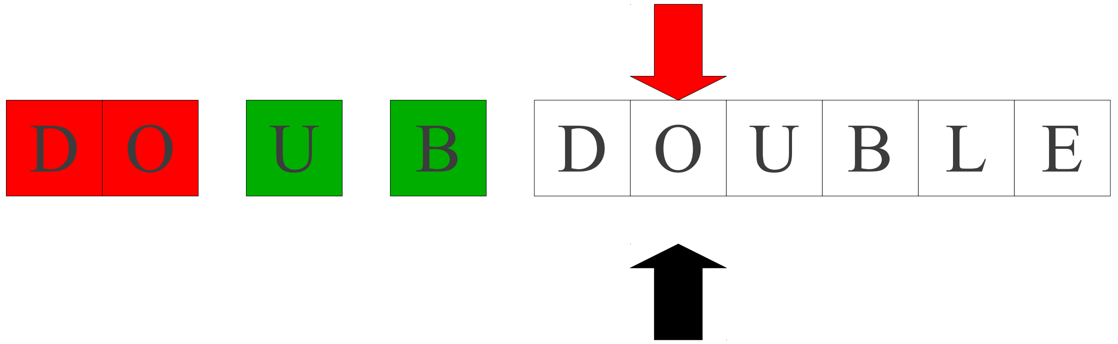
T_Do	do
T_Double	double
T_Mystery	[A-Za-z]



Implementing Maximal Munch

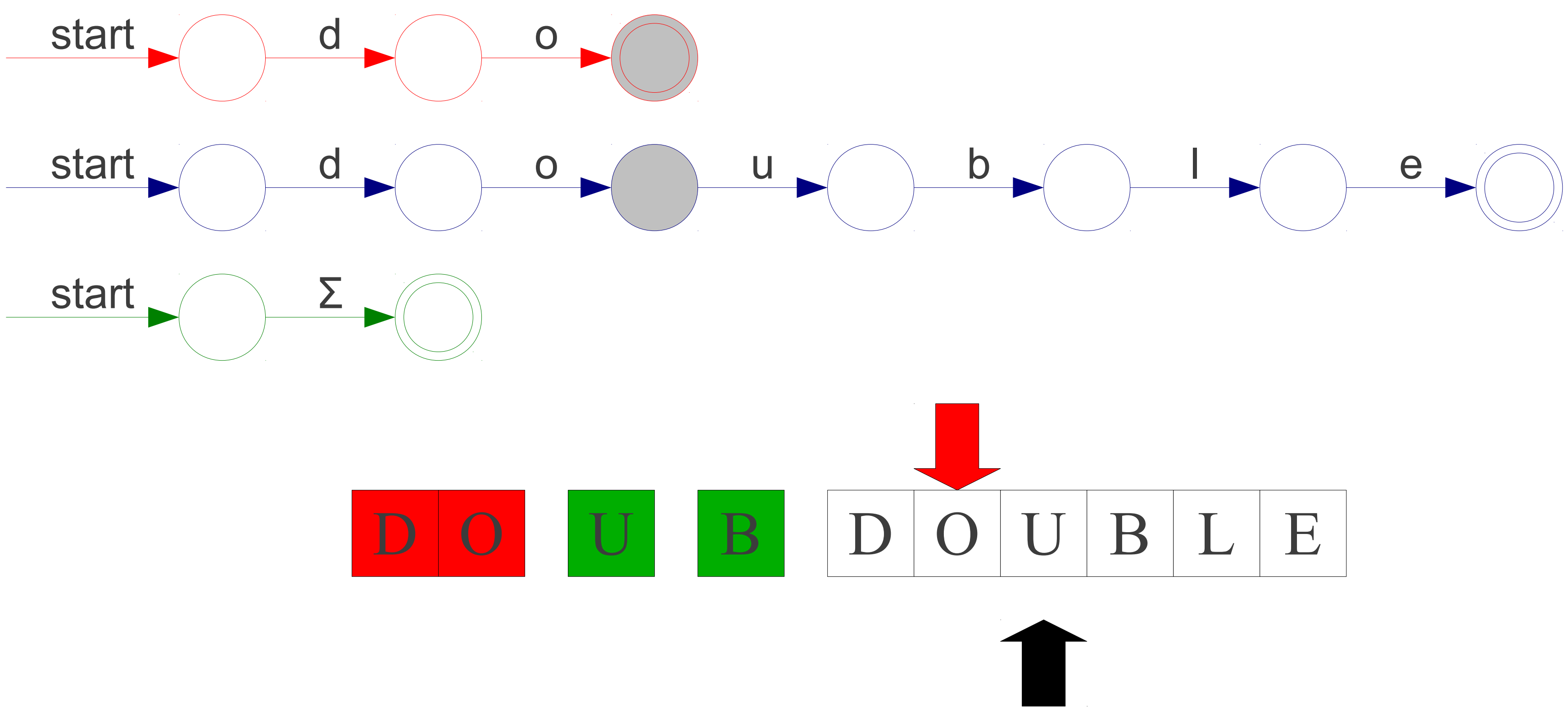
T_Do	do
T_Double	double
T_Mystery	[A-Za-z]





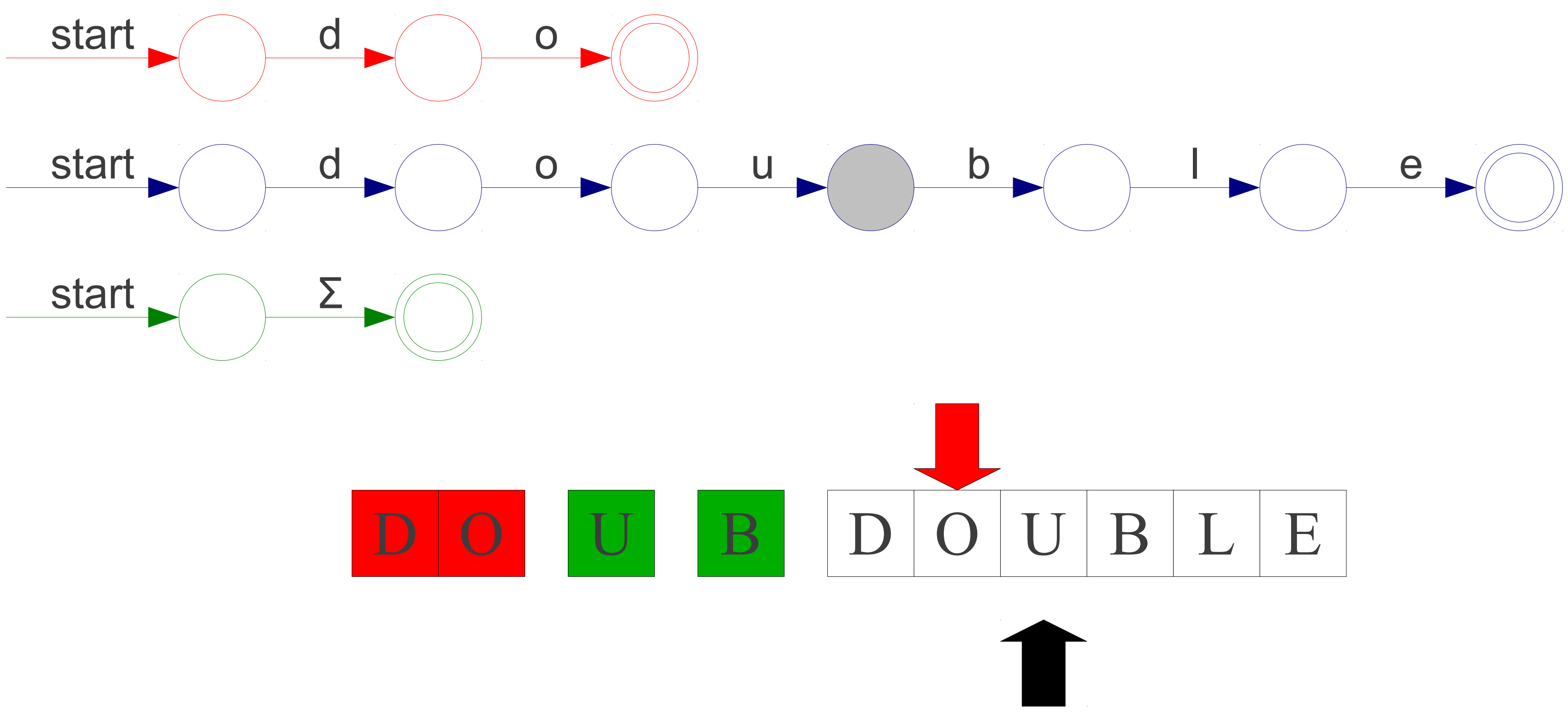
Implementing Maximal Munch

```
T_Do          do
T_Double      double
T_Mystery     [A-Za-z]
```



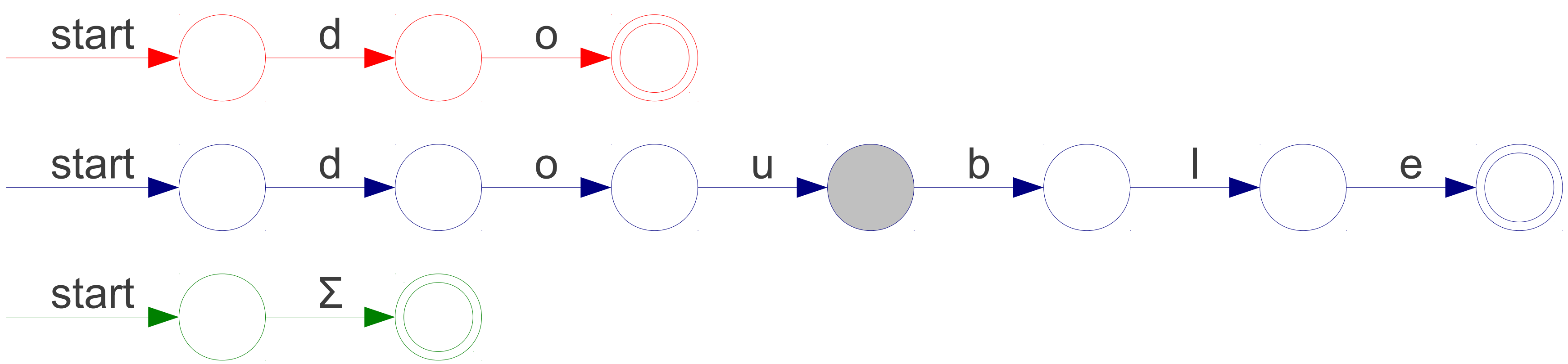
Implementing Maximal Munch

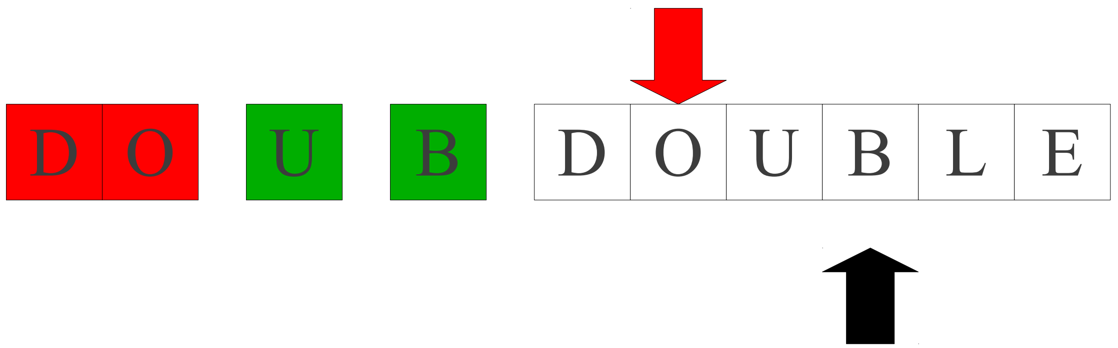
```
T_Do        do
T_Double    double
T_Mystery   [A-Za-z]
```



Implementing Maximal Munch

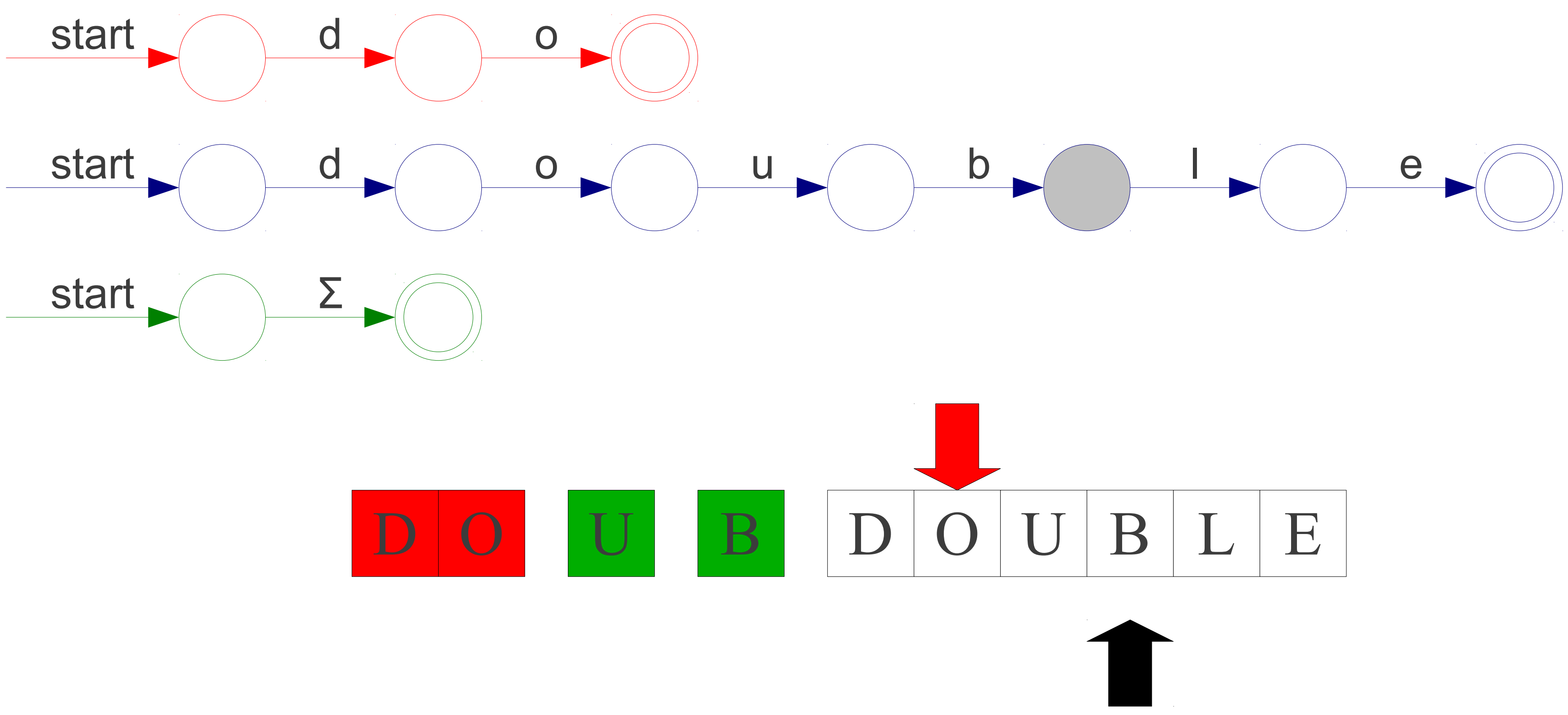
```
T_Do        do
T_Double    double
T_Mystery   [A-Za-z]
```





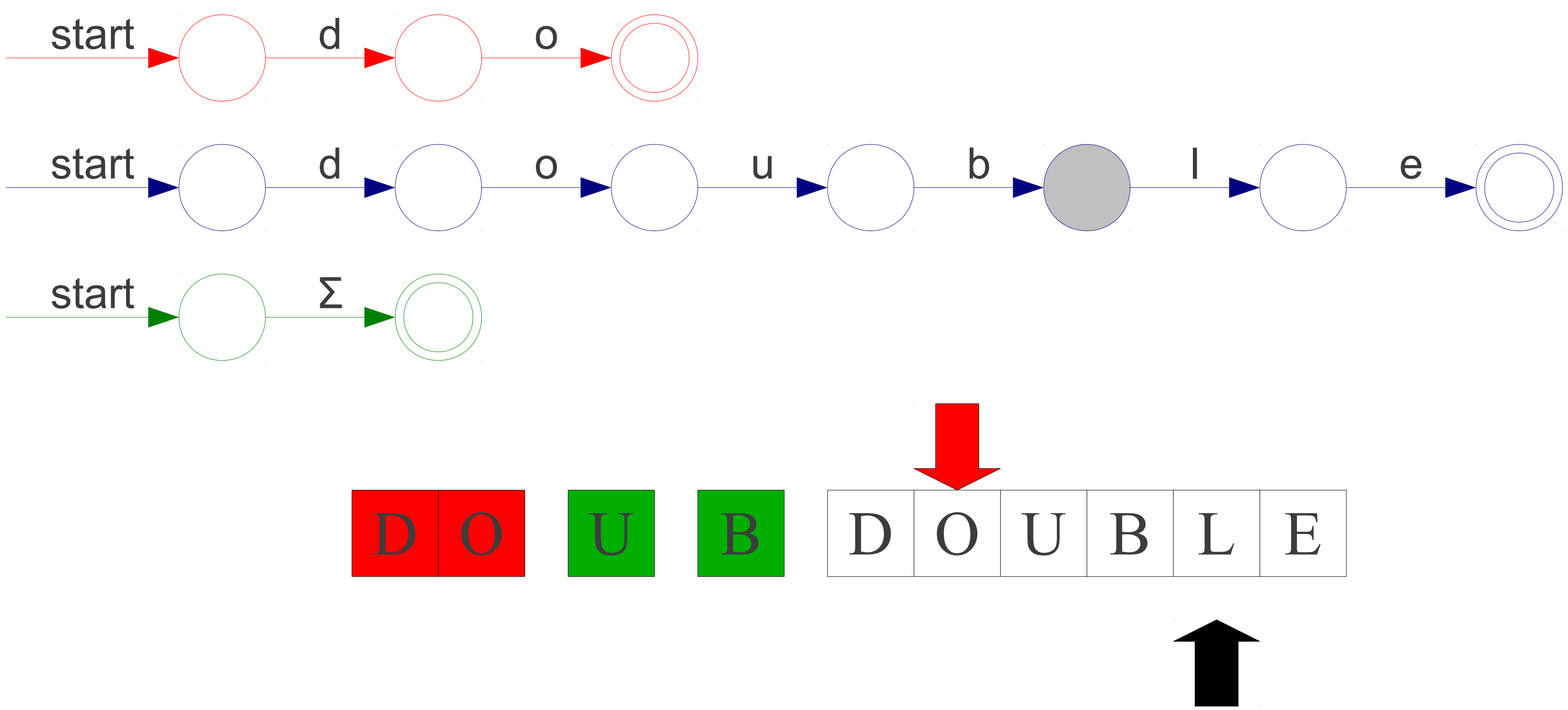
Implementing Maximal Munch

```
T_Do          do
T_Double      double
T_Mystery     [A-Za-z]
```



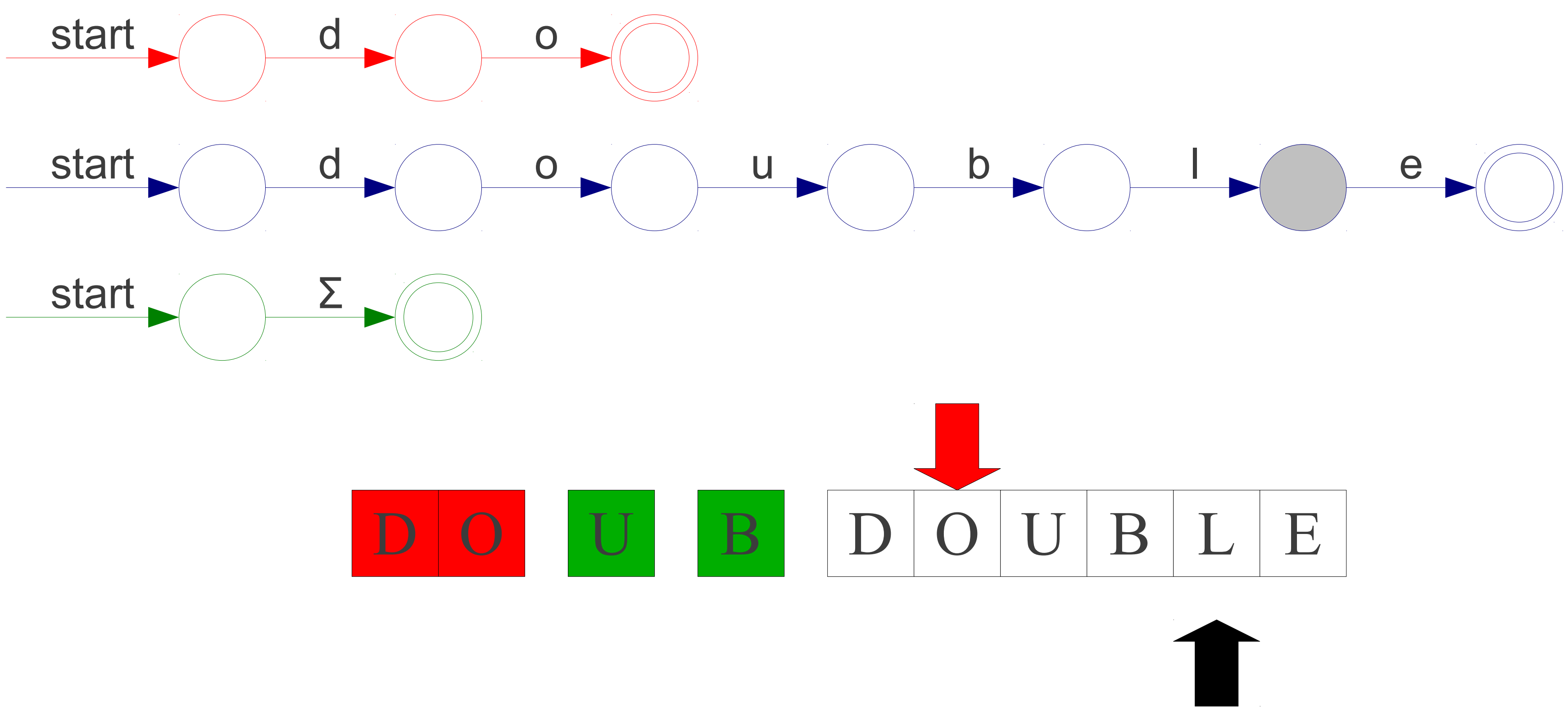
Implementing Maximal Munch

```
T_Do          do
T_Double      double
T_Mystery     [A-Za-z]
```



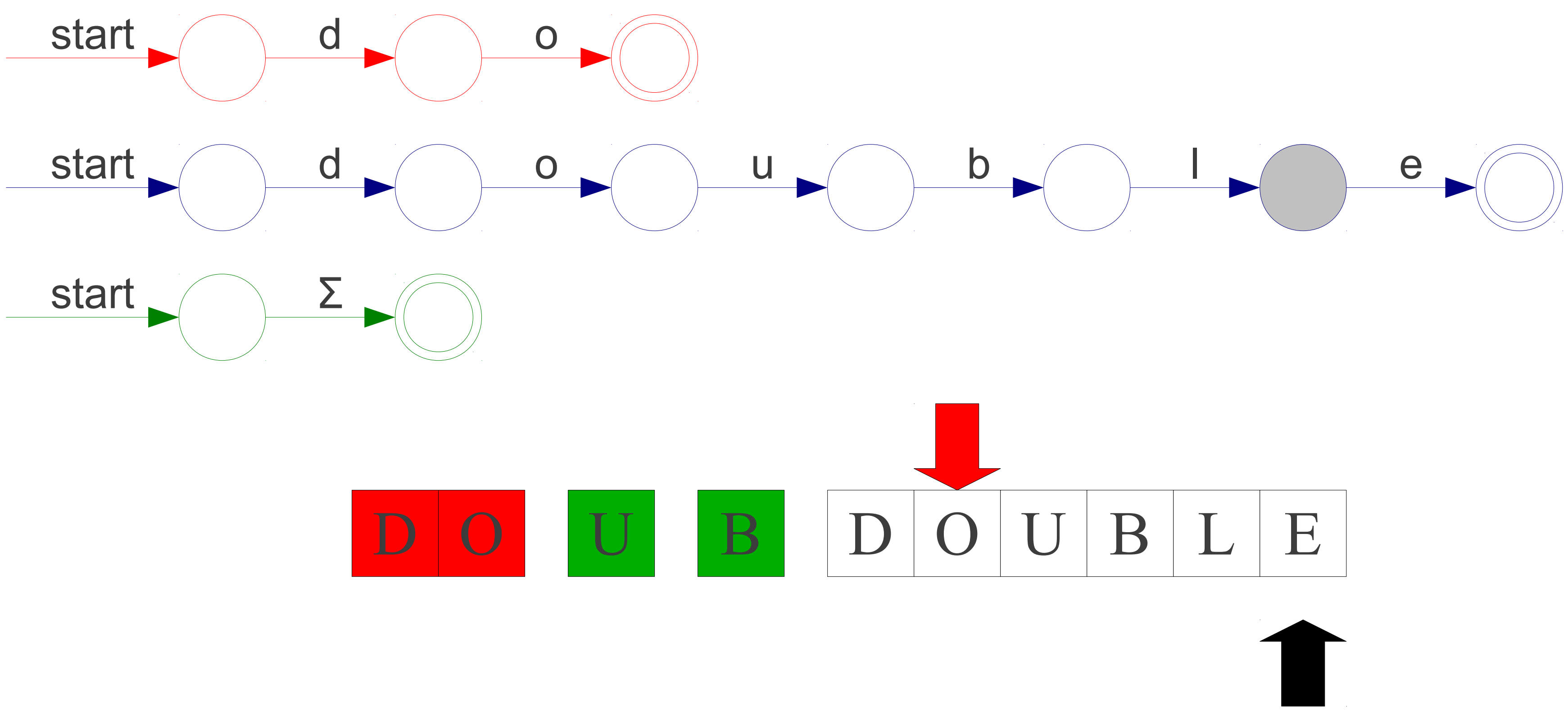
Implementing Maximal Munch

T_Do	do
T_Double	double
T_Mystery	[A-Za-z]



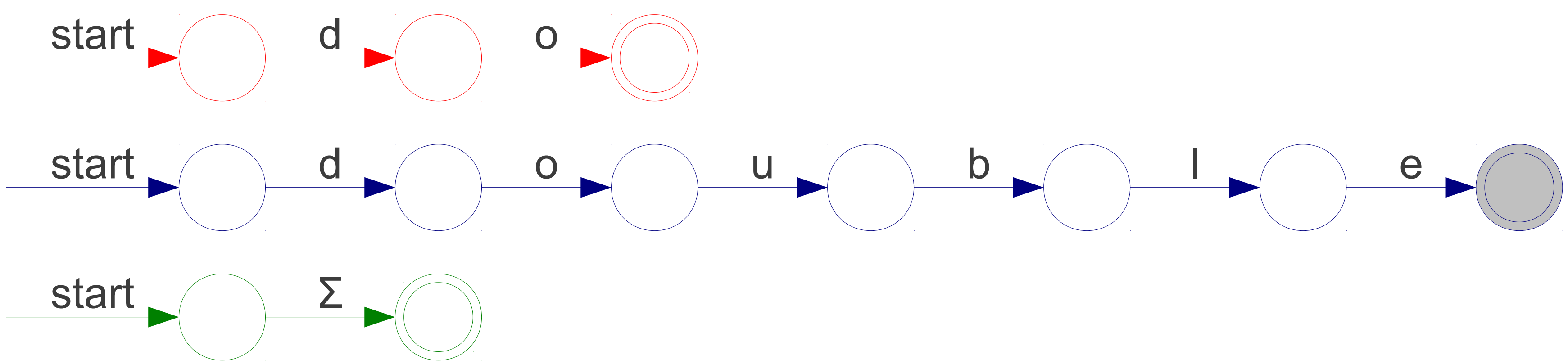
Implementing Maximal Munch

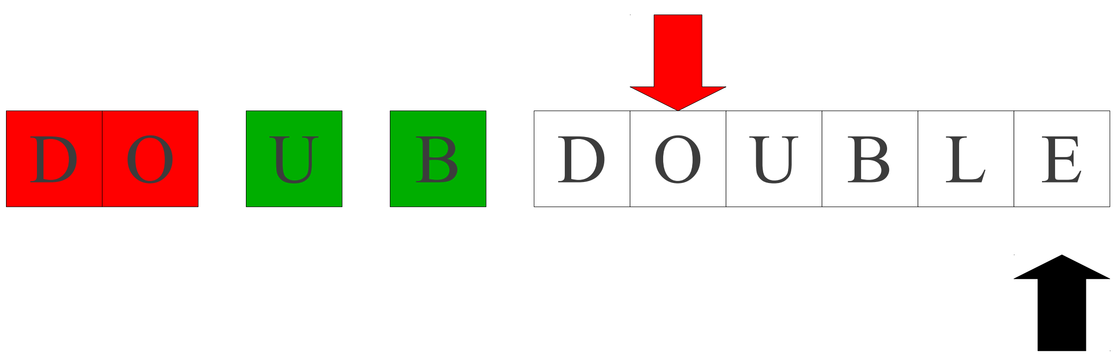
```
T_Do          do
T_Double      double
T_Mystery     [A-Za-z]
```



Implementing Maximal Munch

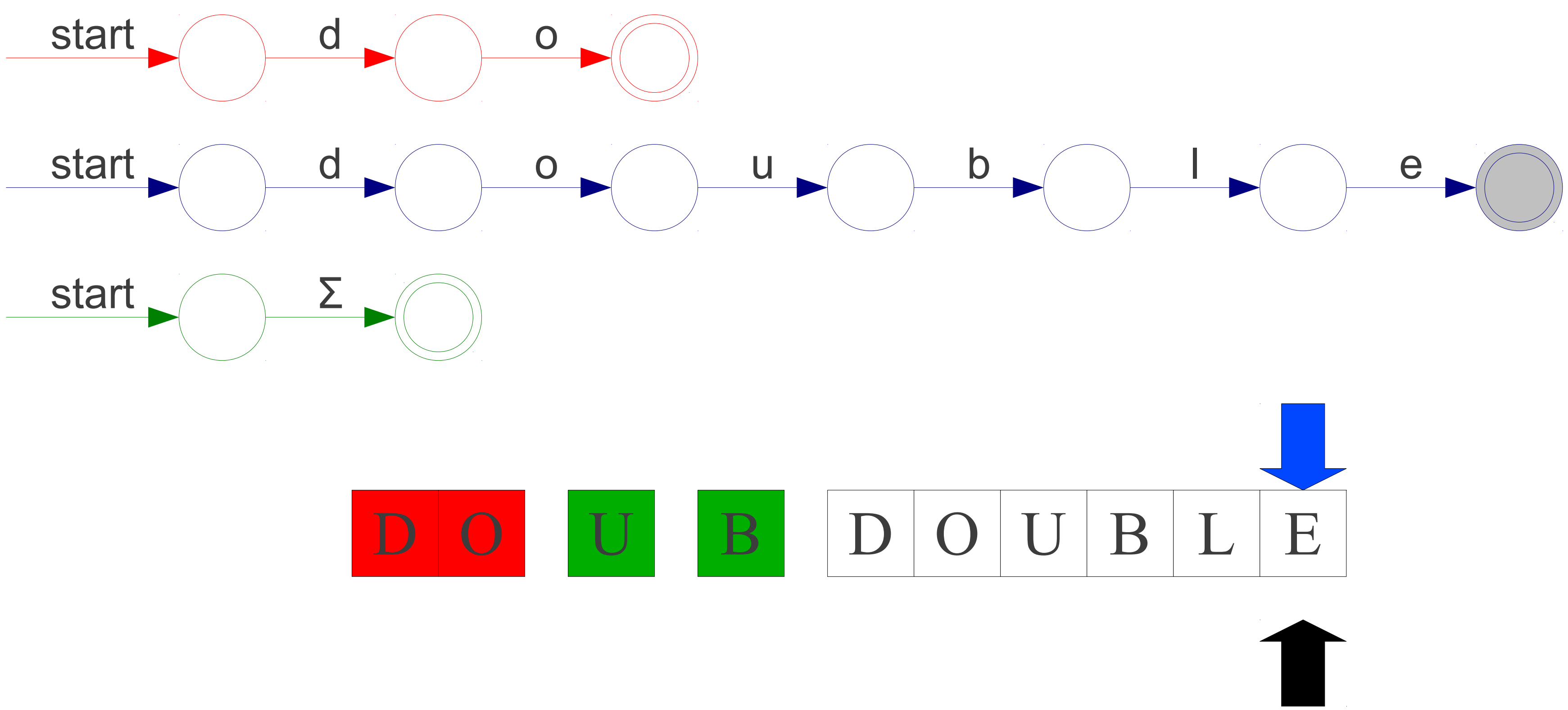
```
T_Do         do
T_Double     double
T_Mystery    [A-Za-z]
```





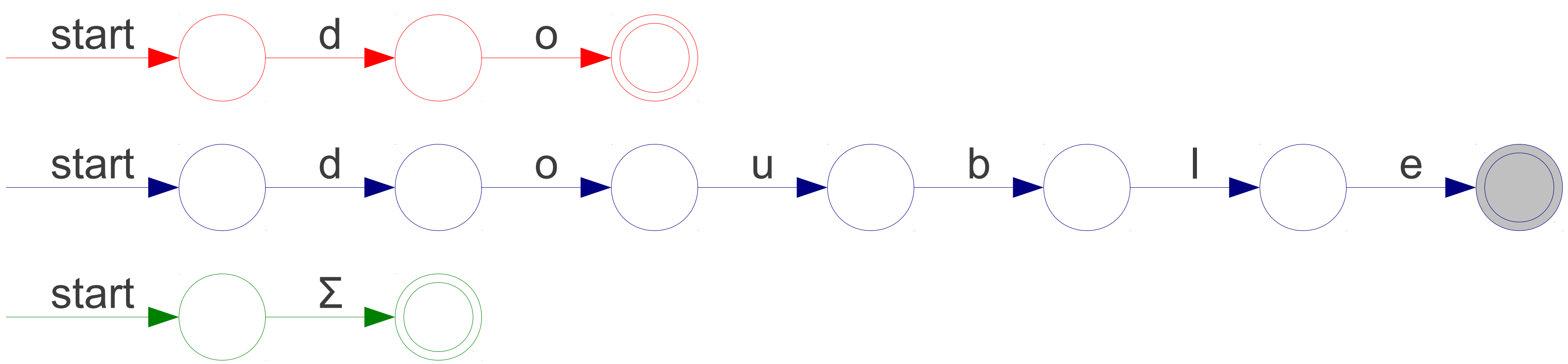
Implementing Maximal Munch

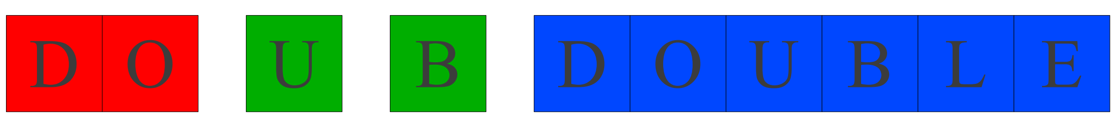
T_Do	do
T_Double	double
T_Mystery	[A-Za-z]



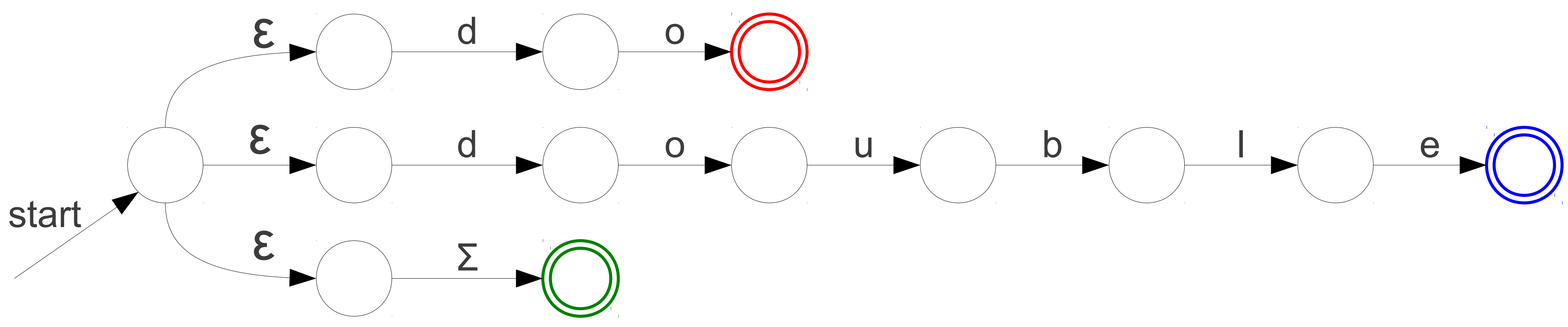
Implementing Maximal Munch

`T_Do`	`do`
`T_Double`	`double`
`T_Mystery`	`[A-Za-z]`





A Minor Simplification



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

d	o	u	b	l	e
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

d	o	u	b	l	e

Implement a lexical analyzer

- Step 1: Use regular expressions to describe token types (keyword, identifier, integer constant..)

  Number = digit + …
  Keyword = ‘if’ + ‘else’ + …
  Identifier = letter (letter + digit)*
  OpenPar = ‘(‘
  …

  Then construct Regular language R, matching all lexemes for all tokens

  R = Keyword + Identifier + Number + …
  = R1 + R2 + …

- Step 2: Use DFA/NFA to recognize the regular language

- But...good news. you don’t need to implement the algorithms to transform your regular expressions to DFA/NFA to recognize it

  - **flex**: given regular expressions -> output c code that does lexical analysis (it internally generates DFA)

Lexical analyzer

REs + priorities + longest matching token rule

= definition of a lexical analyzer

DFA vs. NFA

- NFAs and DFAs recognize the same set of languages (regular languages)
  - For a given NFA, there exists a DFA, and vice versa

- DFAs are faster to execute
  - There are no choices to consider
  - Tradeoff: simplicity
    - For a given language DFA can be exponentially larger than NFA.

Automating Lexical Analyzer (scanner) Construction

To convert a specification into code:

1 Write down the RE for the input language

2 Build a big NFA

3 Build the DFA that simulates the NFA

4 Systematically shrink the DFA

5 Turn it into code

Scanner generators

- Lex and Flex work along these lines
- Algorithms are well-known and well-understood

Automating Lexical Analyzer (scanner) Construction

RE→ NFA *(Thompson's construction)*

- Build an NFA for each term
- Combine them with ε-moves

NFA → DFA *(subset construction)*

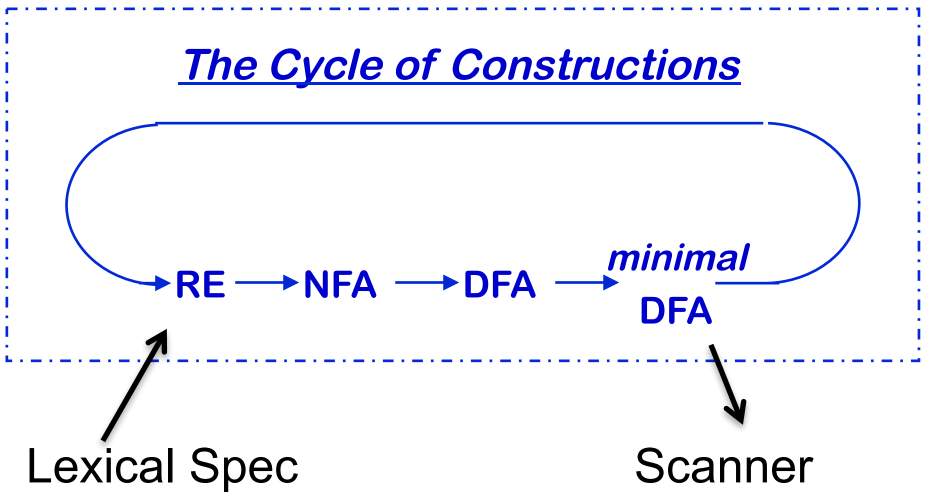
- Build the simulation

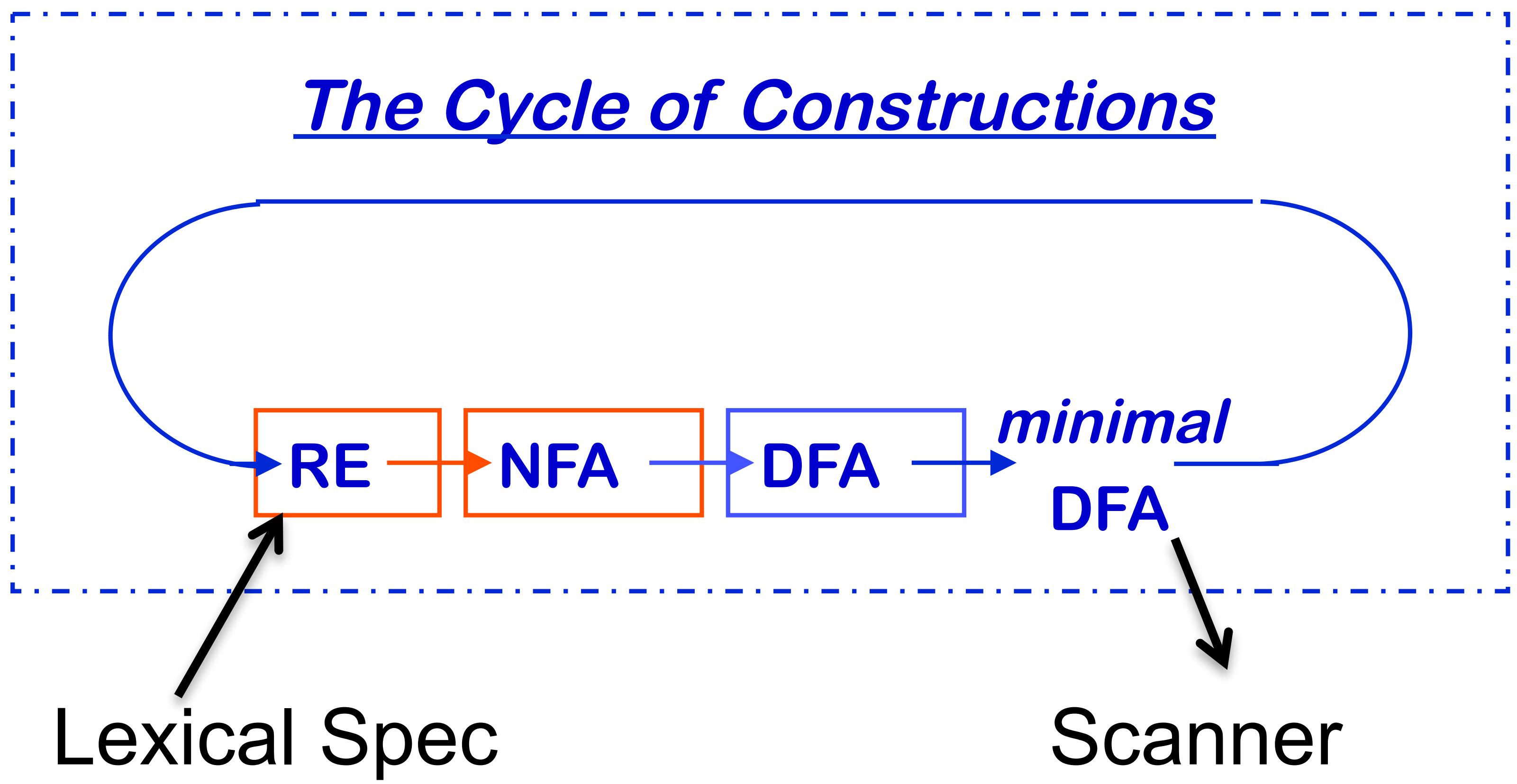
DFA → Minimal DFA

- Hopcroft's algorithm

DFA →RE *(Not part of the scanner construction)*

- All pairs, all paths problem
- Take the union of all paths from s_0 to an accepting state

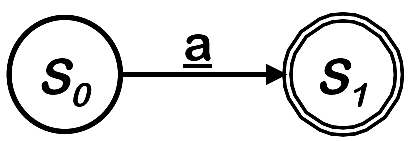



The Cycle of Constructions
RE
NFA
DFA
minimal
DFA
Lexical Spec
Scanner

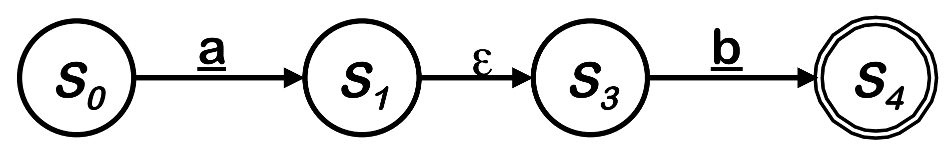
RE →NFA using Thompson's Construction

Key idea

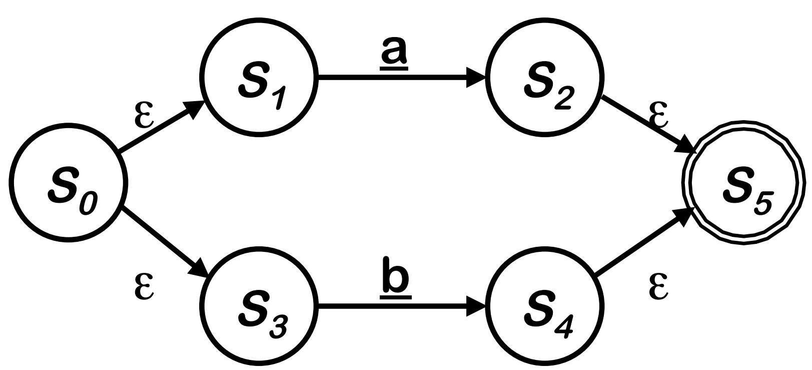
- NFA pattern for each symbol & each operator
- Join them with ε moves in precedence order



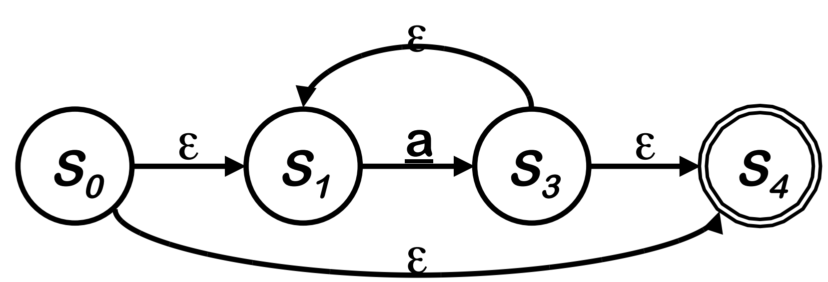
NFA for a



NFA for ab



NFA for a | b



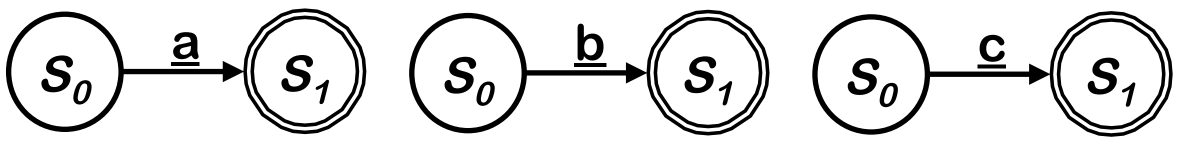
NFA for a^*

Ken Thompson, CACM, 1968

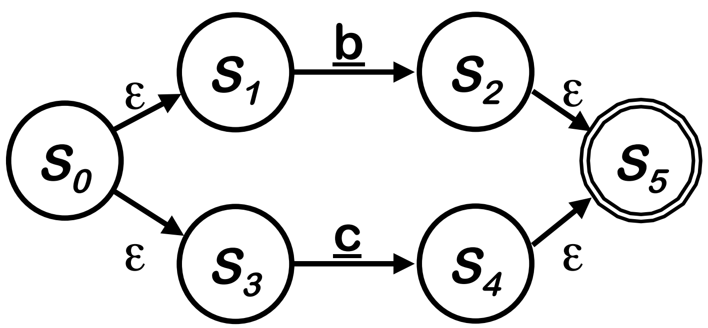
Example of Thompson's Construction

Let's try <u>a</u> (<u>b</u> | <u>c</u>)*

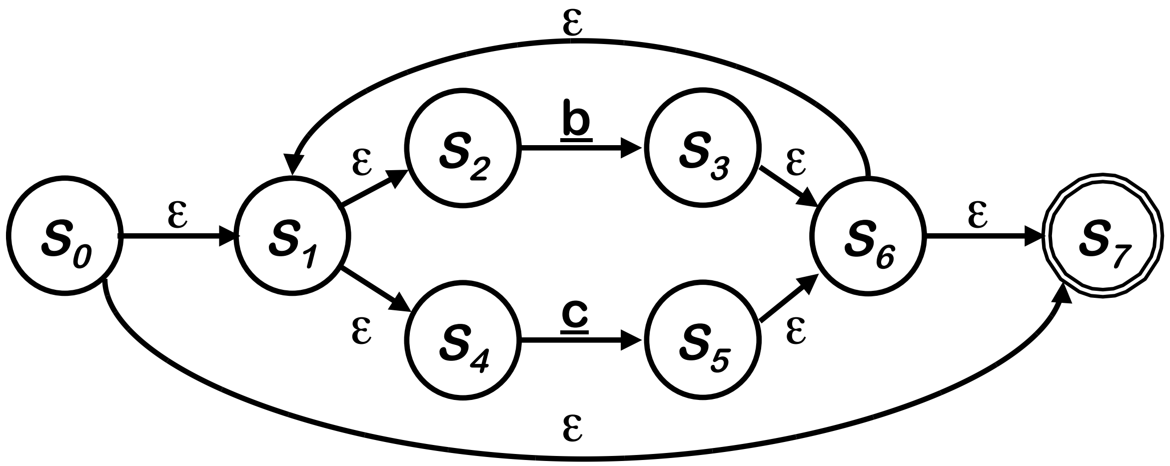
1. <u>a</u>, <u>b</u>, & <u>c</u>



2. <u>b</u> | <u>c</u>

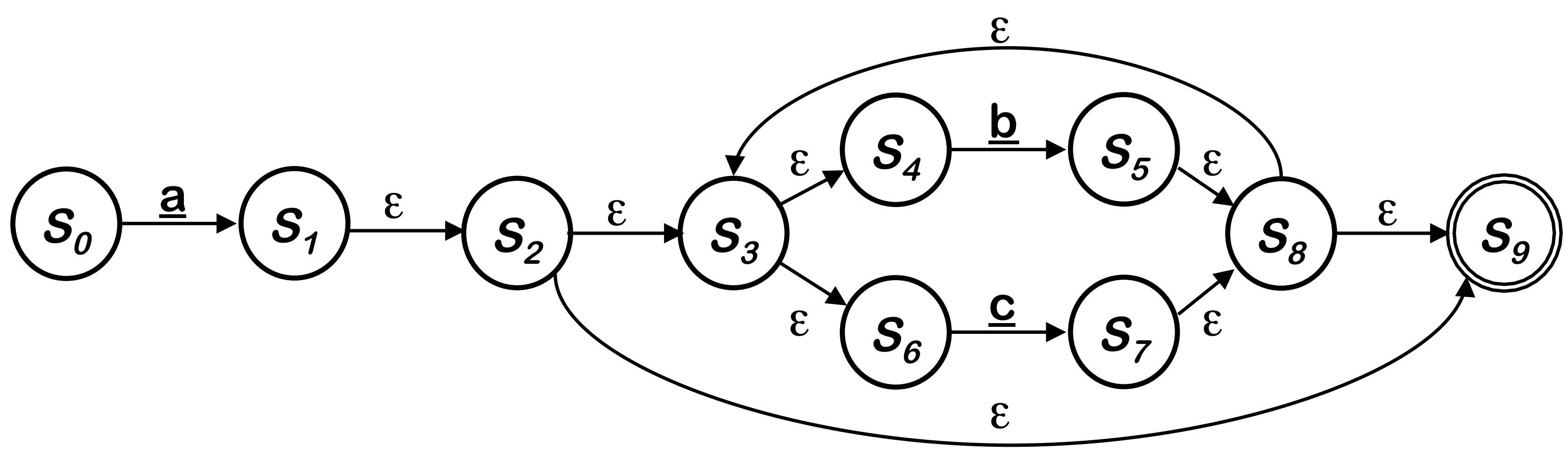


3. (<u>b</u> | <u>c</u>)*

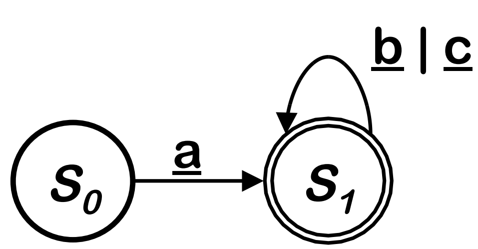


Example of Thompson's Construction *(con't)*

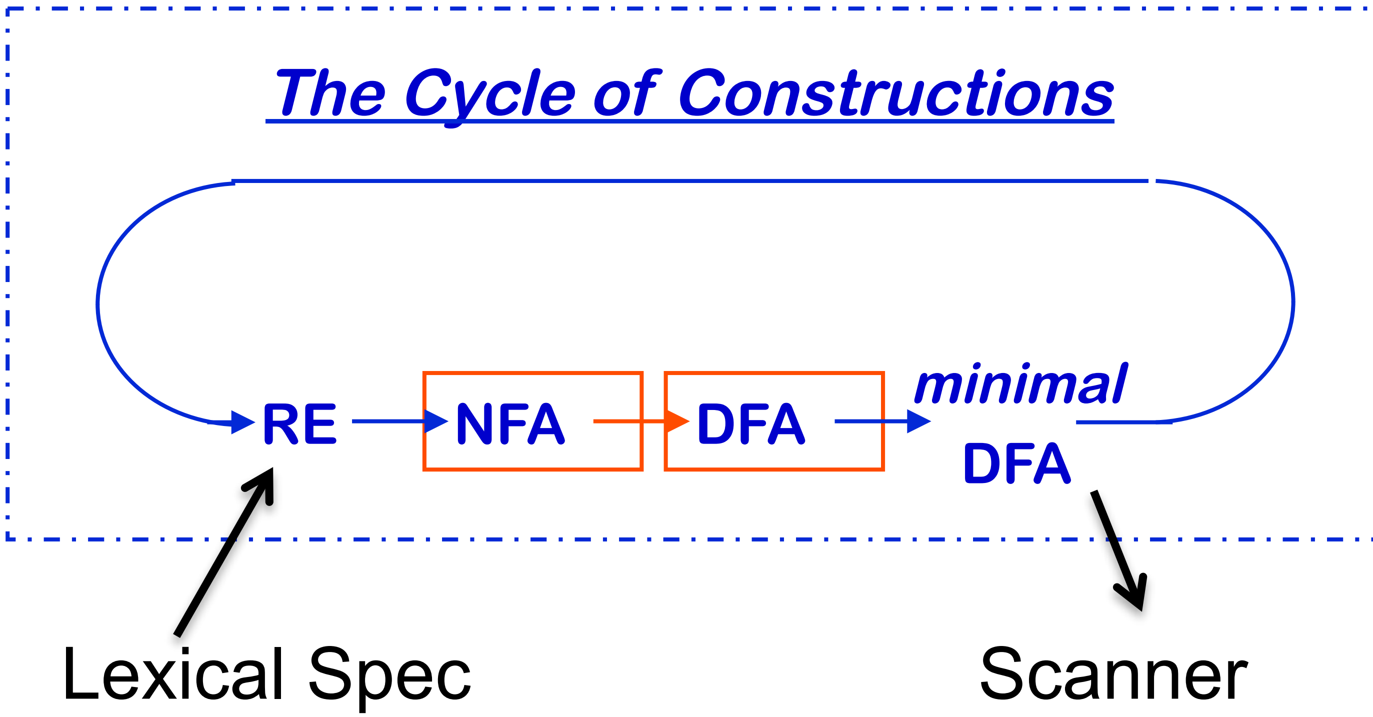
4. a (b | c)*



Of course, a human would design something simpler ...



But, we can automate production of the more complex one ...



The Cycle of Constructions
RE
NFA
DFA
minimal
DFA
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Scanner

NFA to DFA : Trick

- Simulate the NFA
- Each state of DFA

  = a non-empty subset of states of the NFA
- Start state

  = the set of NFA states reachable through e-moves from NFA start state
- Add a transition $S \rightarrow^{a} S'$ to DFA iff
  - S' is the set of NFA states reachable from any state in S after seeing the input a, considering ε-moves as well

NFA to DFA : cont..

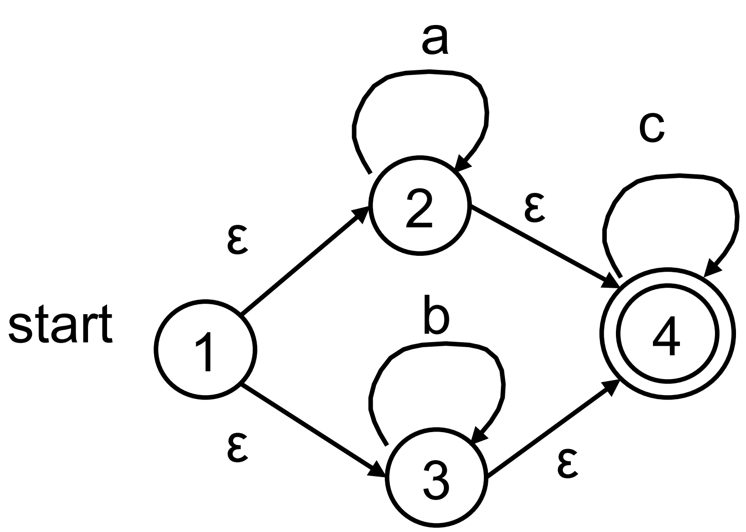
- An NFA may be in many states at any time
- How many different states ?
- If there are N states, the NFA must be in some subset of those N states
- How many subsets are there?

  $2^N - 1$ = finitely many

NFA to DFA

- Remove the non-determinism
  - States with multiple outgoing edges due to same input
  - ε transitions

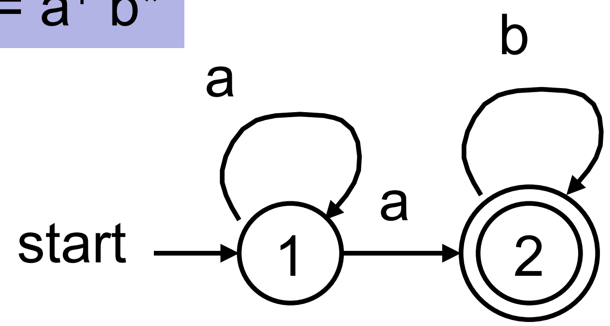
(a*| b*) c*



NFA to DFA (2)

- Multiple transitions
  - Solve by subset construction
  - Build new DFA based upon the set of states each representing a unique subset of states in NFA

$R = a^{+} b^{*}$

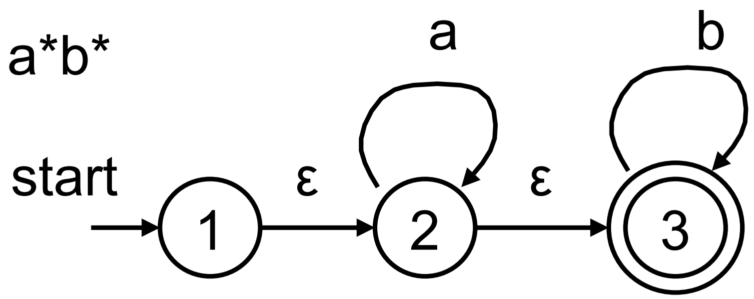


ε-closure(1) = {1} include state “1”
(1,a) → {1,2} include state “1/2”
(1,b) → ERROR

NFA to DFA (3)

- ε transitions
  - Any state reachable by an ε transition is “part of the state”
  - ε-closure - Any state reachable from S by ε transitions is in the ε-closure; treat ε-closure as 1 big state, always include ε-closure as part of the state

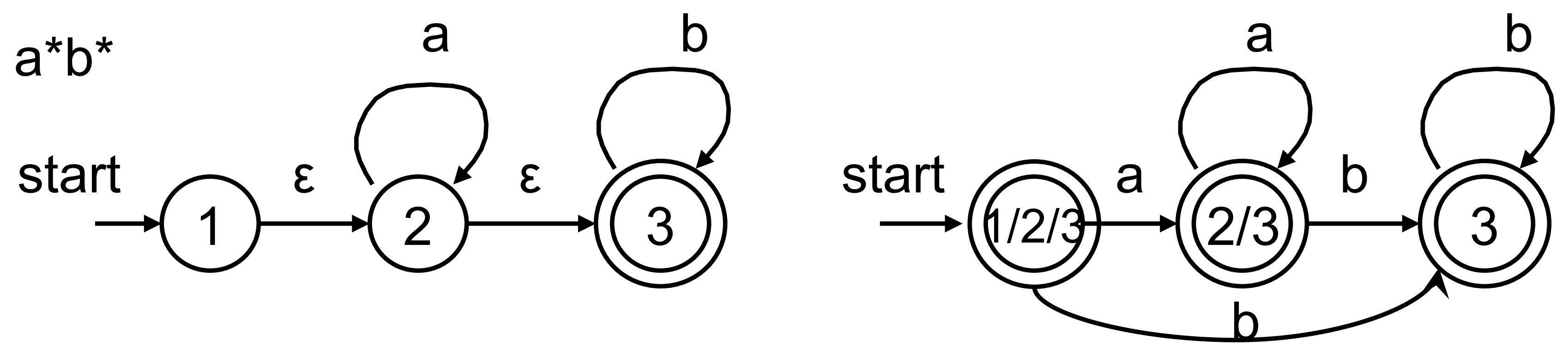
a*b*



1. ε-closure(1) = {1,2,3}; include1/2/3
2. Move(1/2/3, a) = {2, 3} + ε-closure(2,3) = {2,3} ; include 2/3
3. Move(1/2/3, b) = {3} + ε-closure(3) = {3} ; include state 3
4. Move(2/3, a) = {2} + ε-closure(2) = {2,3}
5. Move(2/3, b) = {3} + ε-closure(3) = {3}
6. Move(3, b) = {3} + ε-closure(3) = {3}

NFA to DFA (3)

- ε transitions
  - Any state reachable by an ε transition is “part of the state”
  - ε-closure - Any state reachable from S by ε transitions is in the ε-closure; treat ε-closure as 1 big state, always include ε-closure as part of the state



1. ε-closure(1) = {1,2,3}; include1/2/3
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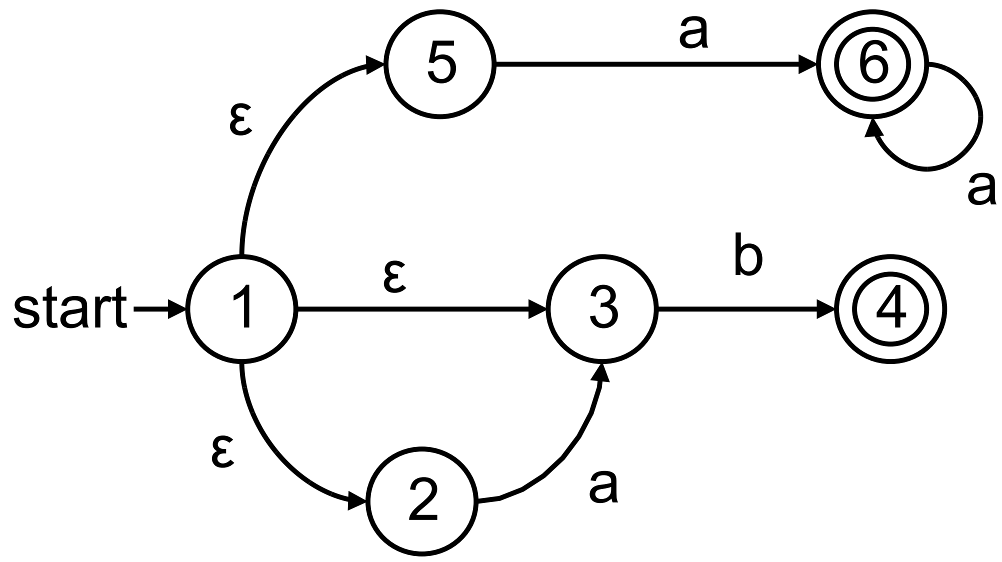
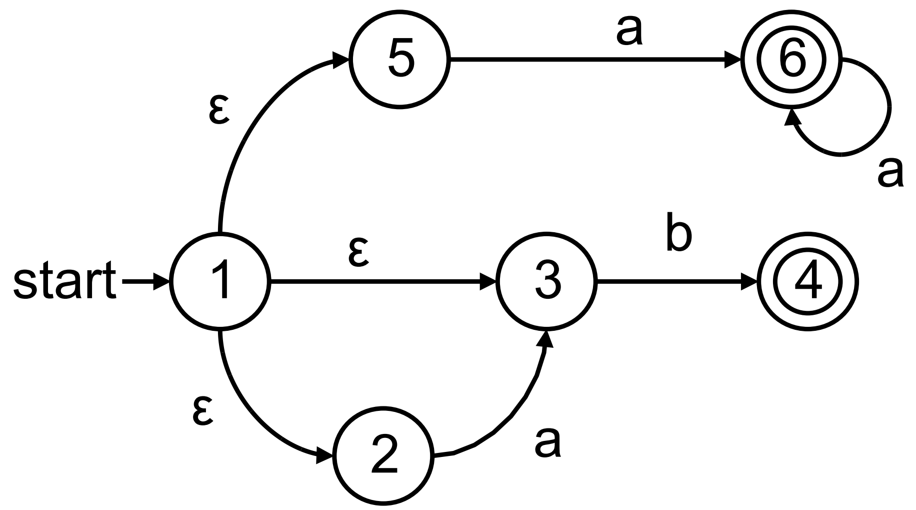
5. Move(2/3, b) = {3} + ε-closure(3) = {3}
6. Move(3, b) = {3} + ε-closure(3) = {3}

NFA to DFA - Example



NFA to DFA - Example



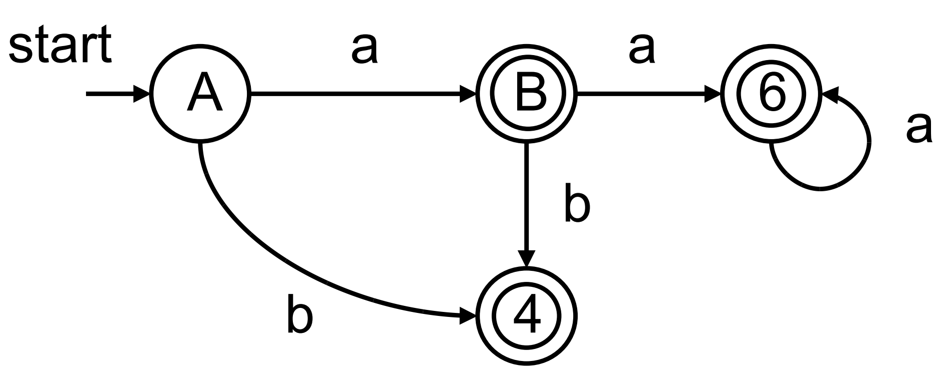
ε-closure(1) = {1, 2, 3, 5}

Create a new state A = {1, 2, 3, 5}

move(A, a) = {3, 6} + ε-closure(3,6) = {3,6}

Create B = {3,6}

move(A, b) = {4} + ε-closure(4) = {4}



move(B, a) = {6} + ε-closure(6) = {6}

move(B, b) = {4} + ε-closure(4) = {4}

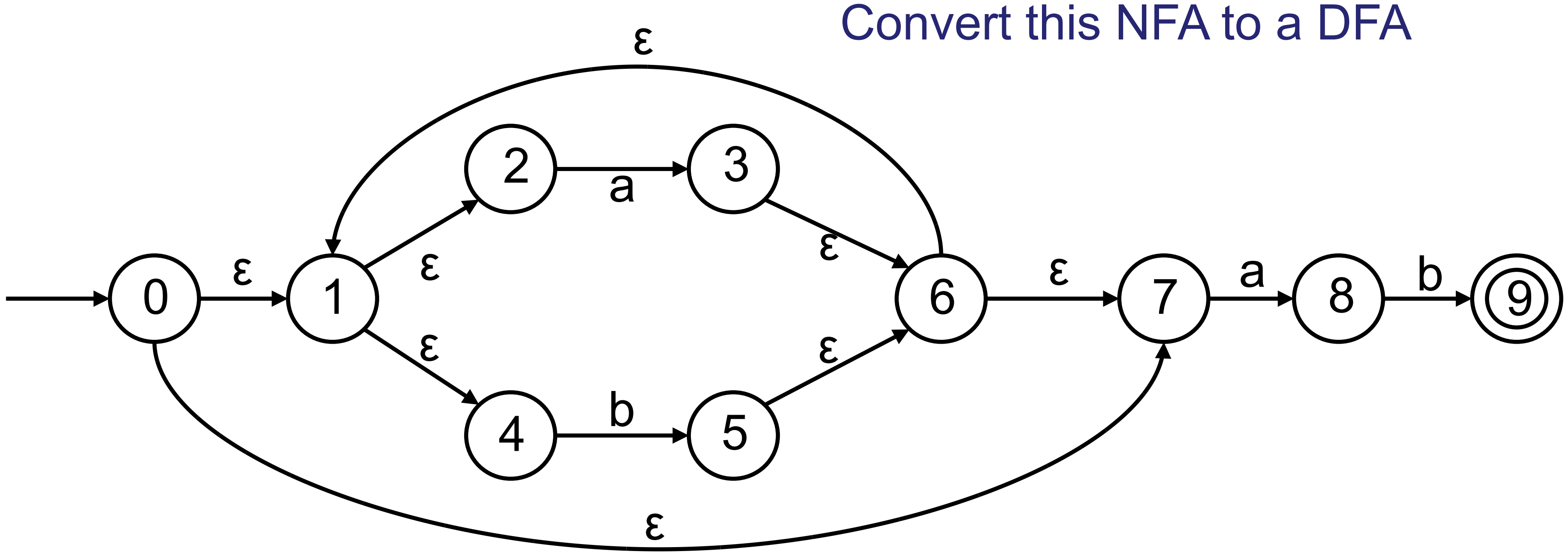
move(6, a) = {6} + ε-closure(6) = {6}

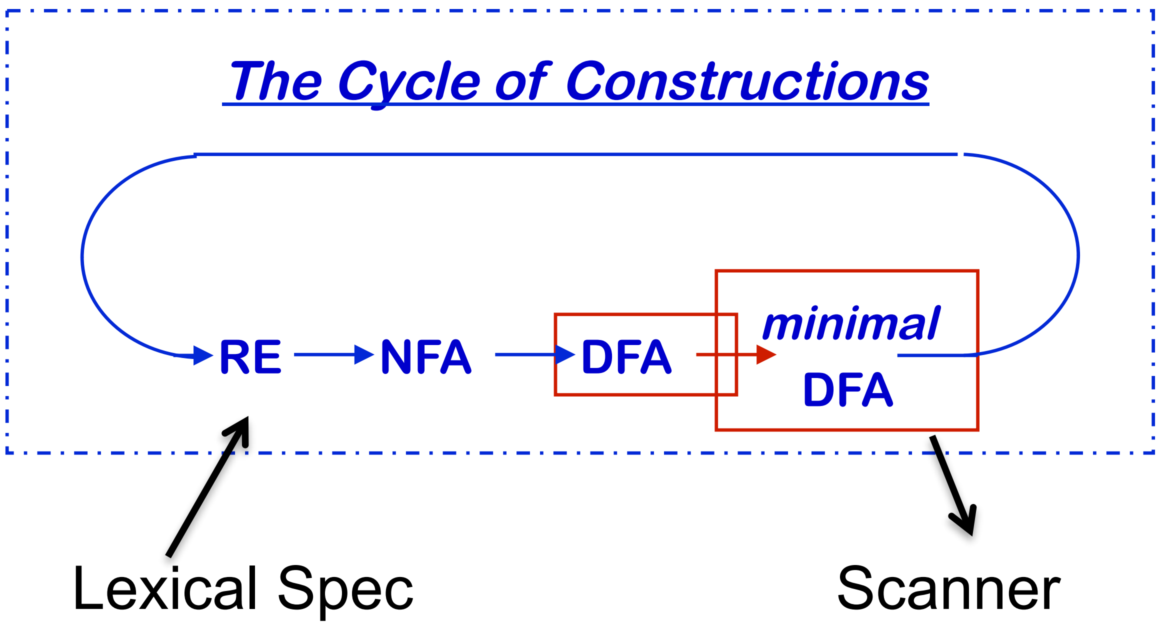
move(6, b) → ERROR

move(4, a|b) → ERROR

Class Problem

Convert this NFA to a DFA

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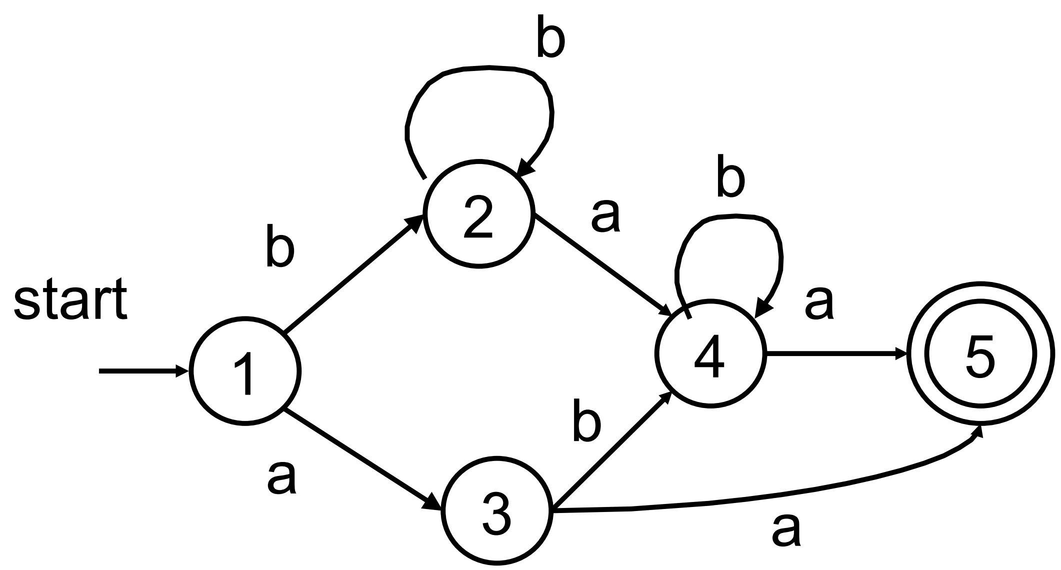
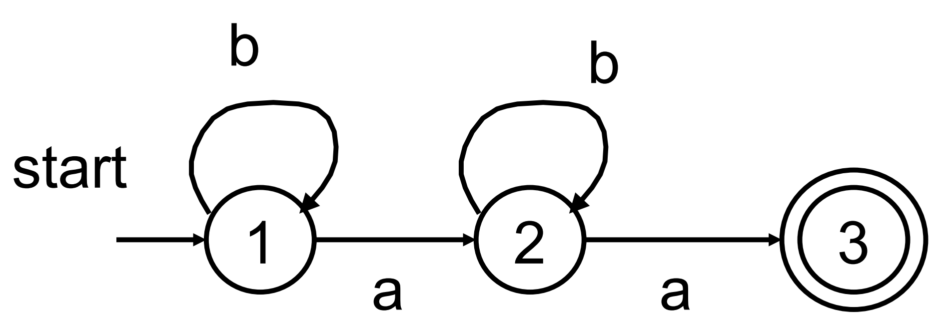
State Minimization

- Resulting DFA can be quite large
  - Contains redundant or equivalent states

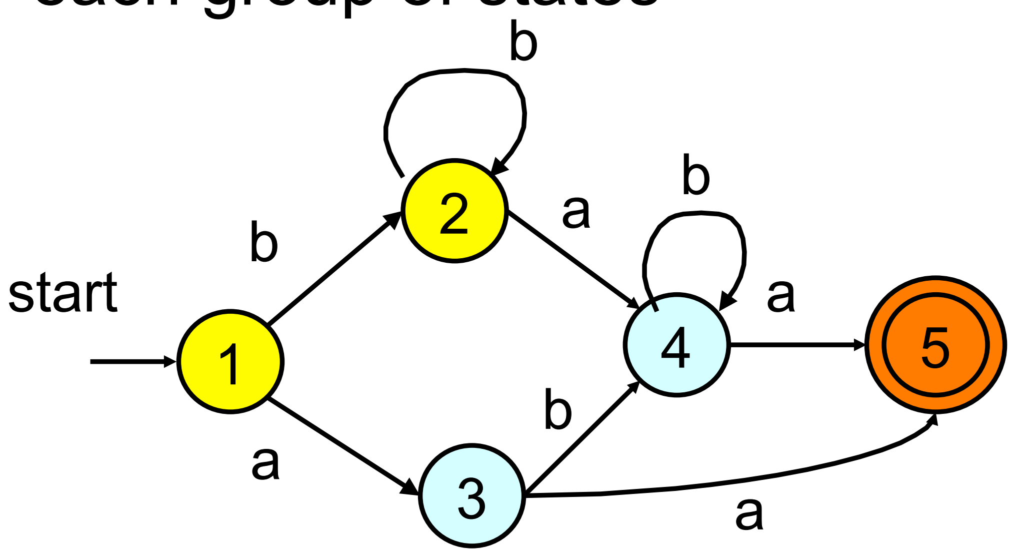




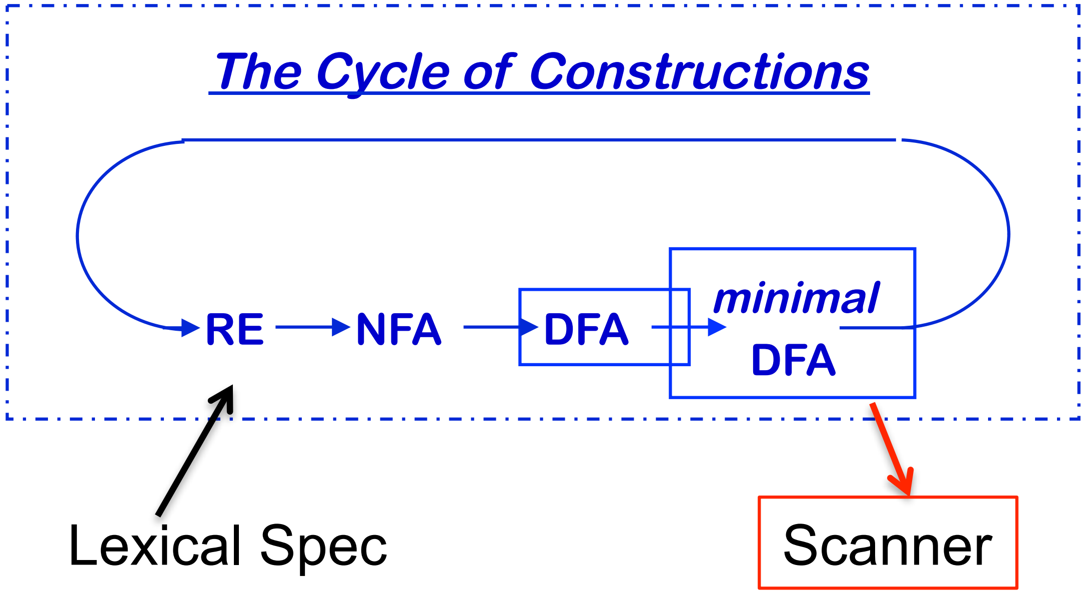
Both DFAs accept
b*ab*a

State Minimization (2)

- Idea – find groups of equivalent states and merge them
  - All transitions from states in group G1 go to states in another group G2
  - Construct minimized DFA such that there is 1 state for each group of states



Basic strategy: identify distinguishing transitions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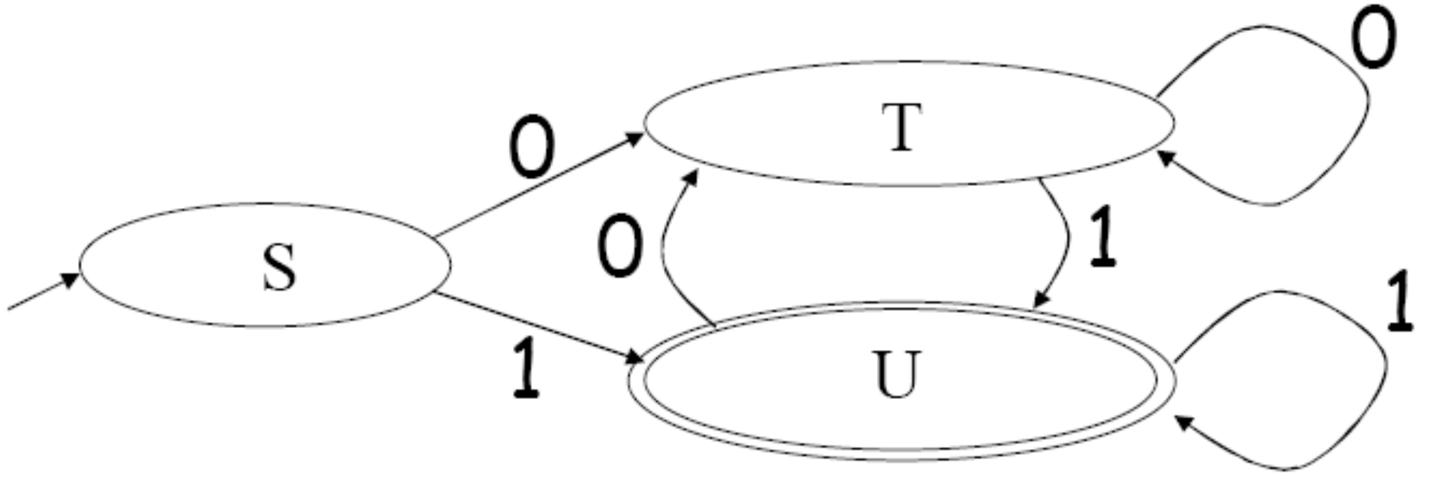
DFA Implementation

- A DFA can be implemented by a 2D table T
  - One dimension is “states”
  - Other dimension is “input symbol”
  - For every transition Si $\rightarrow^{a}$ Sk define T[i,a] = k
- DFA “execution”
  - If in state Si and input a, read T[i,a] = k and skip to state Sk
  - Very efficient

DFA Table Implementation : Example



	0	1
S	T	U
T	T	U
U	T	U

Implementation Cont ..

- NFA -> DFA conversion is at the heart of tools such as flex

- But, DFAs can be huge

- In practice, flex-like tools trade off speed for space in the choice of NFA and DFA representations