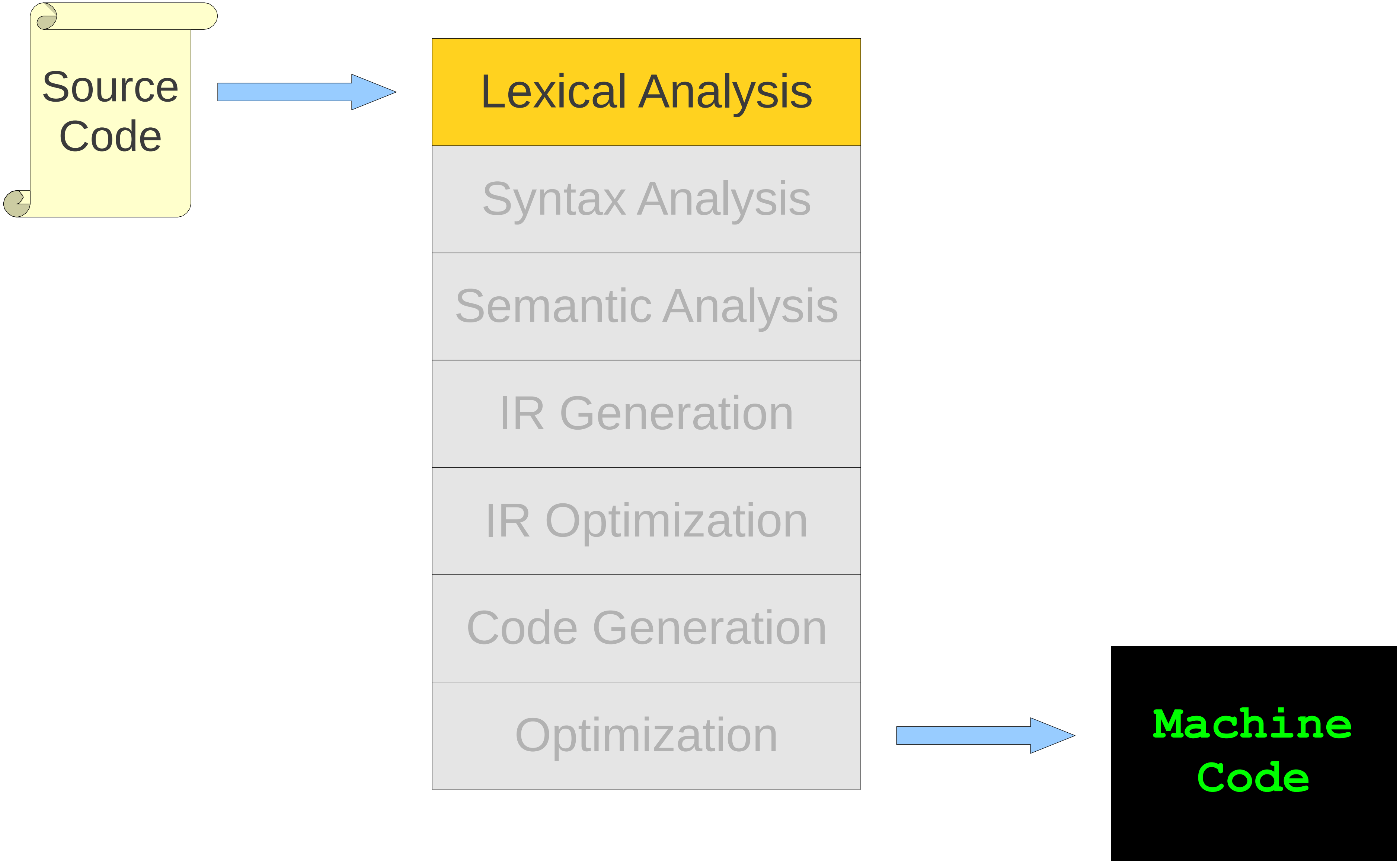
Lexical Analysis

Where We Are



Source Code

Lexical Analysis

Syntax Analysis

Semantic Analysis

IR Generation

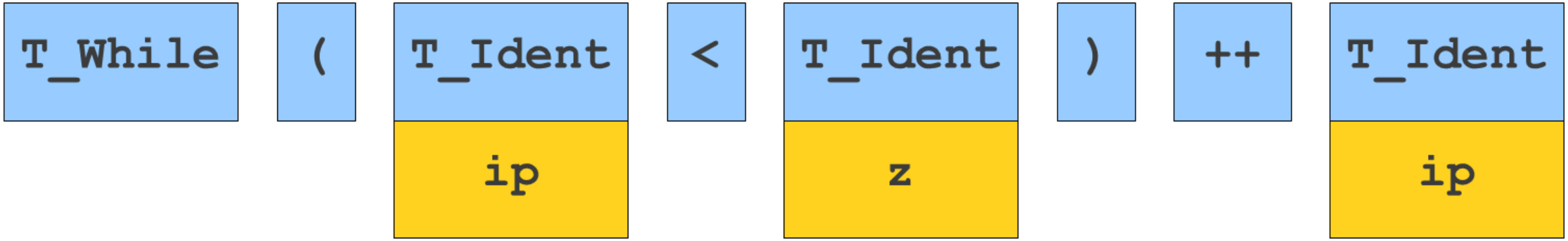
IR Optimization

Code Generation

Optimization

Machine Code

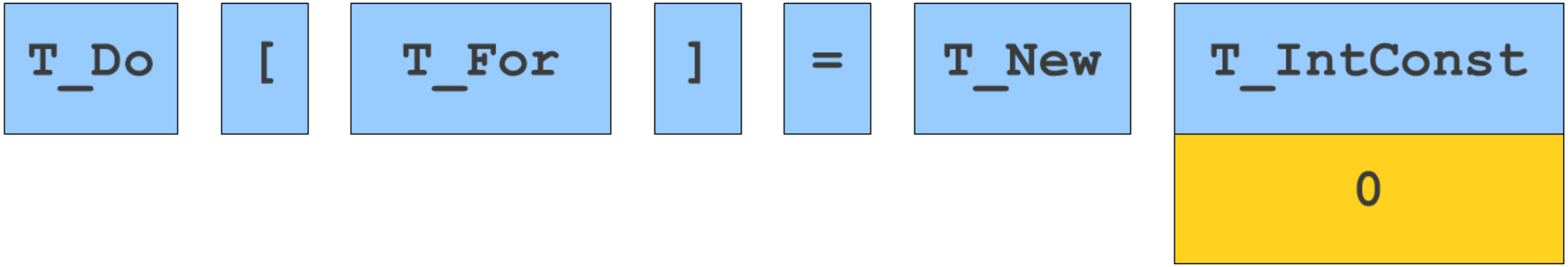
```
while (ip < z)
++ip;
```



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

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

```
do[for] = new 0;
```



T_Do

[

T_For

]

=

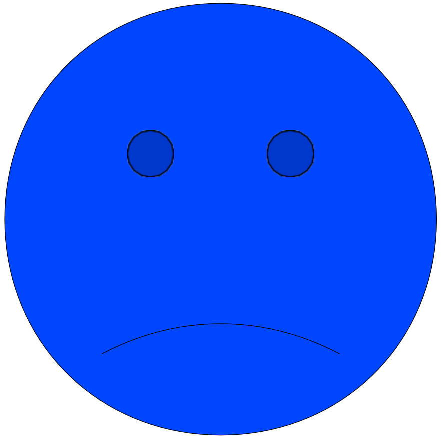
T_New

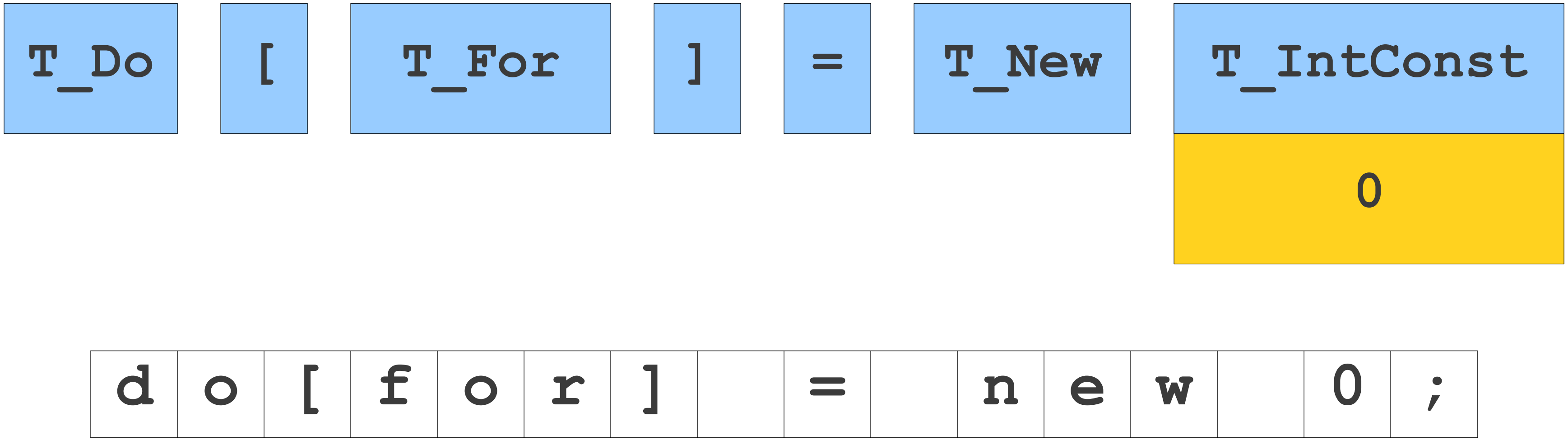
T_IntConst

0

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

```
do[for] = new 0;
```





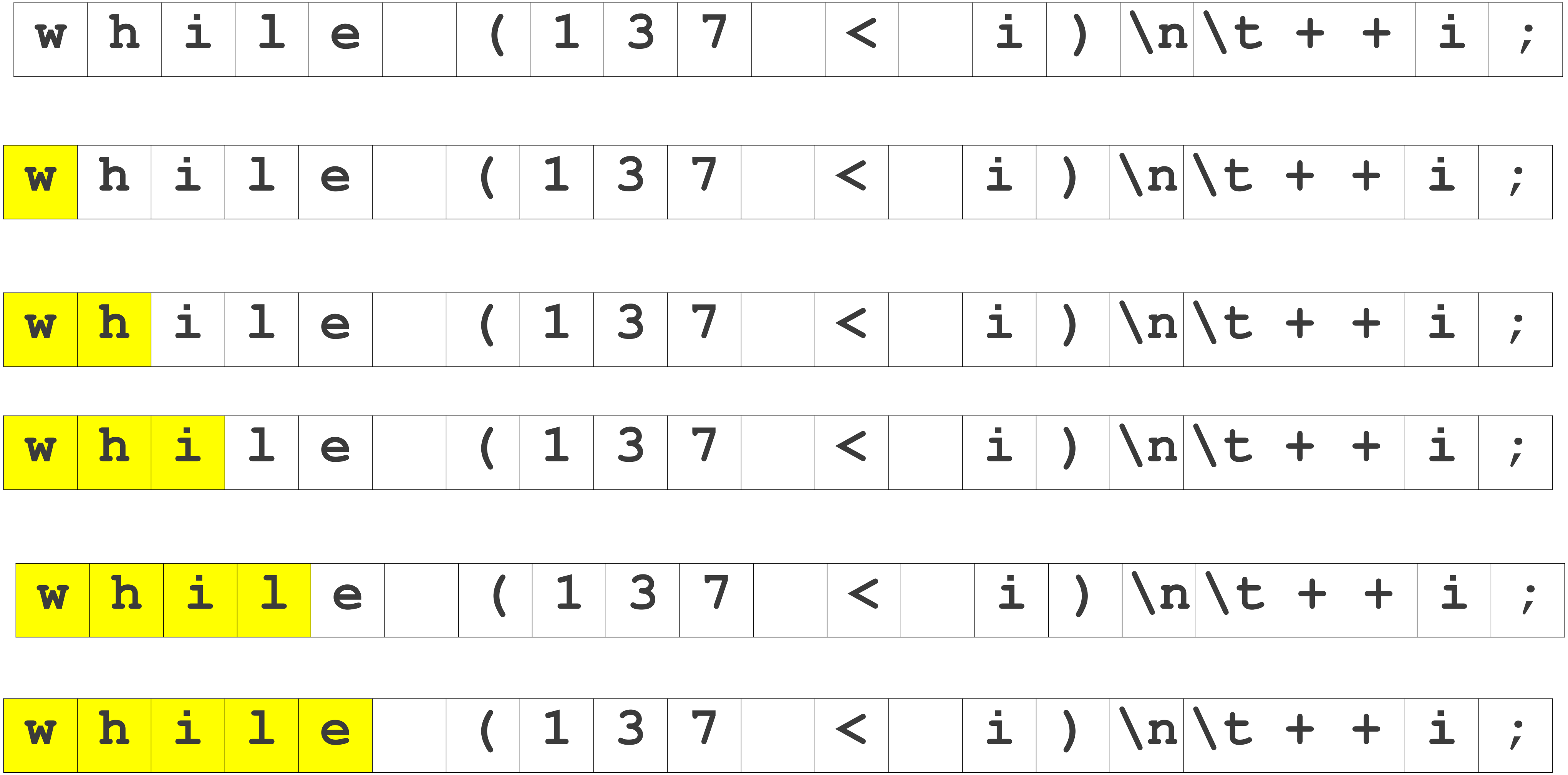
T_Do [T_For] = T_New T_IntConst

0

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

```
do[for] = new 0;
```

Scanning a Source File



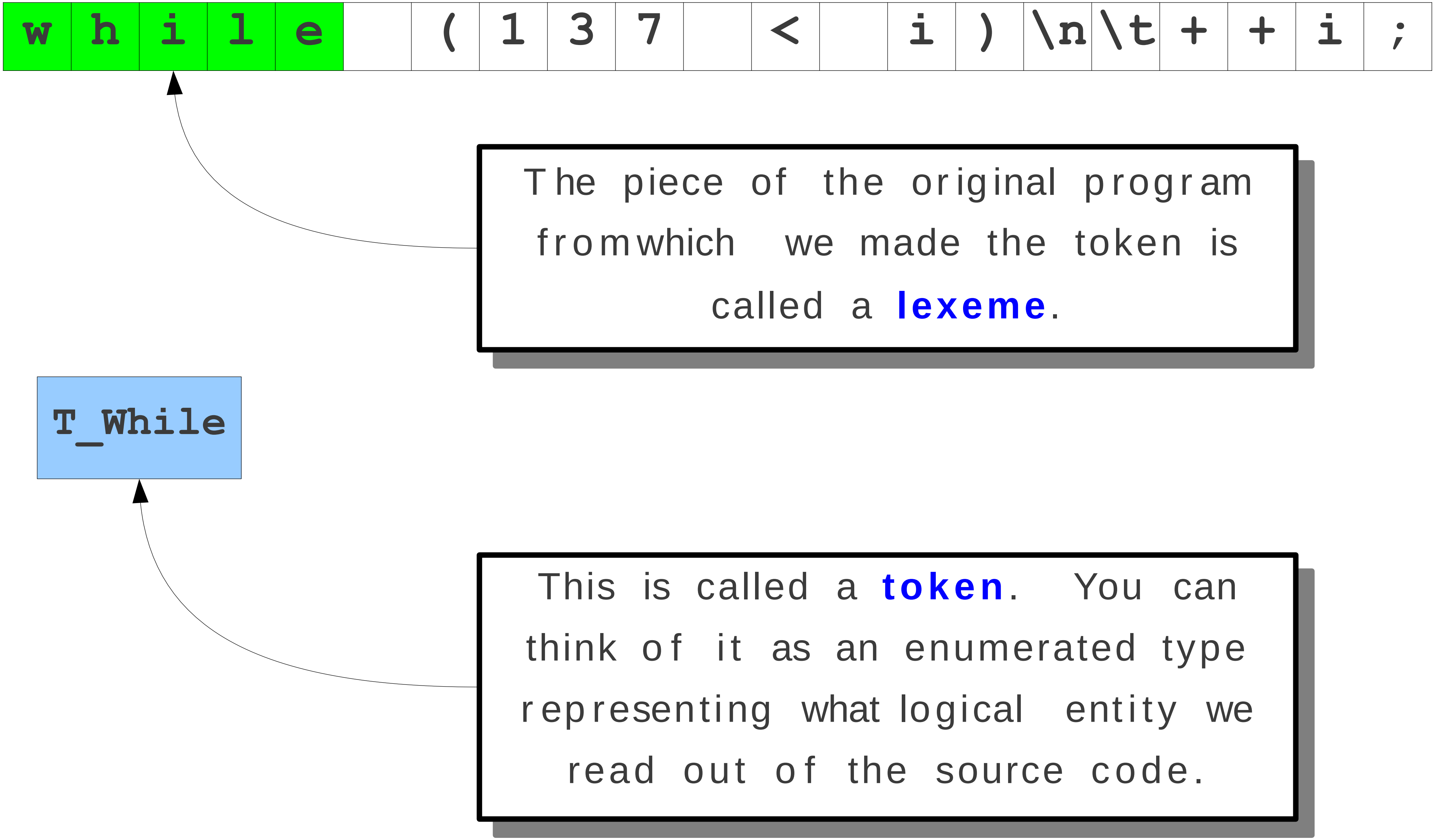
w	h	i	l	e		(	1	3	7		<		i	)	\n	\t	+	+	i	;
w	h	i	l	e		(	1	3	7		<		i	)	\n	\t	+	+	i	;
w	h	i	l	e		(	1	3	7		<		i	)	\n	\t	+	+	i	;
w	h	i	l	e		(	1	3	7		<		i	)	\n	\t	+	+	i	;
w	h	i	l	e		(	1	3	7		<		i	)	\n	\t	+	+	i	;
w	h	i	l	e		(	1	3	7		<		i	)	\n	\t	+	+	i	;

Scanning a Source File

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

T_While

Scanning a Source File

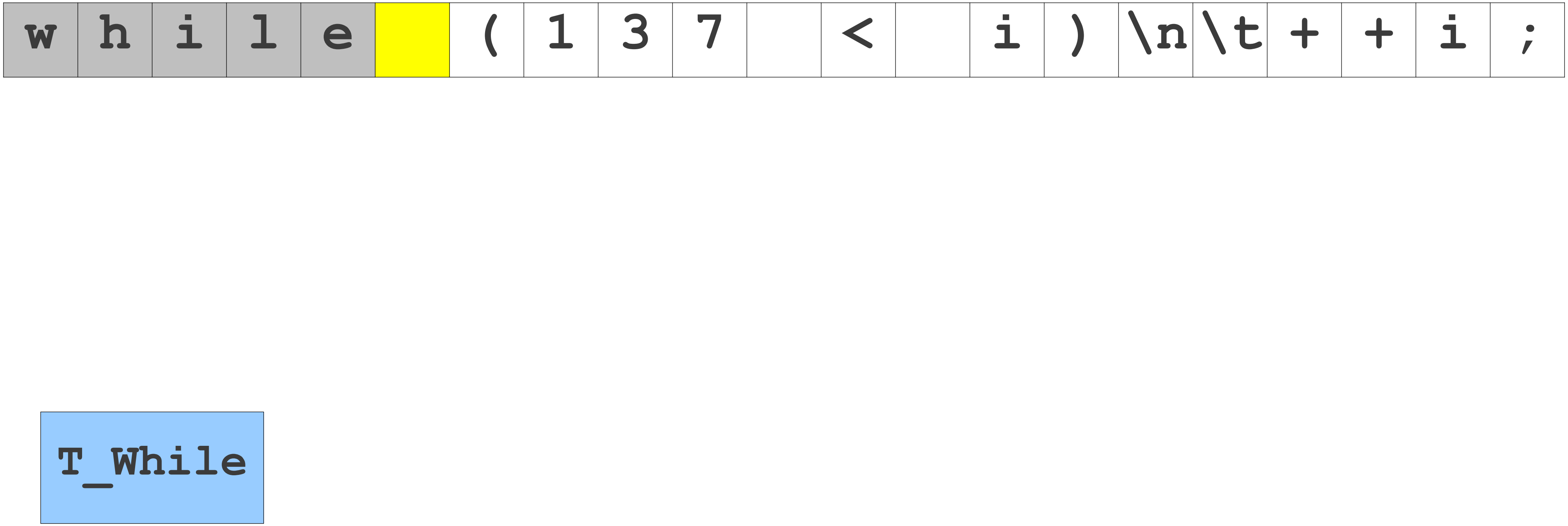


w	h	i	l	e		(	1	3	7		<		i	)	\n	\t	+	+	i	;

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

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.

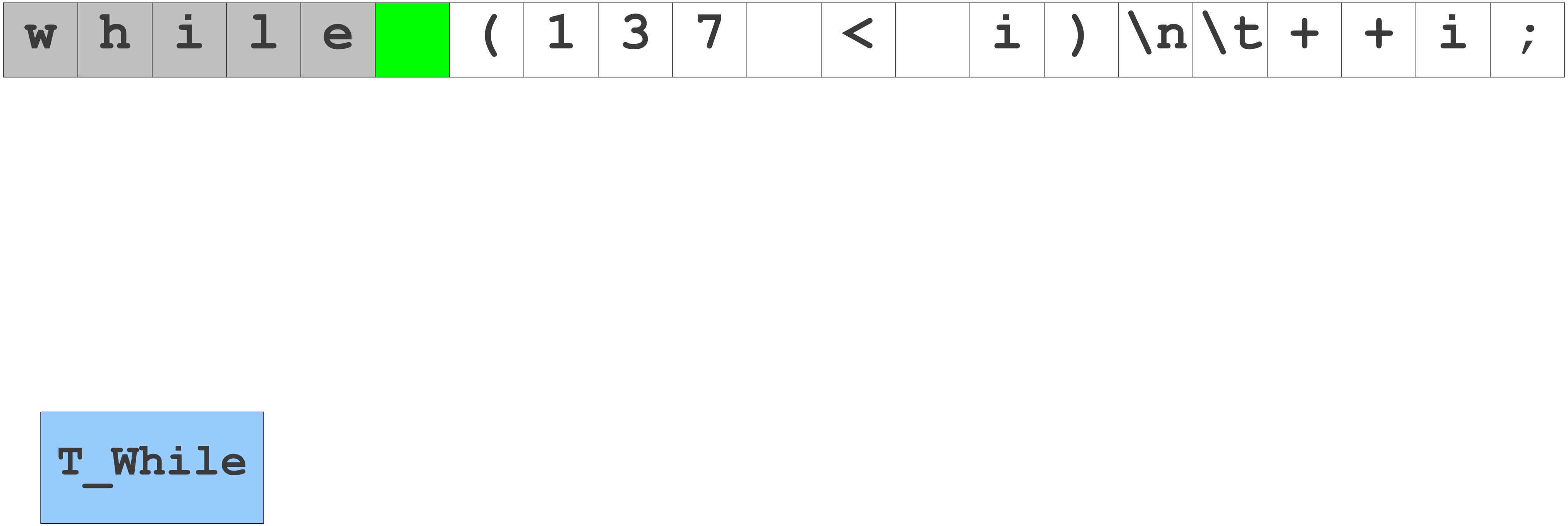
Scanning a Source File



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

T_While

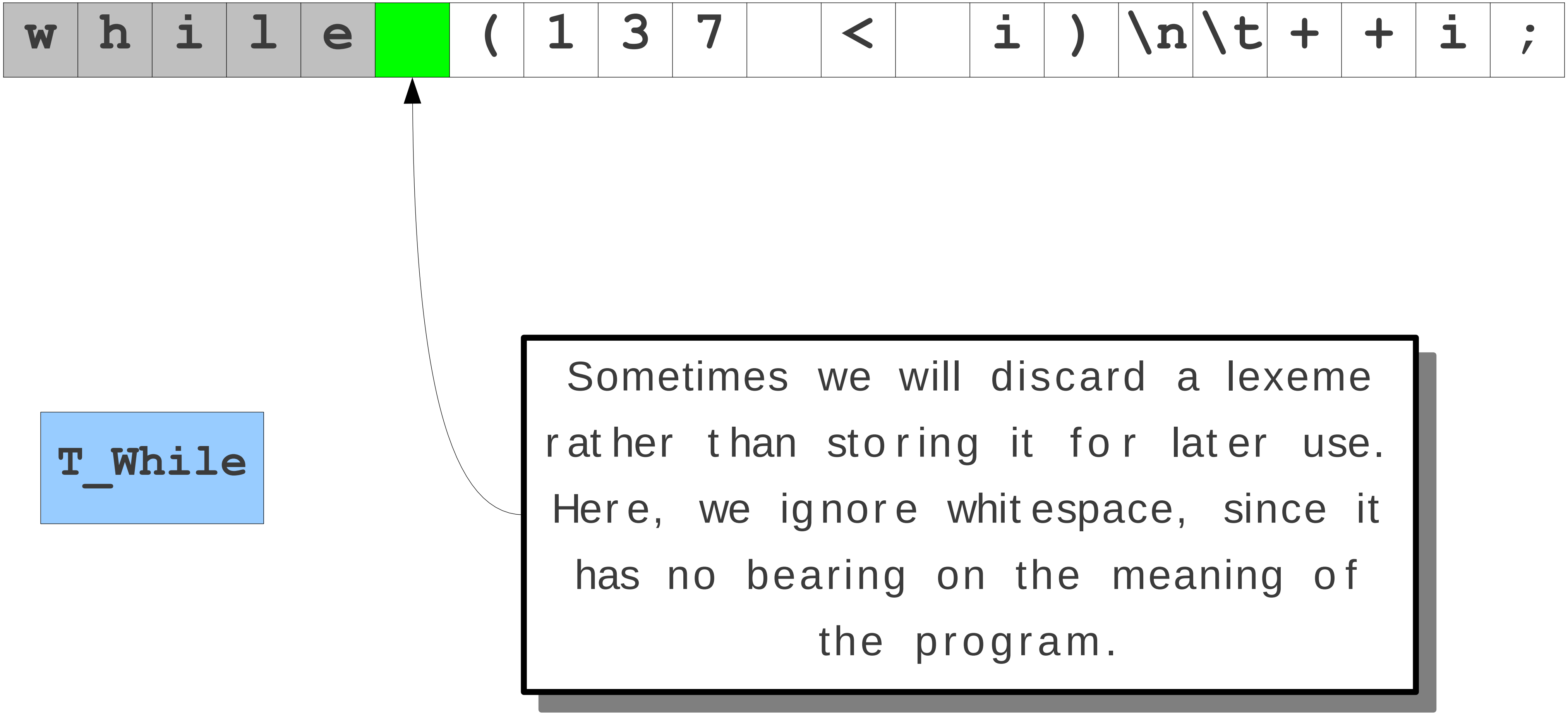
Scanning a Source File



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

T_While

Scanning a Source File

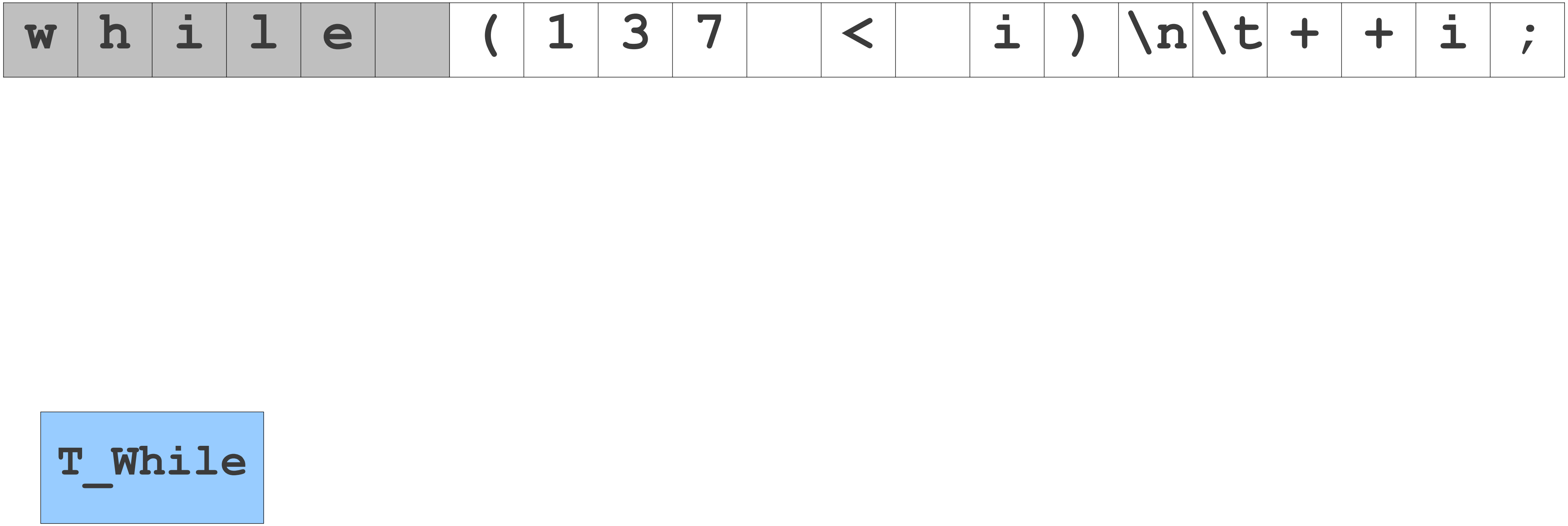


w	h	i	l	e		(	1	3	7		<		i	)	\n	\t	+	+	i	;

T_While

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.

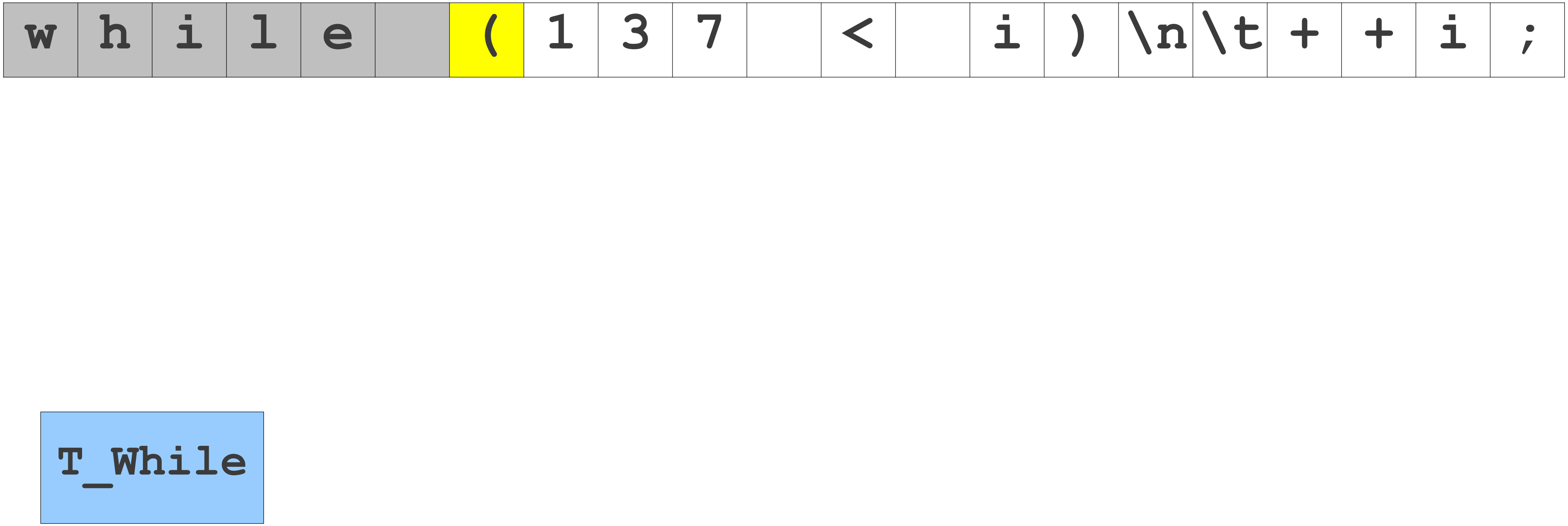
Scanning a Source File



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

(

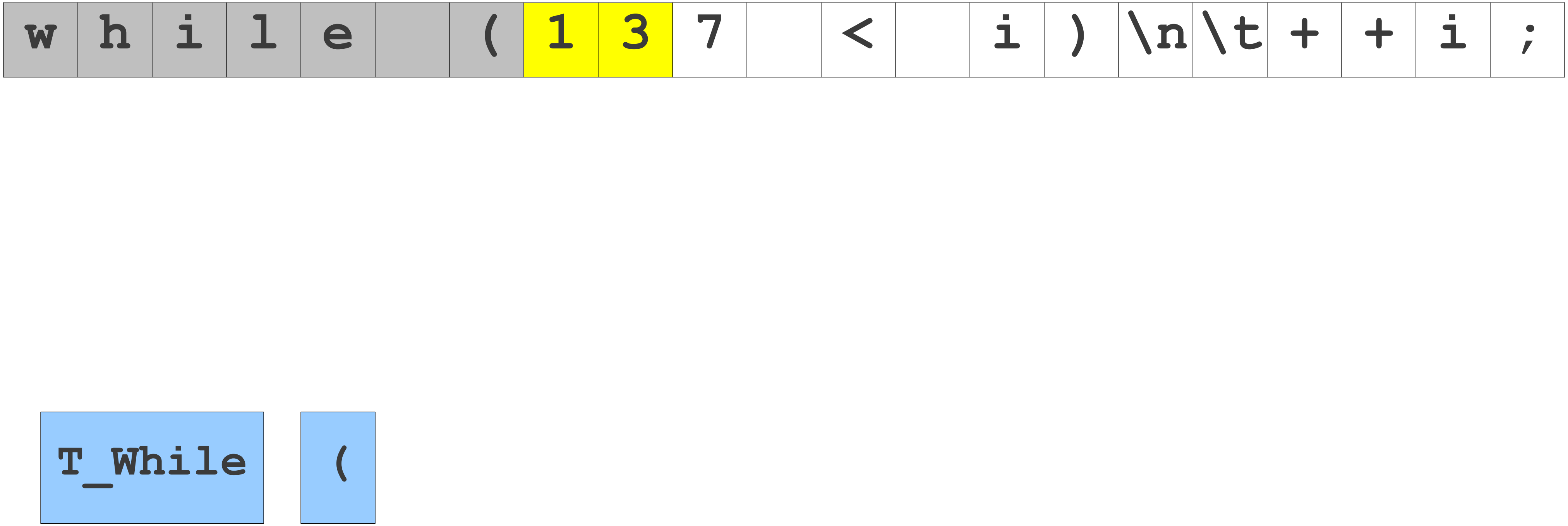
Scanning a Source File

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

T_While

(

Scanning a Source File

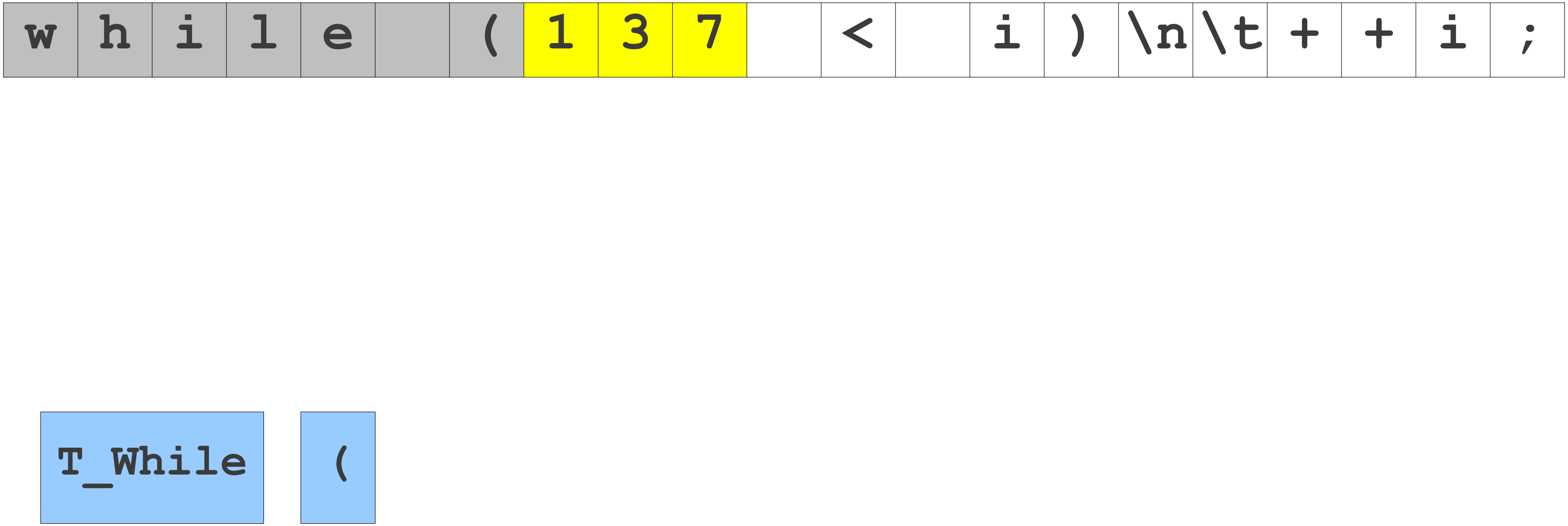


w	h	i	l	e		(	1	3	7		<		i	)	\n	\t	+	+	i	;

T_While

(

Scanning a Source File



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

T_While (

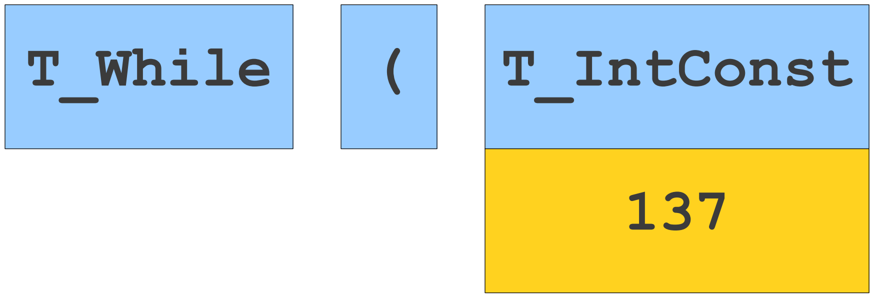
Scanning a Source File

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	;

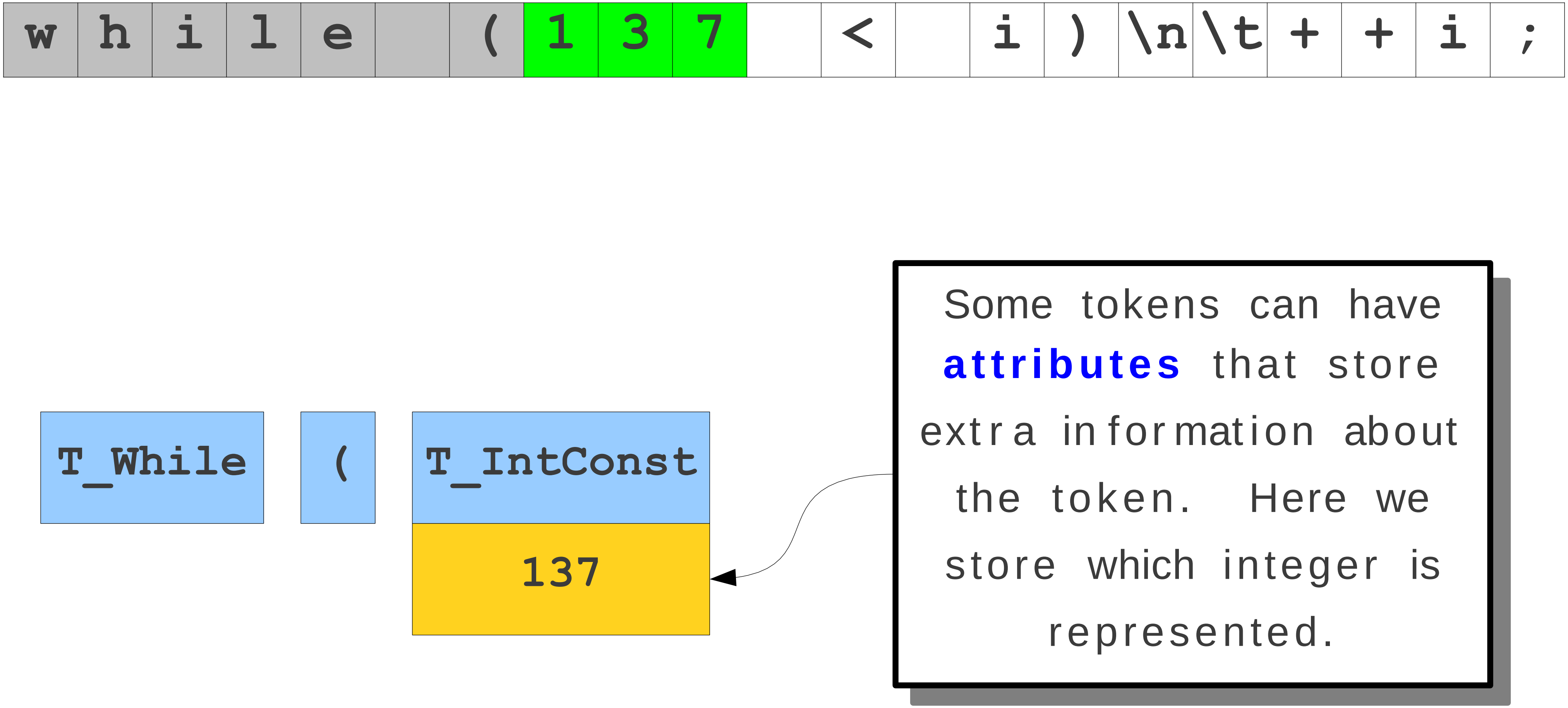

T_While

(

T_IntConst

137

Scanning a Source File



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

Some tokens can have **attributes** that store extra information about the token. Here we store which integer is represented.

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
<<
=
(
)
+
+
```

```
{
}
;
<
[
]
```

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
```

Thanks to Prof. Alex Aiken

Scanning is Hard

- FORTRAN: Whitespace is irrelevant

```
DO 5 I = 1,25
 DO5I   = 1.25
```

Thanks to Prof. Alex Aiken

Scanning is Hard

- FORTRAN: Whitespace is irrelevant

```
DO 5 I = 1,25
 DO5I  = 1.25
```

- Can be difficult to tell when to partition input.

Thanks to Prof. Alex Aiken

Scanning is Hard

- C++: Nested template declarations

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

Thanks to Prof. Alex Aiken

Scanning is Hard

- C++: Nested template declarations

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

Thanks to Prof. Alex Aiken

Scanning is Hard

- C++: Nested template declarations

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

Thanks to Prof. Alex Aiken

Scanning is Hard

- C++: Nested template declarations

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

- Again, can be difficult to determine where to split.

Thanks to Prof. Alex Aiken

Scanning is Hard

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

Thanks to Prof. Alex Aiken

Scanning is Hard

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

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

Thanks to Prof. Alex Aiken

Scanning is Hard

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

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

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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 lexemes.

Thanks to Prof. Alex Aiken

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?

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 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.
- 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, including the **`flex`** tool we will use in this course.

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, **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, **$R_1 \mid R_2$** 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.

Operator Precedence

- Regular expression operator precedence is

$$(R)$$

$$R^*$$

$$R_1R_2$$

$$R_1 \mid R_2$$

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

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)*

Simple Regular Expressions

- Suppose the only characters are **`0`** and **`1`**.
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(0 | 1)*00(0 | 1)*

Simple Regular Expressions

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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

Simple Regular Expressions

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

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 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:

Simple Regular Expressions

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- Here is a regular expression for strings that contain at most one zero:

1*(0 | ε)1*

Simple Regular Expressions

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Simple Regular Expressions

- Suppose the only characters are `0` and `1`.
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1*(0 | ε)1*

11110111
111111
0111
0

Simple Regular Expressions

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- Here is a regular expression for strings that contain at most one zero:

1*(0 | ε)1*

11110111

111111

0111

0

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?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*)*

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cs143@cs.stanford.edu
first.middle.last@mail.site.org
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Applied Regular Expressions

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a^+ (.aa*)* @ aa*.aa* (.aa*)*

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$$a^{+} \quad (.a^{+})^{*} \quad @ \quad a^{+}.a^{+} \quad (.a^{+})^{*}$$

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Applied Regular Expressions

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$$\mathbf{a^+(.a^+)^*@a^+(.a^+)^+}$$

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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)

Applied Regular Expressions

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42
+1370
-3248
-9999912

Applied Regular Expressions

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

42
+1370
-3248
-9999912

Applied Regular Expressions

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

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

42
+1370
-3248
-9999912

Applied Regular Expressions

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

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

42

+1370

-3248

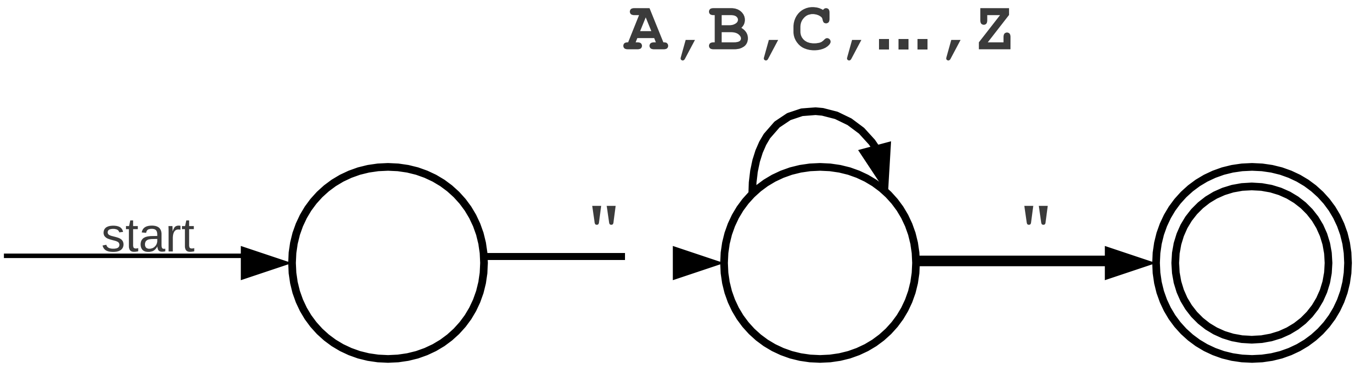
-9999912

Matching Regular Expressions

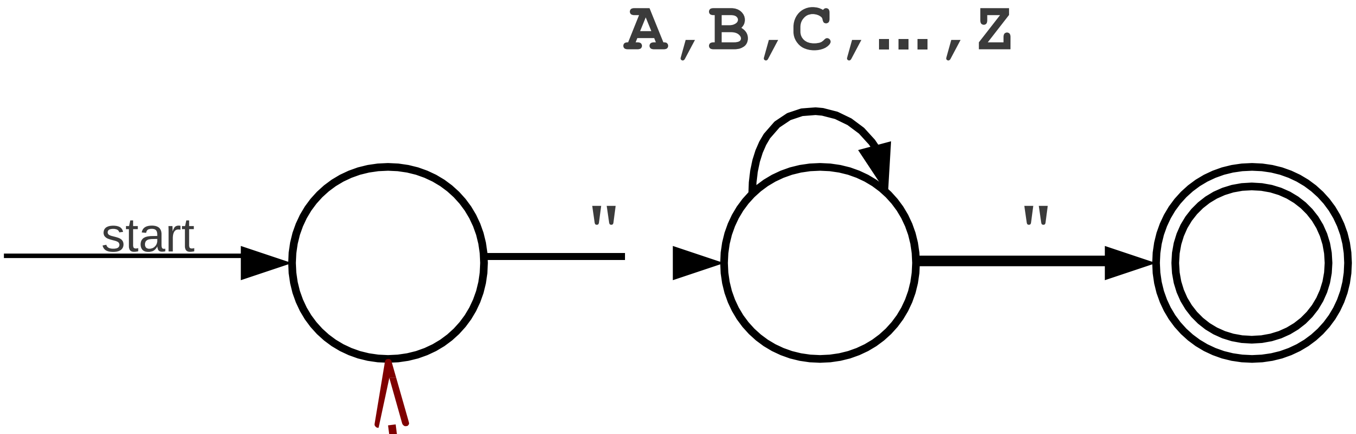
Implementing Regular Expressions

- 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.
- Automata are best explained by example...

A Simple Automaton

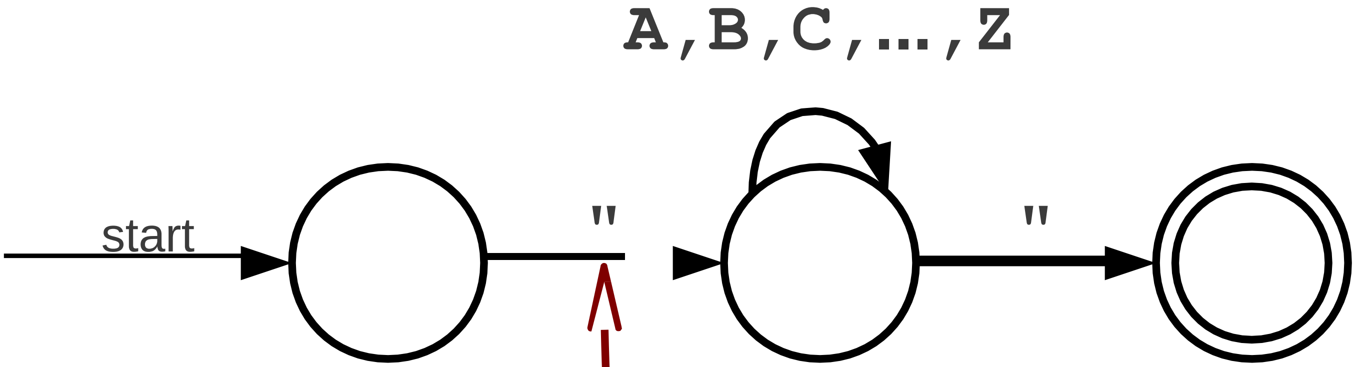


A Simple Automaton



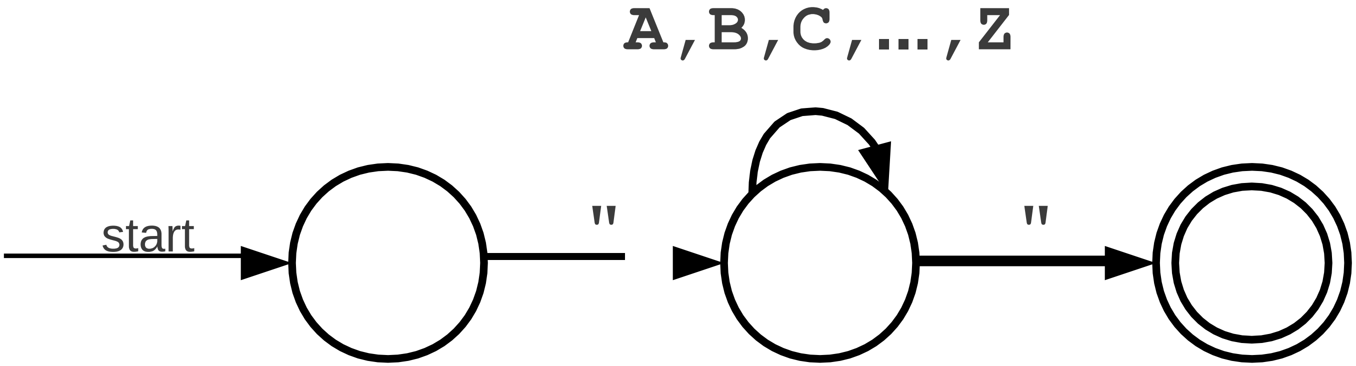
Each circle is a **state** of the automaton. The automaton's configuration is determined by what state(s) it is in.

A Simple Automaton



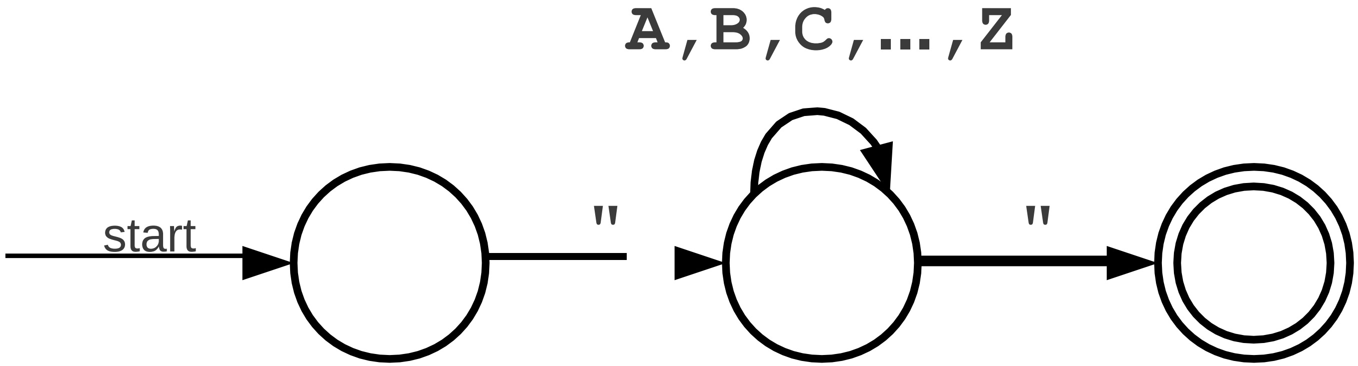
These arrows are called **transitions**. The automaton changes which state(s) it is in by following transitions.

A Simple Automaton



"	H	E	Y	A	"

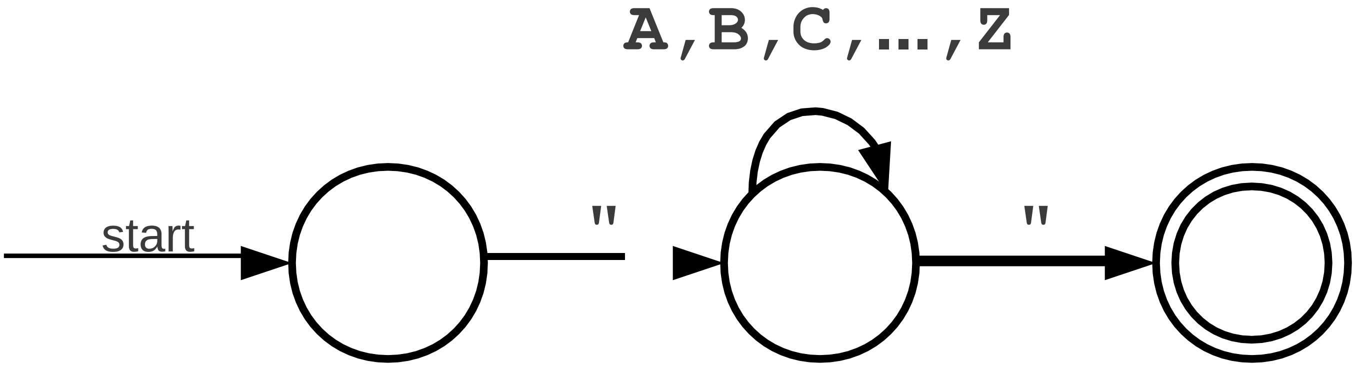
A Simple Automaton

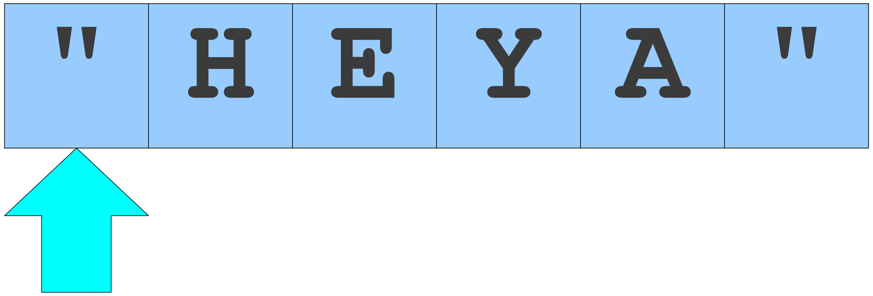


"	H	E	Y	A	"

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

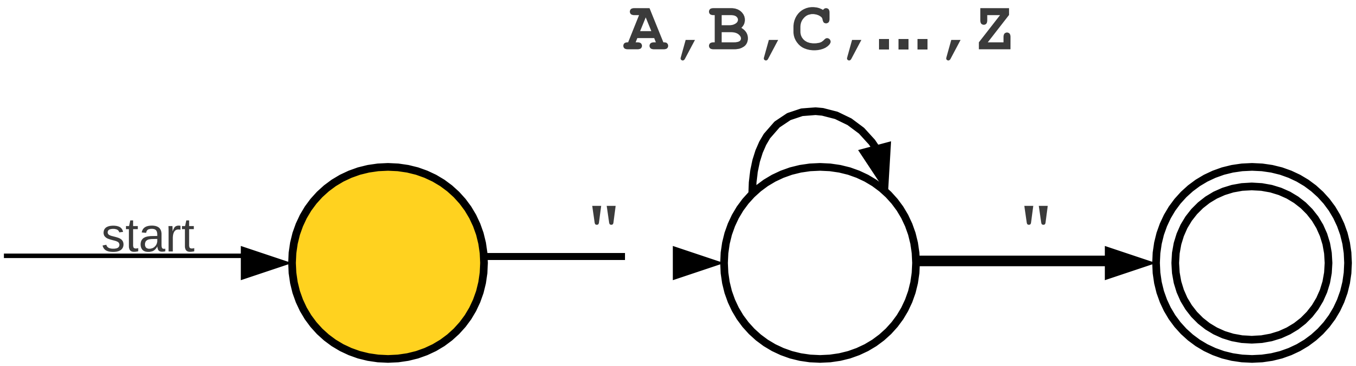
A Simple Automaton

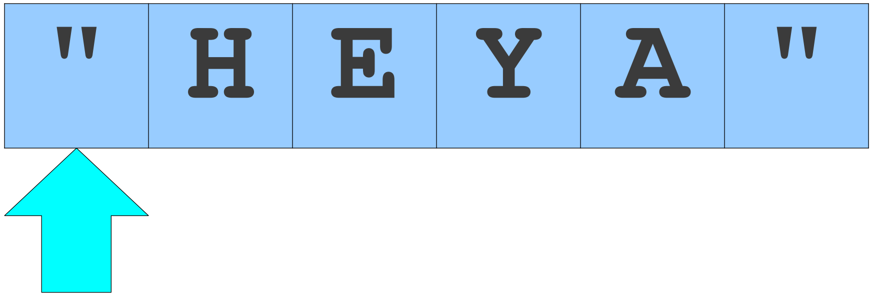




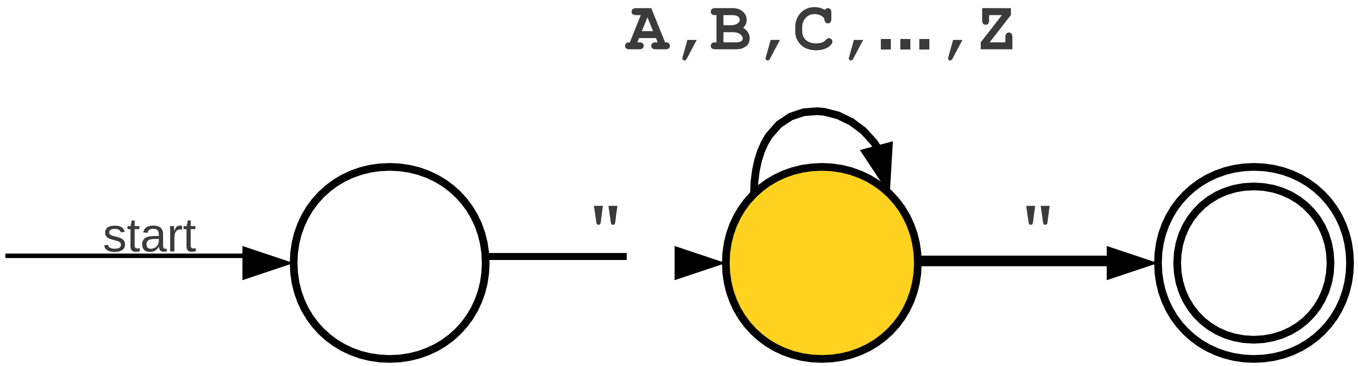
"	H	E	Y	A	"

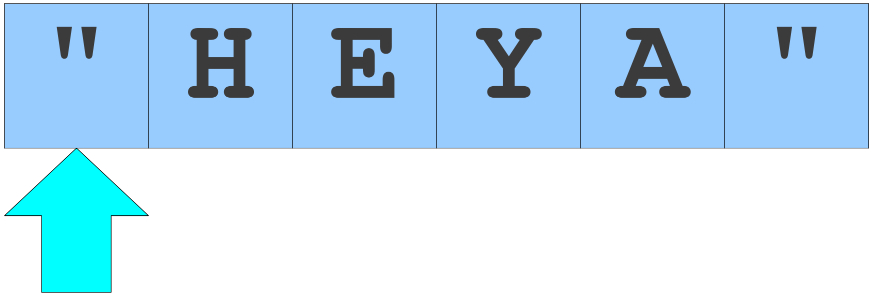
A Simple Automaton





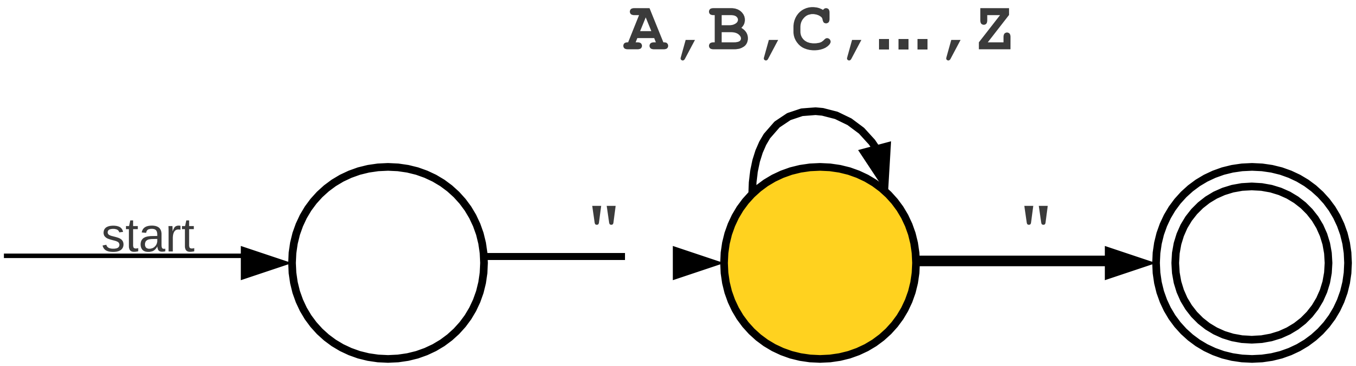
A Simple Automaton

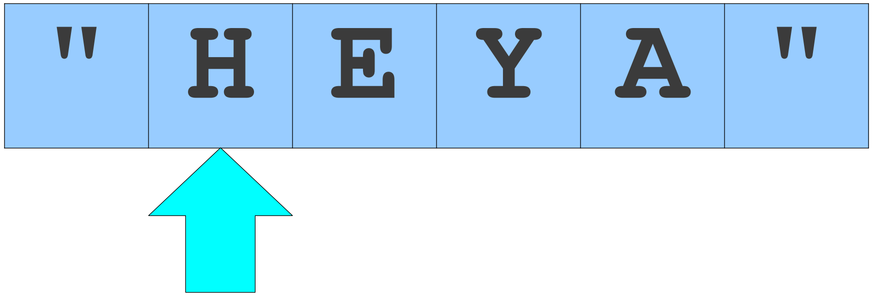




"	H	E	Y	A	"

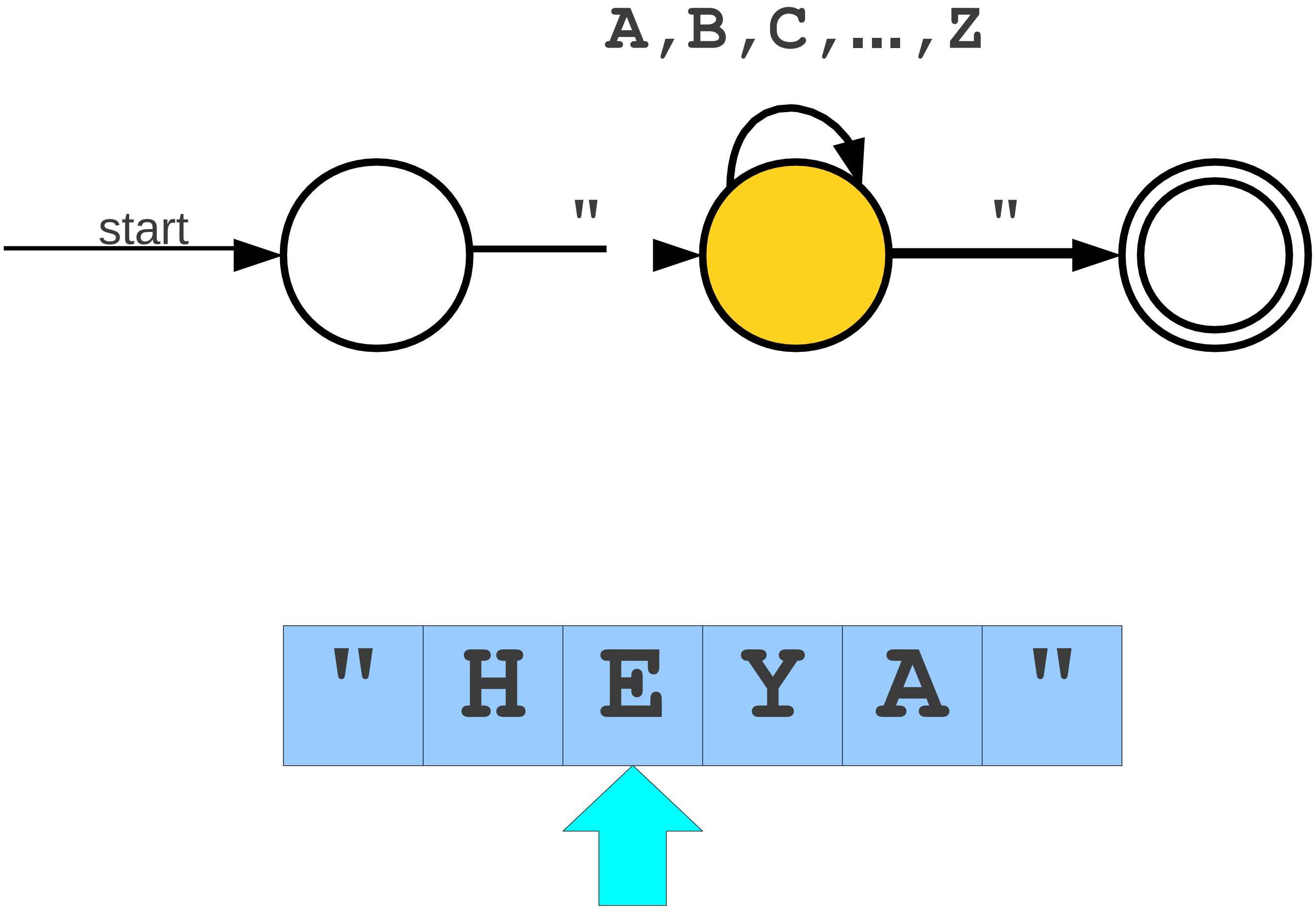
A Simple Automaton





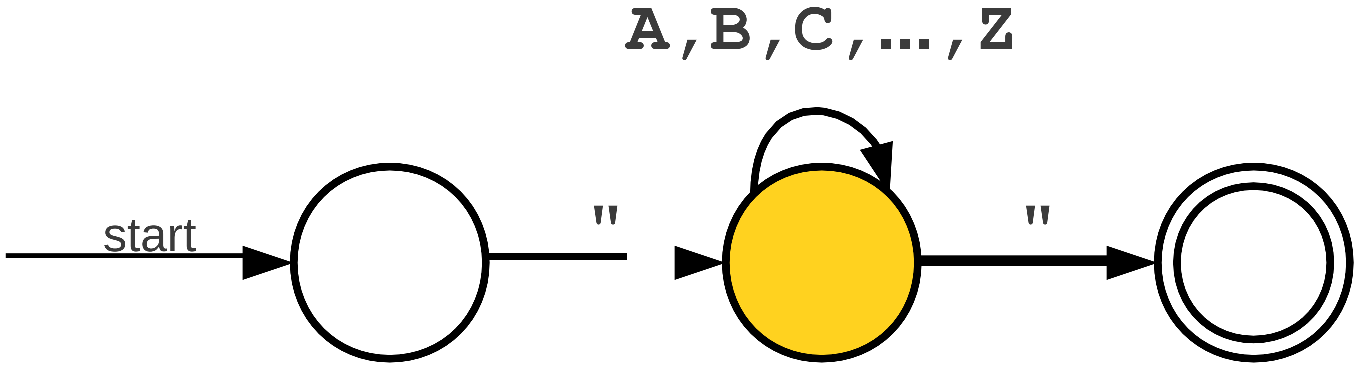
"	H	E	Y	A	"

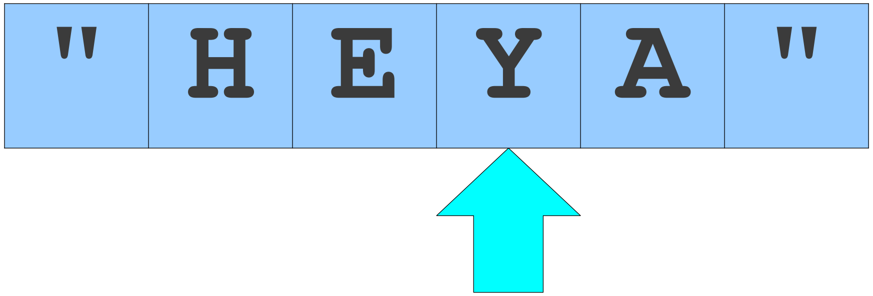
A Simple Automaton



"	H	E	Y	A	"

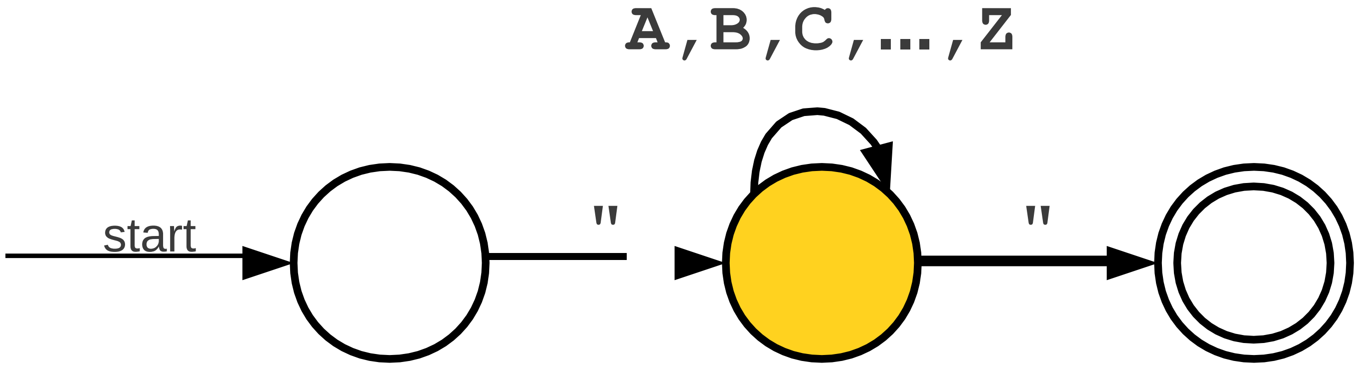
A Simple Automaton

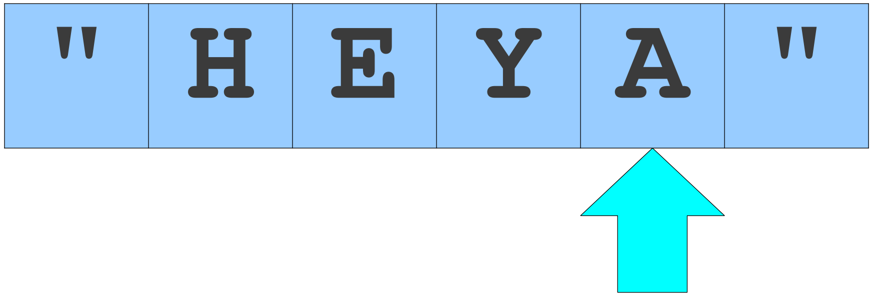




"	H	E	Y	A	"

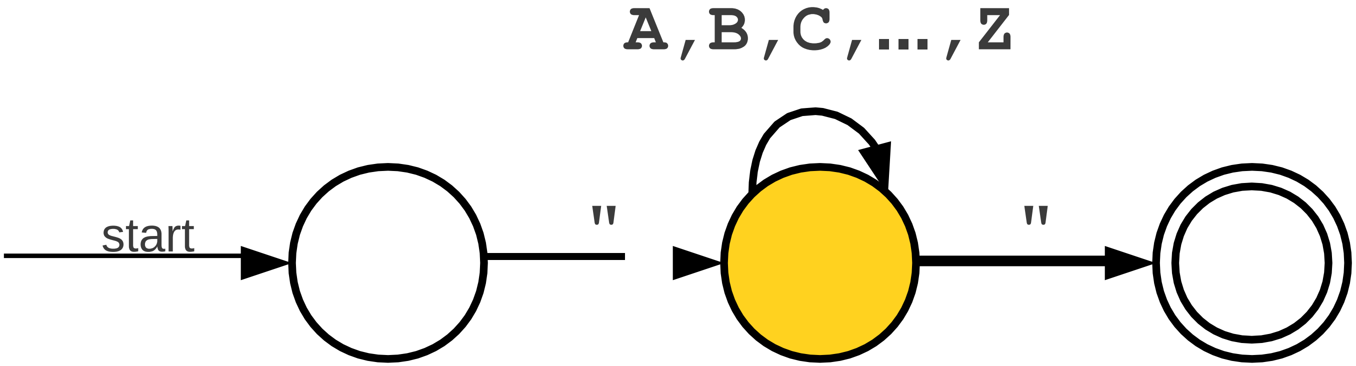
A Simple Automaton

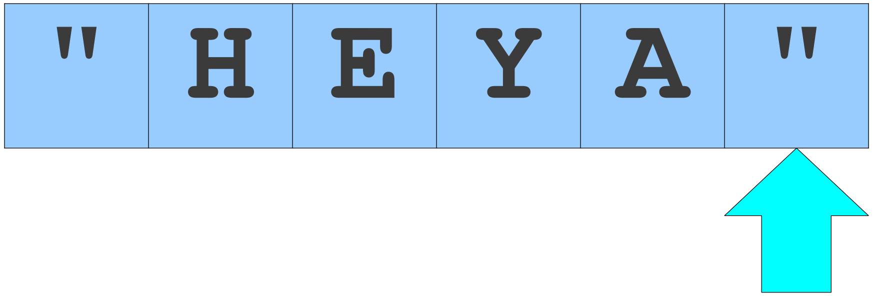




"	H	E	Y	A	"

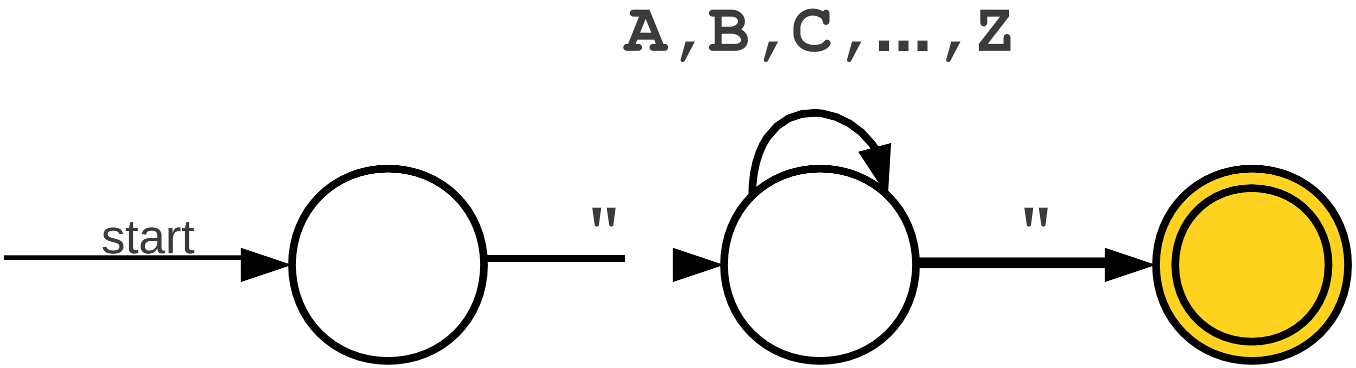
A Simple Automaton

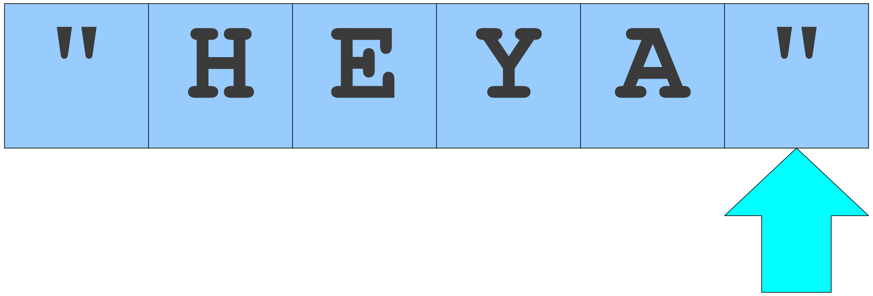




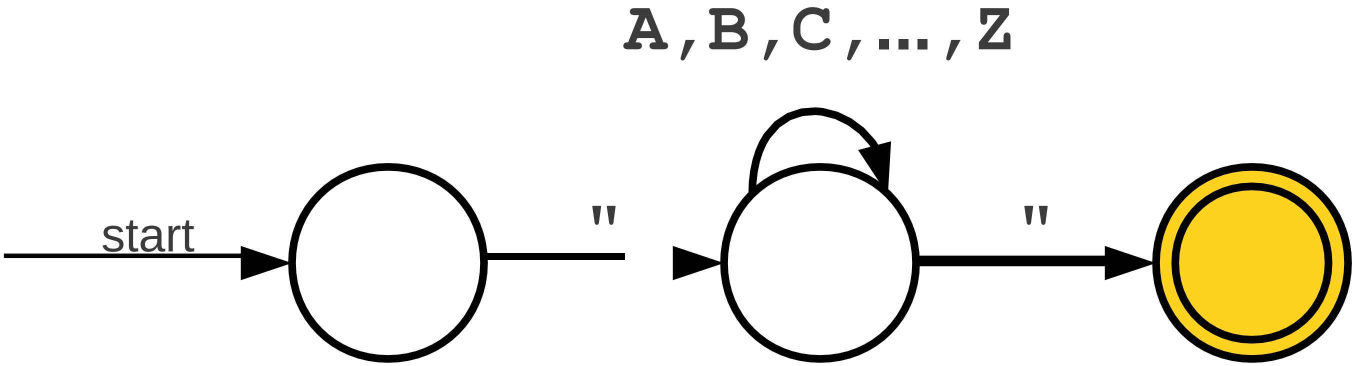
"	H	E	Y	A	"

A Simple Automaton



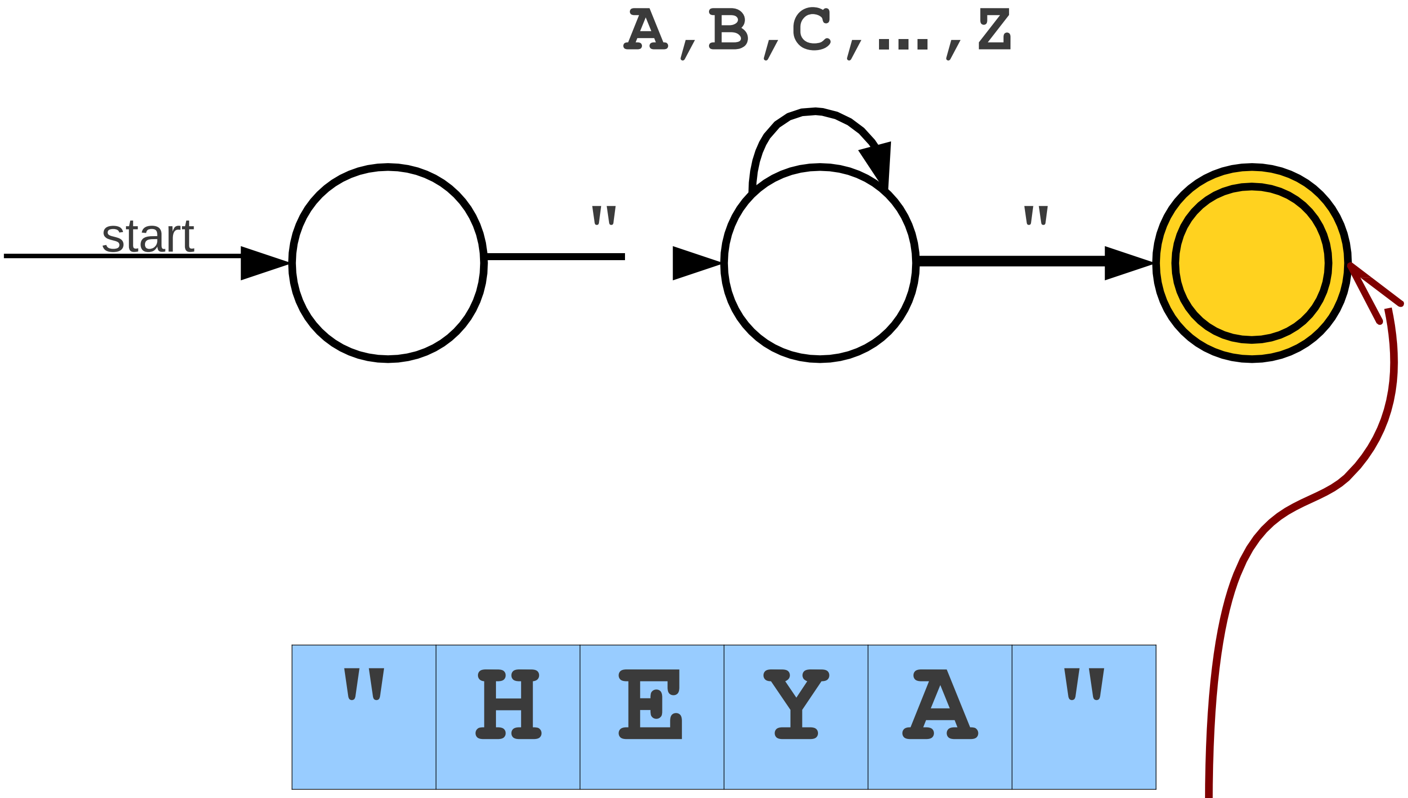


A Simple Automaton



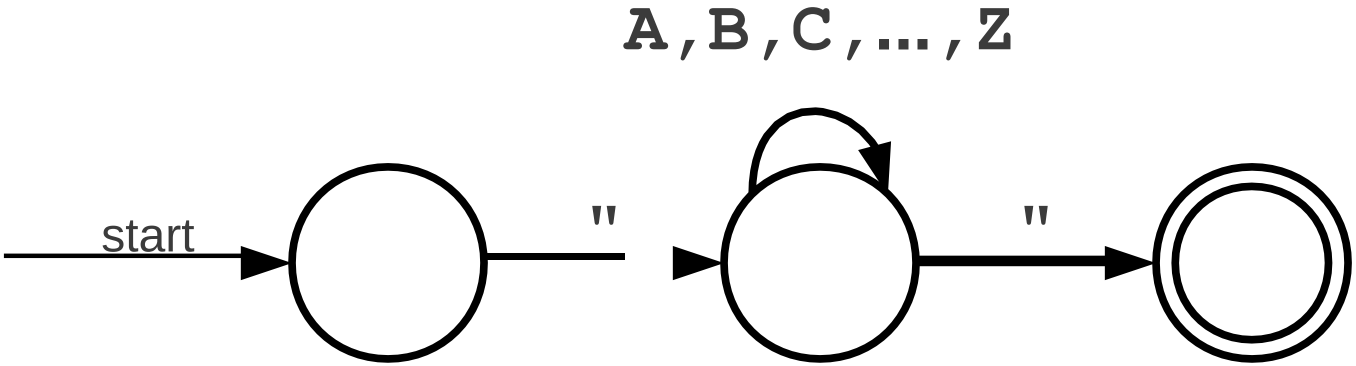
"	H	E	Y	A	"

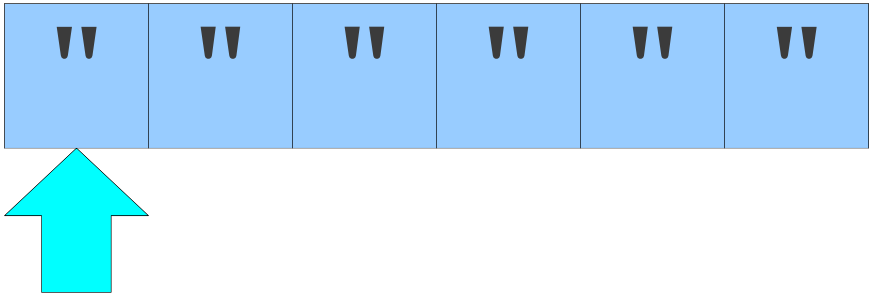
A Simple Automaton



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

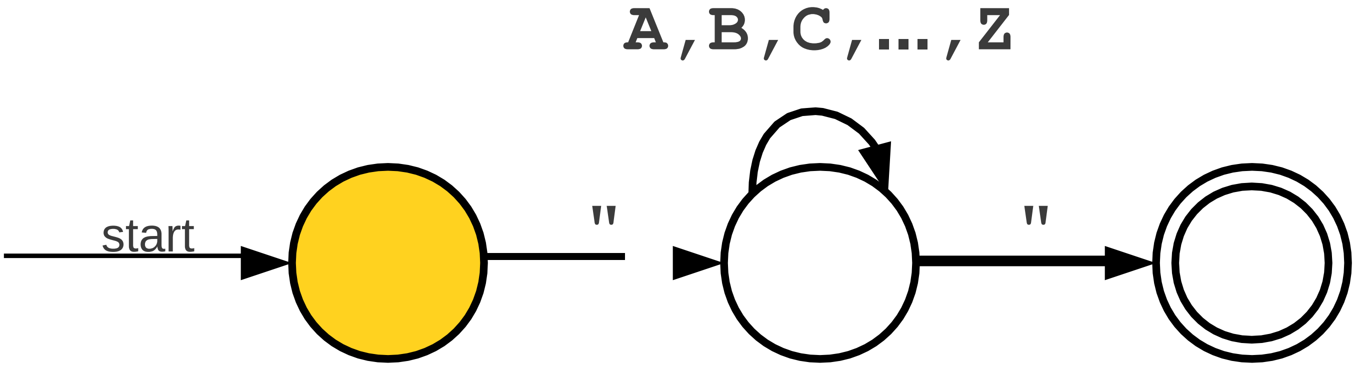
A Simple Automaton

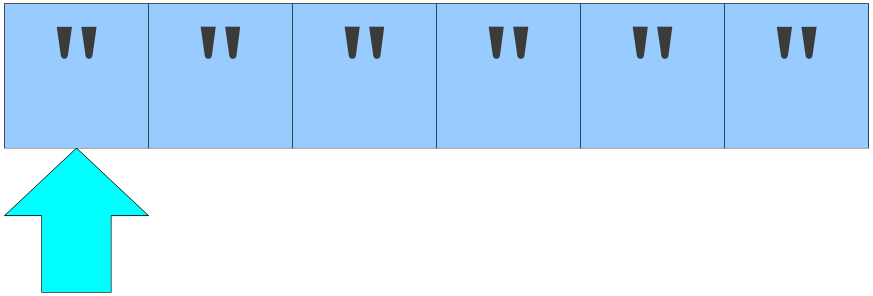




"	"	"	"	"	"

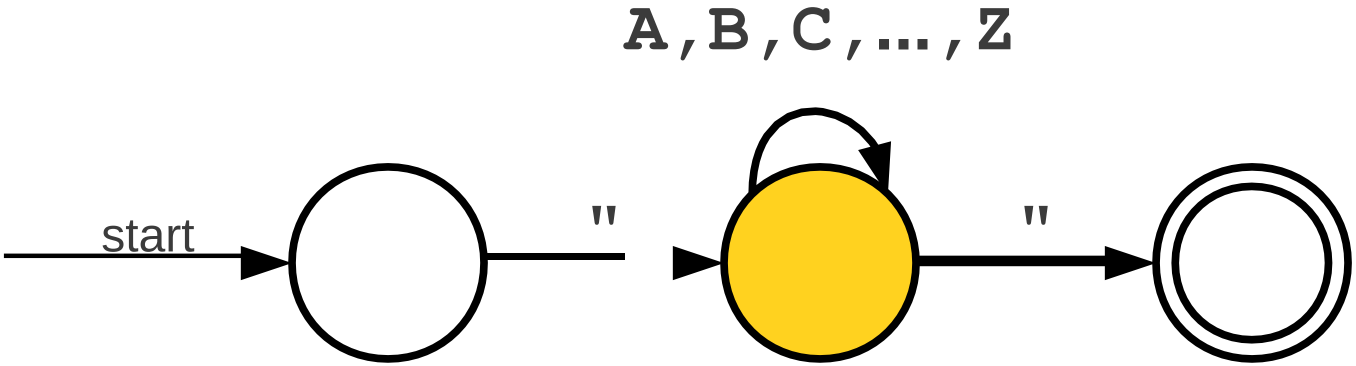
A Simple Automaton

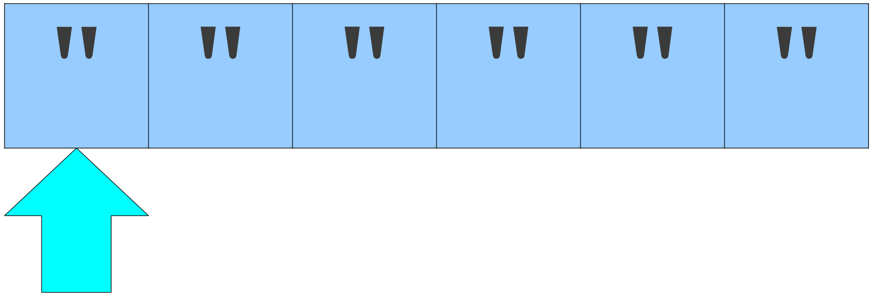




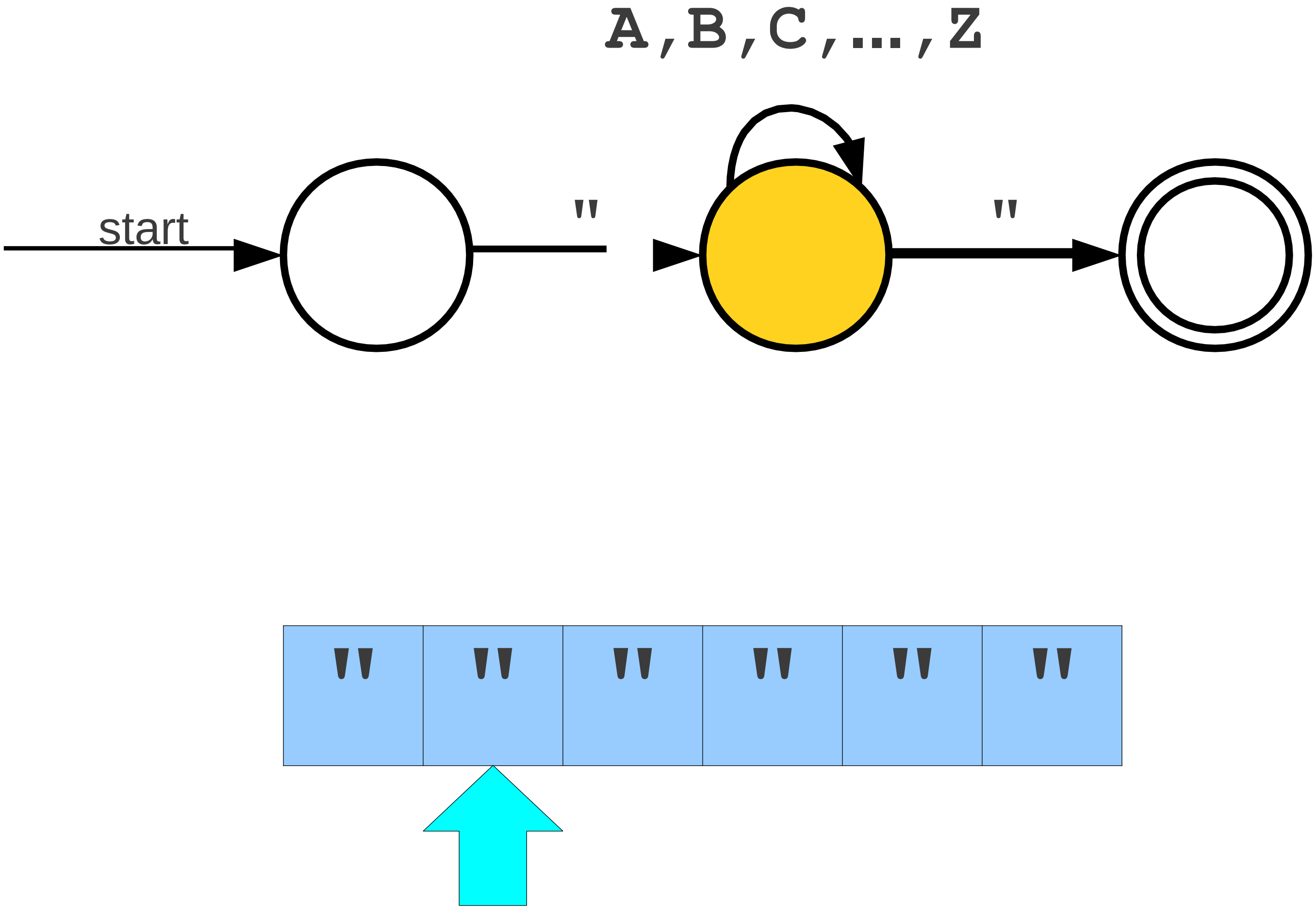
"	"	"	"	"	"

A Simple Automaton

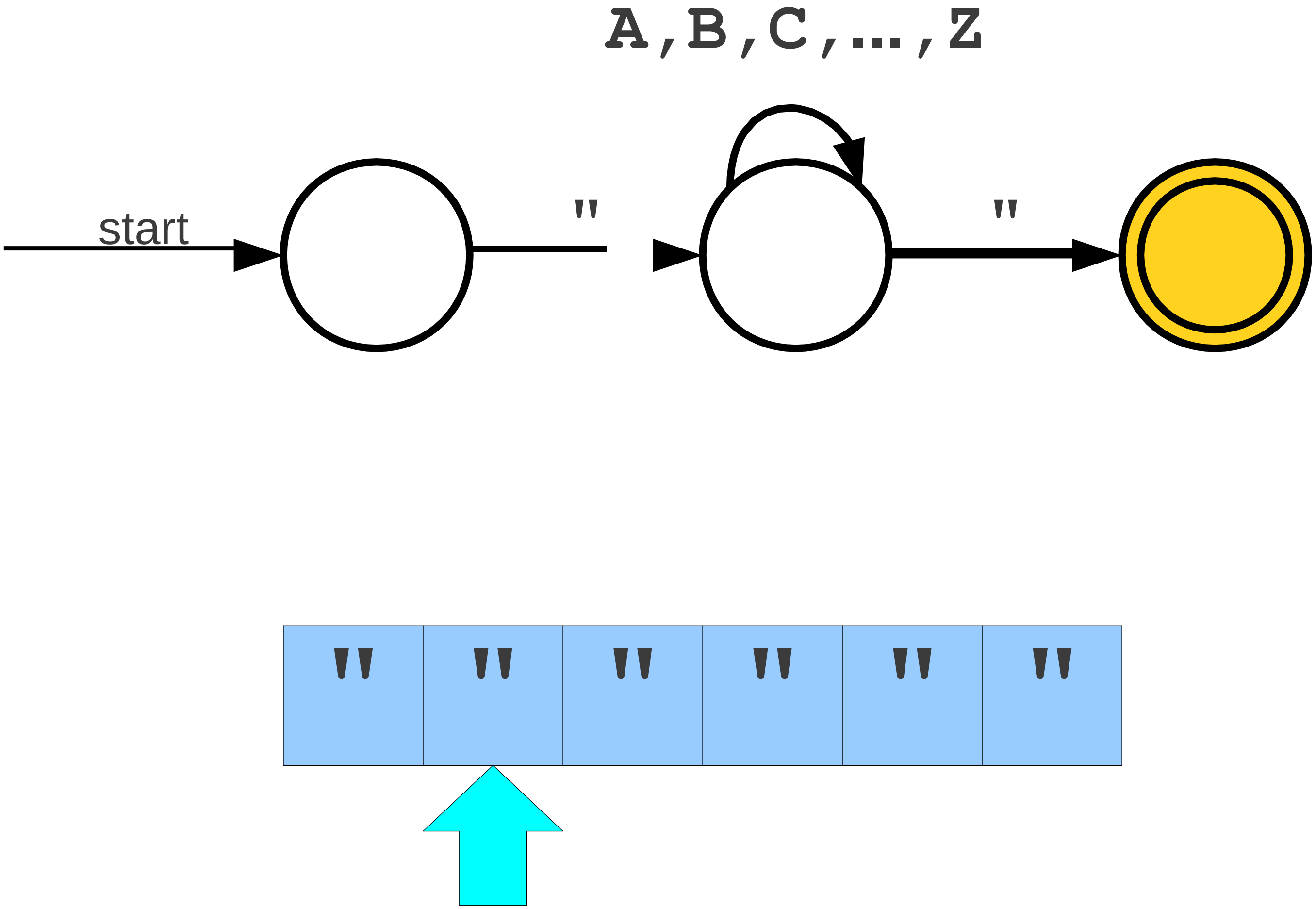




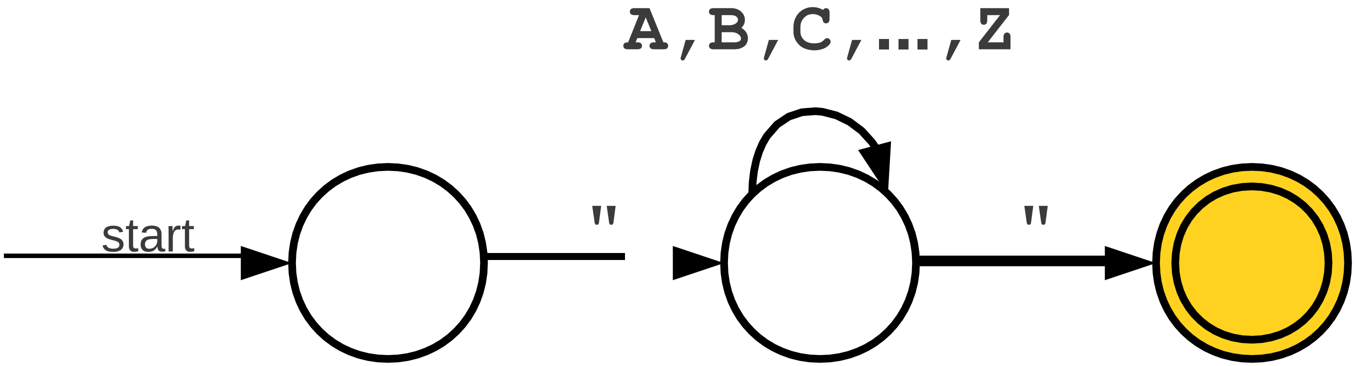
A Simple Automaton

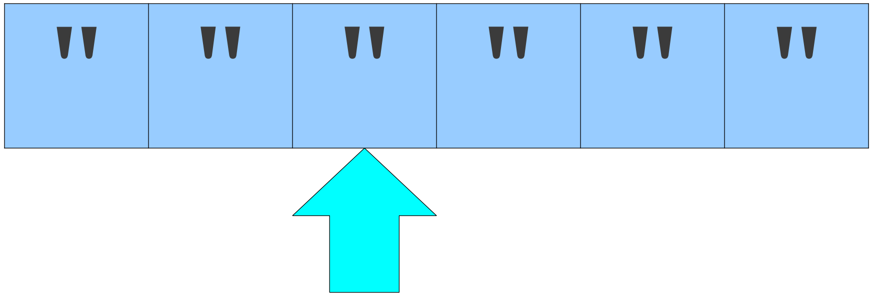


A Simple Automaton



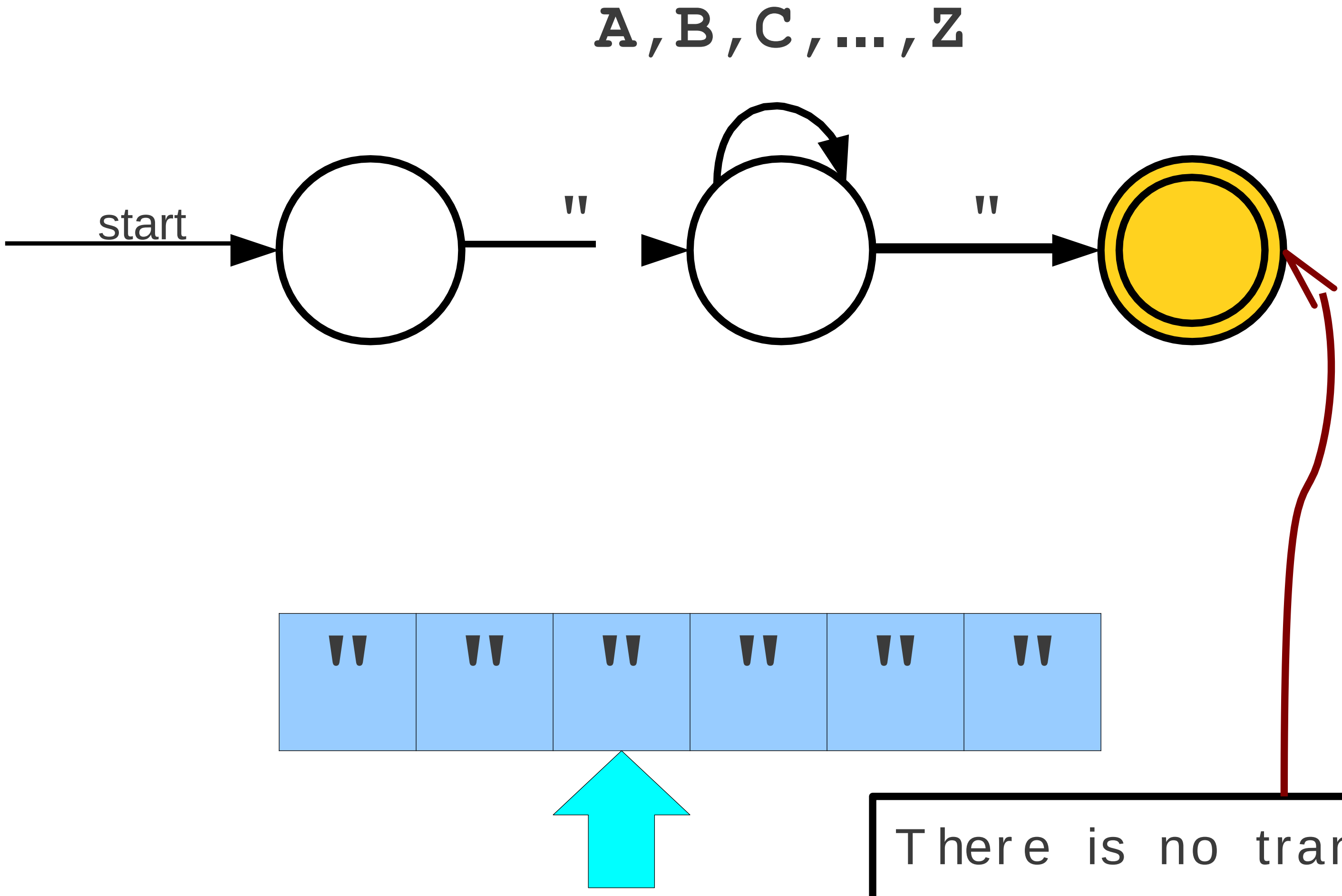
A Simple Automaton





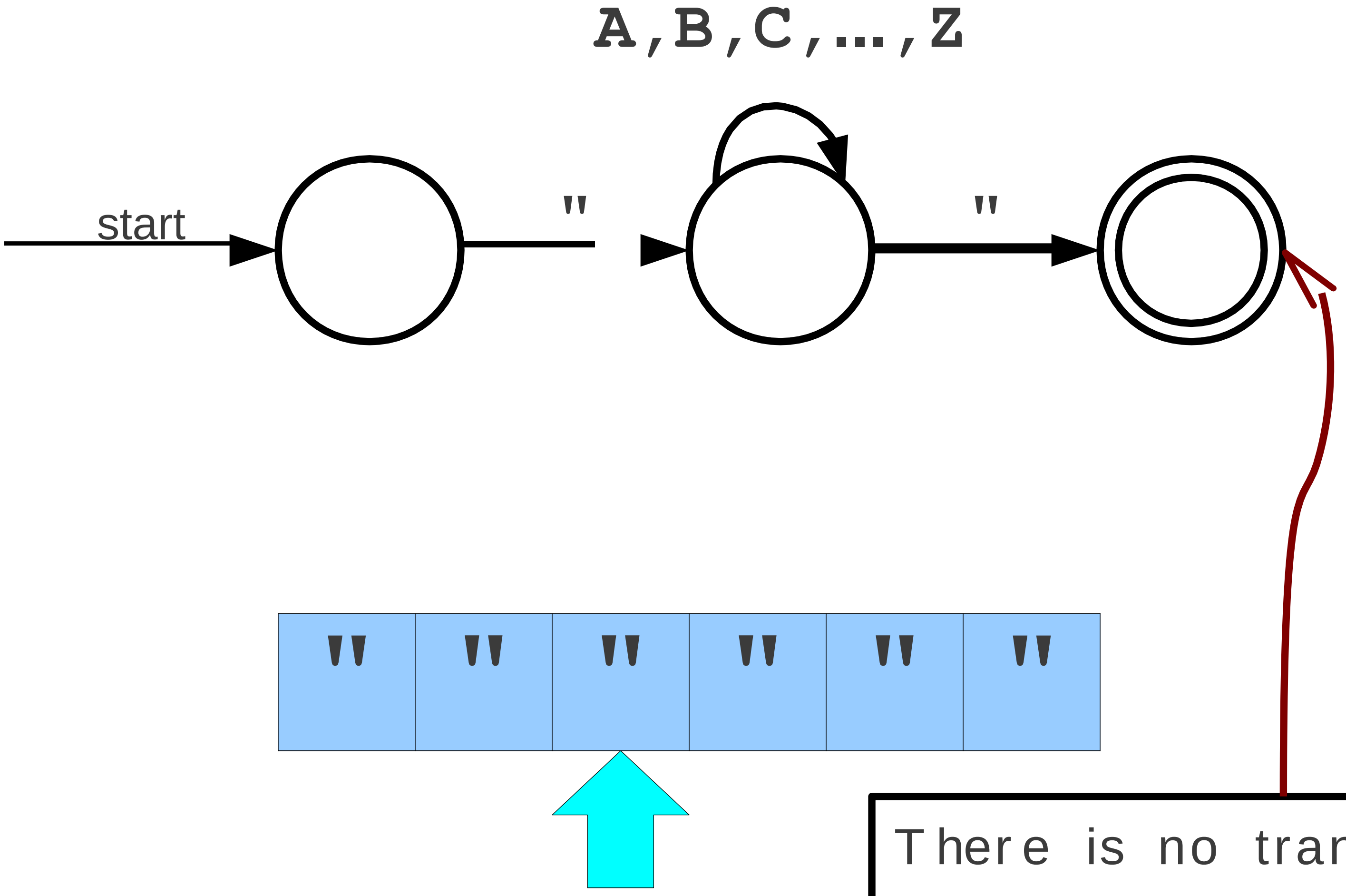
"	"	"	"	"	"

A Simple Automaton



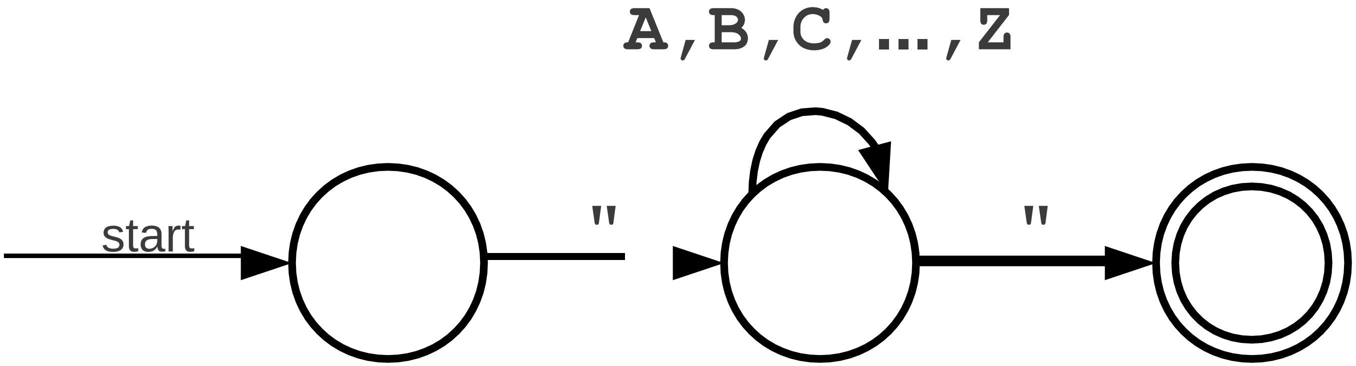
There is no transition on " here, so the automaton **dies** and rejects.

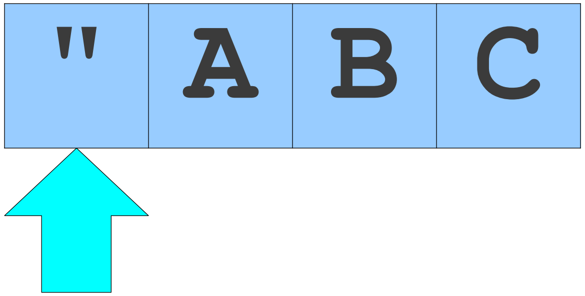
A Simple Automaton



There is no transition on " here, so the automaton **dies** and rejects.

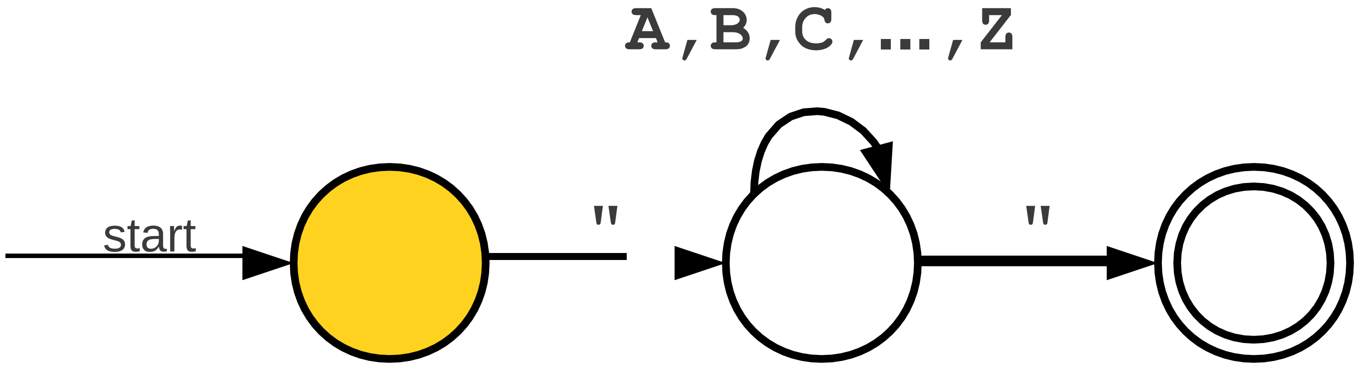
A Simple Automaton

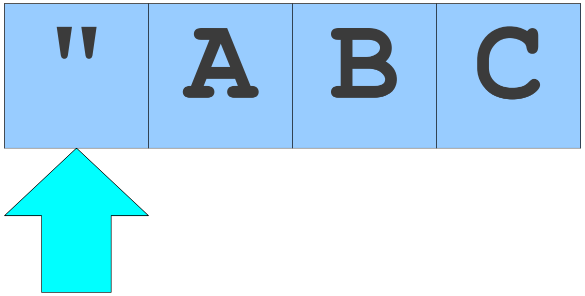




"	A	B	C

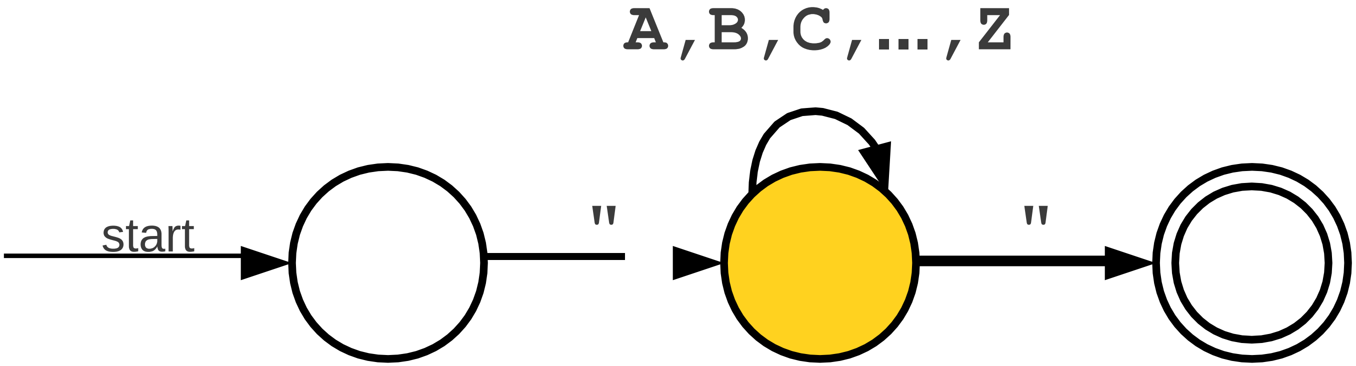
A Simple Automaton

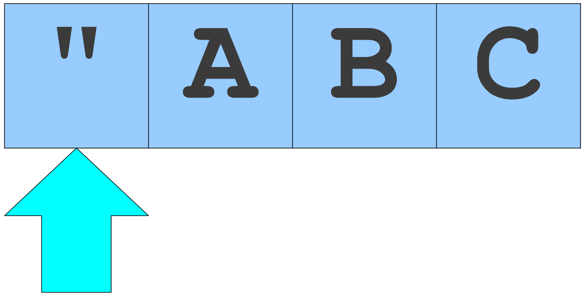




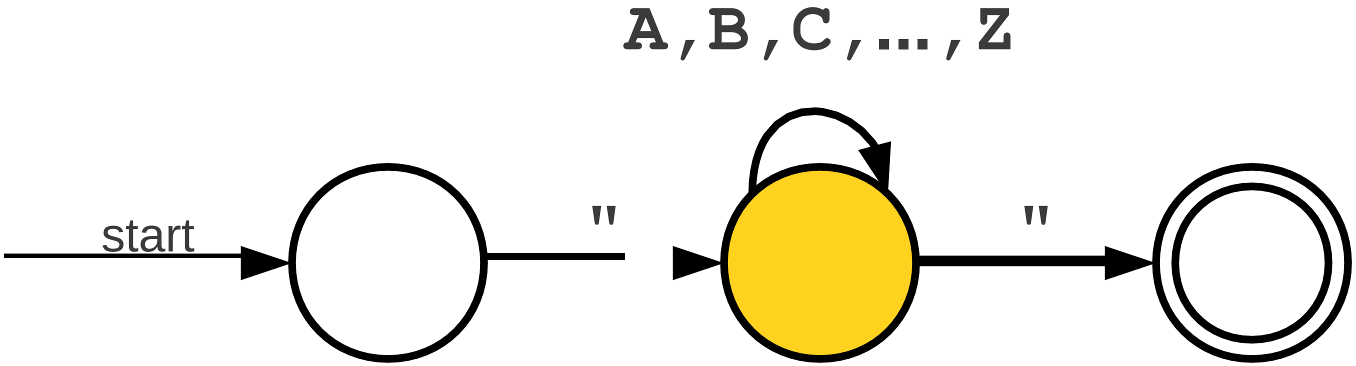
"	A	B	C

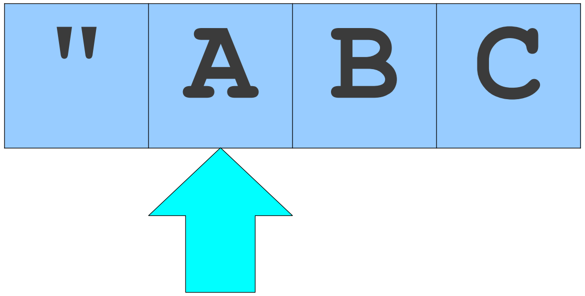
A Simple Automaton



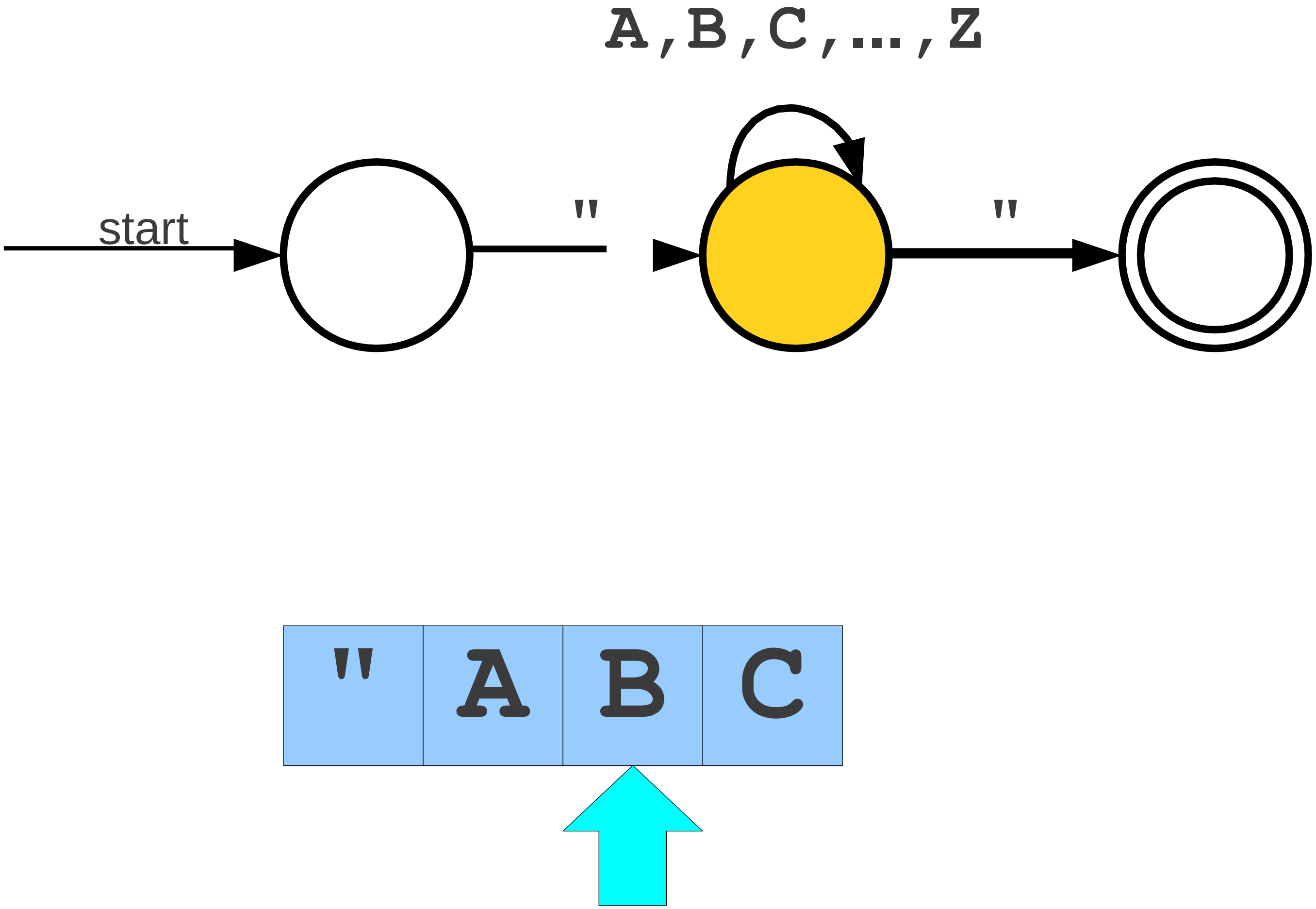


A Simple Automaton

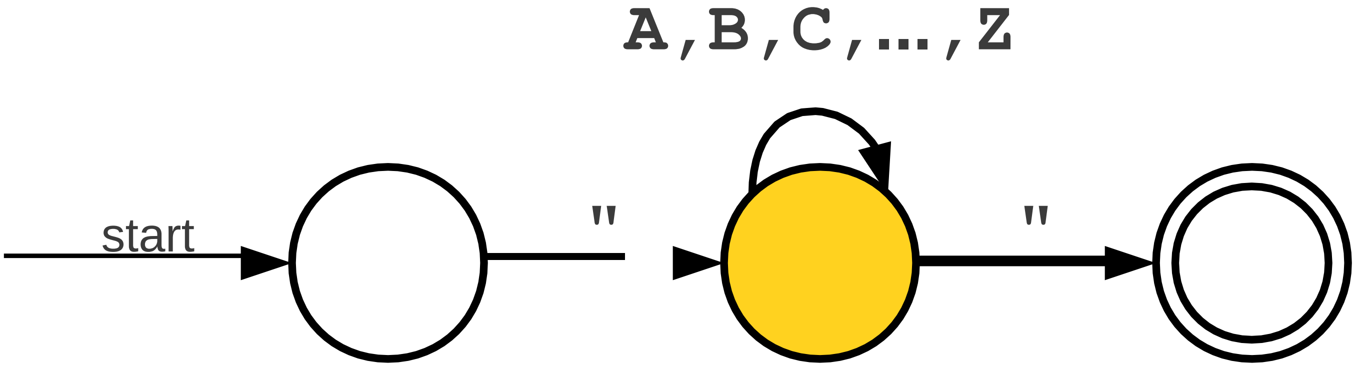


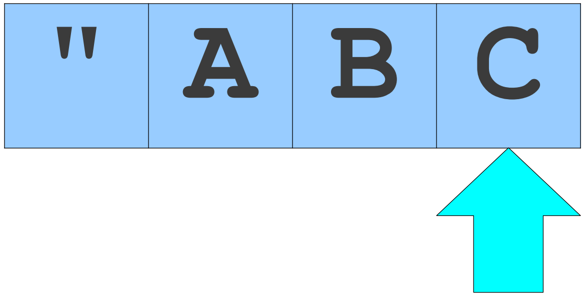


A Simple Automaton



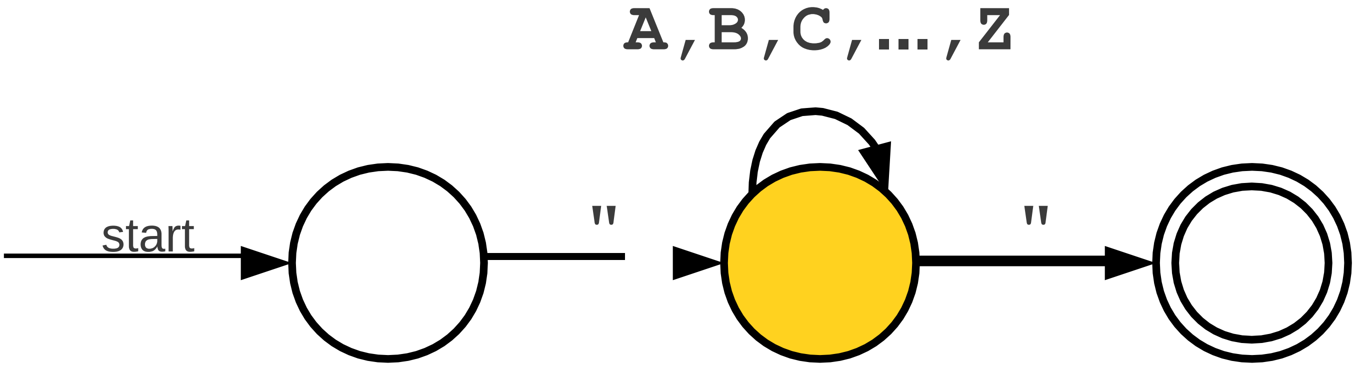
A Simple Automaton





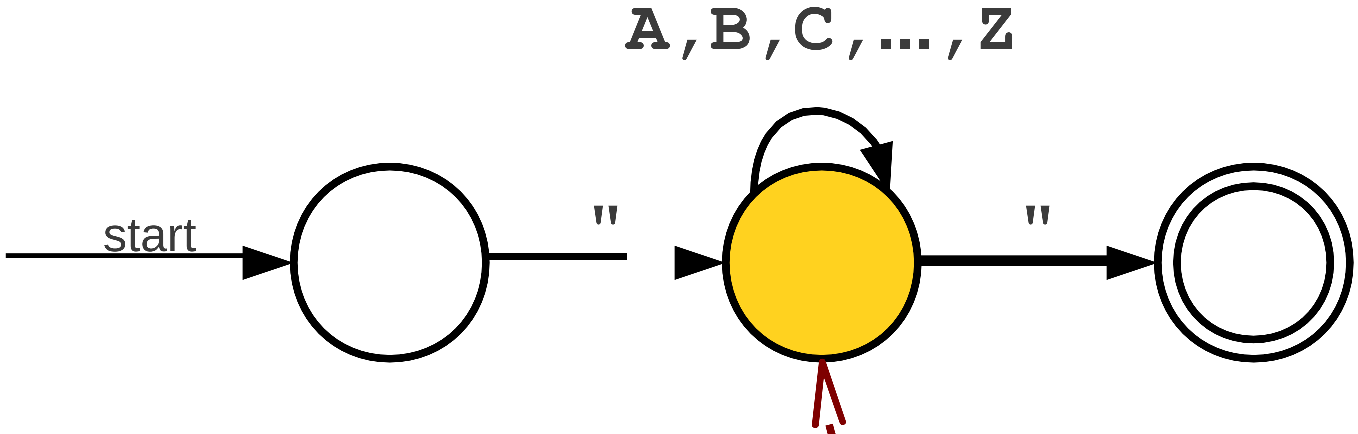
"	A	B	C

A Simple Automaton



"	A	B	C

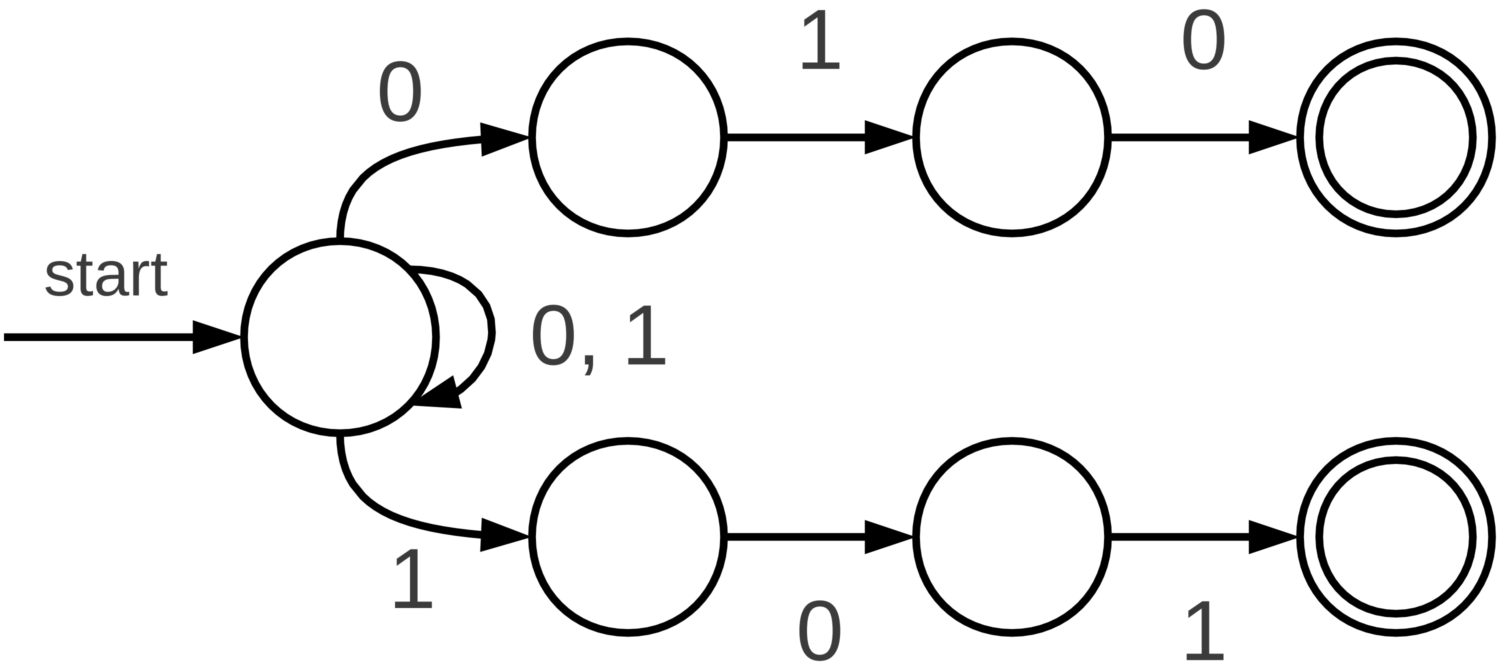
A Simple Automaton



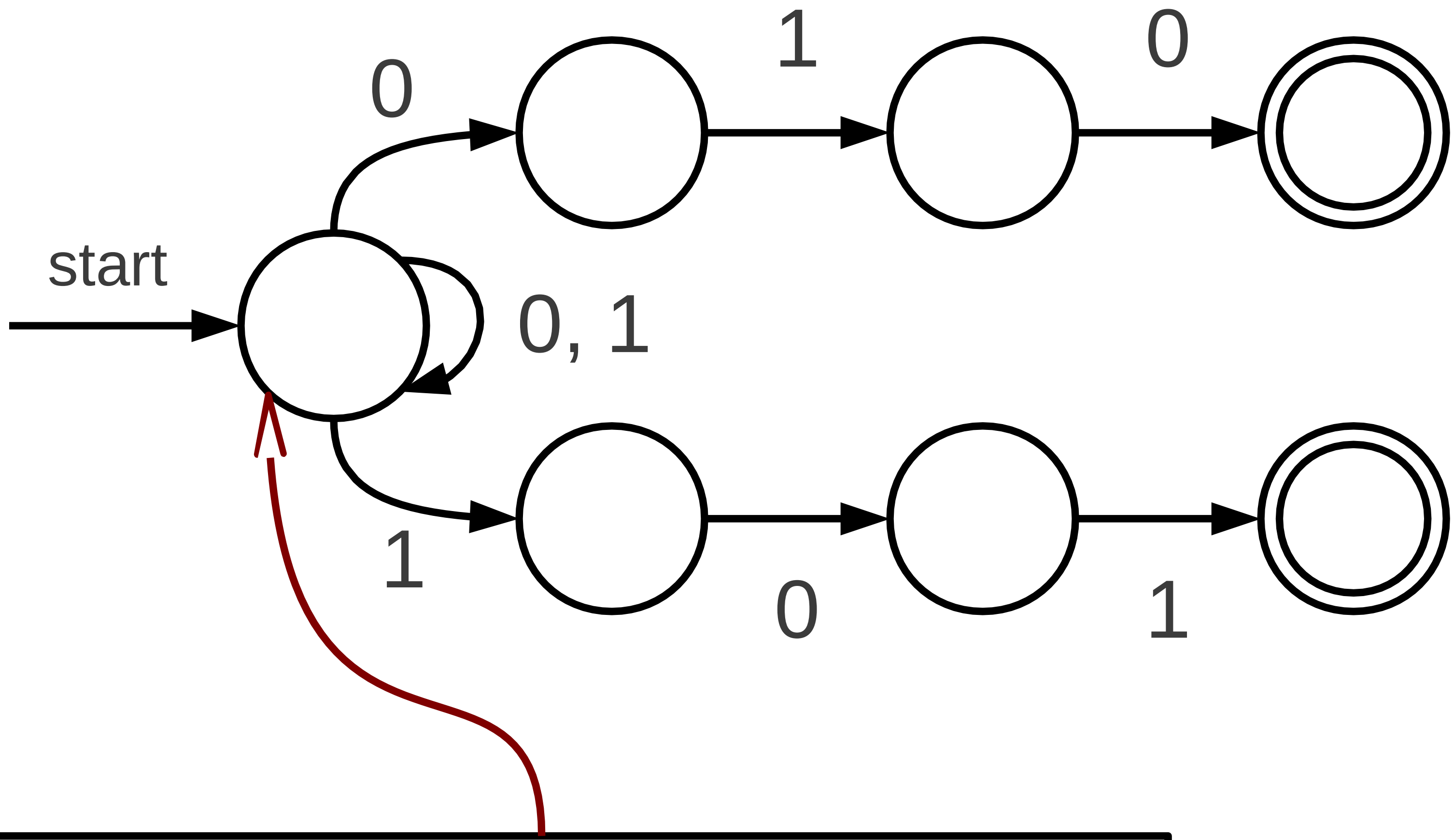
"	A	B	C

This is not an accepting state, so the automaton rejects.

A More Complex Automaton

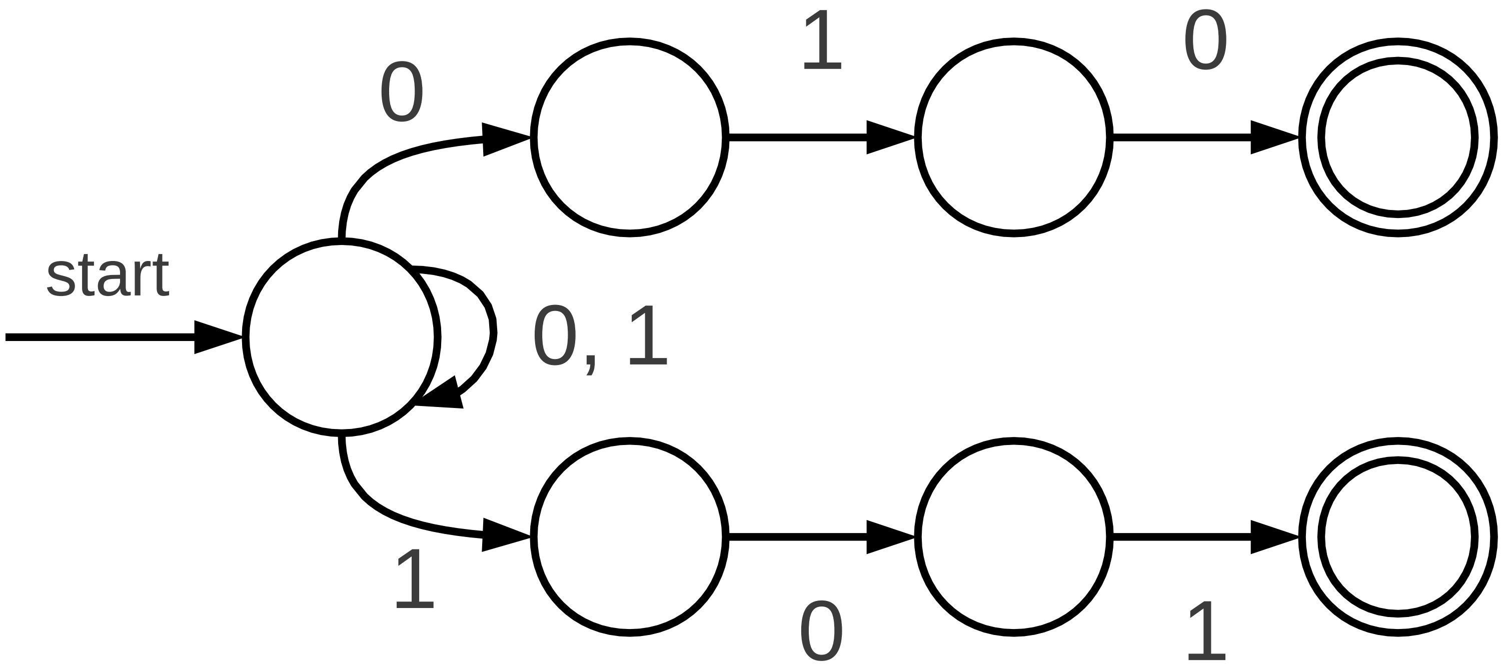


A More Complex Automaton

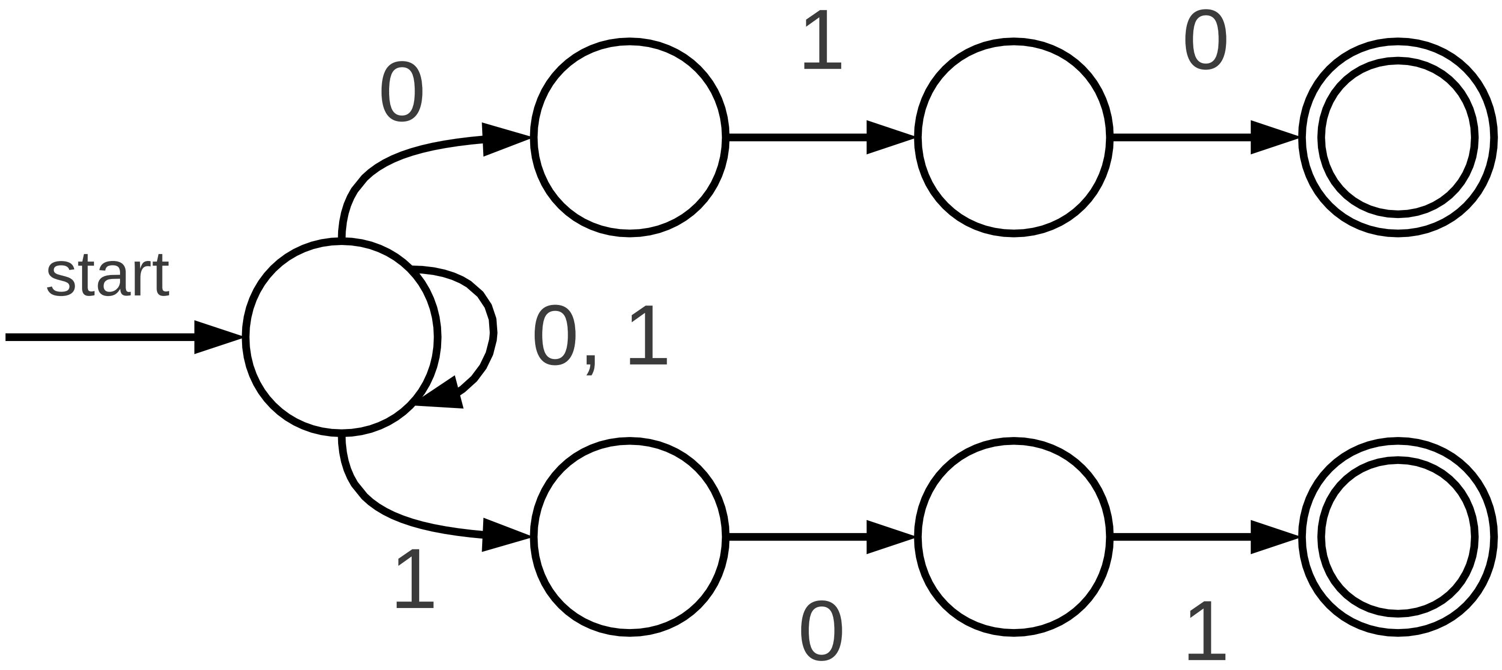


Notice that there are multiple transitions defined here on 0 and 1. If we read a 0 or 1 here, we follow *both* transitions and enter multiple states.

A More Complex Automaton

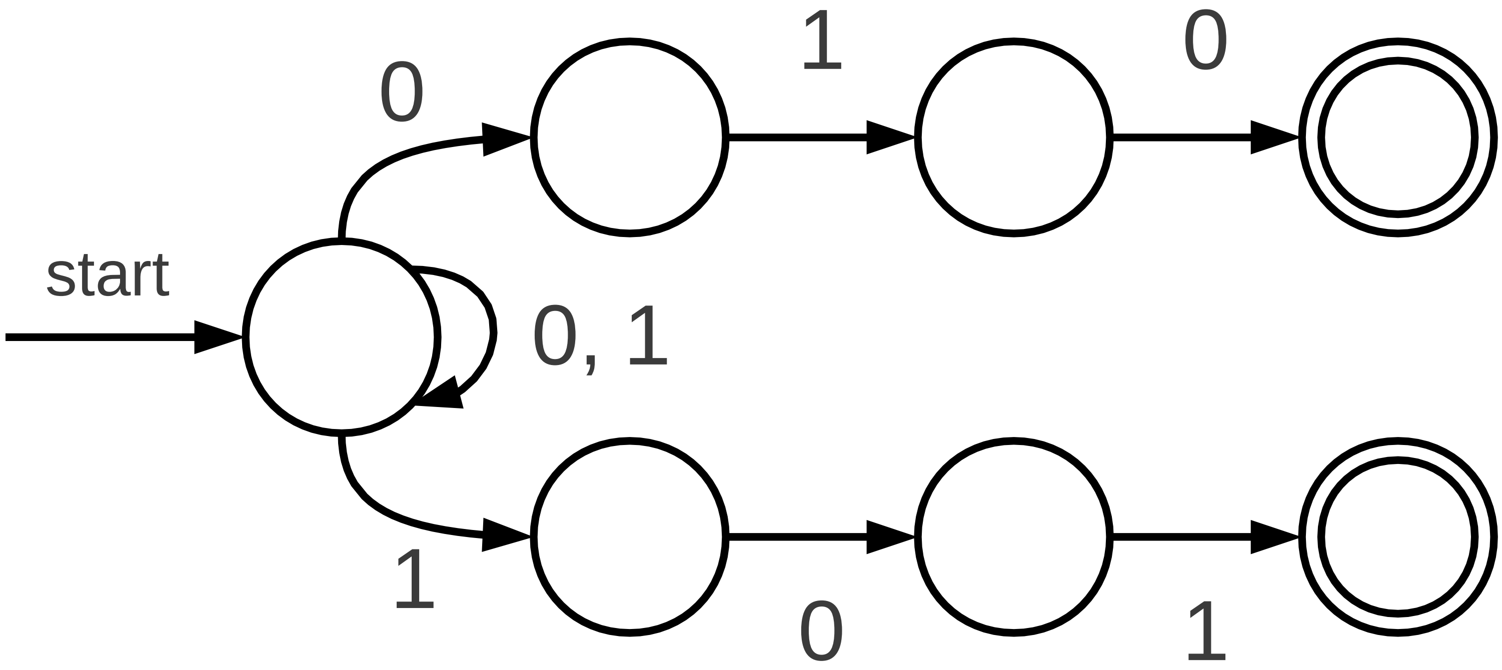


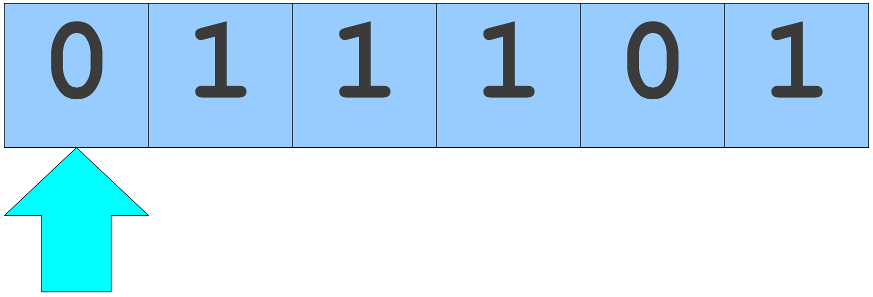
A More Complex Automaton



0	1	1	1	0	1

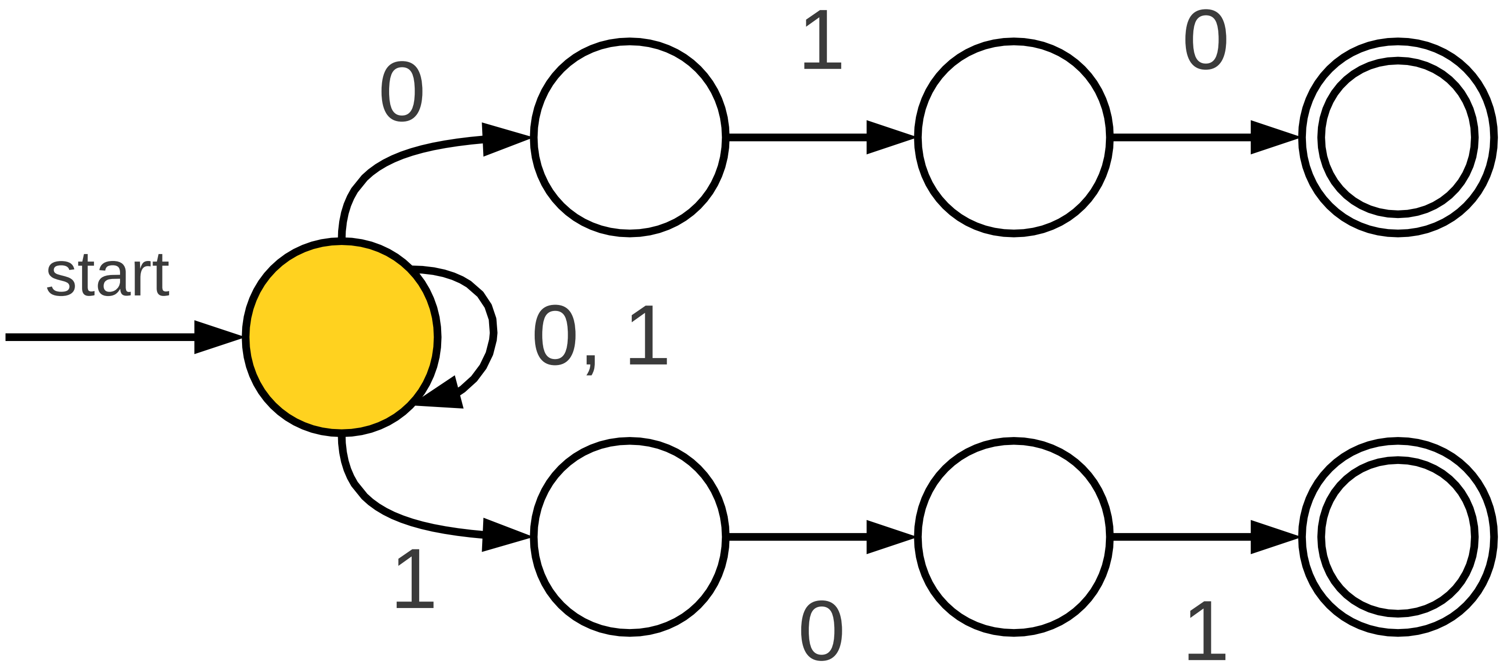
A More Complex Automaton

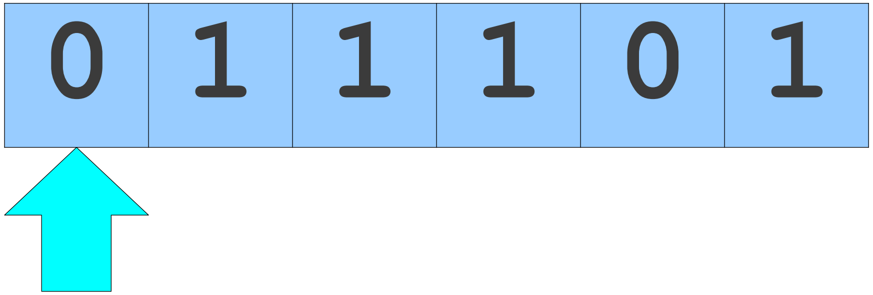




0	1	1	1	0	1

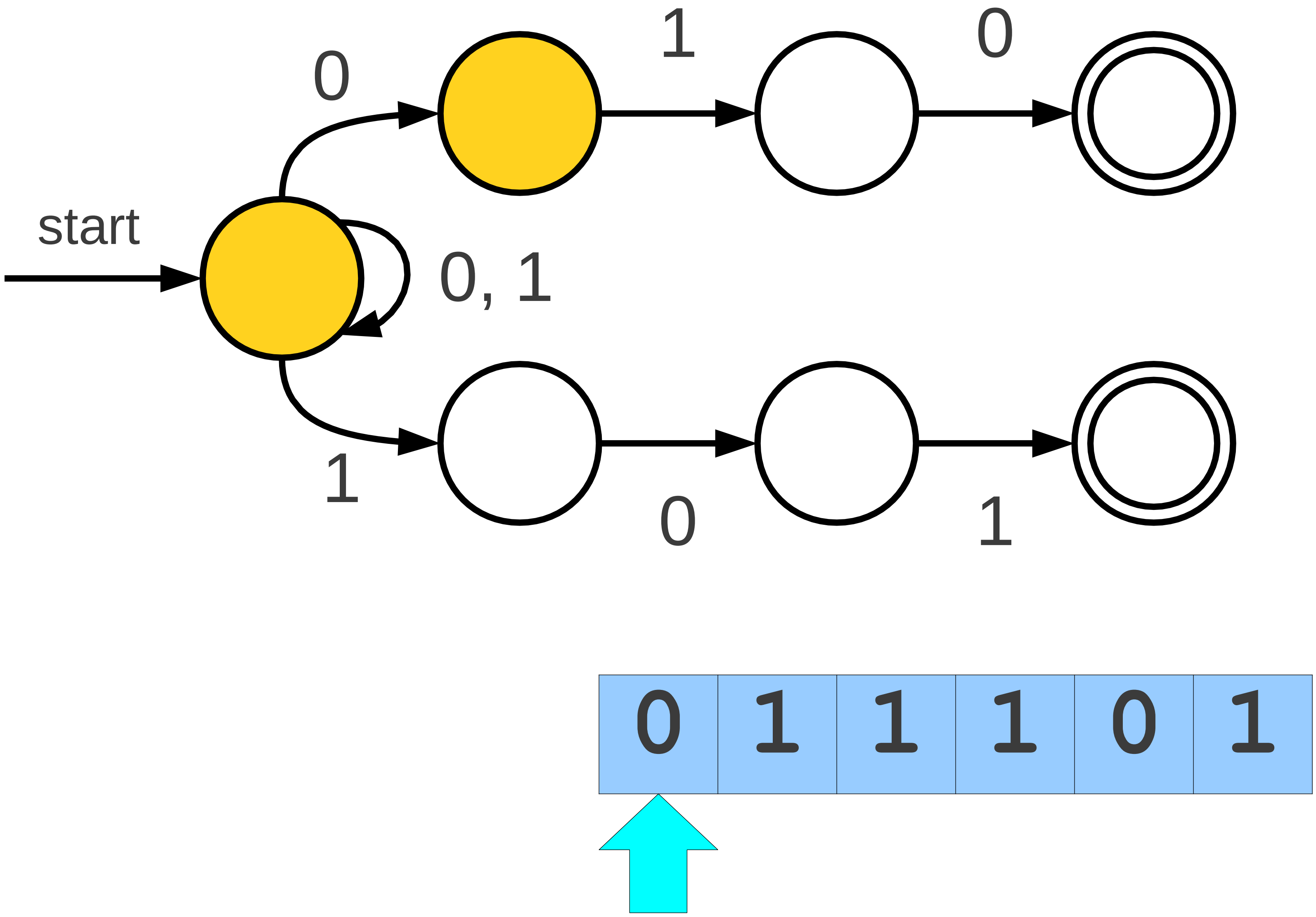
A More Complex Automaton



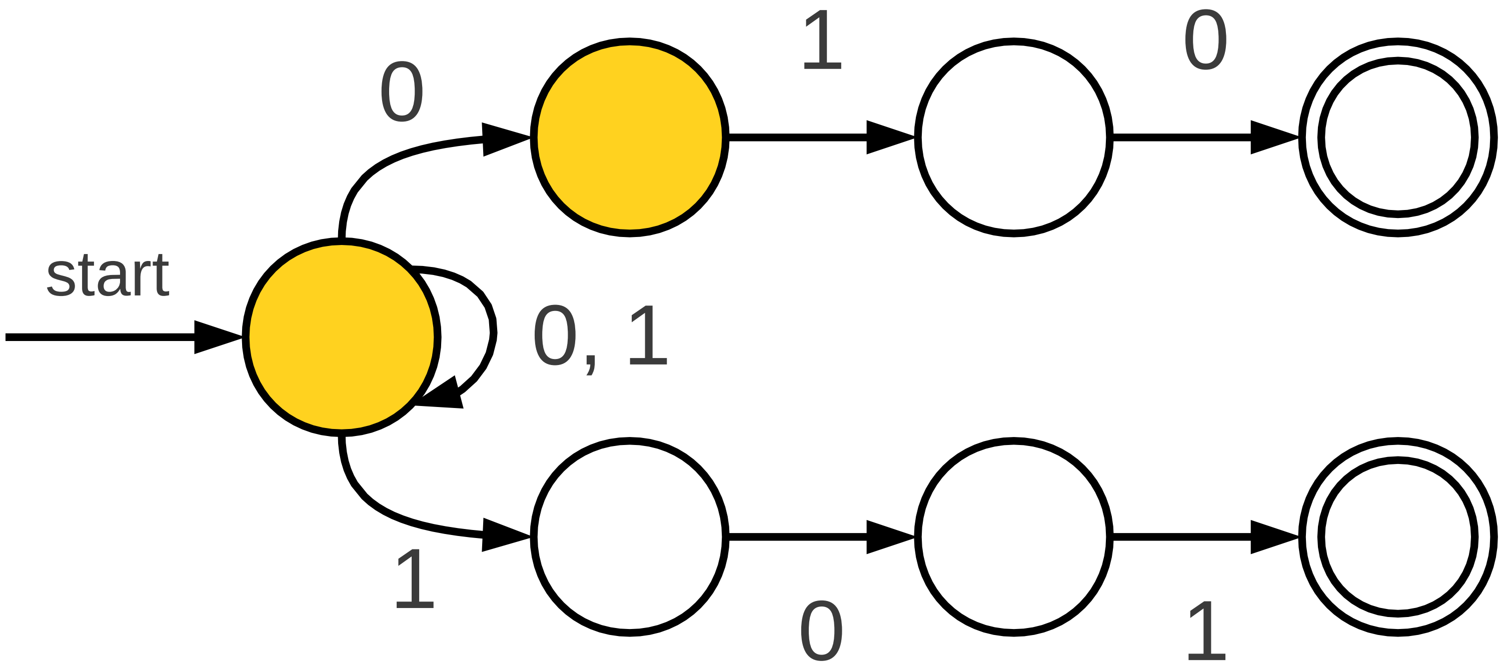


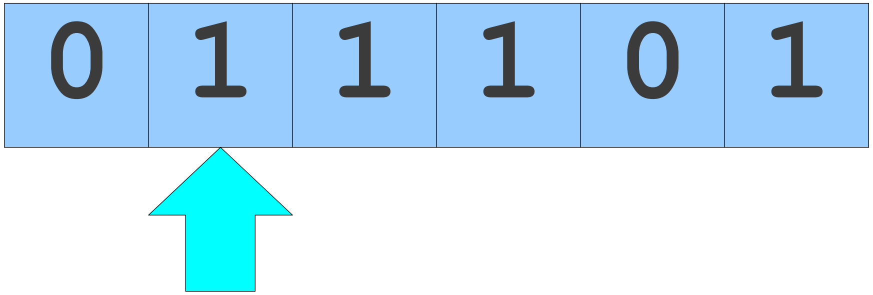
0	1	1	1	0	1

A More Complex Automaton



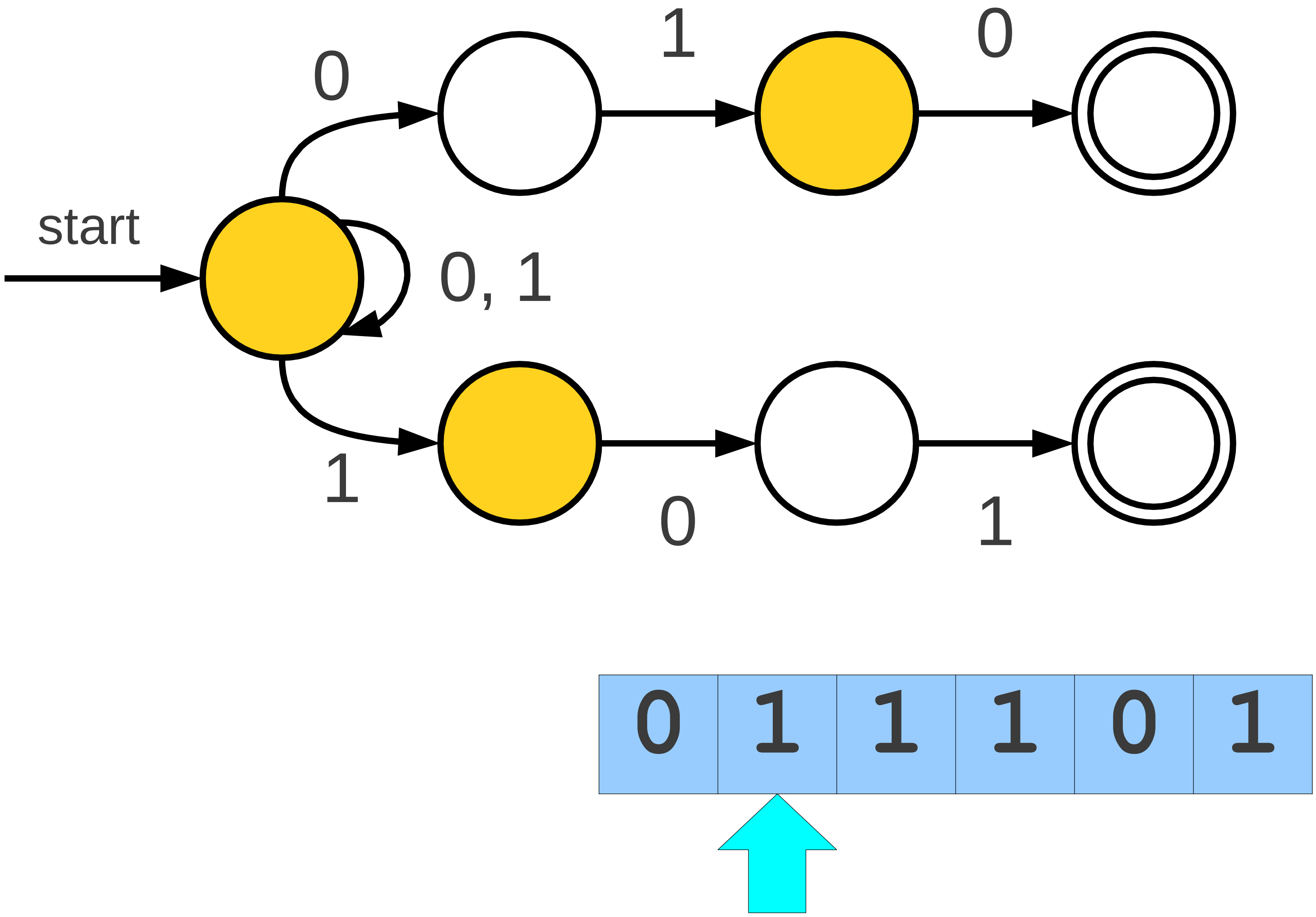
A More Complex Automaton



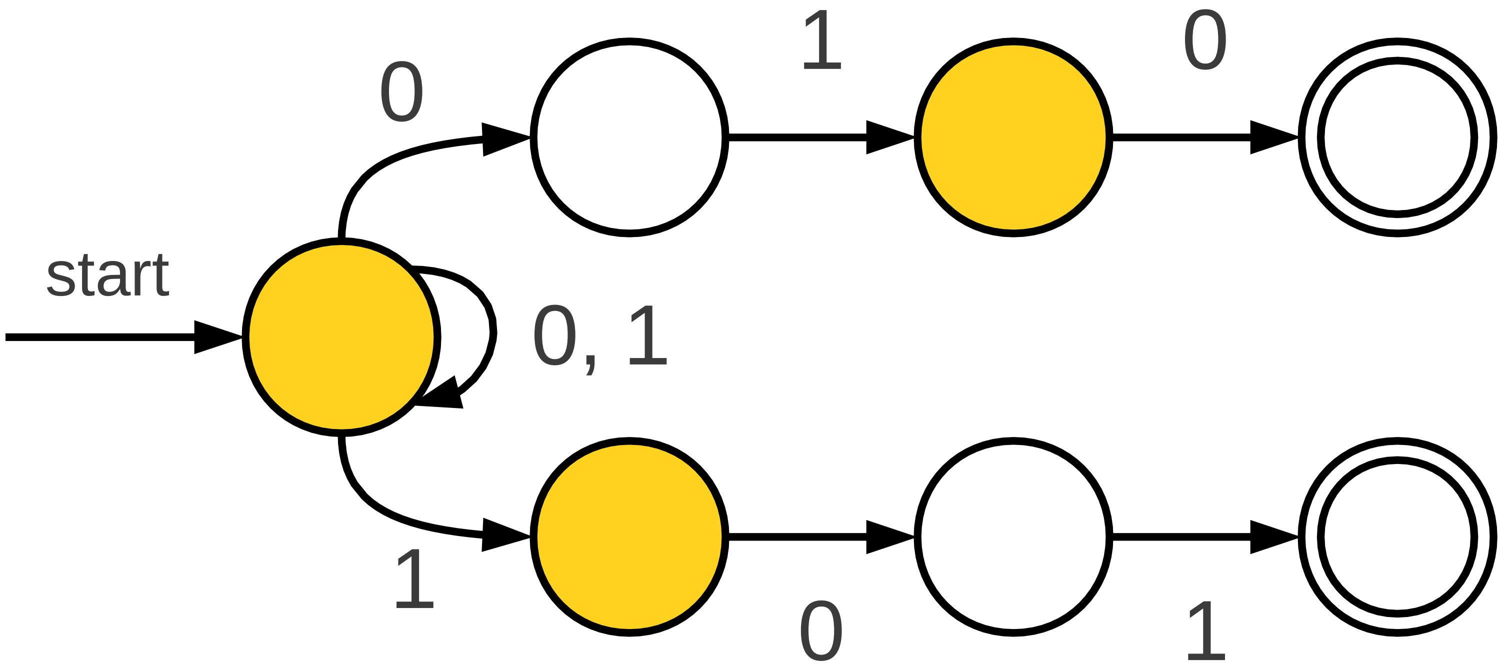


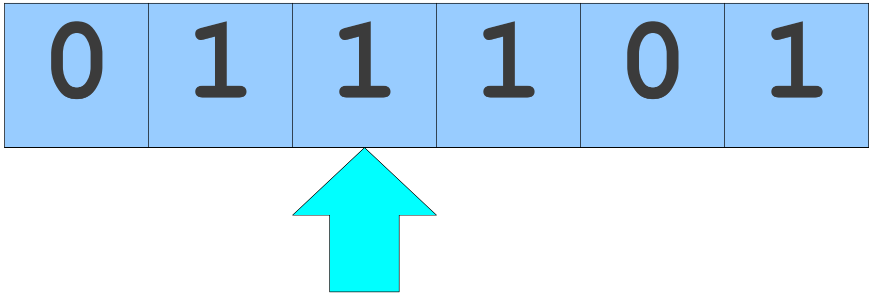
0	1	1	1	0	1

A More Complex Automaton



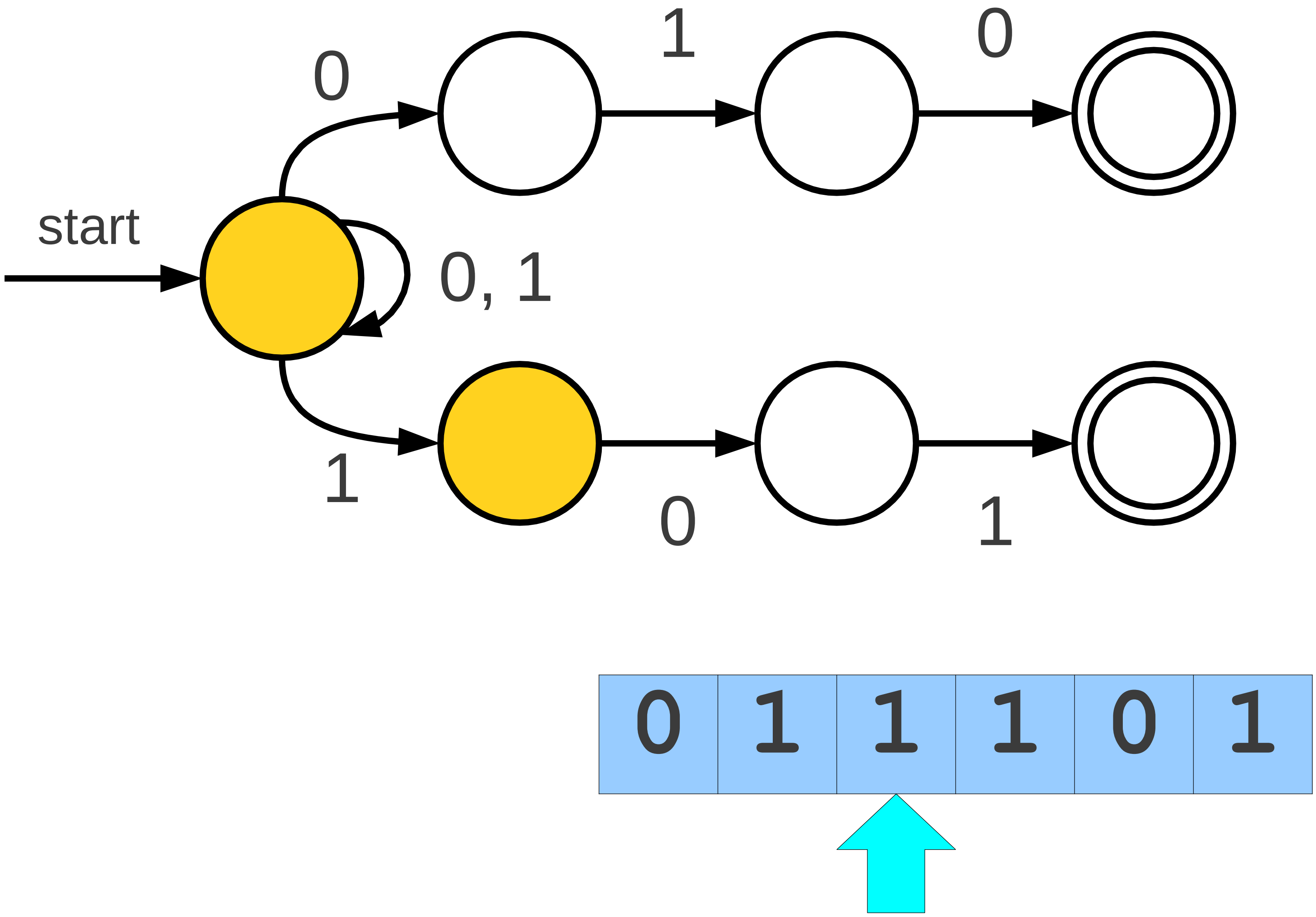
A More Complex Automaton



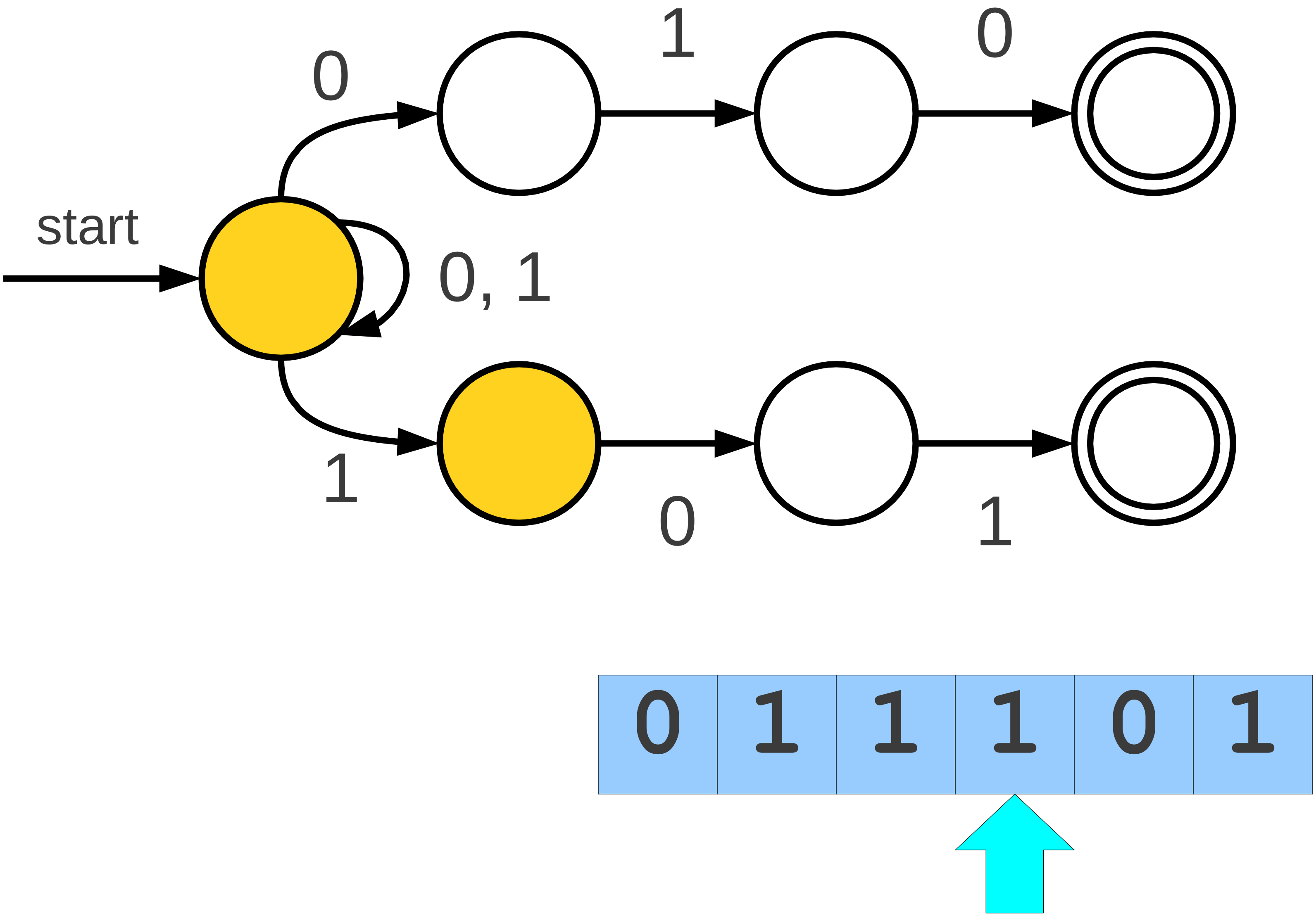


0	1	1	1	0	1

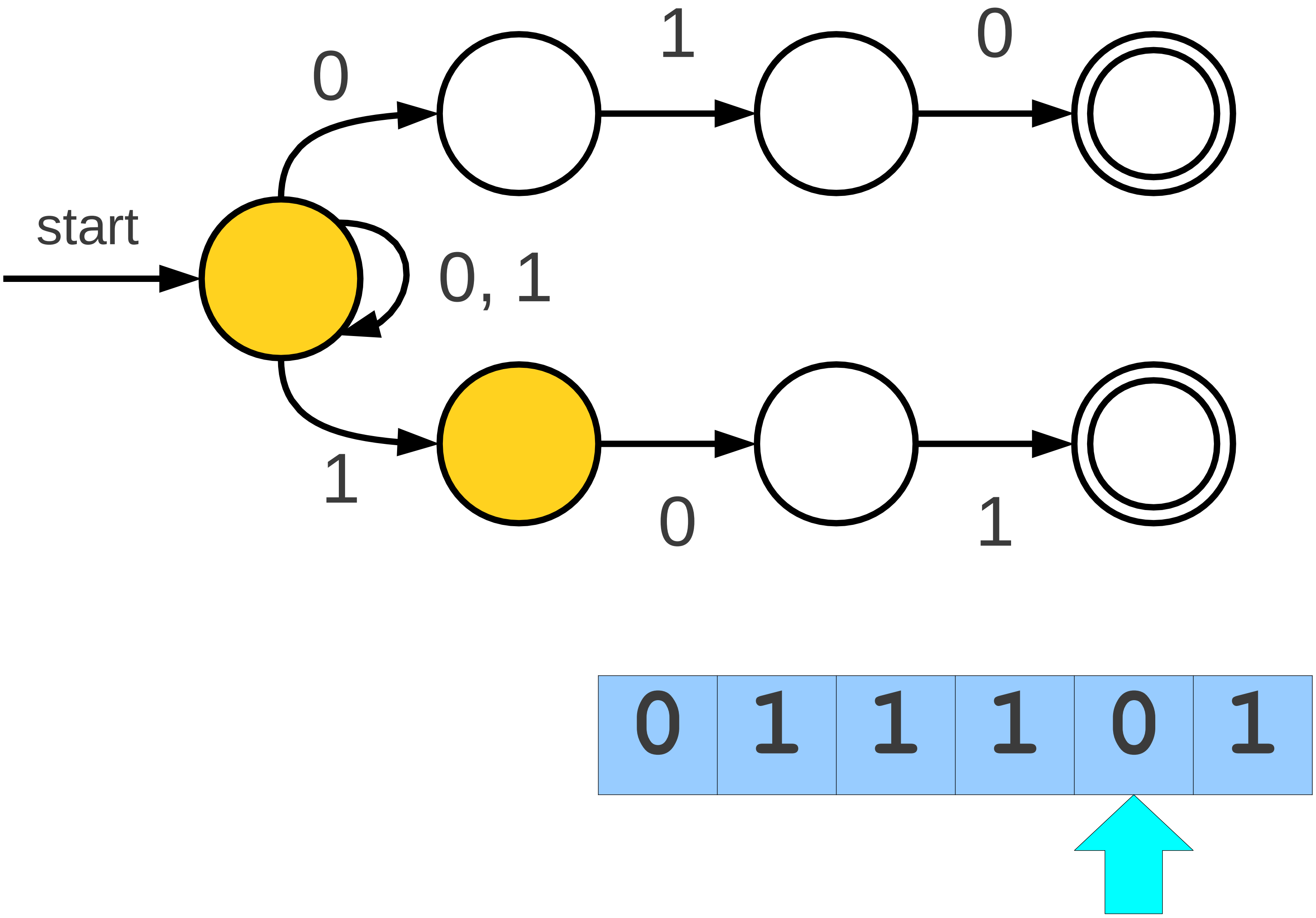
A More Complex Automaton



A More Complex Automaton

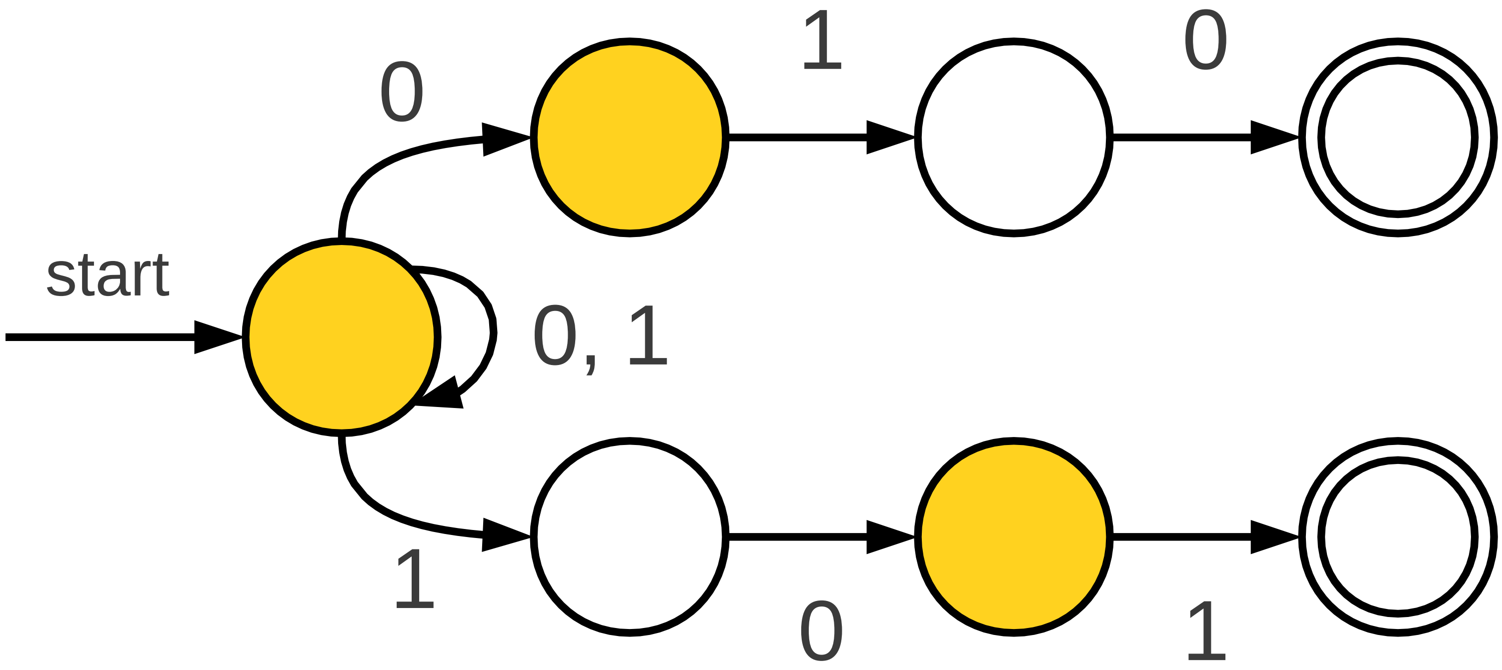


A More Complex Automaton



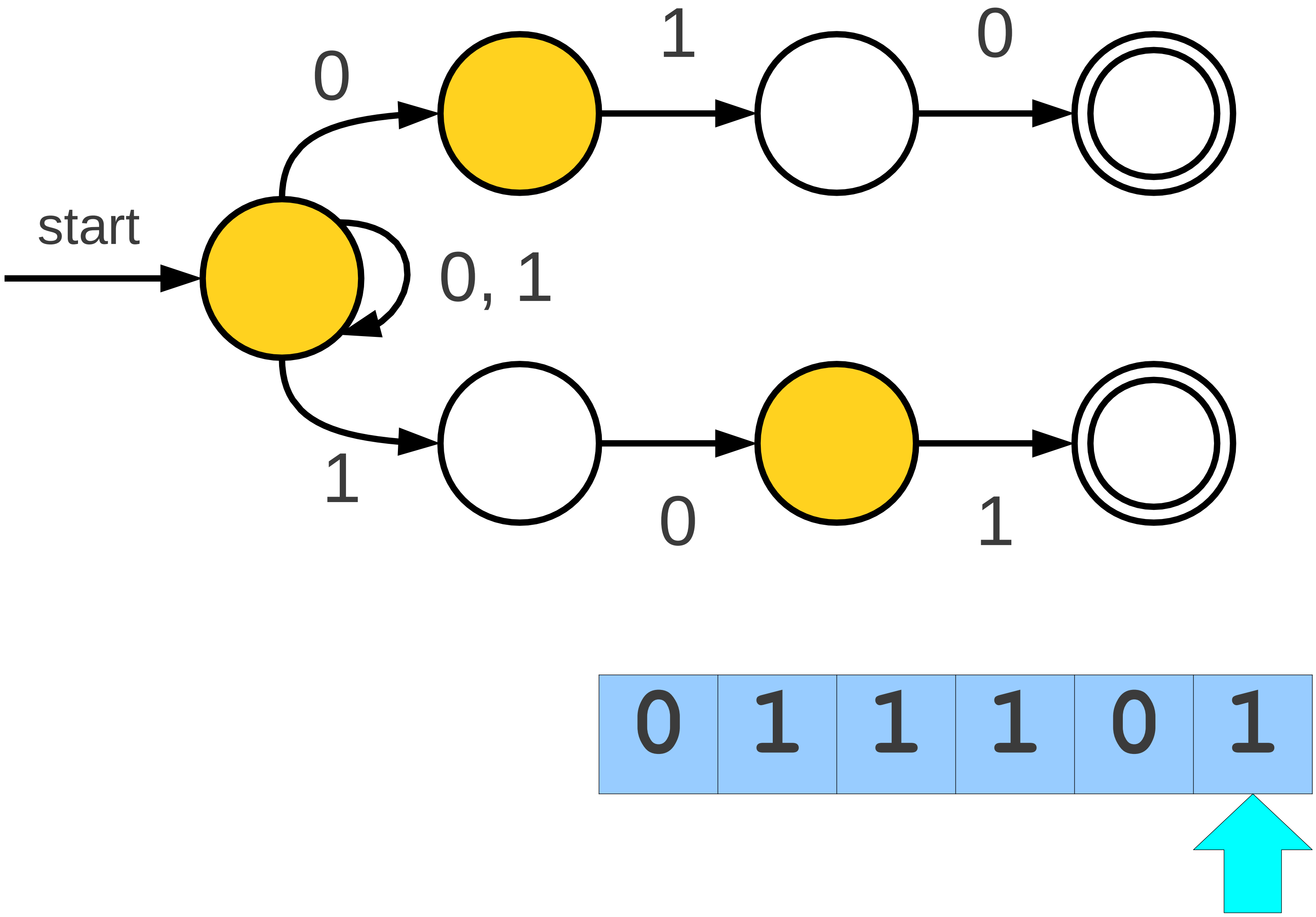
0 1 1 1 0 1

A More Complex Automaton



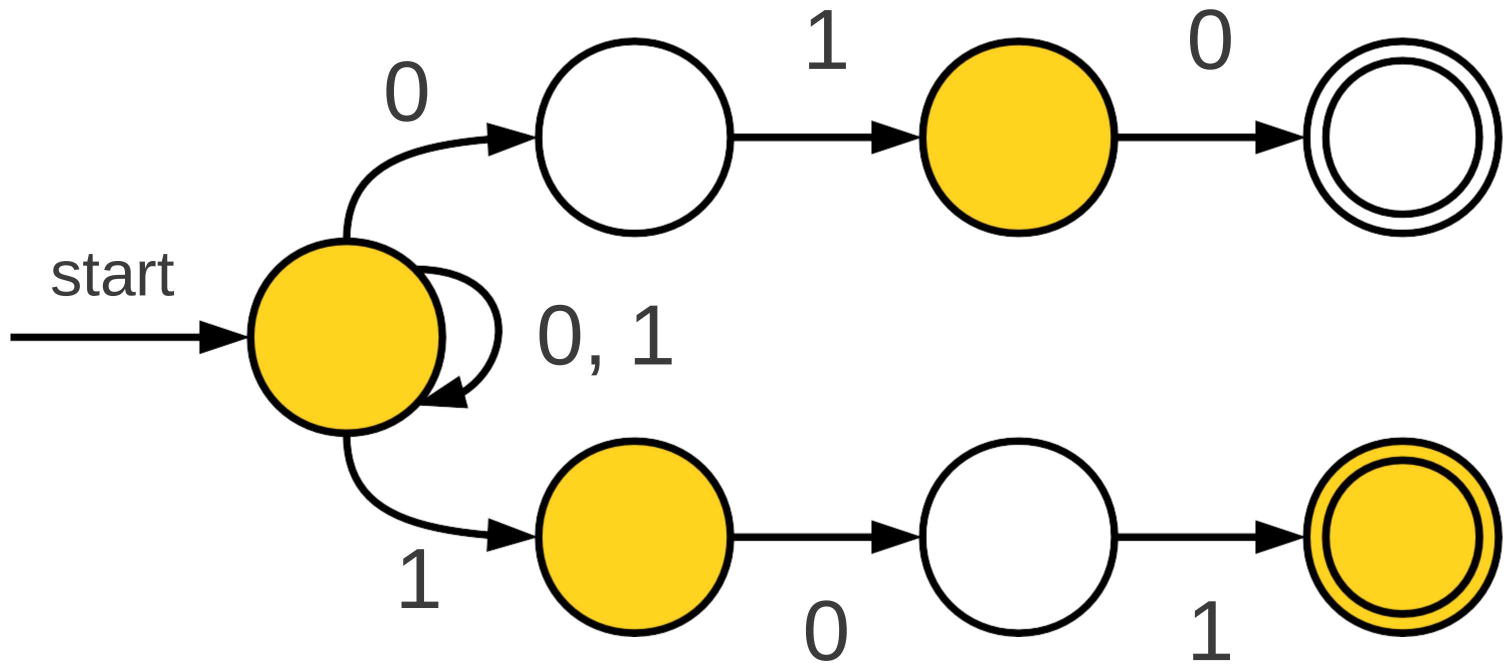
0	1	1	1	0	1

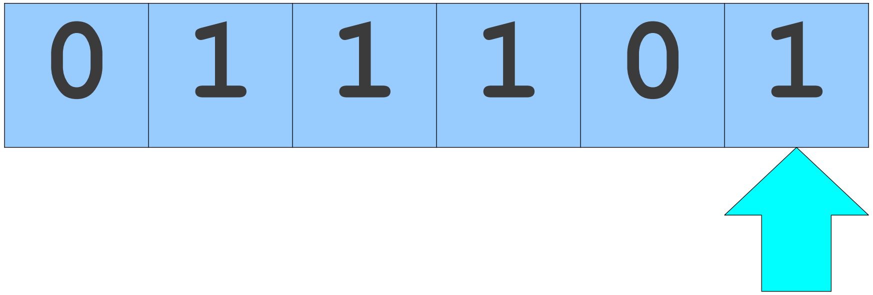
A More Complex Automaton



0	1	1	1	0	1

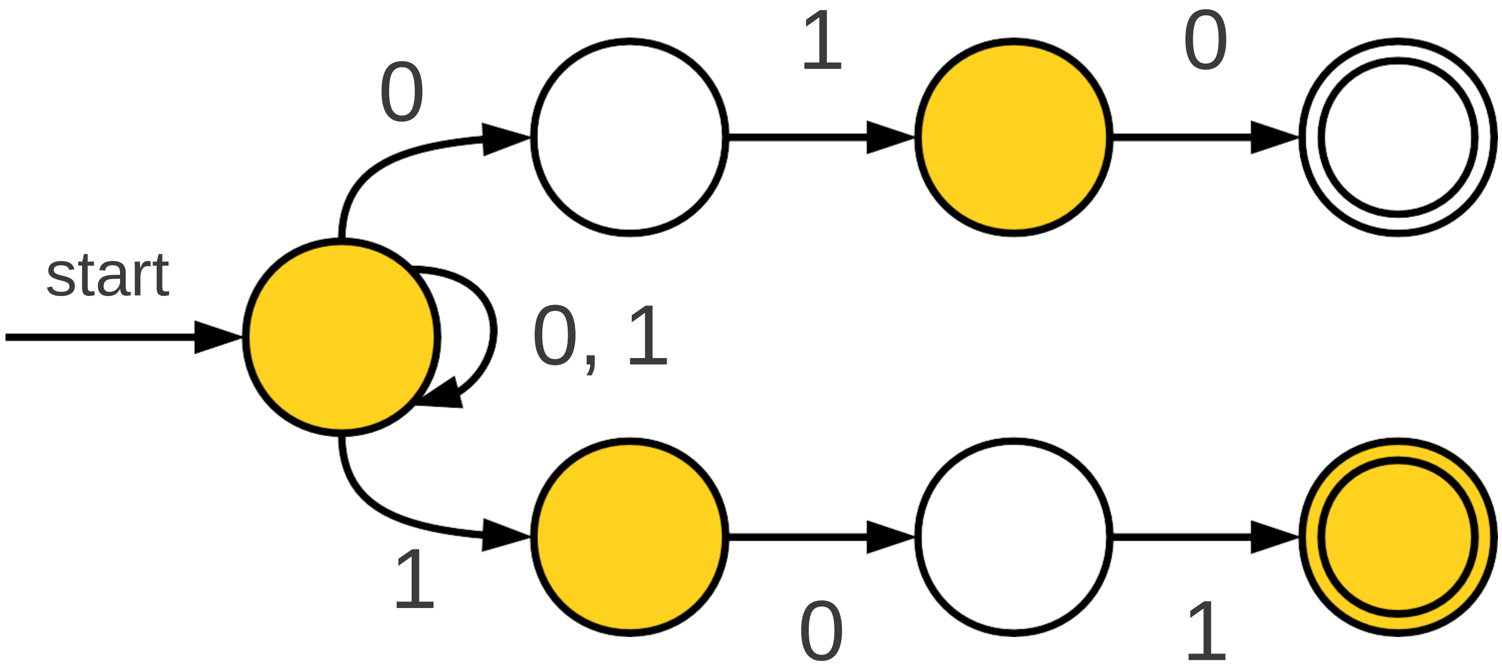
A More Complex Automaton





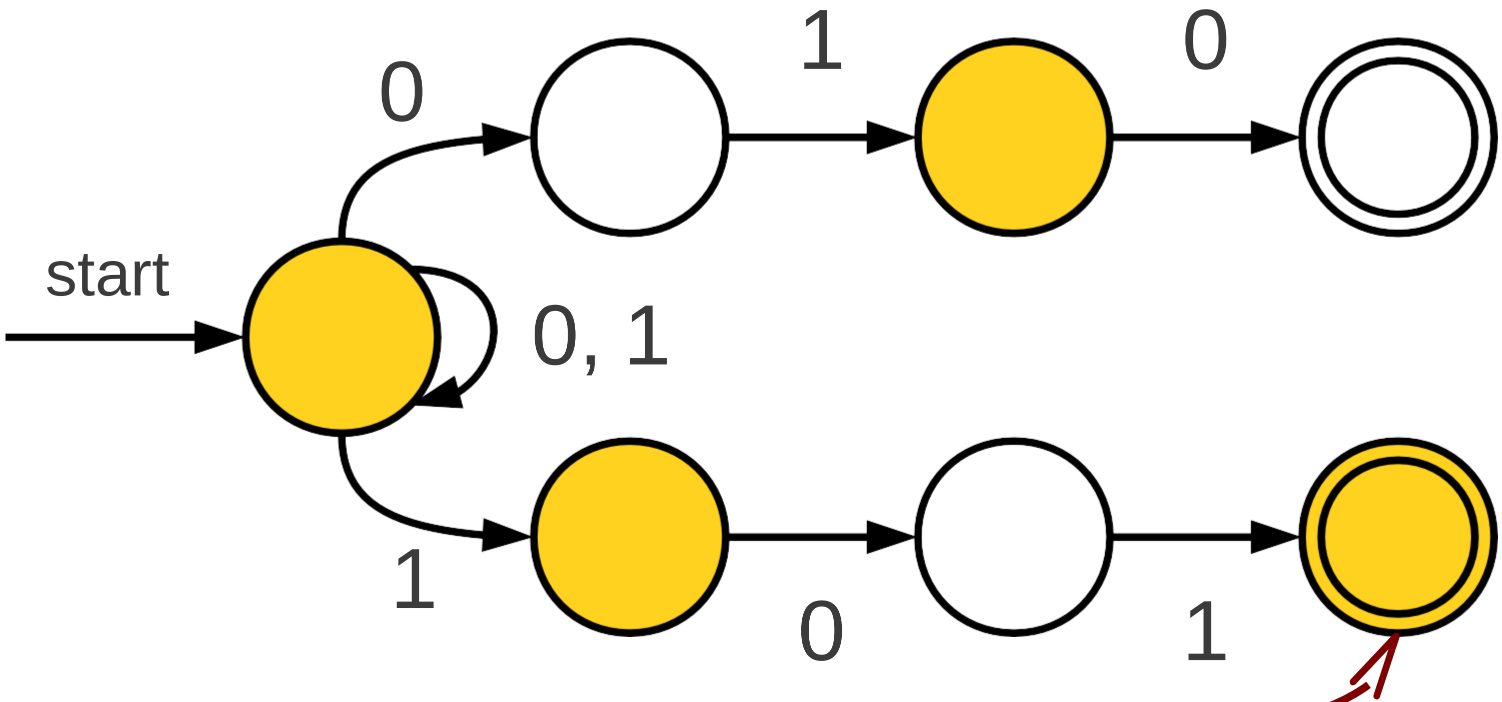
0	1	1	1	0	1

A More Complex Automaton



0	1	1	1	0	1

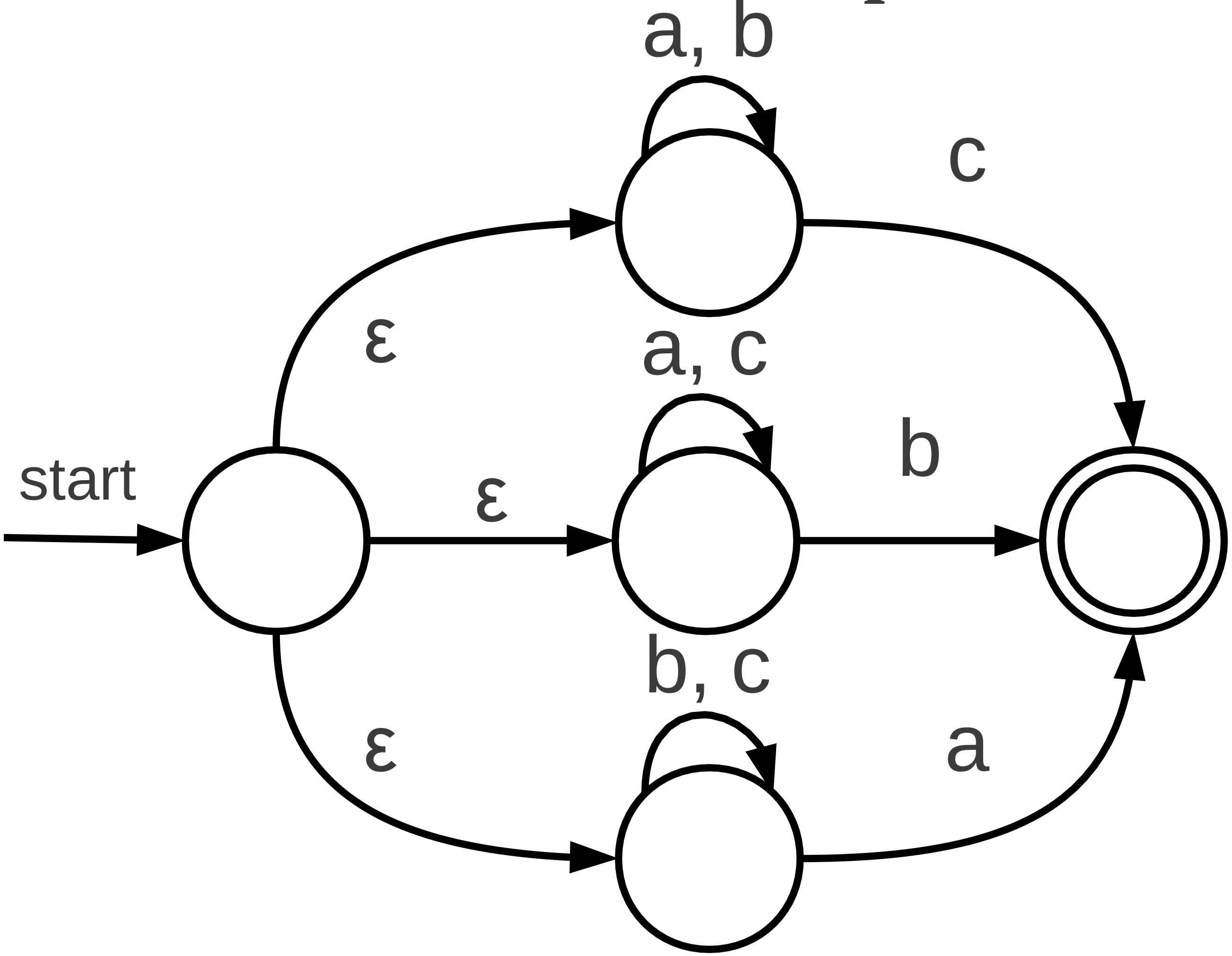
A More Complex Automaton



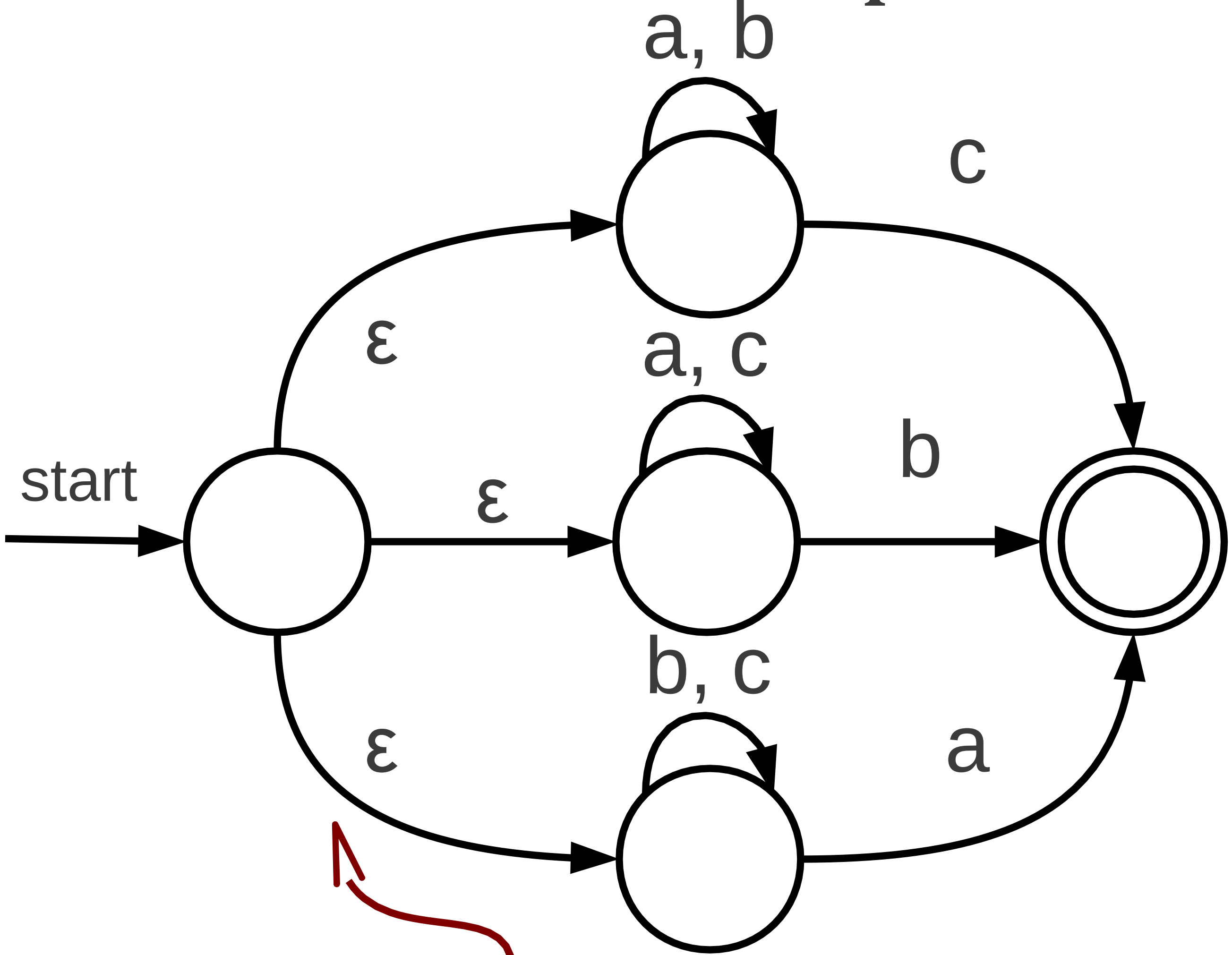
0	1	1	1	0	1

Since we are in at least one accepting state, the automaton accepts.

An Even More Complex Automaton

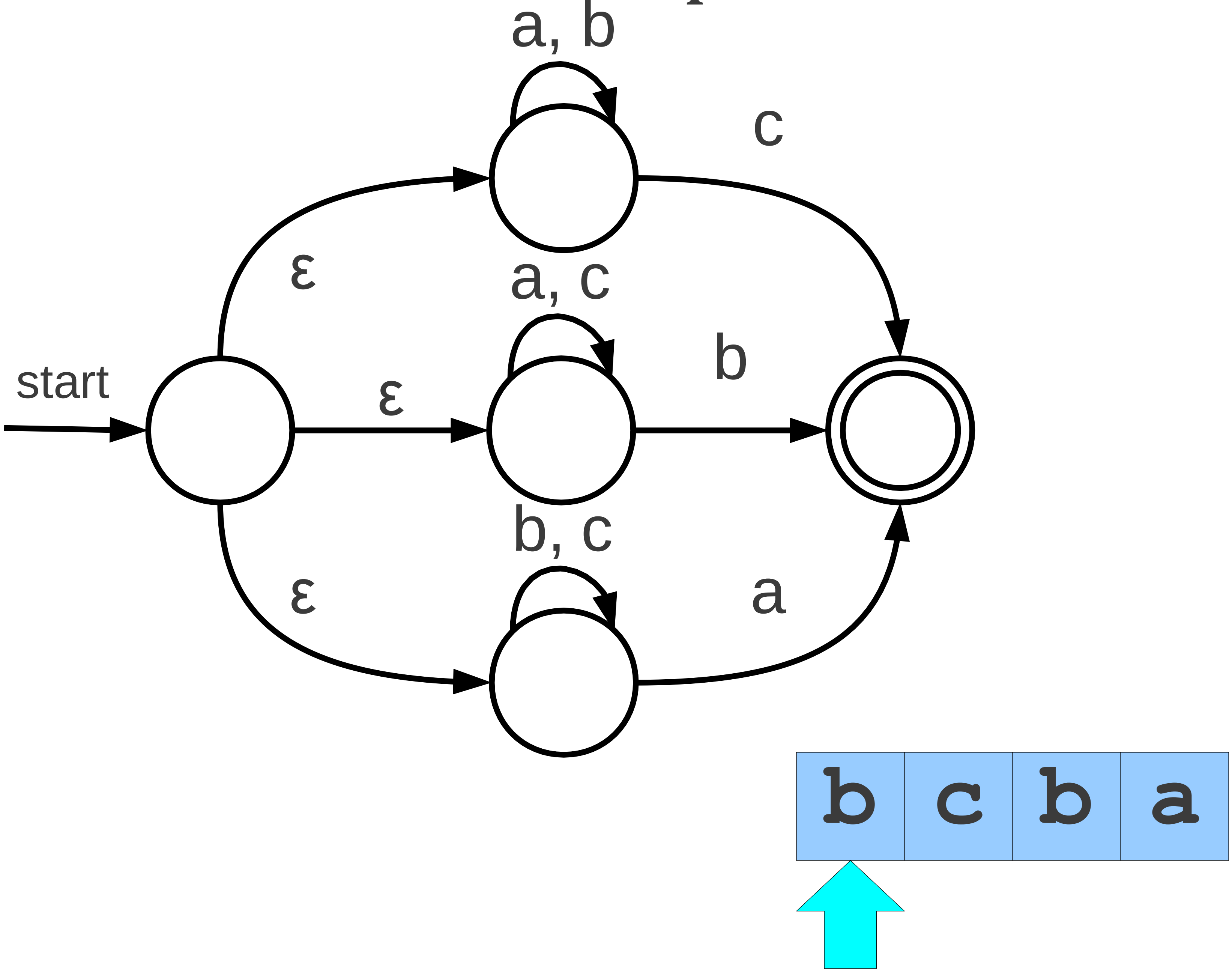


An Even More Complex Automaton

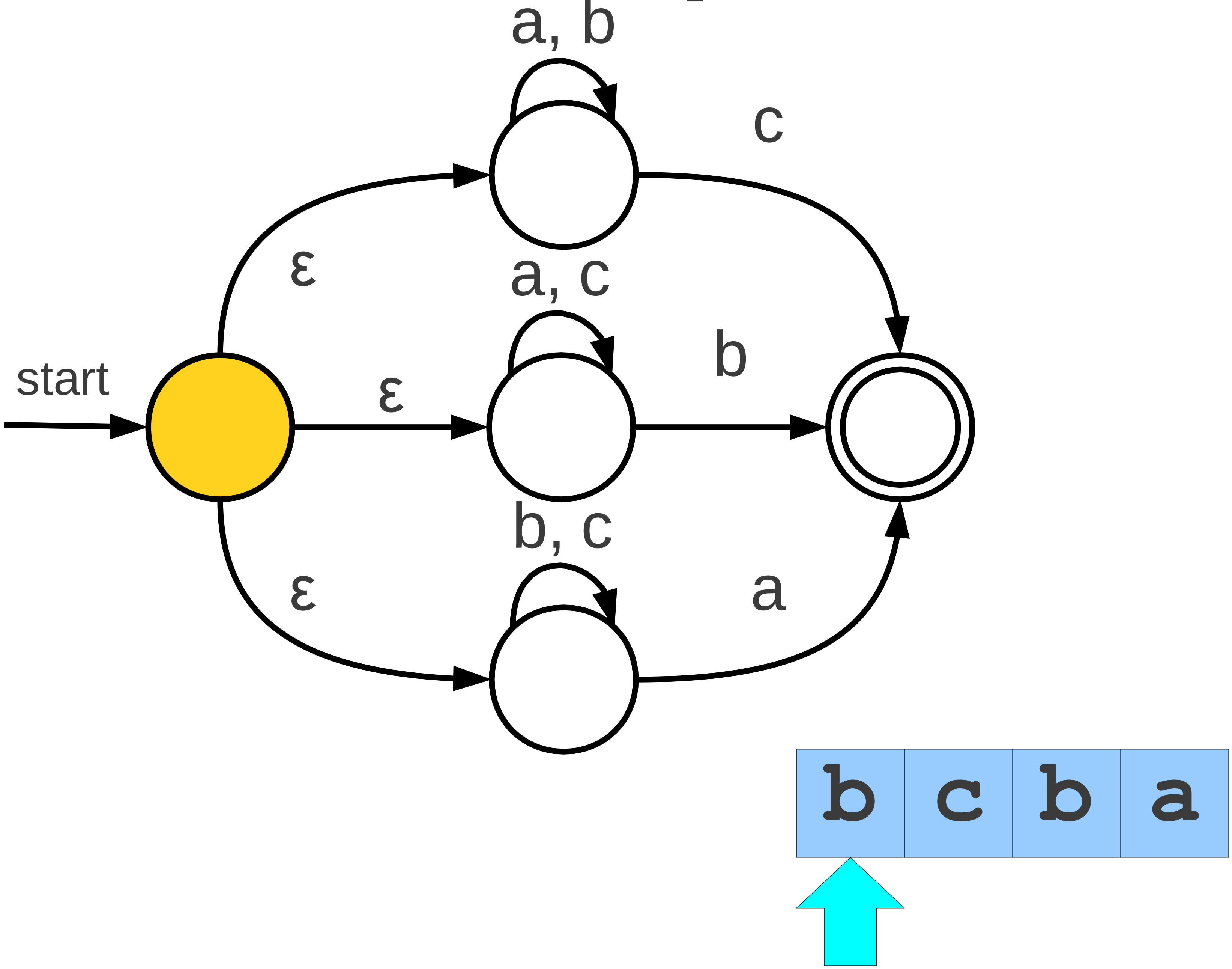


These are called **ε-transitions**. These transitions are followed automatically and without consuming any input.

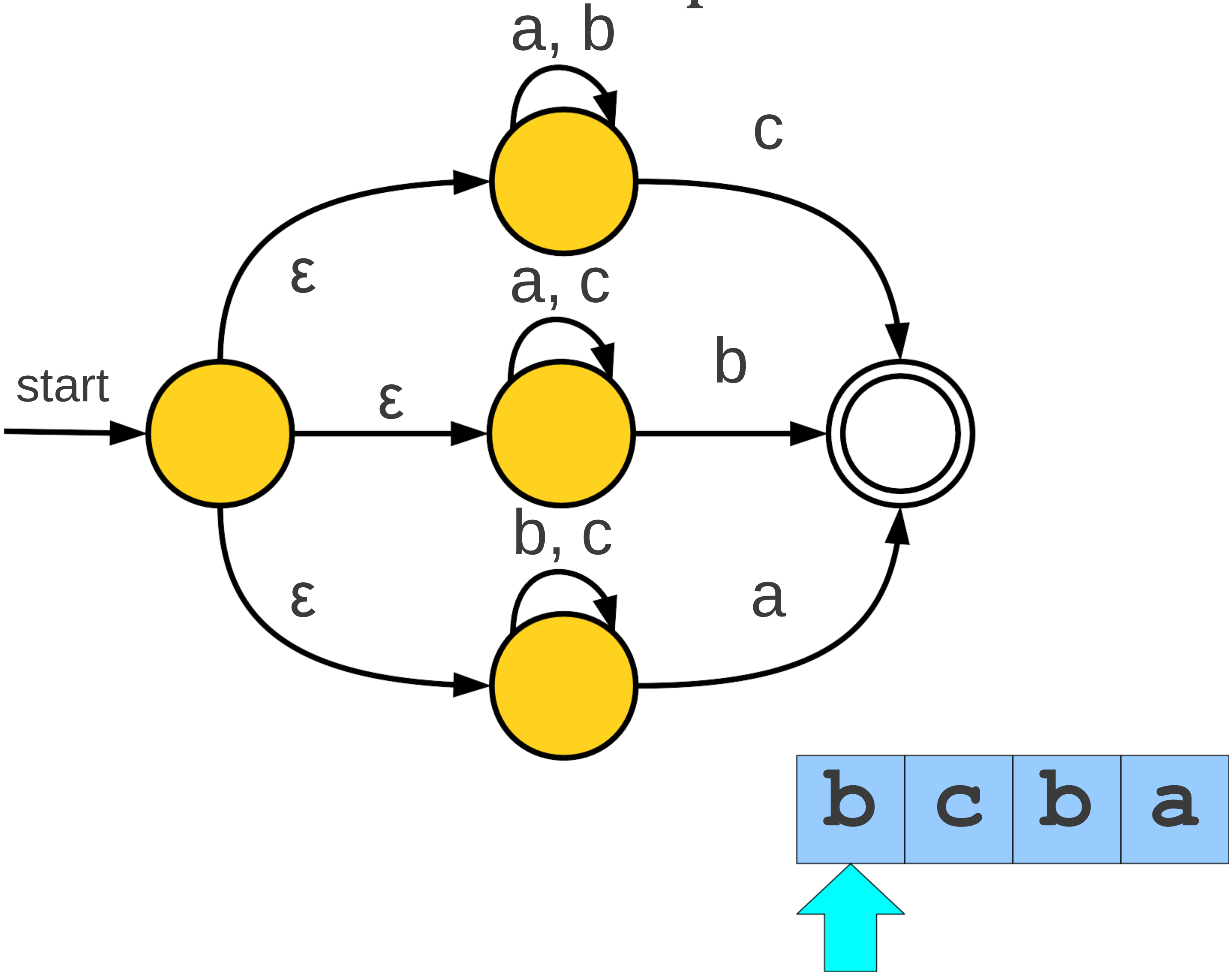
An Even More Complex Automaton



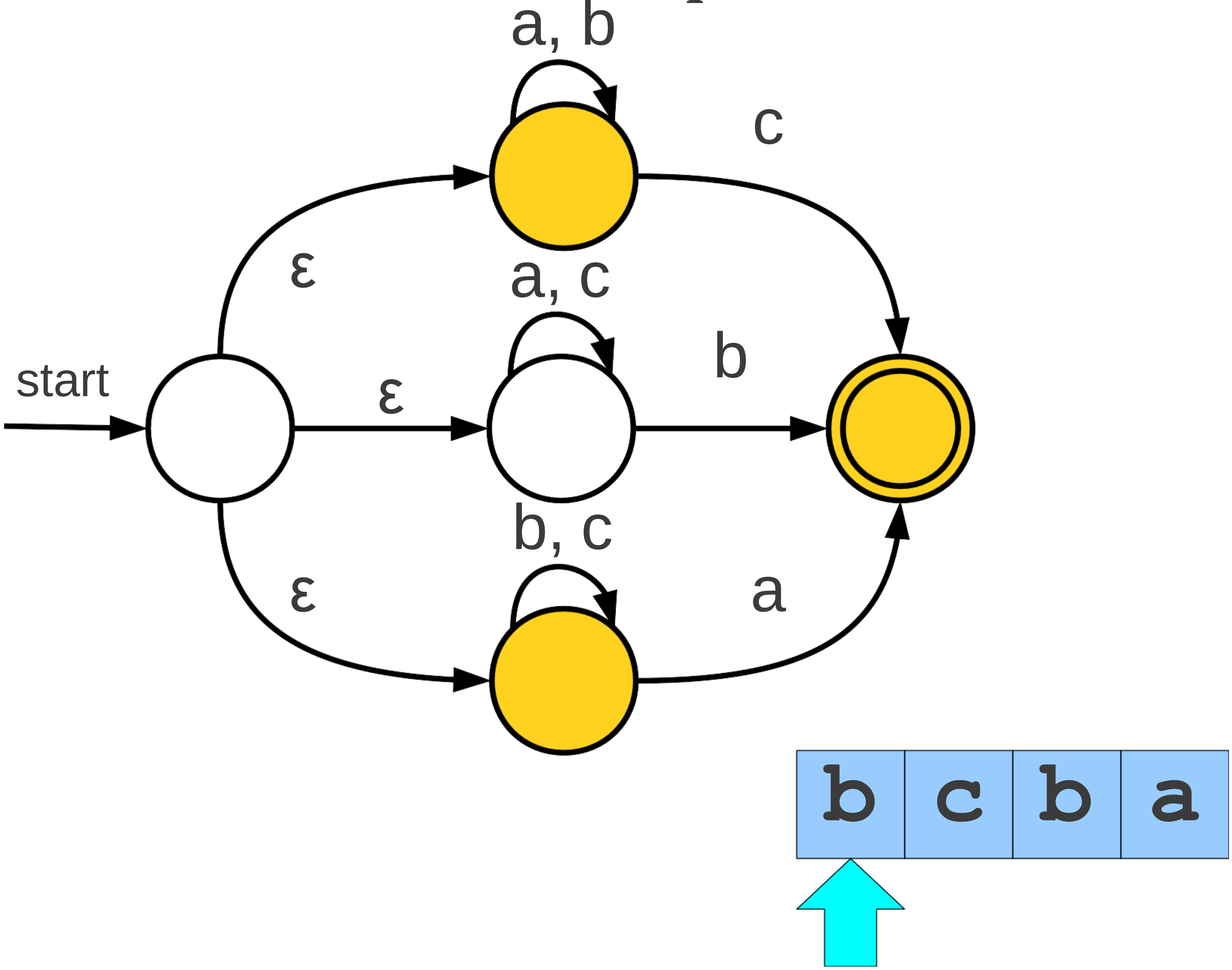
An Even More Complex Automaton



An Even More Complex Automaton



An Even More Complex Automaton



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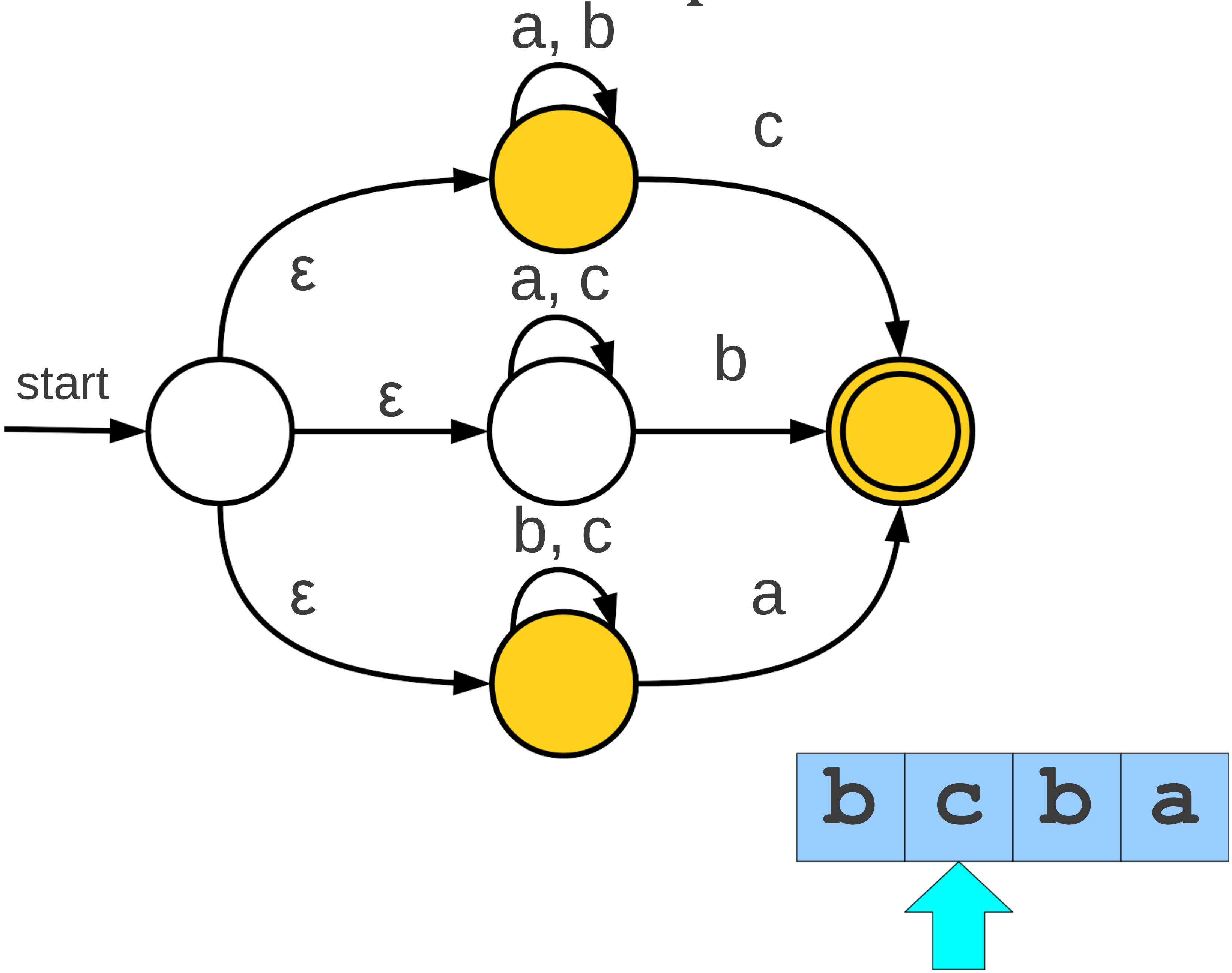

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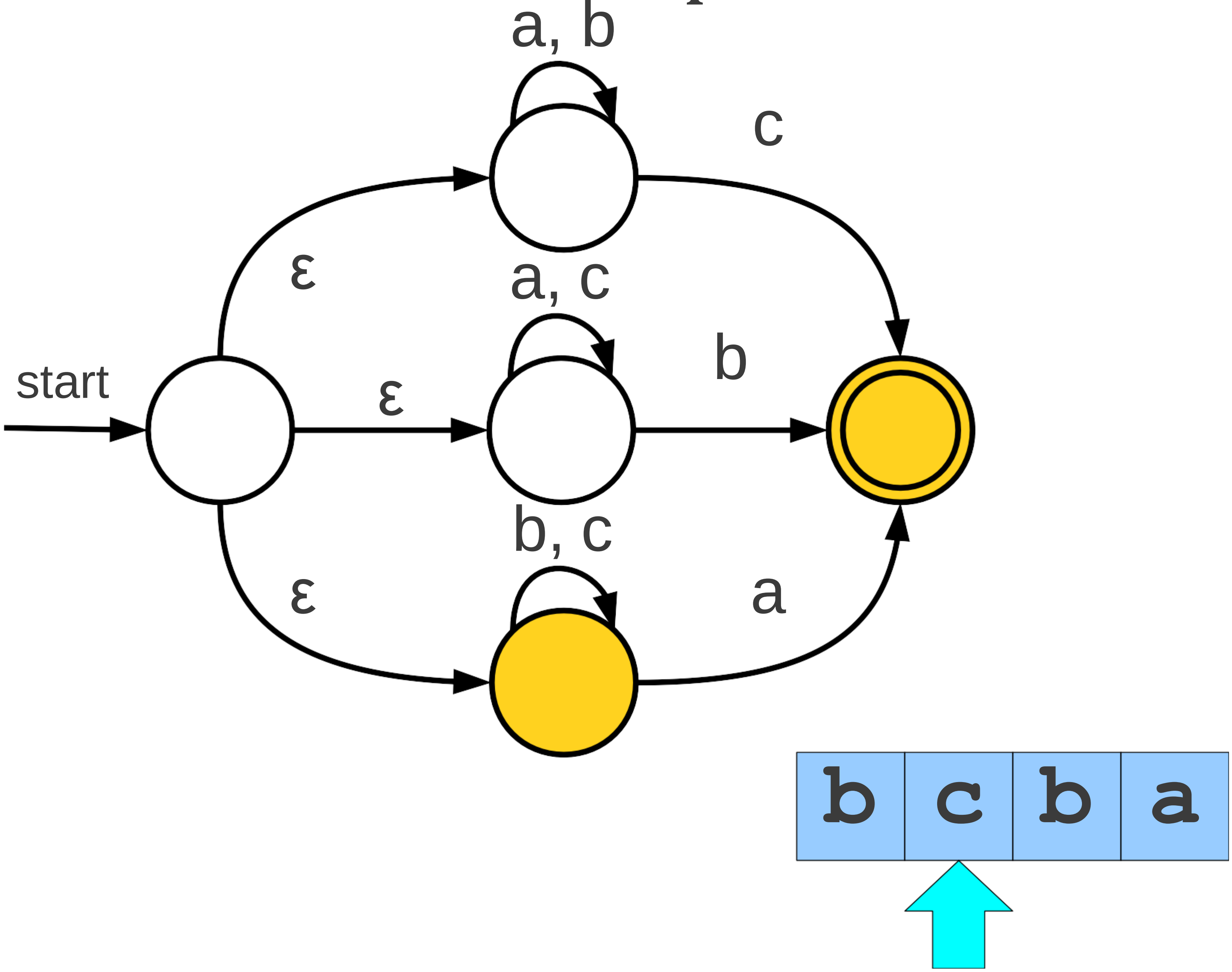
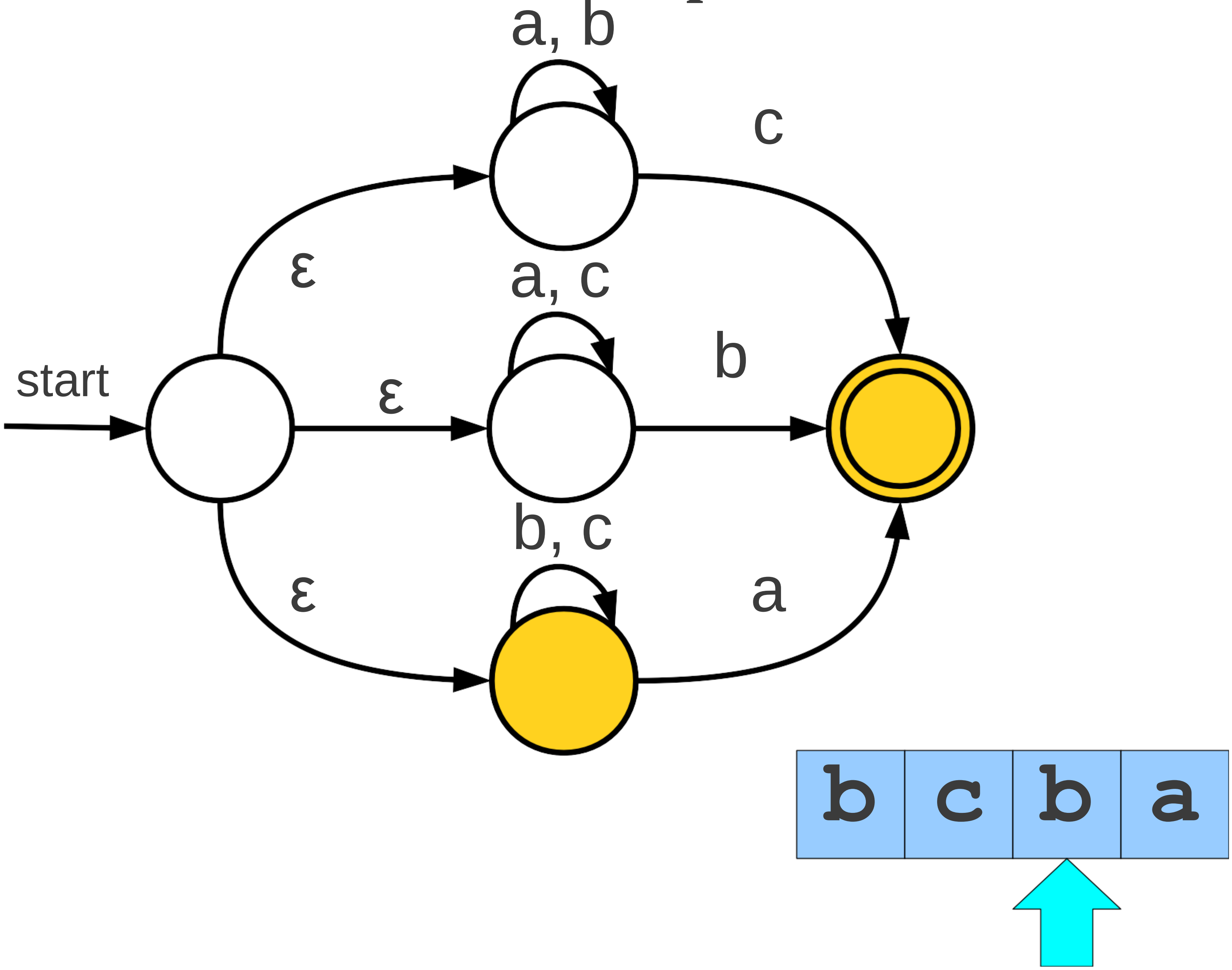


b	c	b	a

An Even More Complex Automaton



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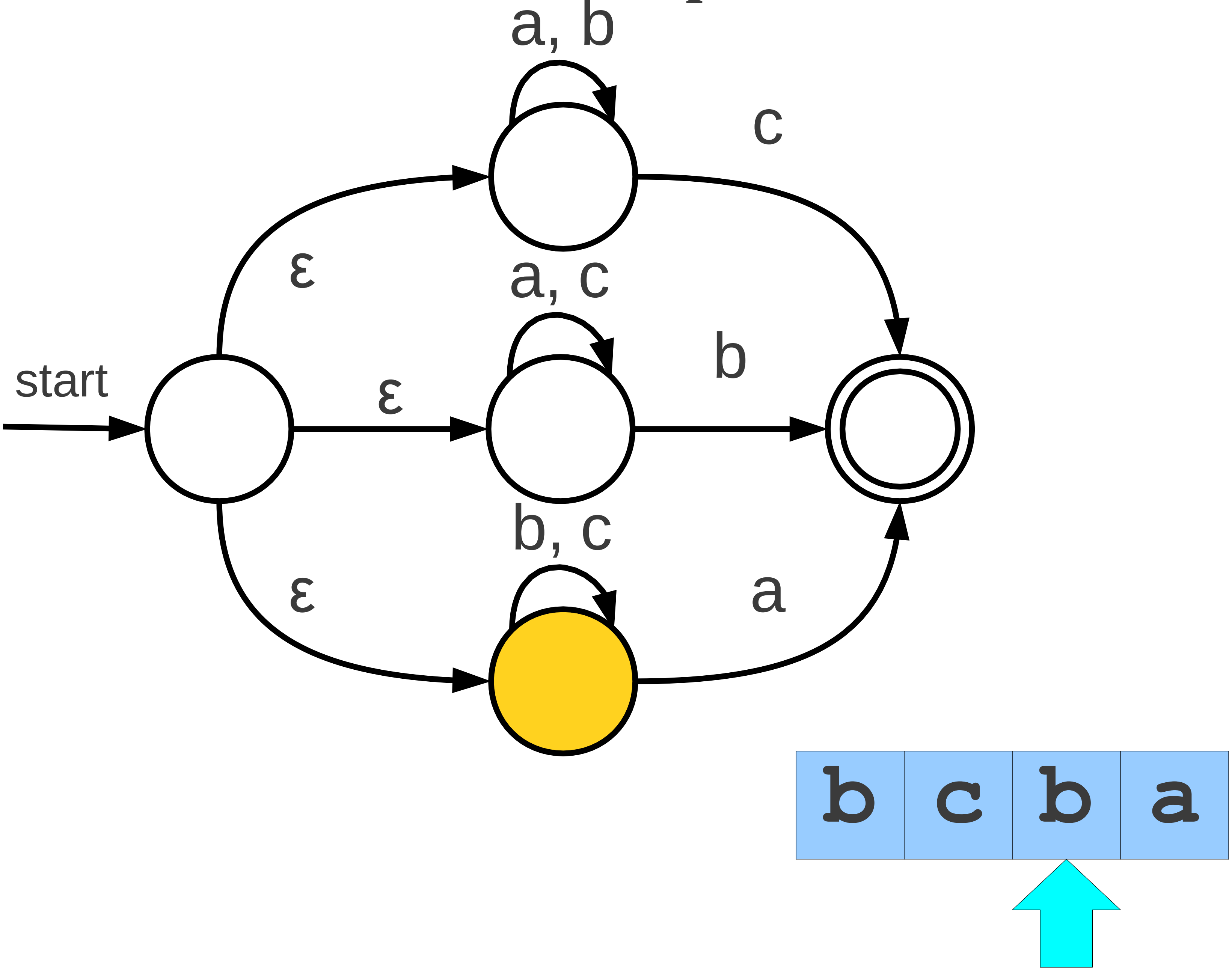

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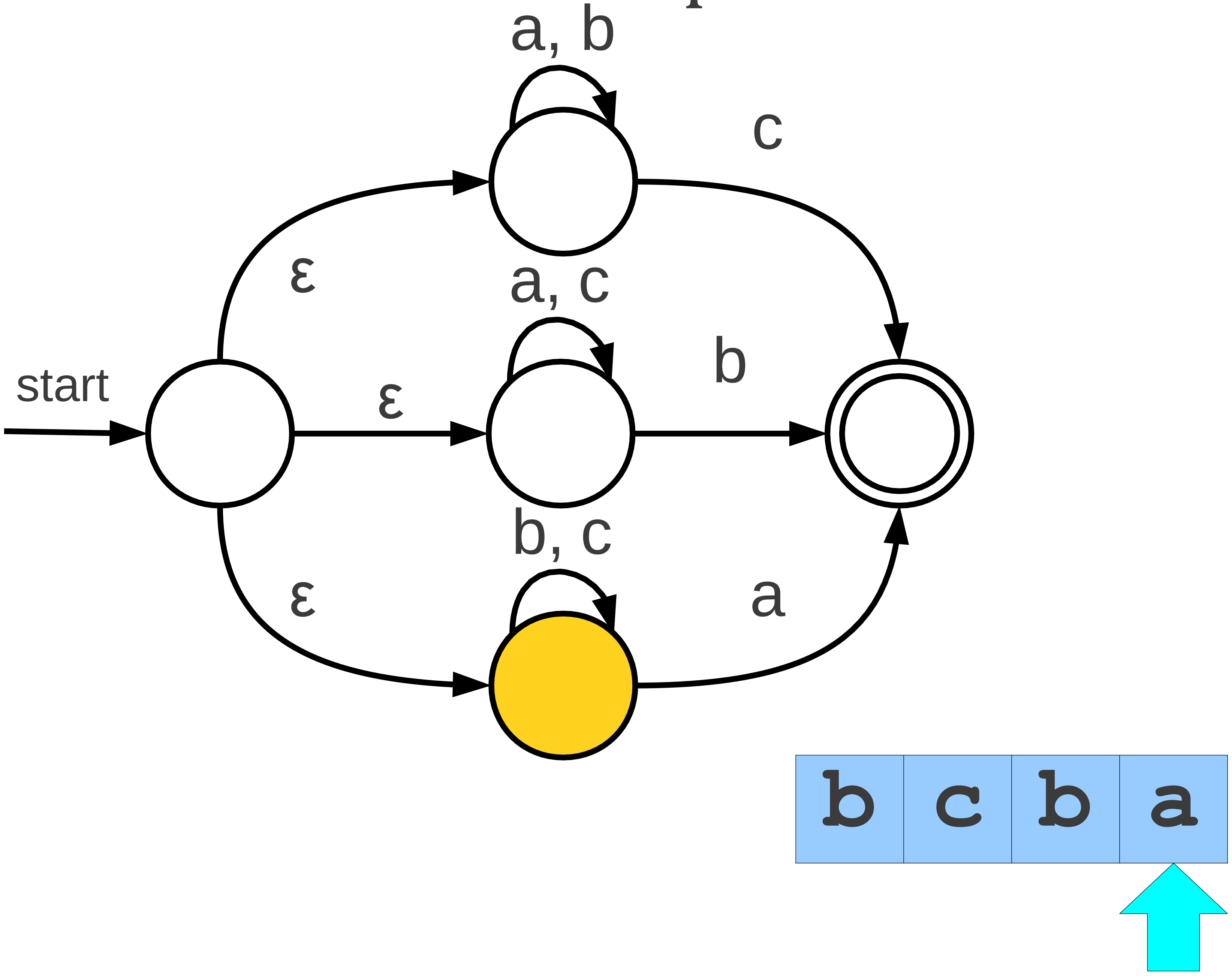
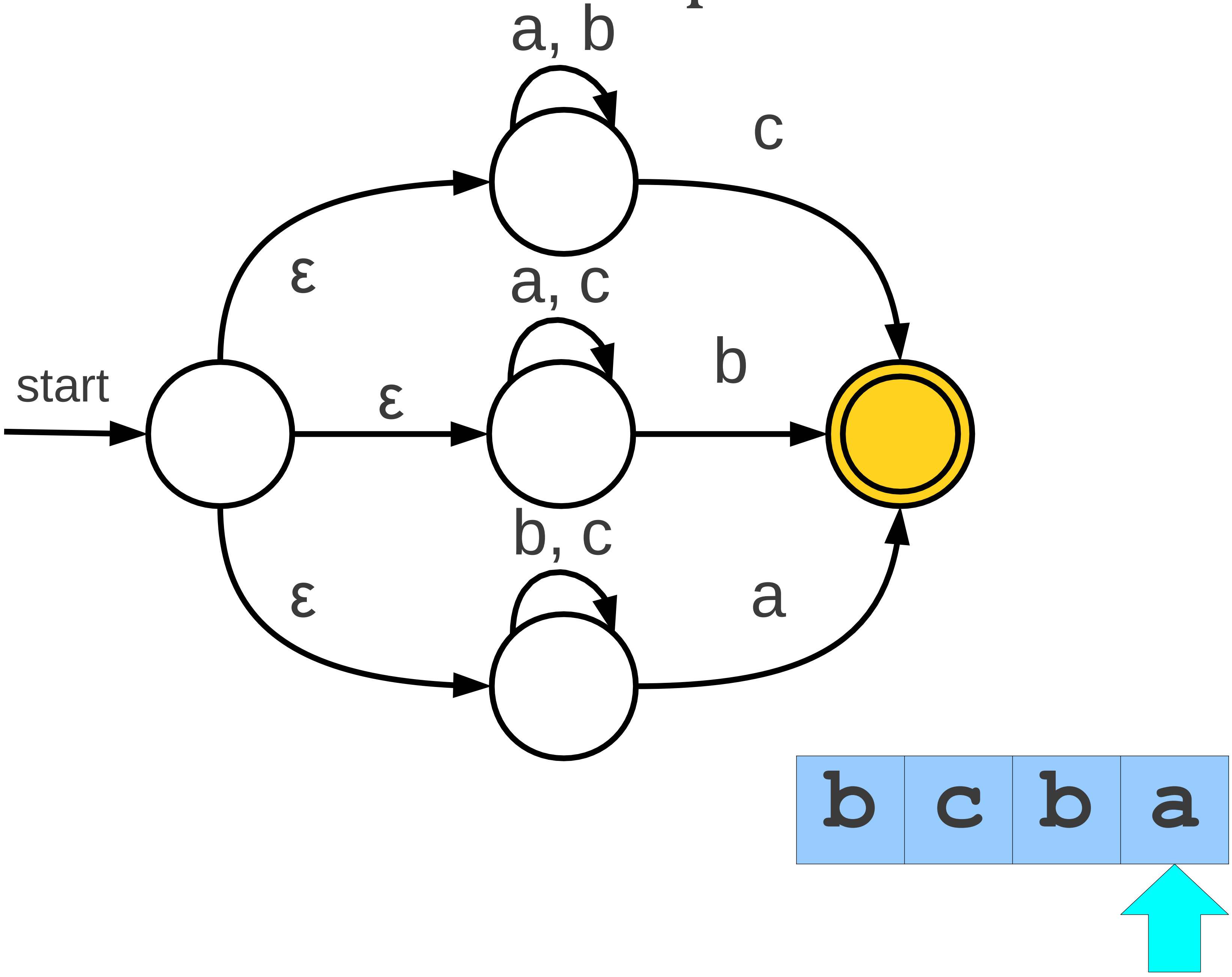
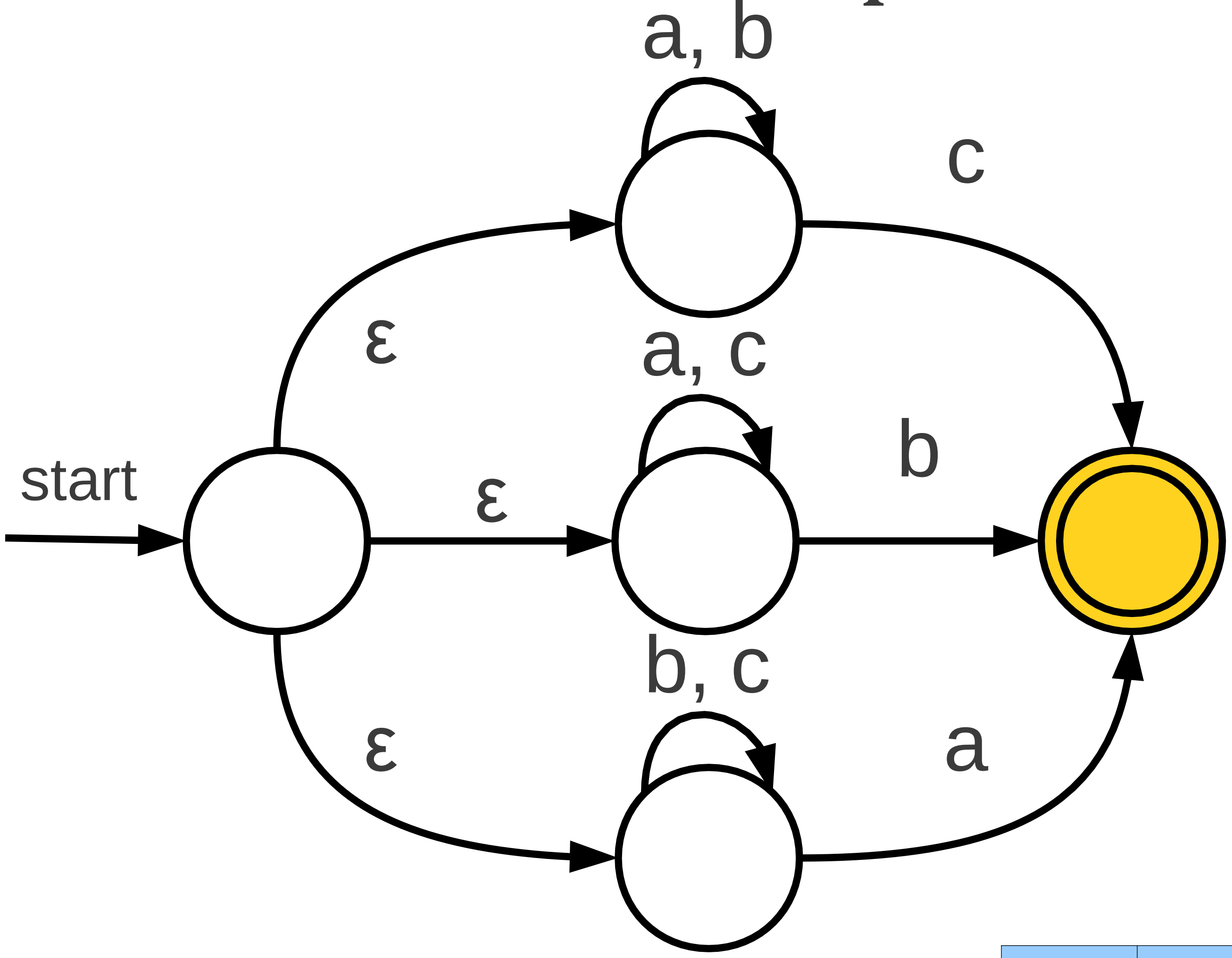


An Even More Complex Automaton



An Even More Complex Automaton



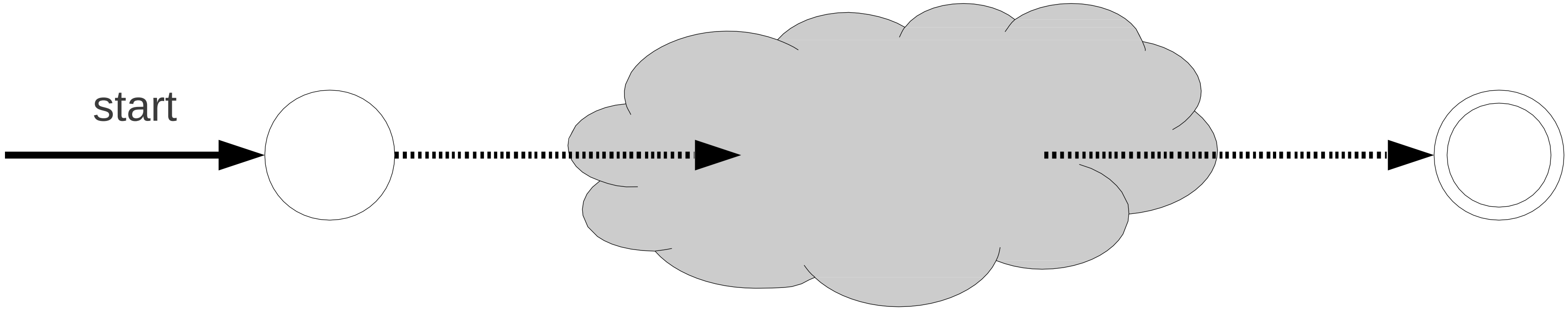
b	c	b	a

Simulating an NFA

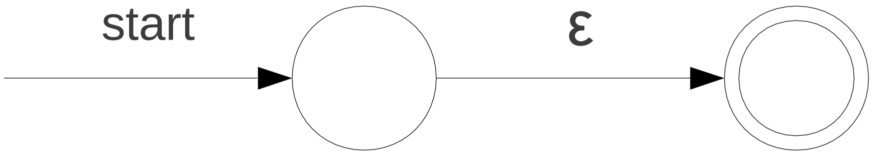
- Keep track of a set of states, initially the start state and everything reachable by ε-moves.
- For each character in the input:
  - Maintain a set of next states, initially empty.
  - For each current state:
    - Follow all transitions labeled with the current letter.
    - Add these states to the set of new states.
  - Add every state reachable by an ε-move to the set of next states.
- Complexity: O(mn^2) for strings of length m and automata with n states.

From Regular Expressions to NFAs

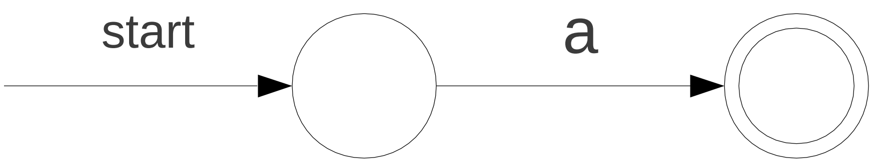
- There is a (beautiful!) procedure from converting a regular expression to an NFA.
- Associate each regular expression with an NFA with the following properties:
  - There is exactly one accepting state.
  - There are no transitions out of the accepting state.
  - There are no transitions into the starting state.
- These restrictions are stronger than necessary, but make the construction easier.



Base Cases



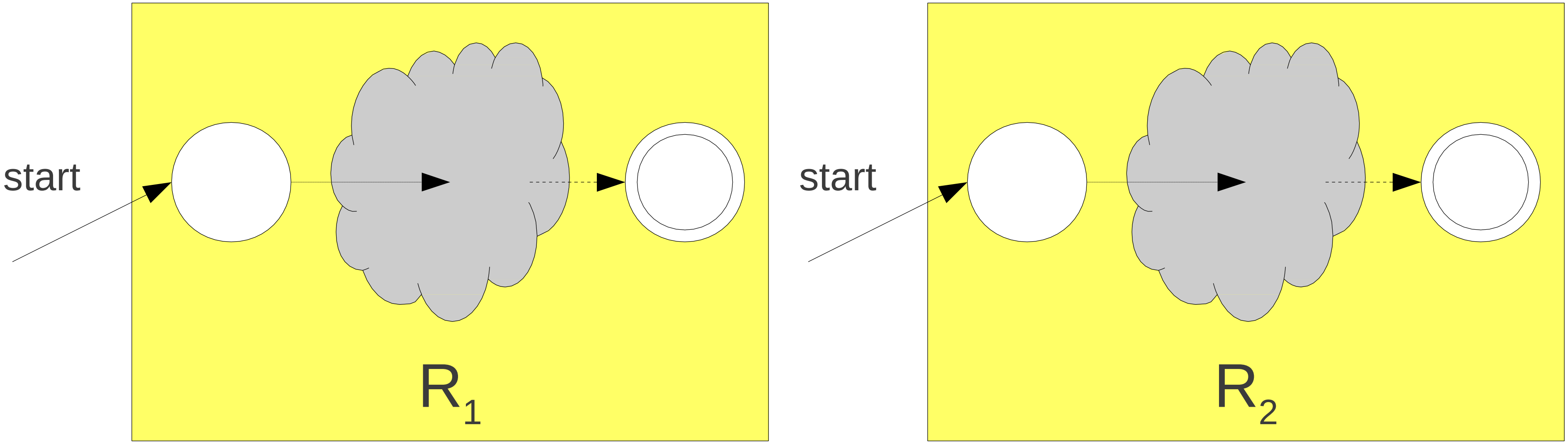
Automaton for ε



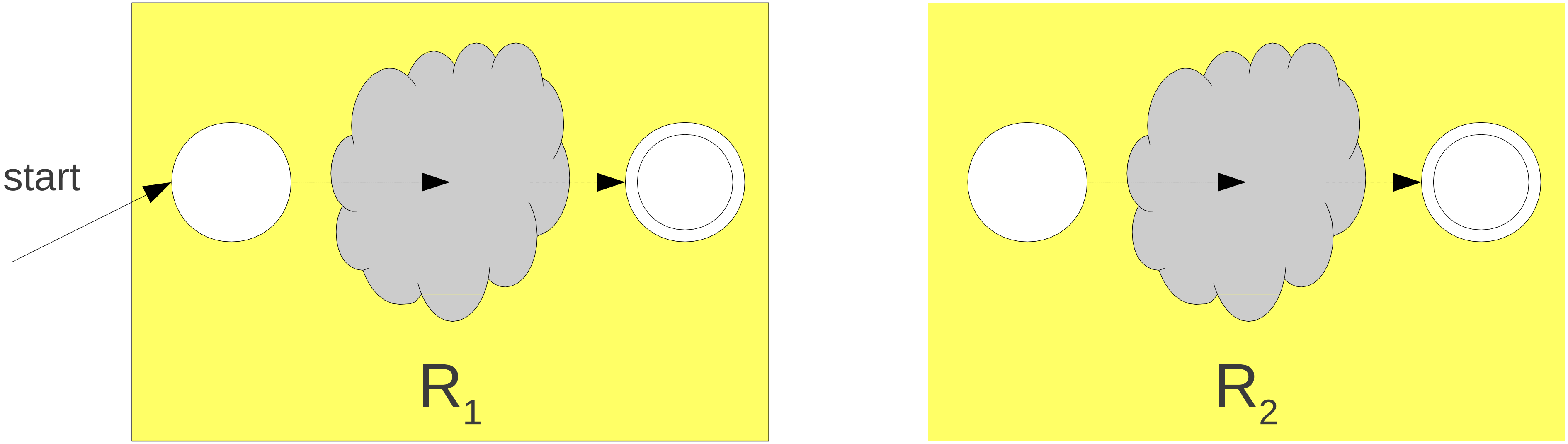
Automaton for single character **a**

Construction for R_1R_2

Construction for R_1R_2



Construction for R_1R_2



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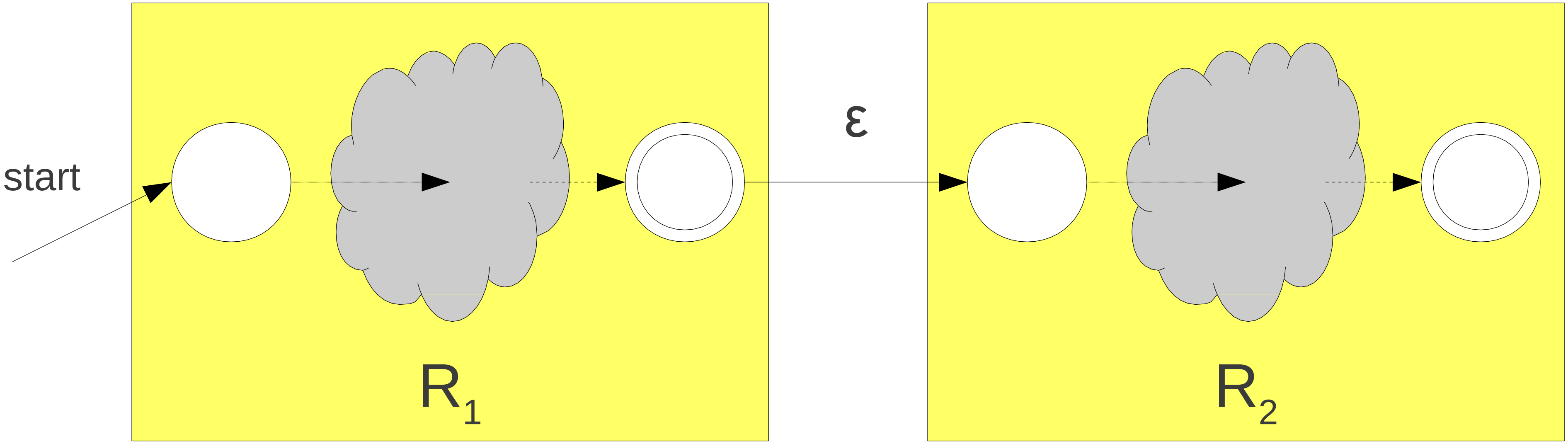
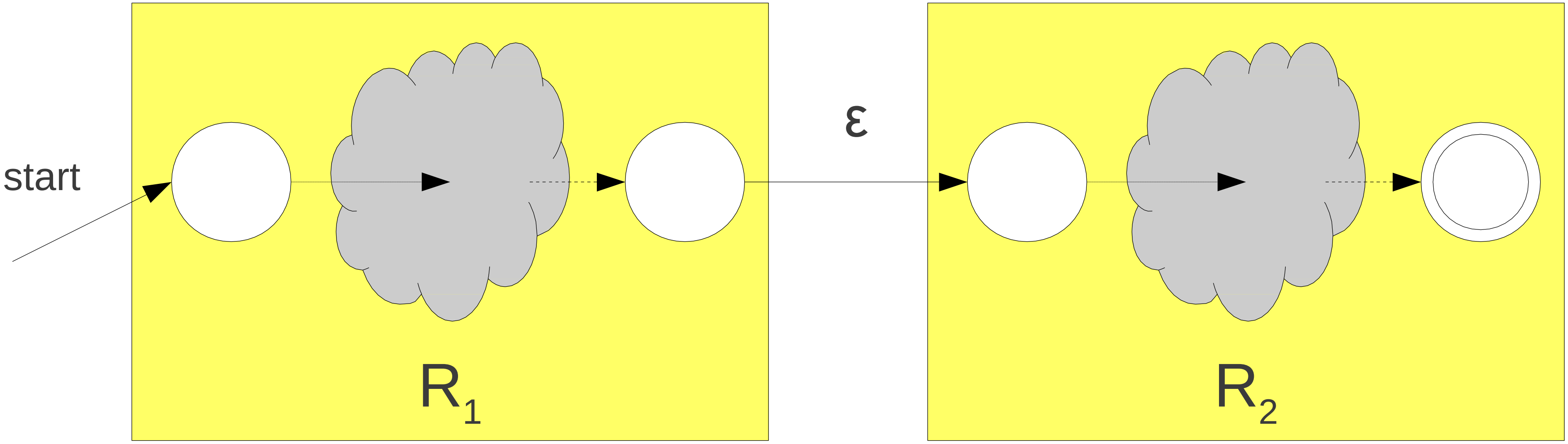
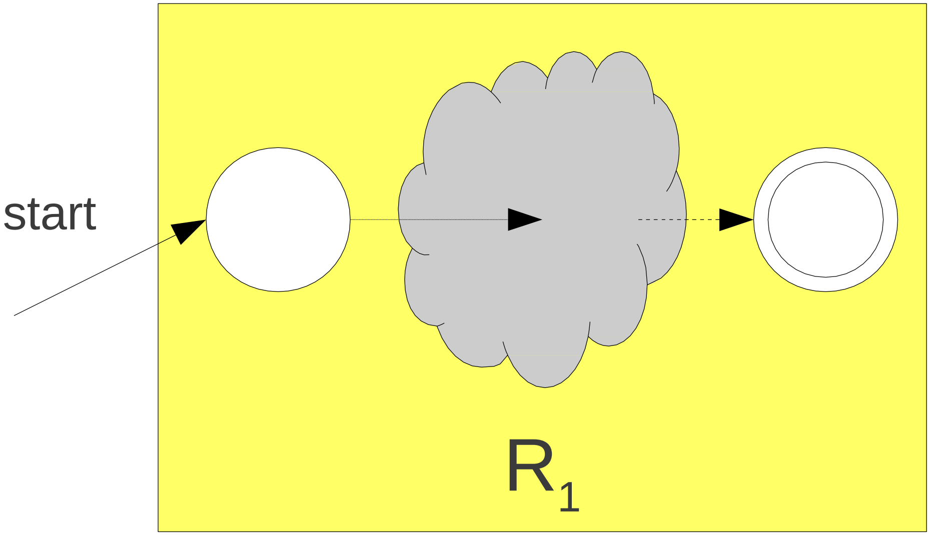


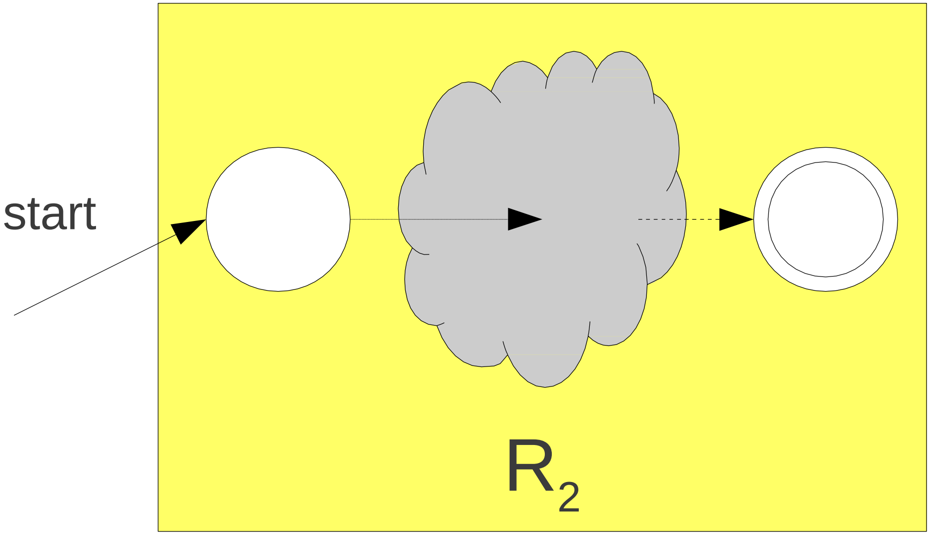
Construction for R_1R_2



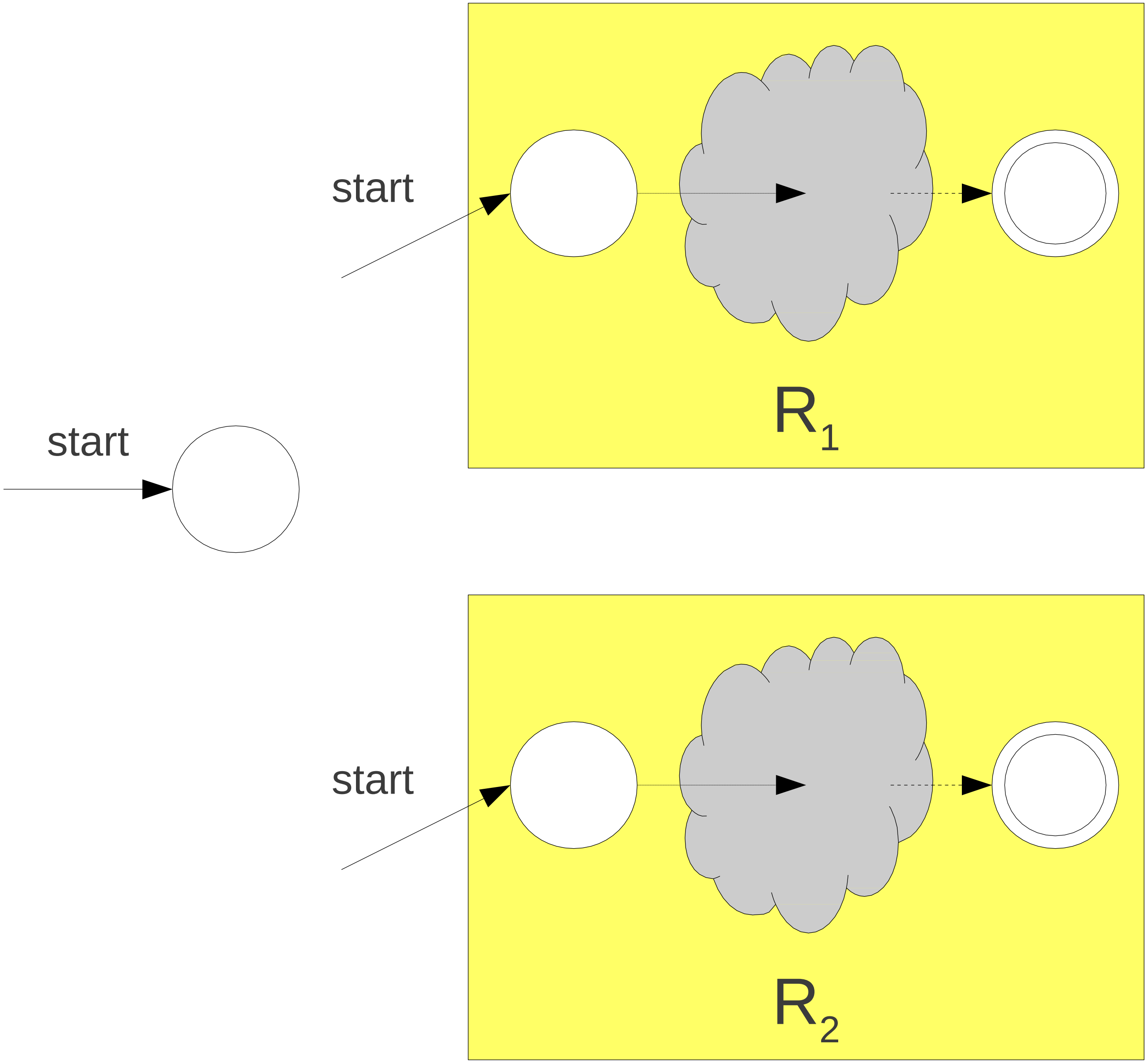
Construction for R_1 | R_2

Construction for $R_1 \mid R_2$

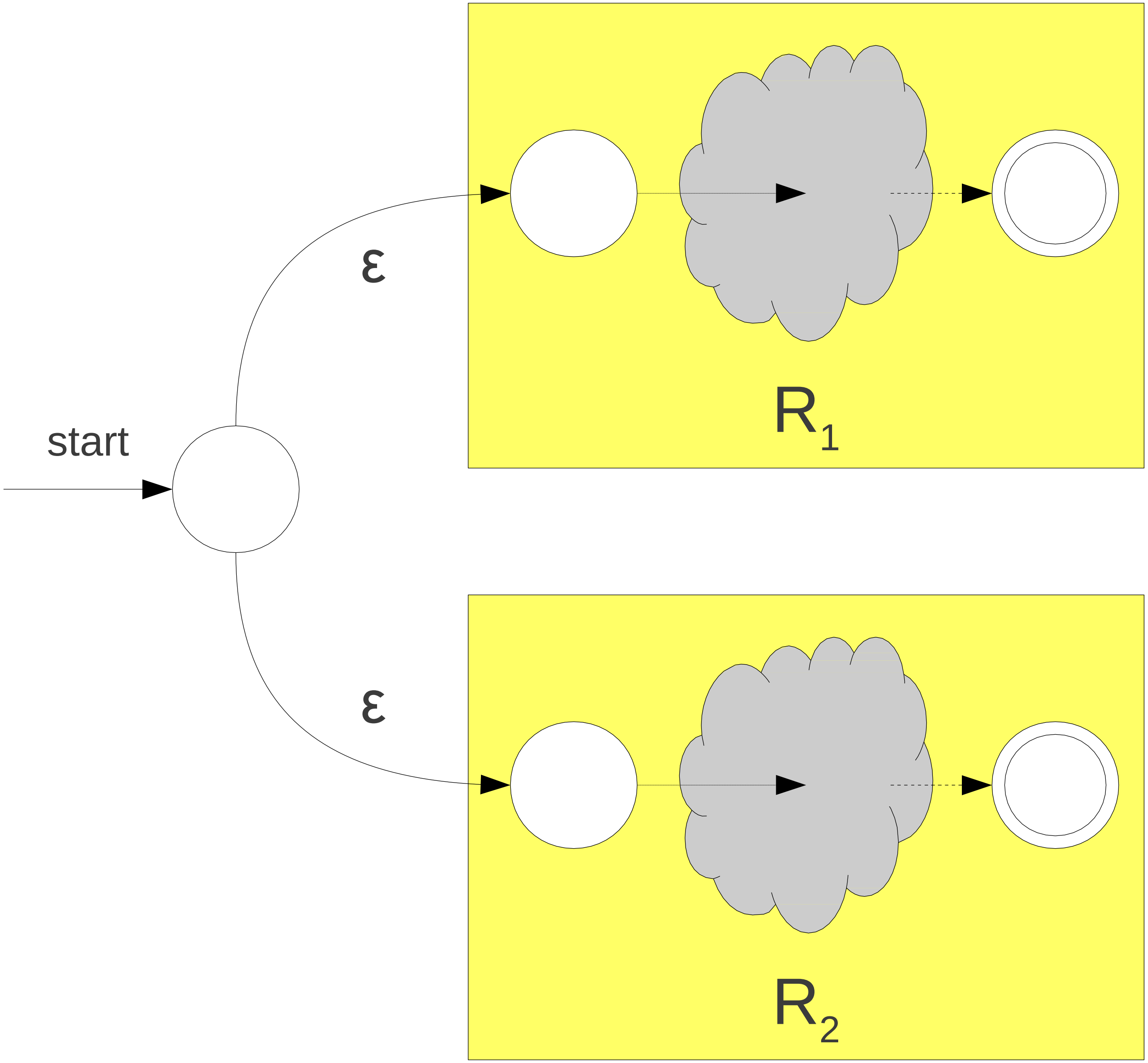




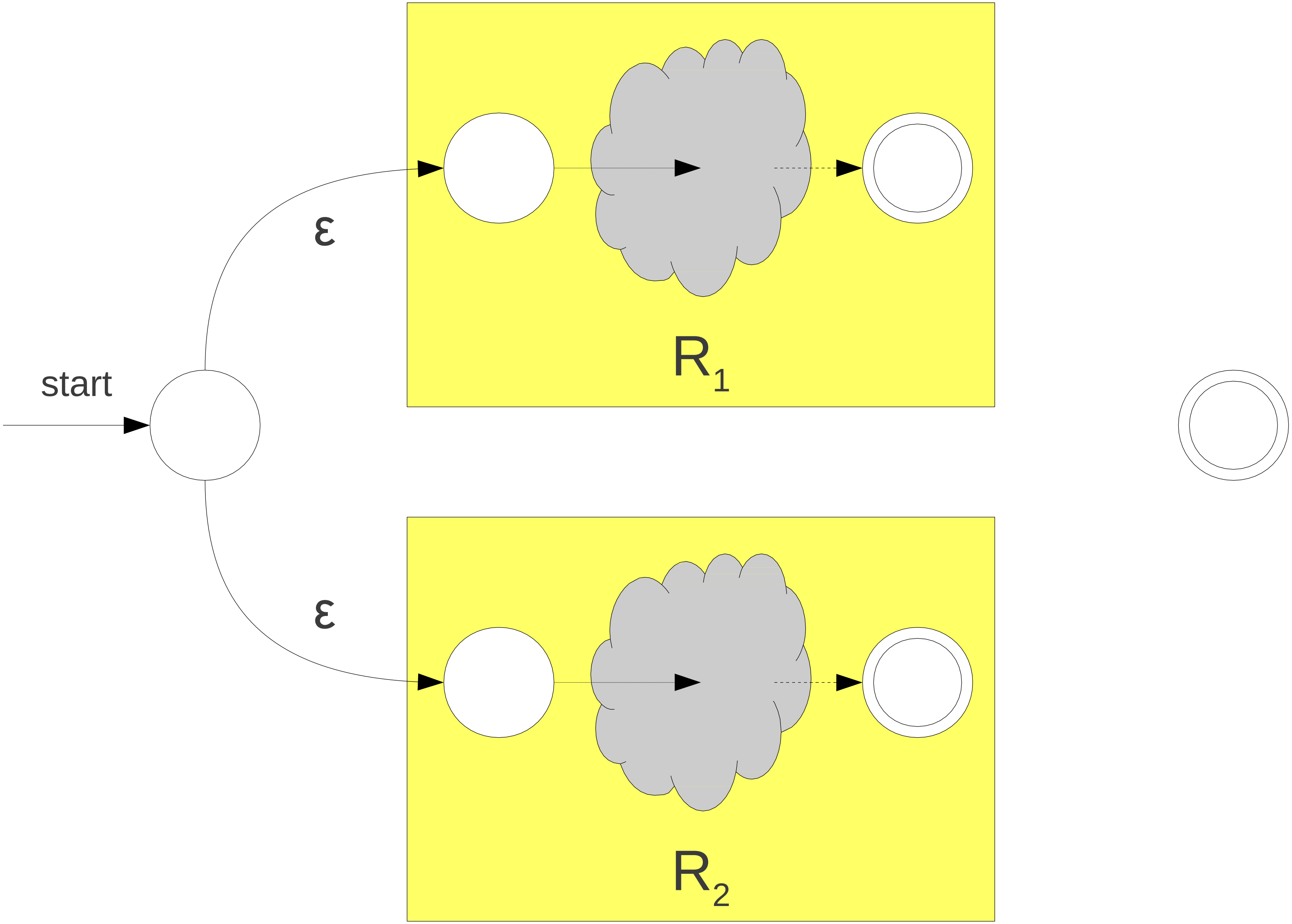
Construction for $R_1 \mid R_2$



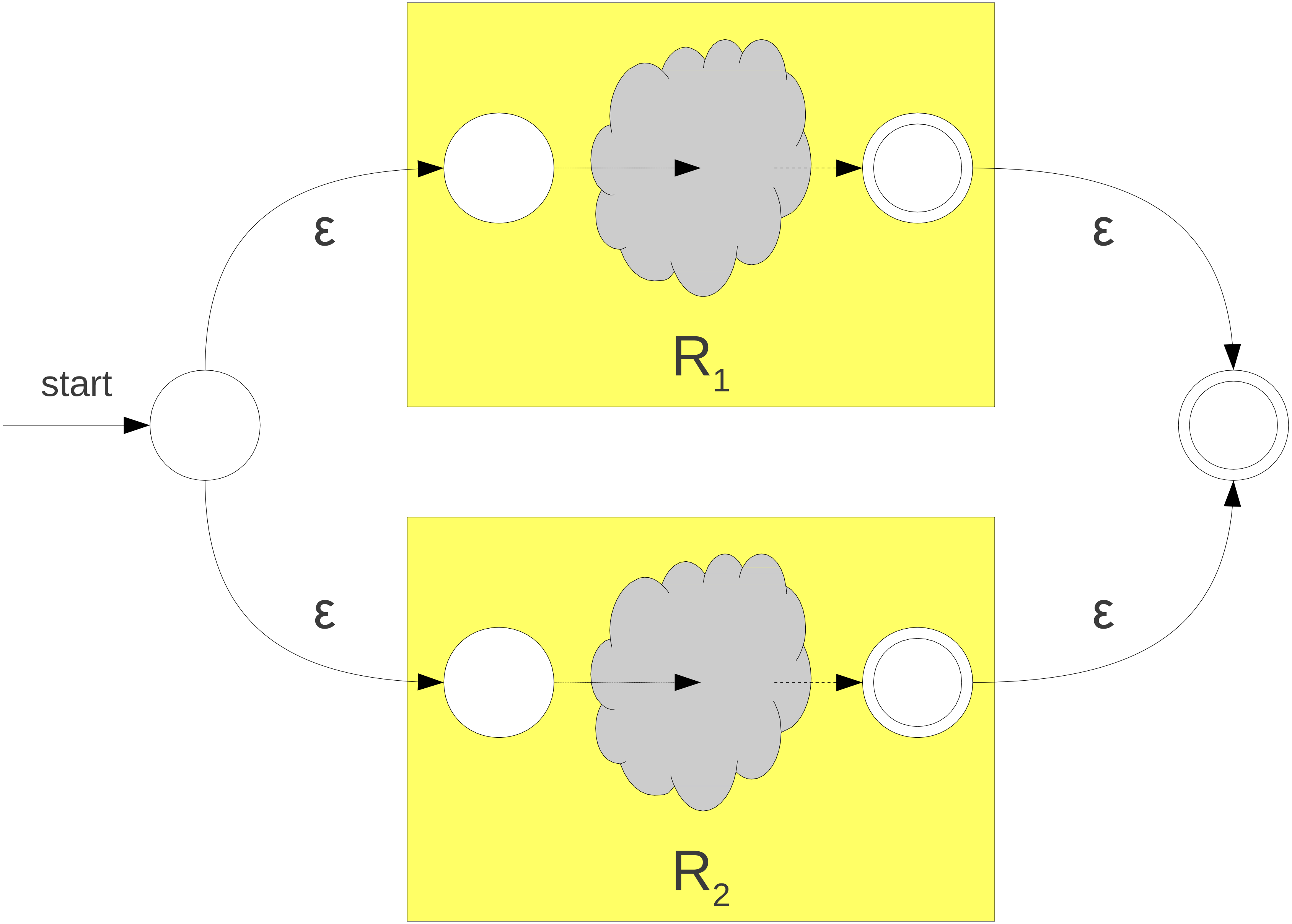
Construction for $R_1 \mid R_2$



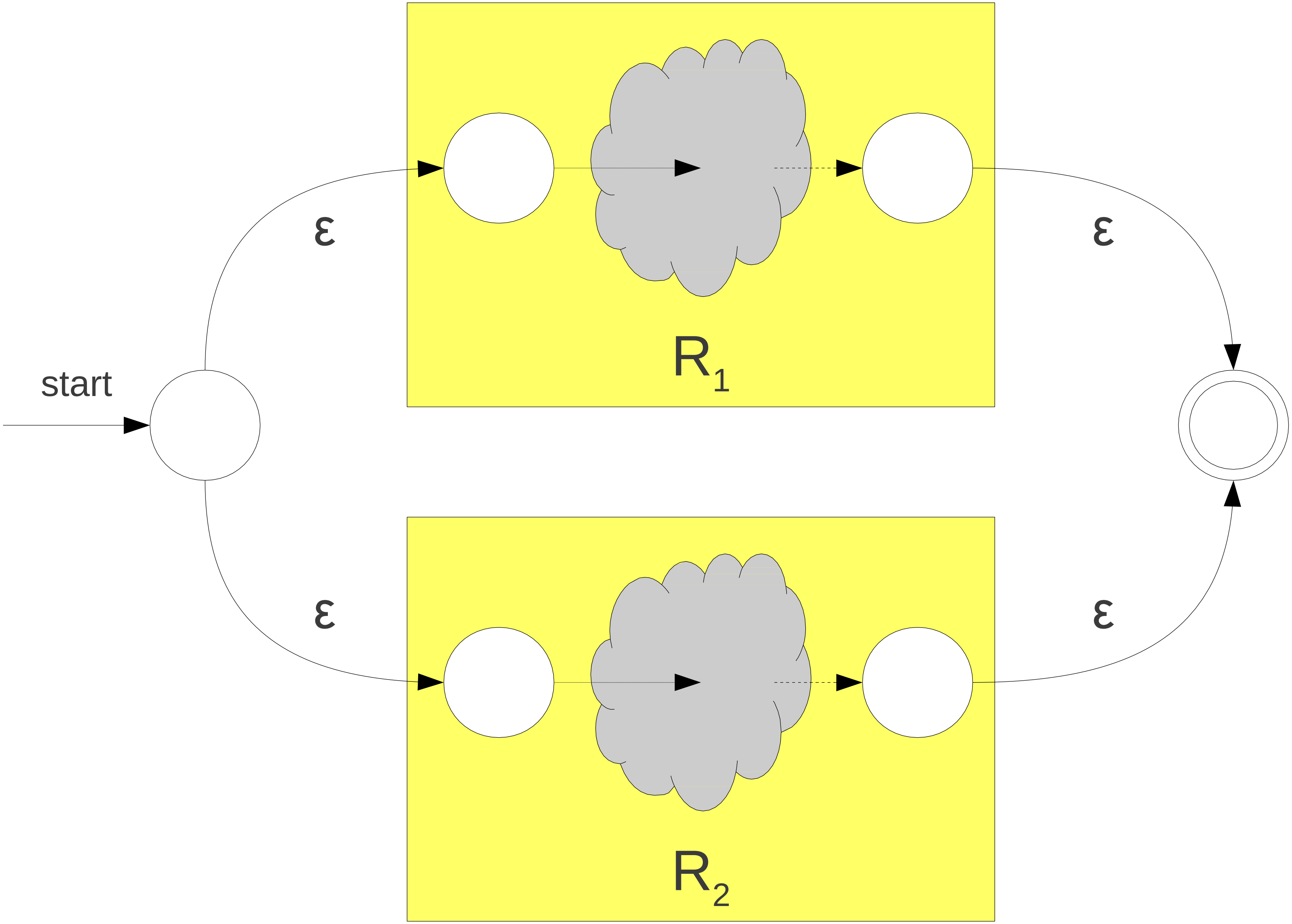
Construction for $R_1 \mid R_2$



Construction for $R_1 \mid R_2$

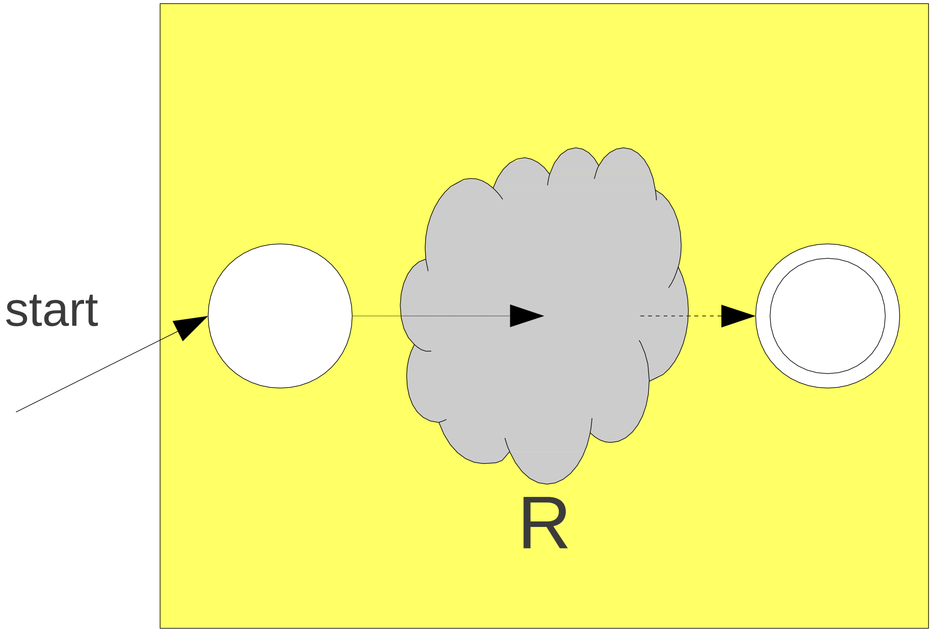


Construction for R_1 | R_2

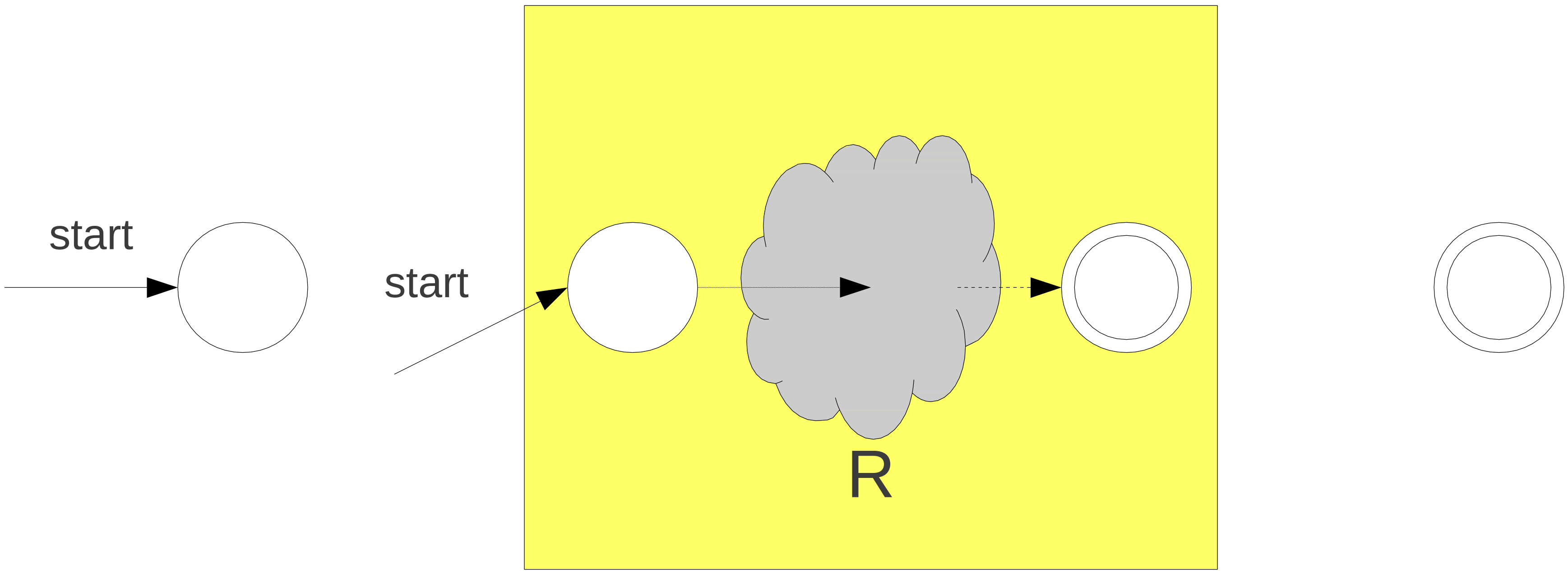


Construction for R*

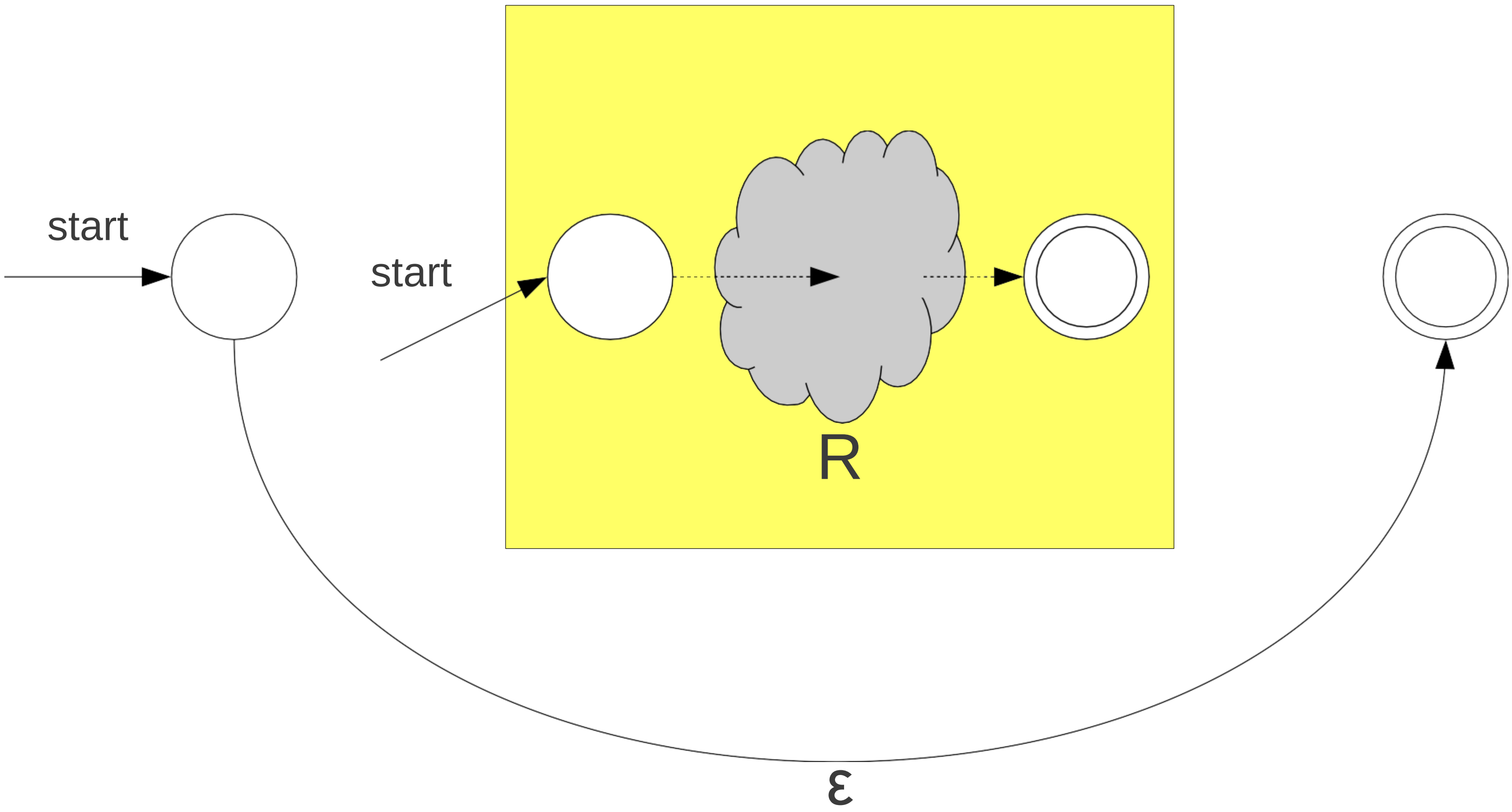
Construction for R*



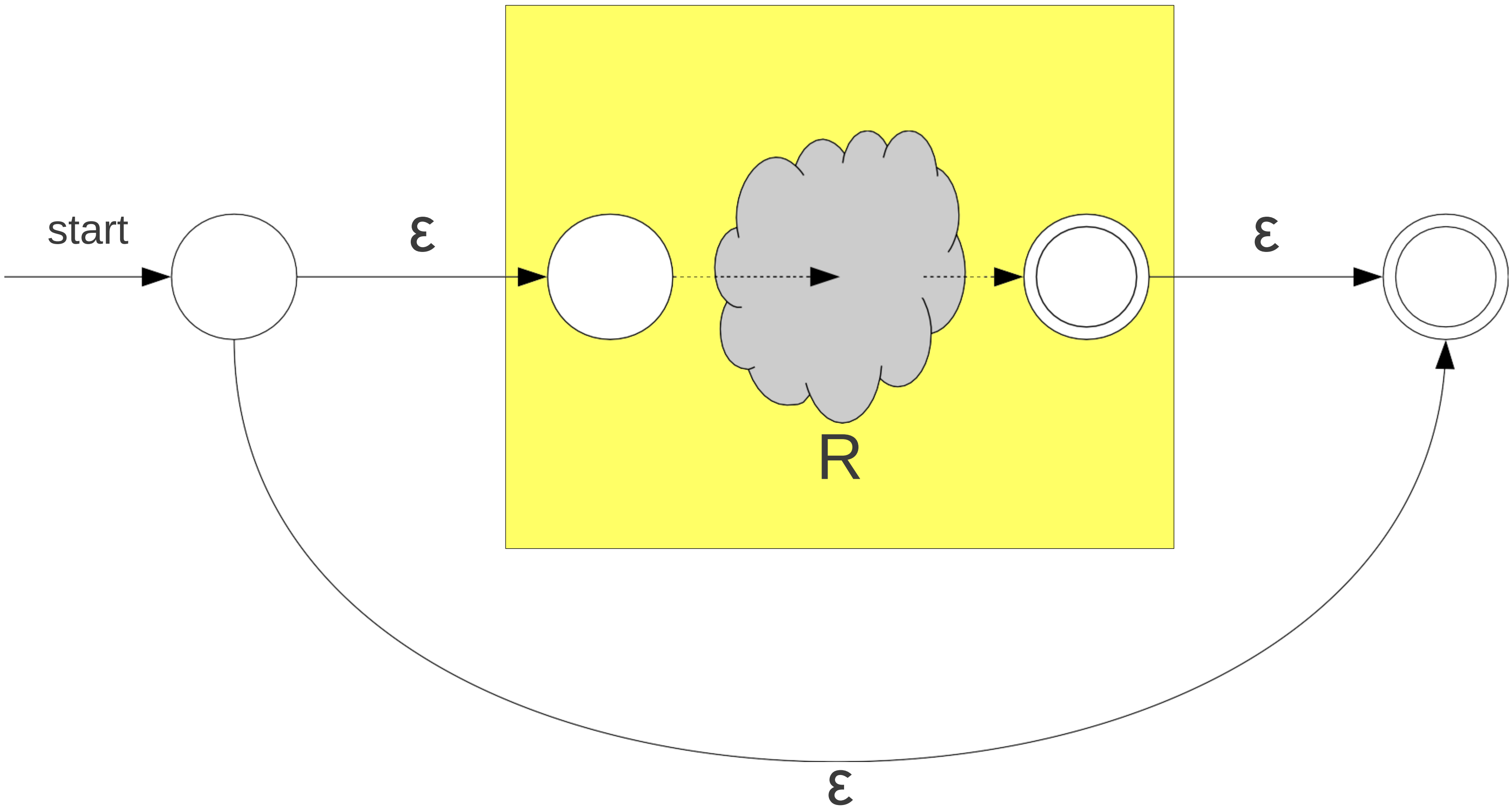
Construction for R*



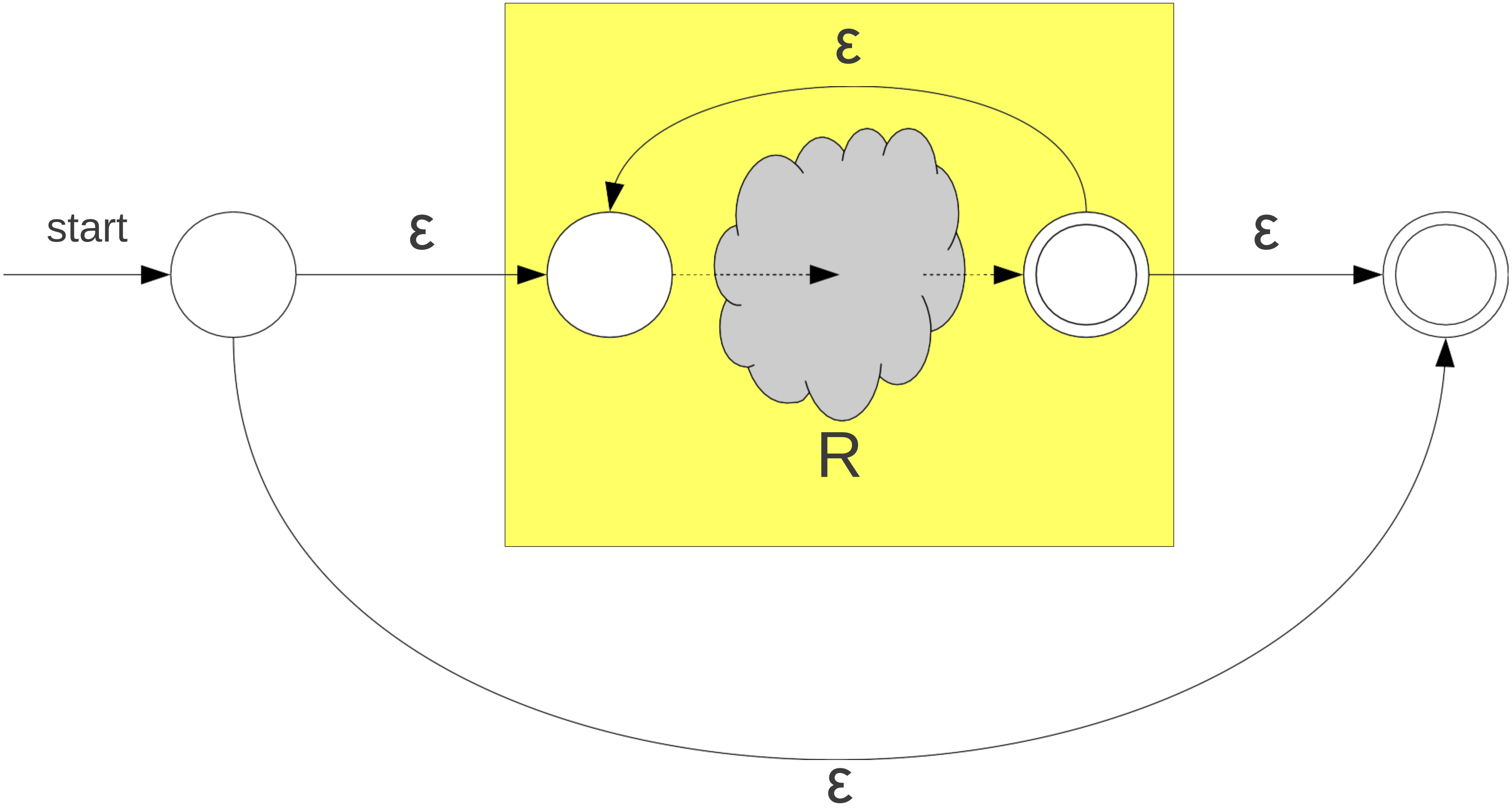
Construction for R*



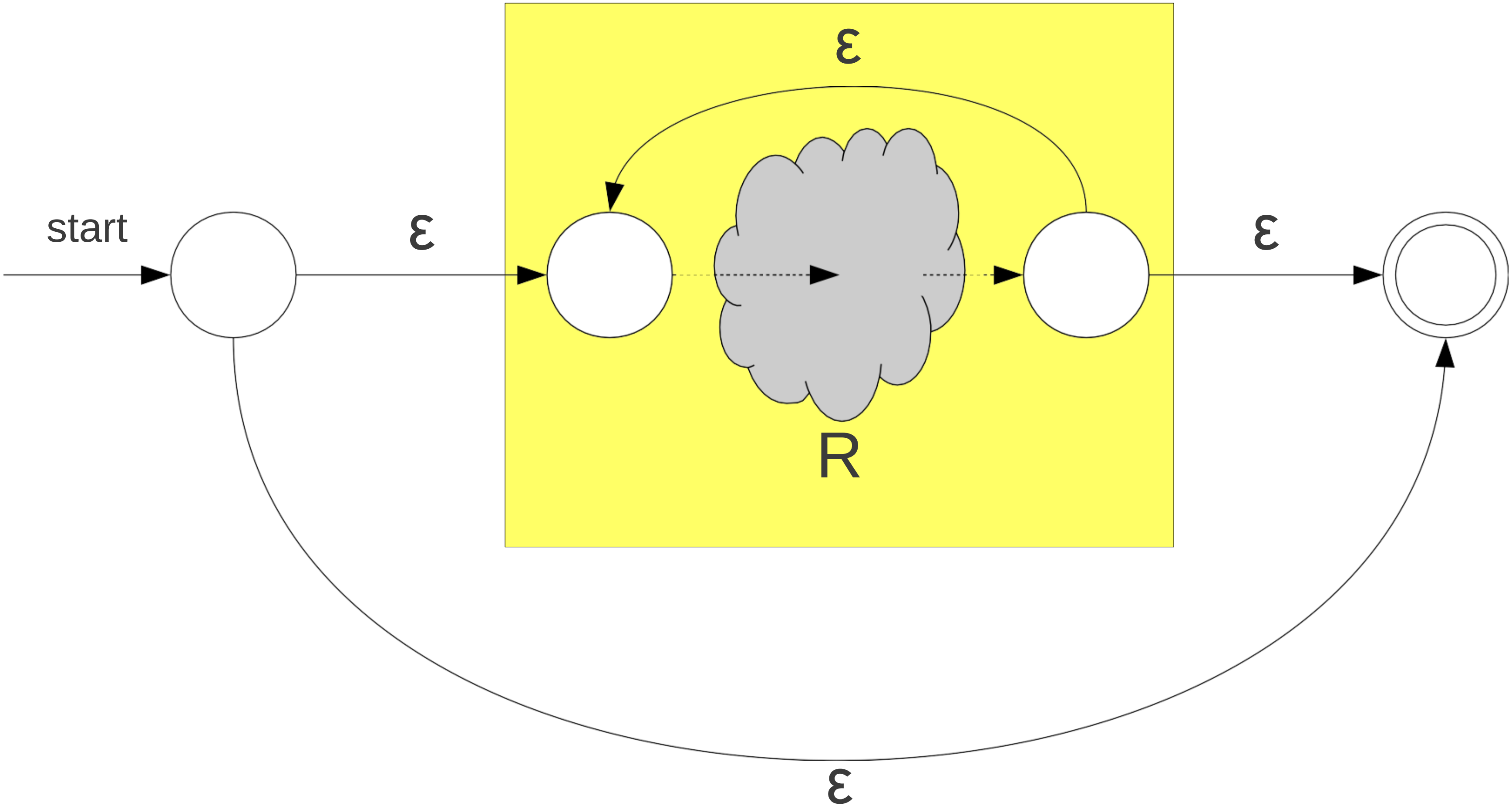
Construction for R*



Construction for R*



Construction for R*



Overall Result

- Any regular expression of length n can be converted into an NFA with O(n) states.
- Can determine whether a string of length m matches a regular expression of length n in time O(mn^2).
- We'll see how to make this O(m) later (this is independent of the complexity of the regular expression!)

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?

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Lexing Ambiguities

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

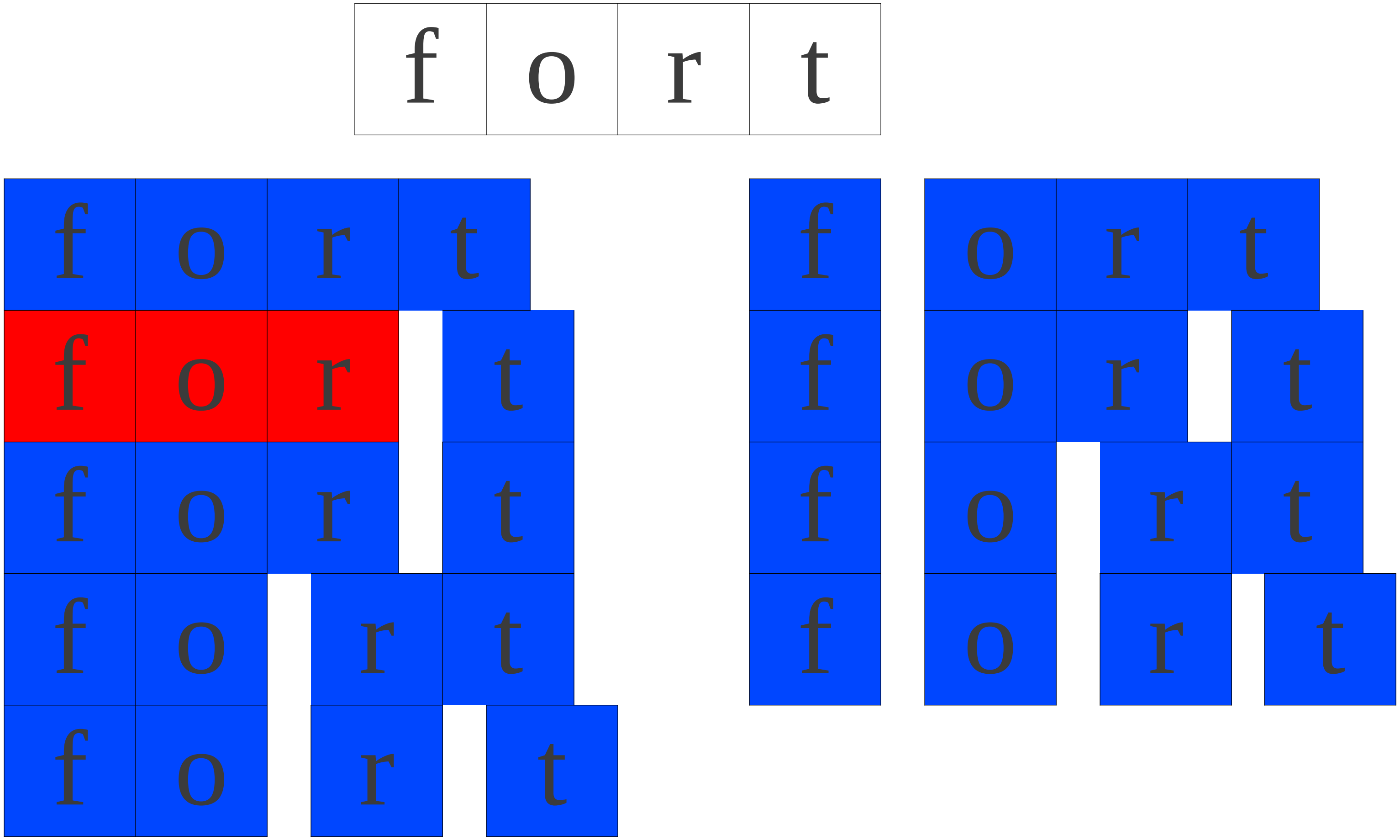
Lexing Ambiguities

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_]*



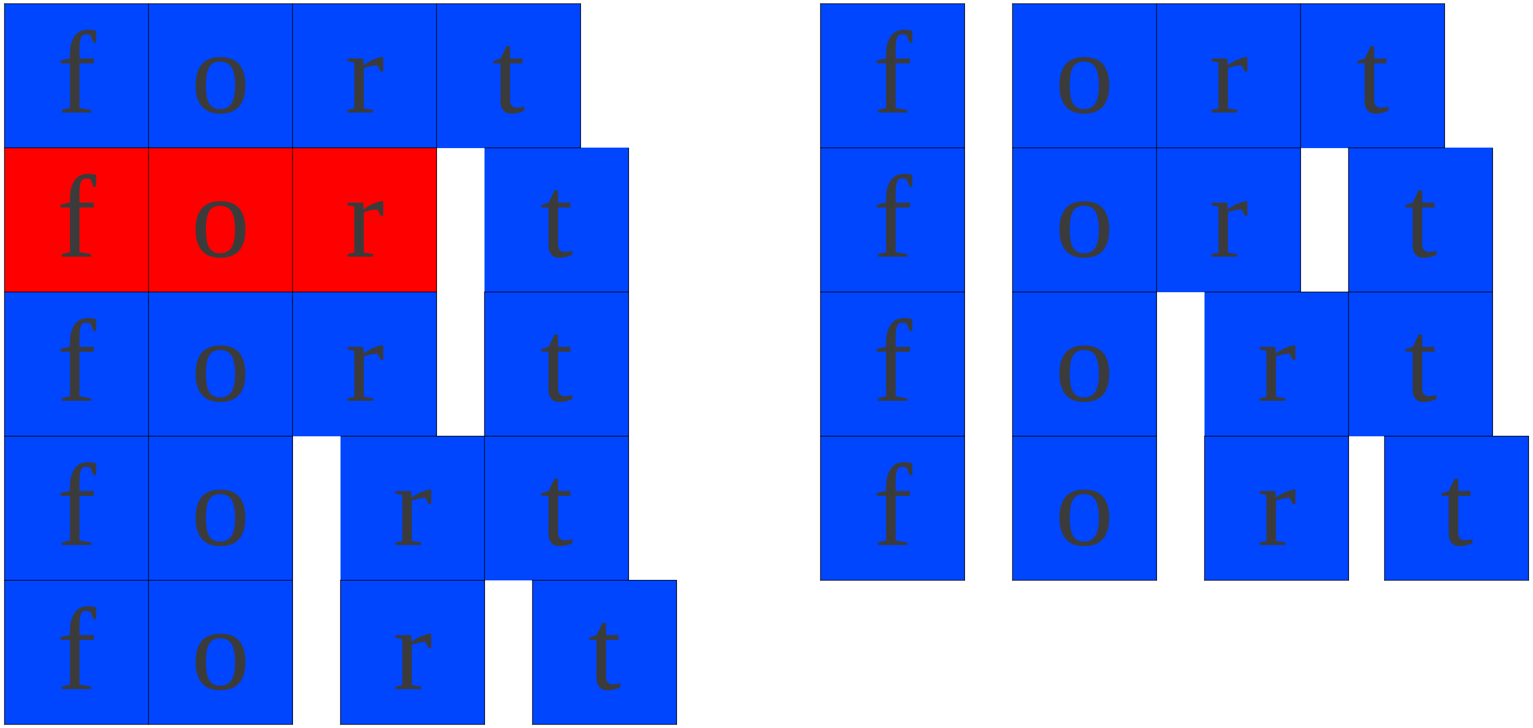
Conflict Resolution

- 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

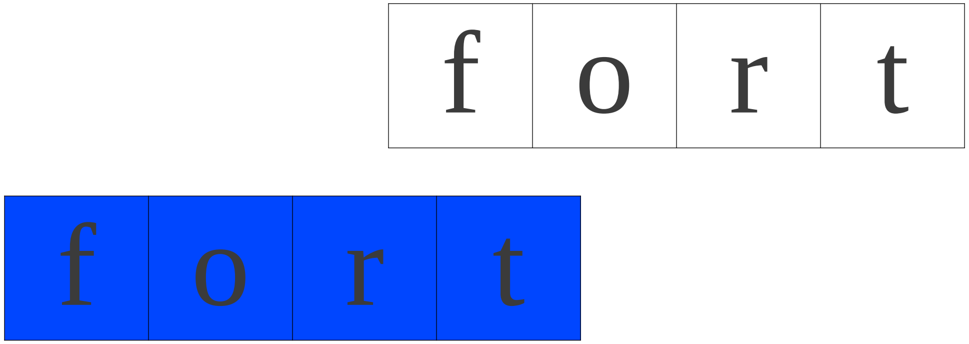
T_For	for
T_Identifier	[A-Za-z_][A-Za-z0-9_]*

f	o	r	t



Lexing Ambiguities

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



f o r t

f o r t

Implementing Maximal Munch

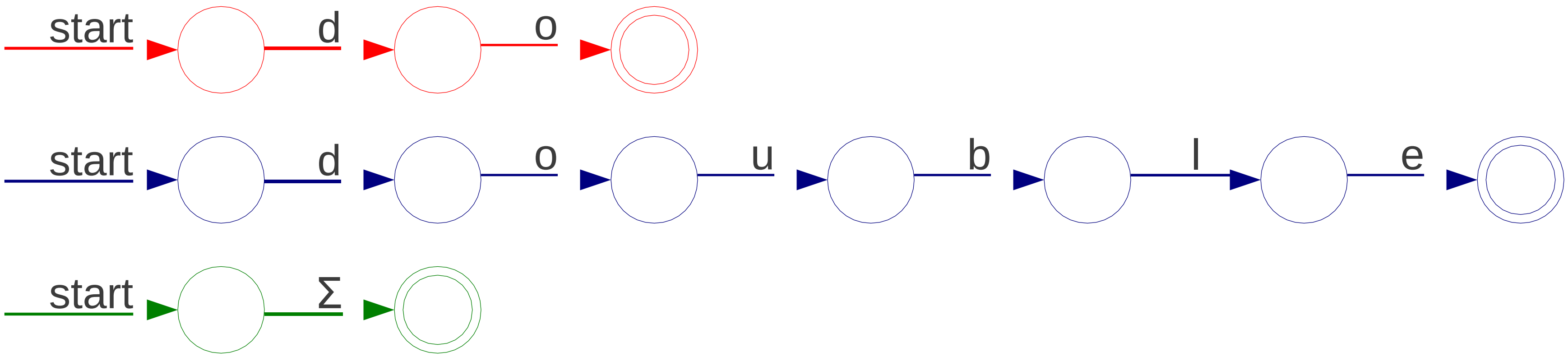
- Given a set of regular expressions, how can we use them to implement maximum munch?
- Idea:
  - Convert expressions to NFAs.
  - Run all NFAs in parallel, keeping track of the last match.
  - When all automata get stuck, report the last match and restart the search at that point.

Implementing Maximal Munch

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

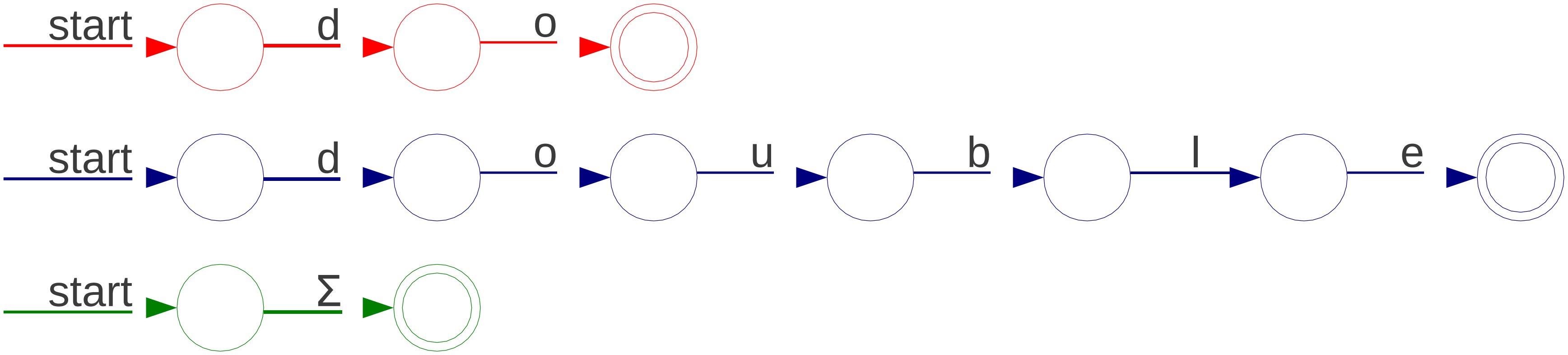
Implementing Maximal Munch

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



Implementing Maximal Munch

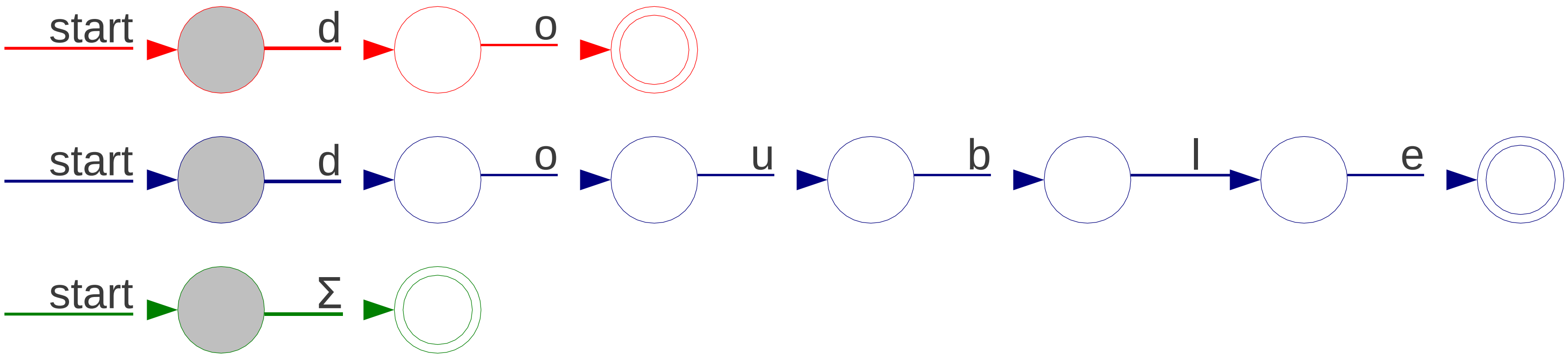
T_Do	do
T_Double	double
T_Mystery	[A-Za-z]



D	O	U	B	D	O	U	B	L	E

Implementing Maximal Munch

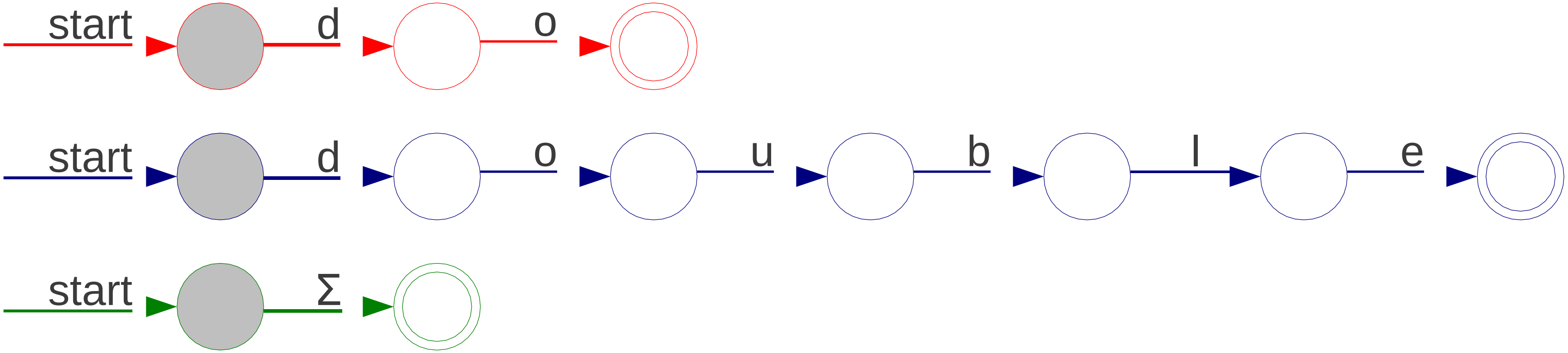
T_Do	do
T_Double	double
T_Mystery	[A-Za-z]

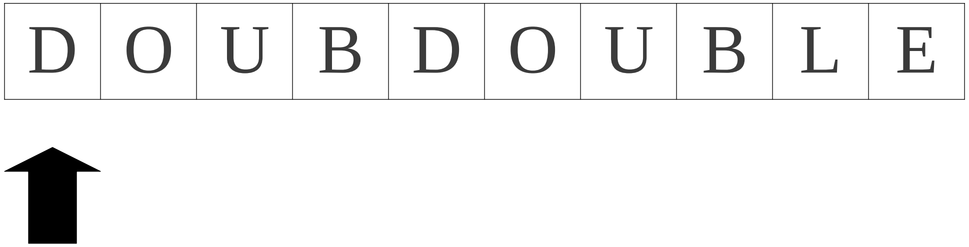


D	O	U	B	D	O	U	B	L	E

Implementing Maximal Munch

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

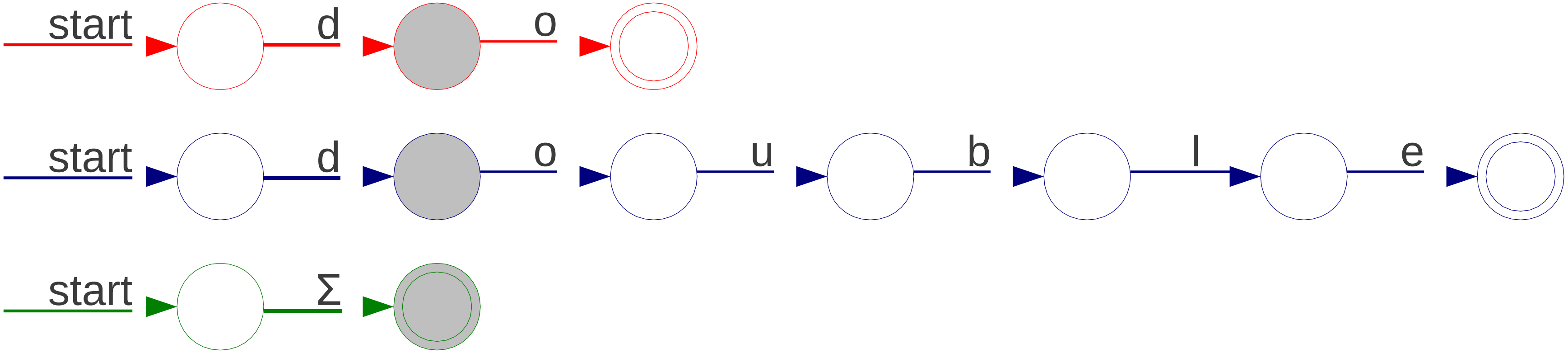


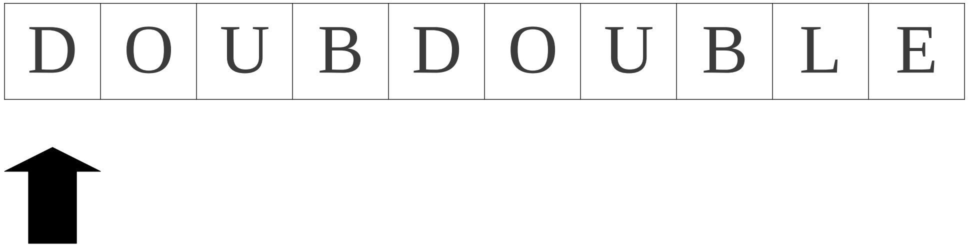


D	O	U	B	D	O	U	B	L	E

Implementing Maximal Munch

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

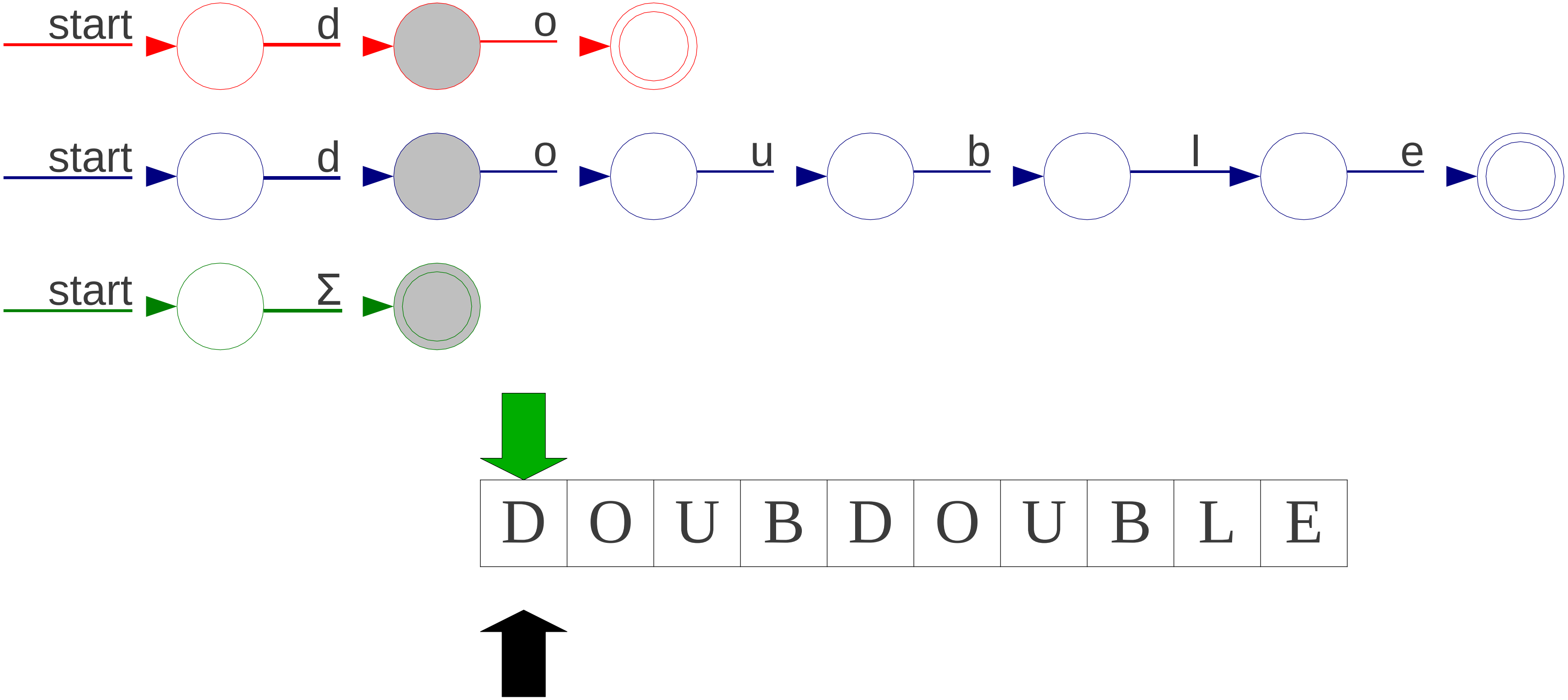




D	O	U	B	D	O	U	B	L	E

Implementing Maximal Munch

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



Implementing Maximal Munch

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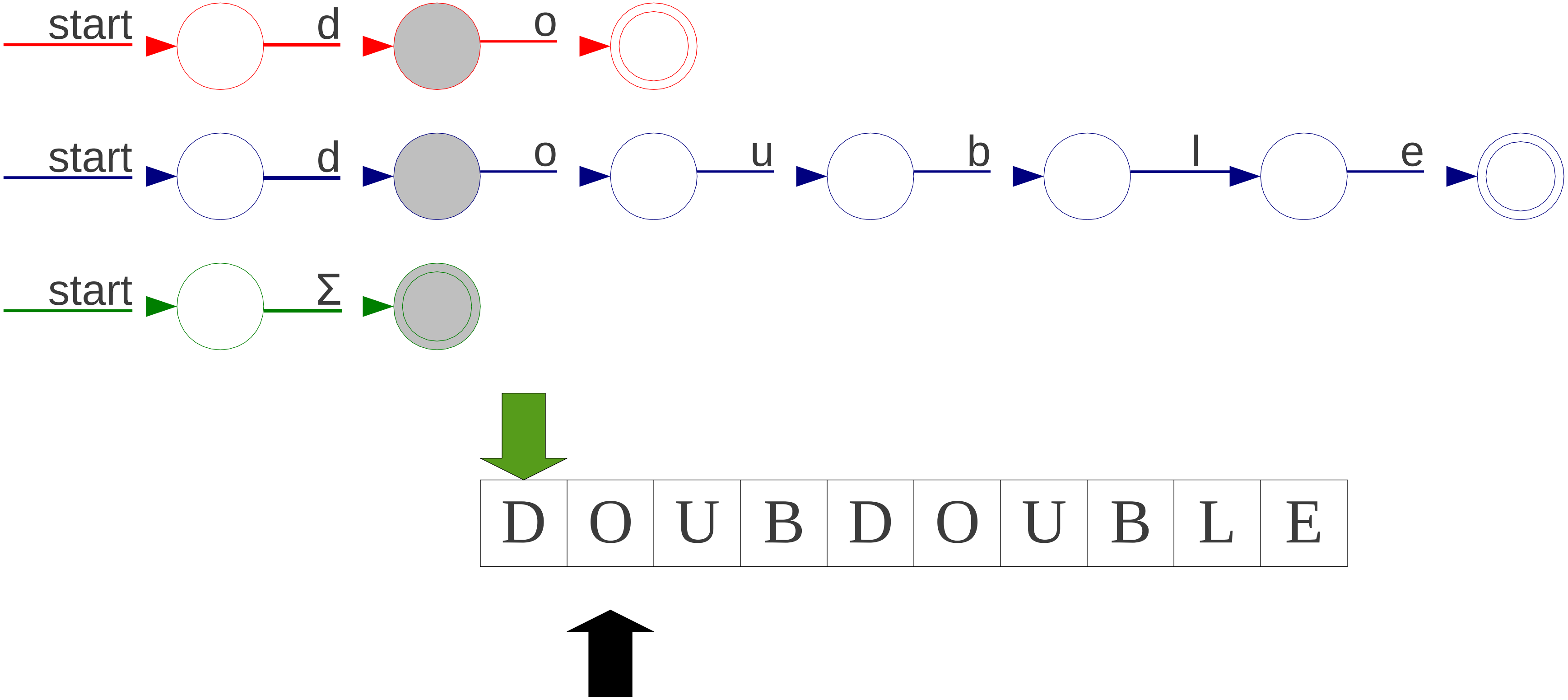
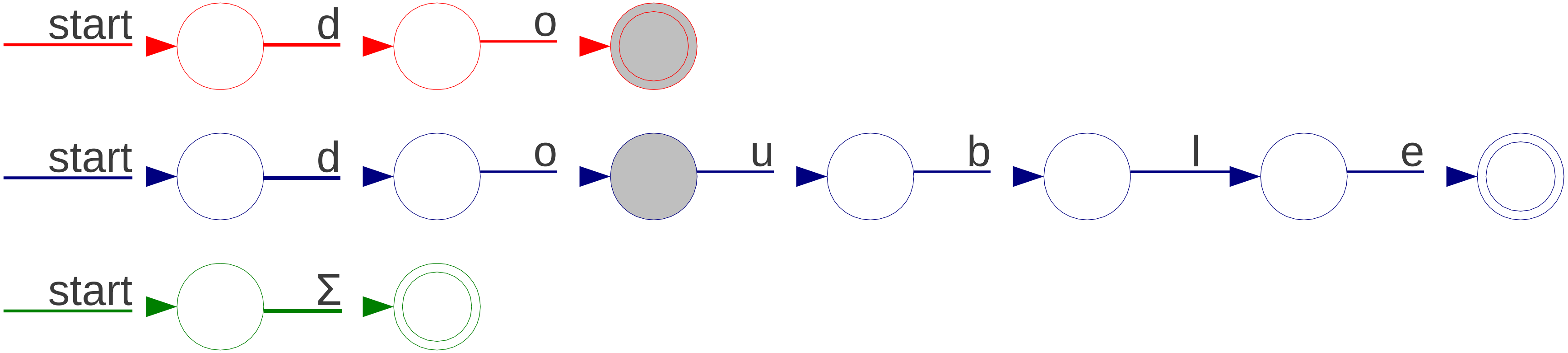
T_Double	double
T_Mystery	[A-Za-z]

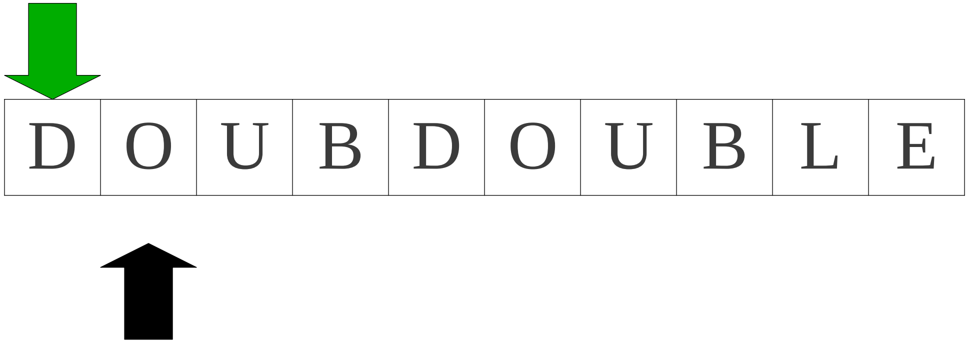


D O U B D O U B L E

Implementing Maximal Munch

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

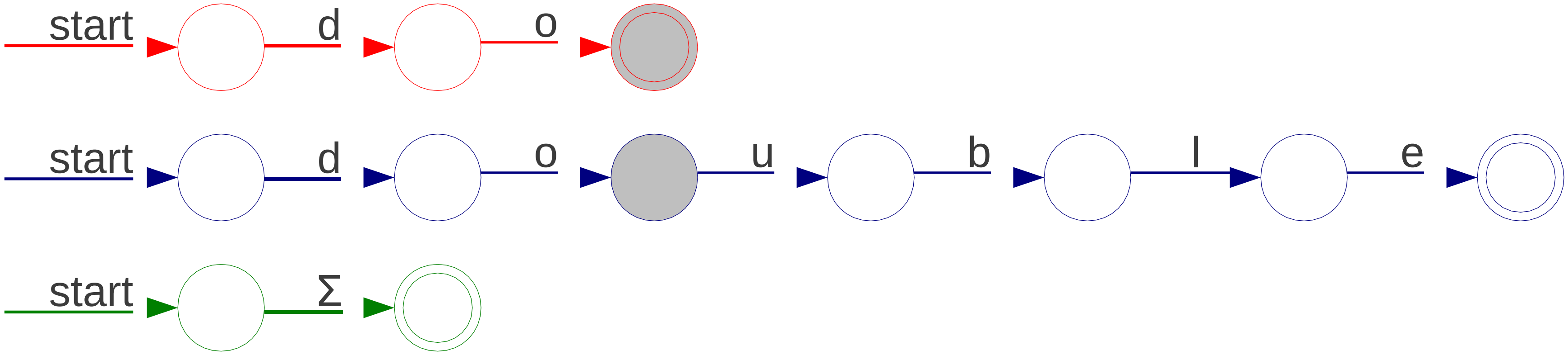


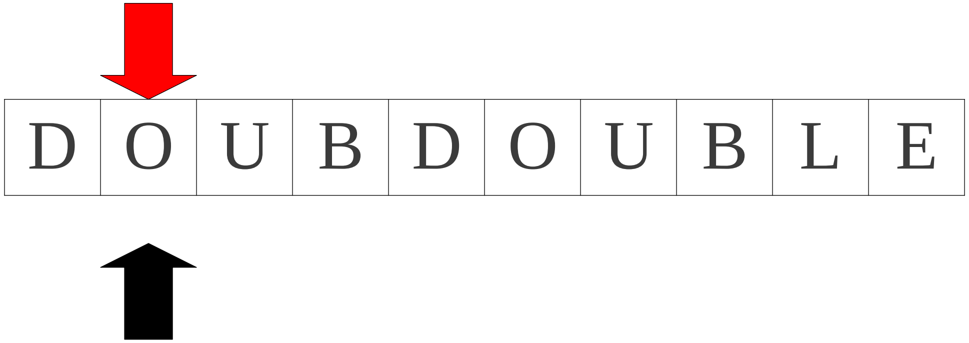


D	O	U	B	D	O	U	B	L	E

Implementing Maximal Munch

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





D	O	U	B	D	O	U	B	L	E

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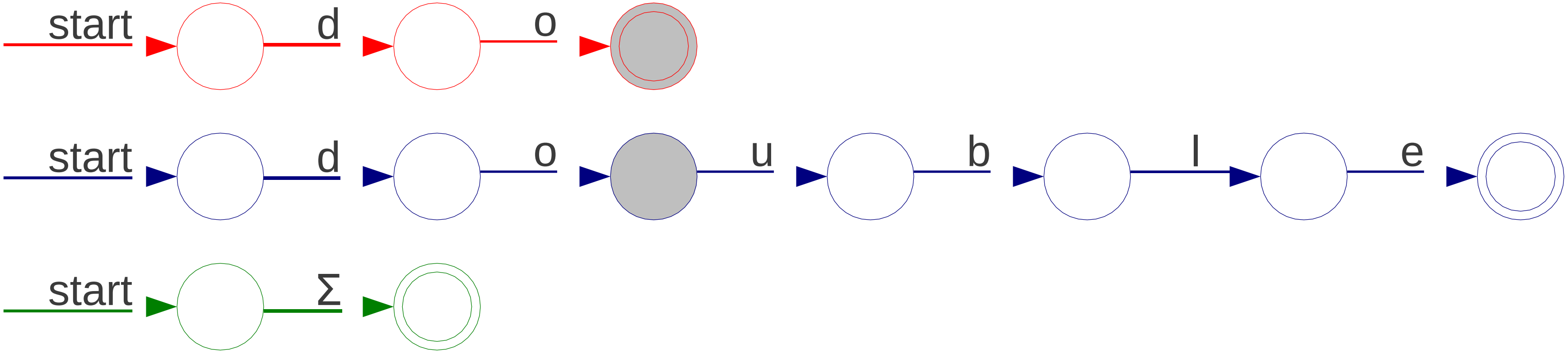

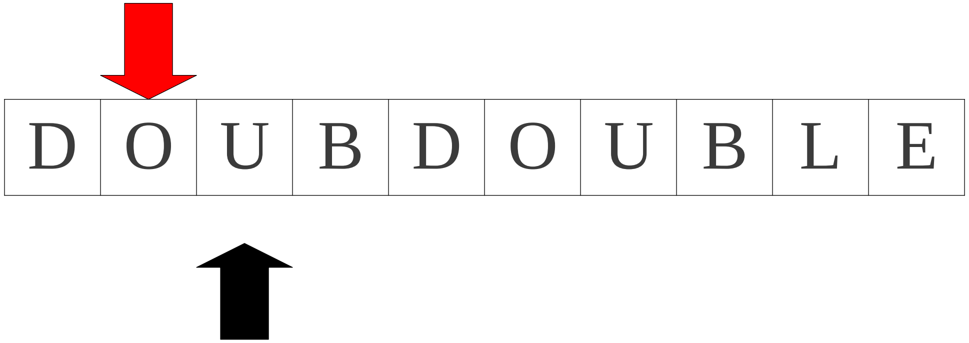

D	O	U	B	D	O	U	B	L	E

Implementing Maximal Munch

T_Do	do
T_Double	double
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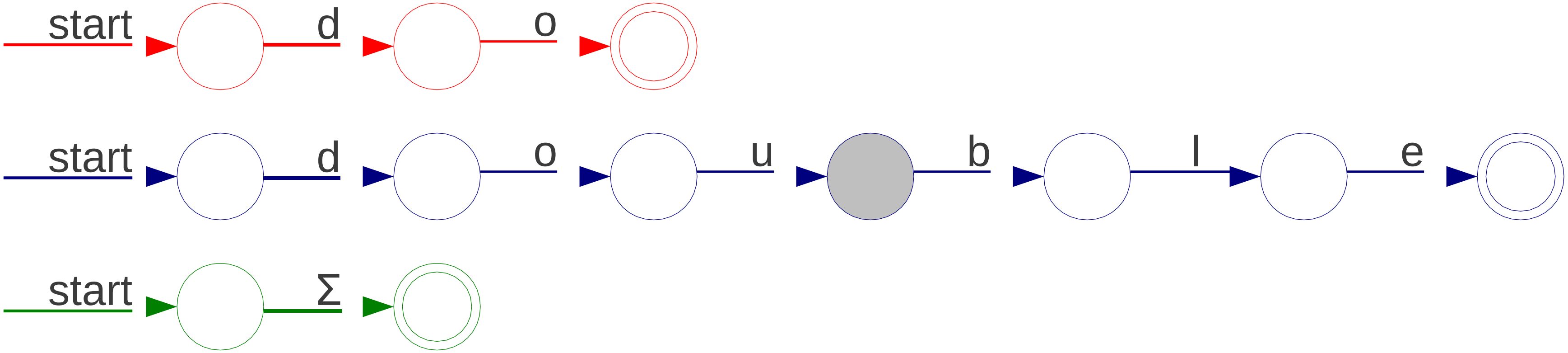
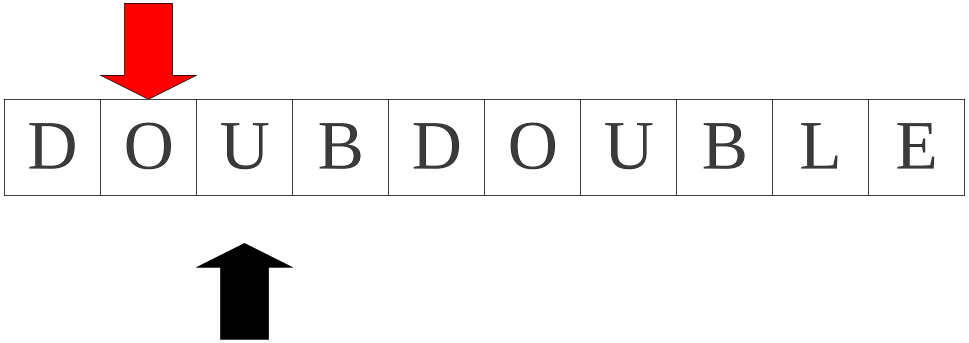
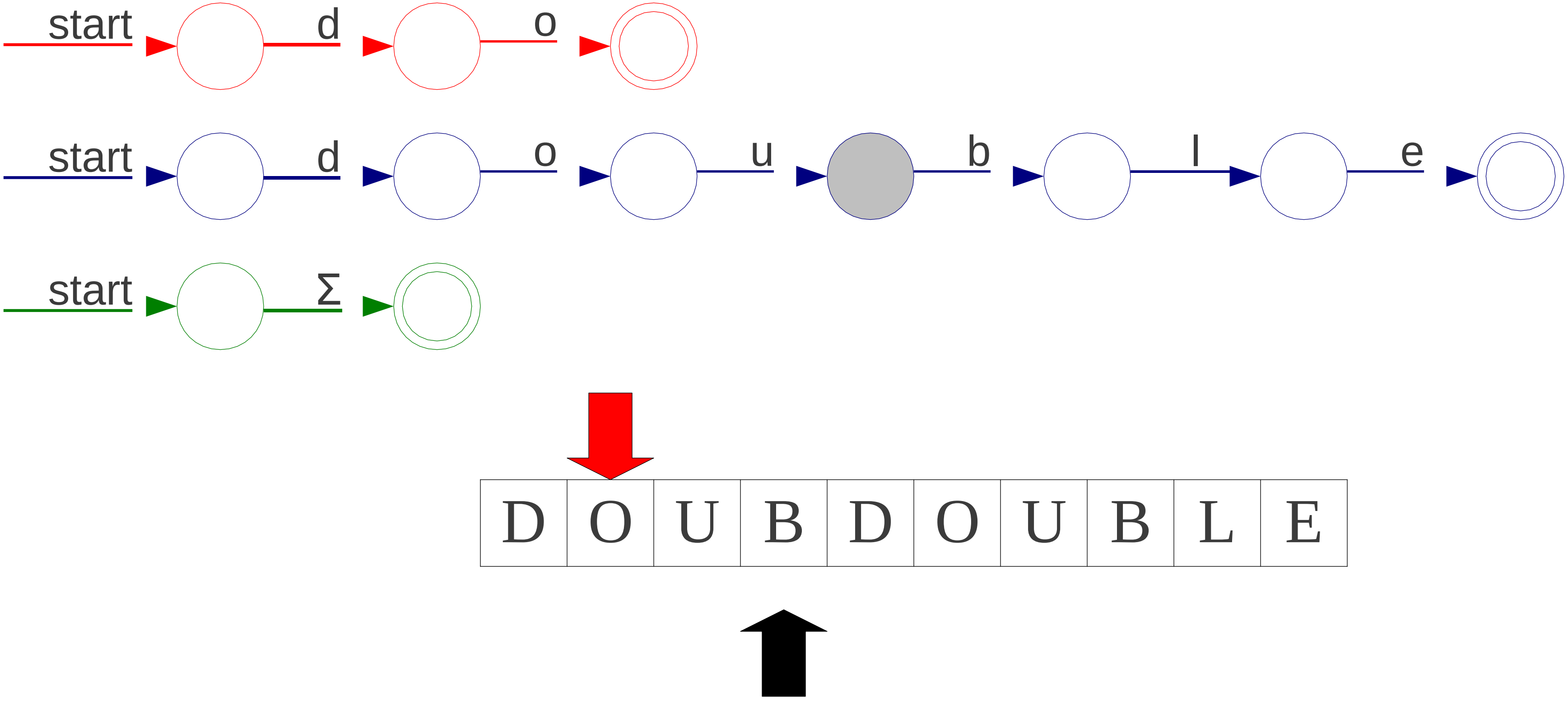




D O U B D O U B L E

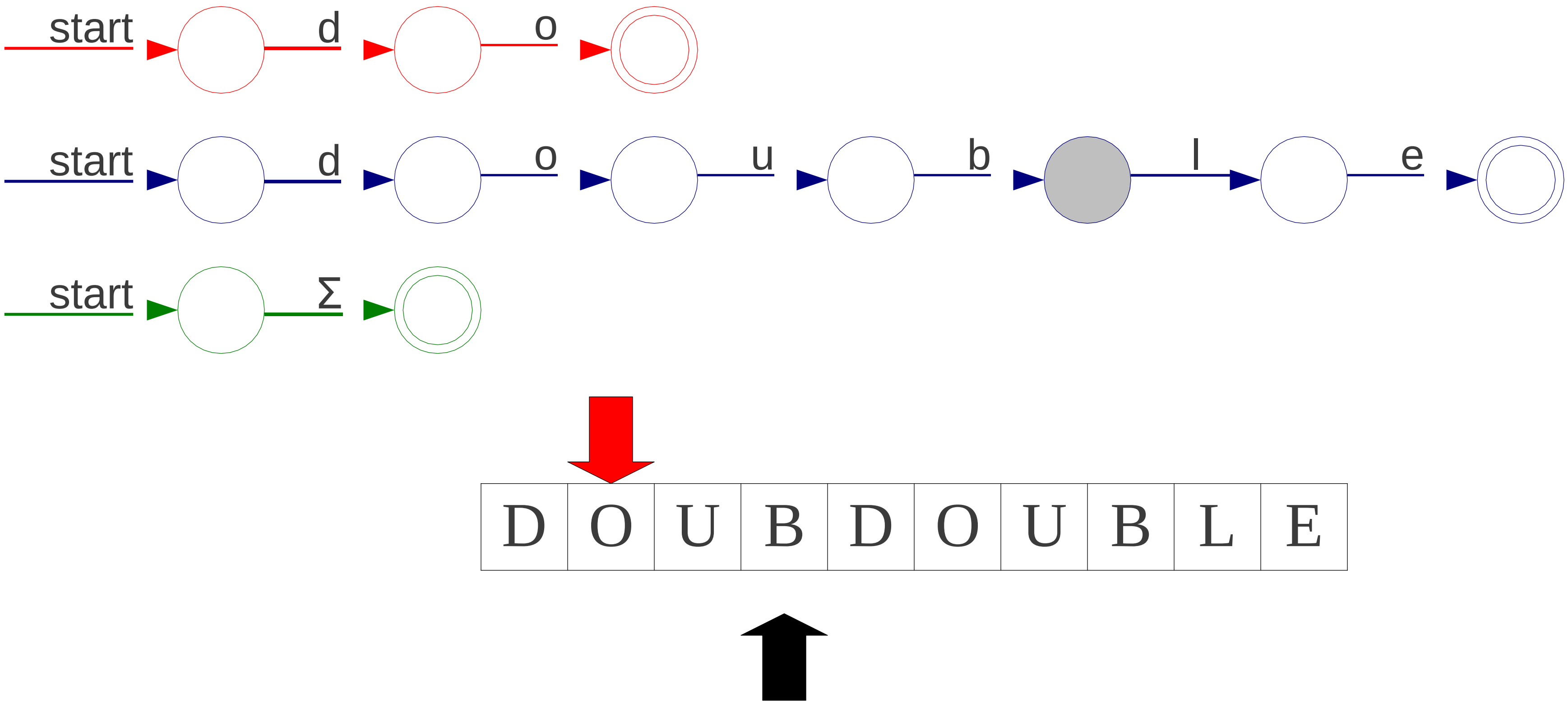
Implementing Maximal Munch

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



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
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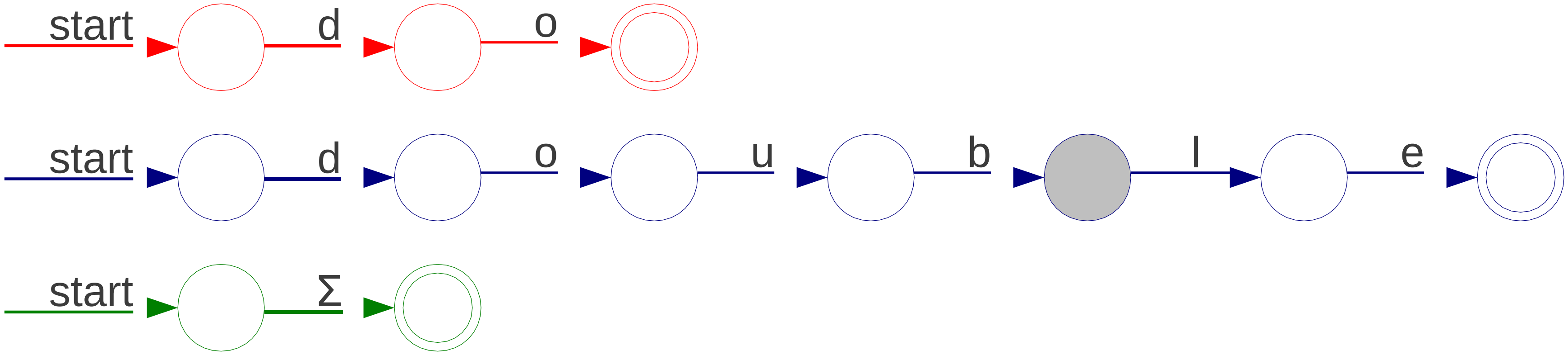
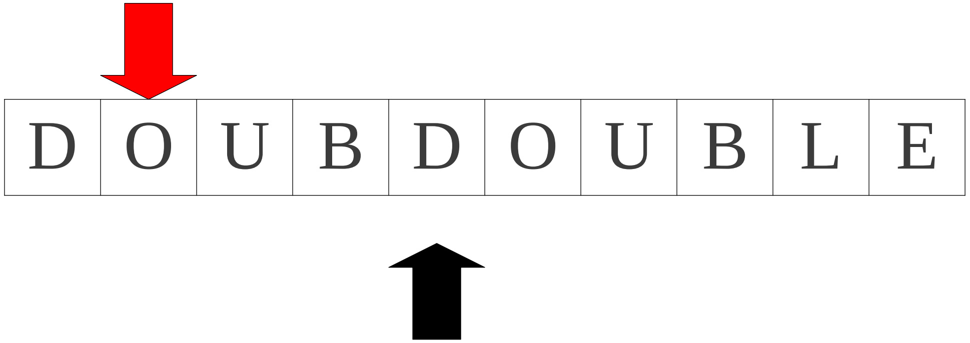
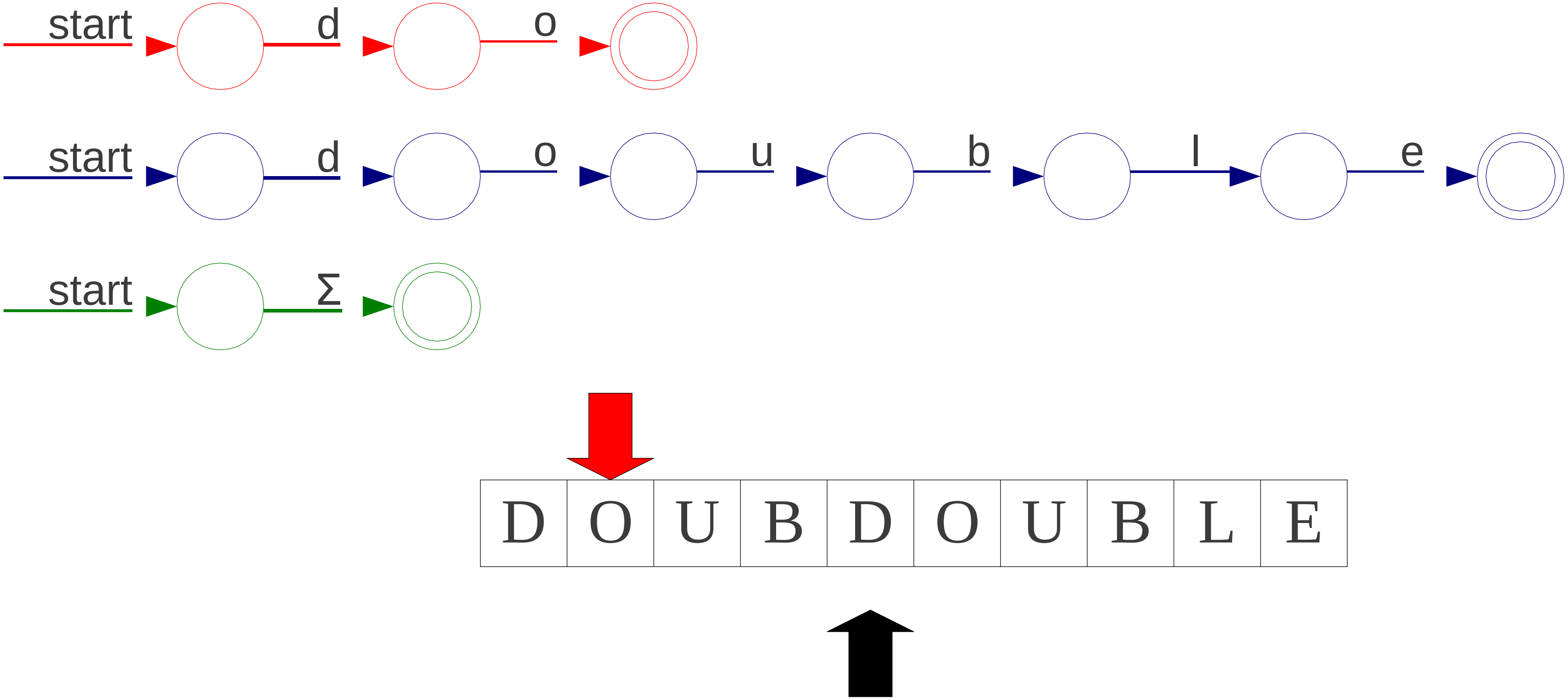




D	O	U	B	D	O	U	B	L	E

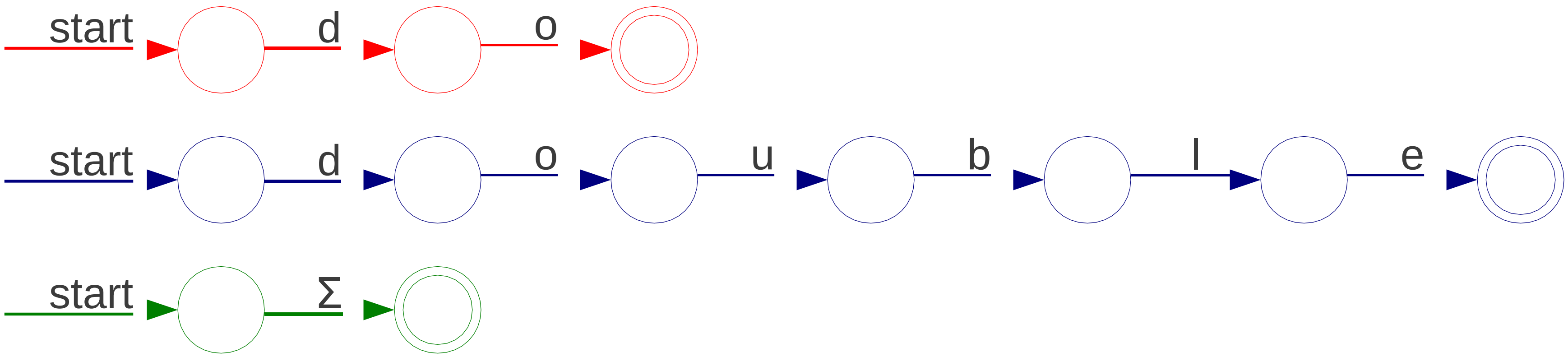
Implementing Maximal Munch

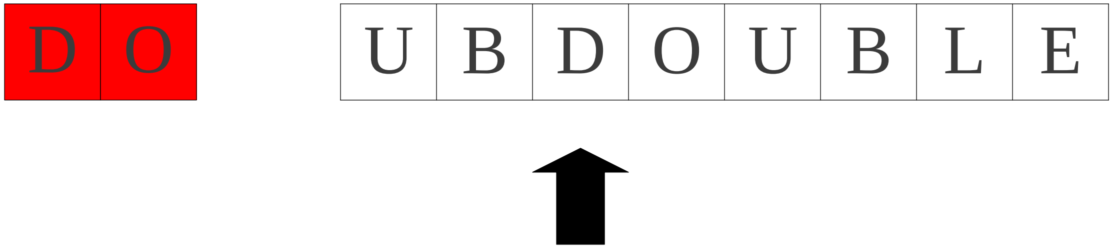
T_Do	do
T_Double	double
T_Mystery	[A-Za-z]



Implementing Maximal Munch

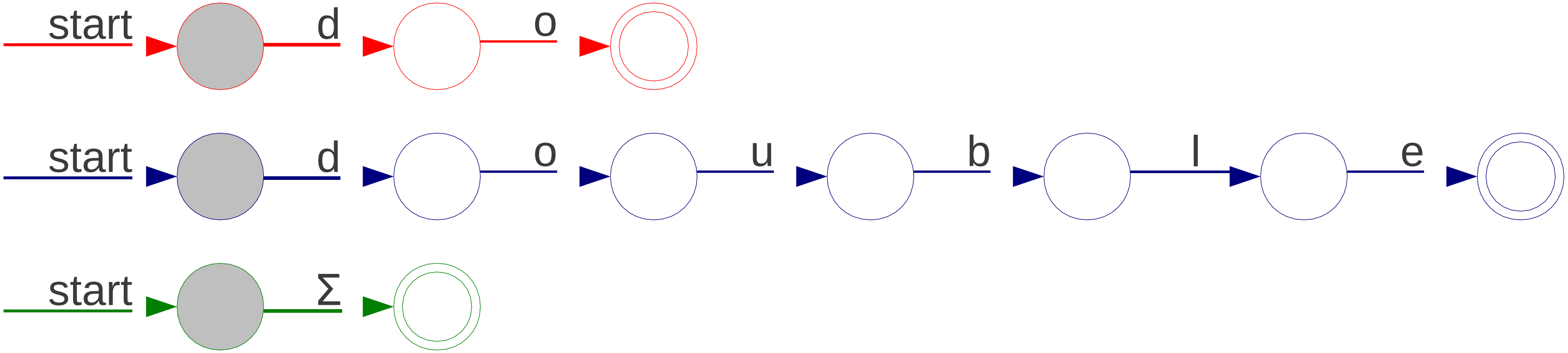
T_Do	do
T_Double	double
T_Mystery	[A-Za-z]





Implementing Maximal Munch

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

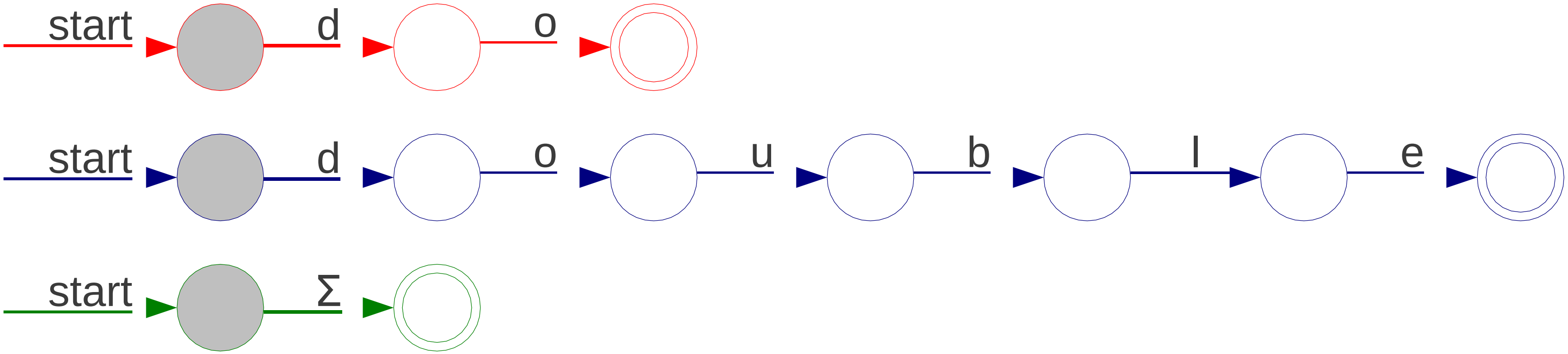


D	O

U	B	D	O	U	B	L	E

Implementing Maximal Munch

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

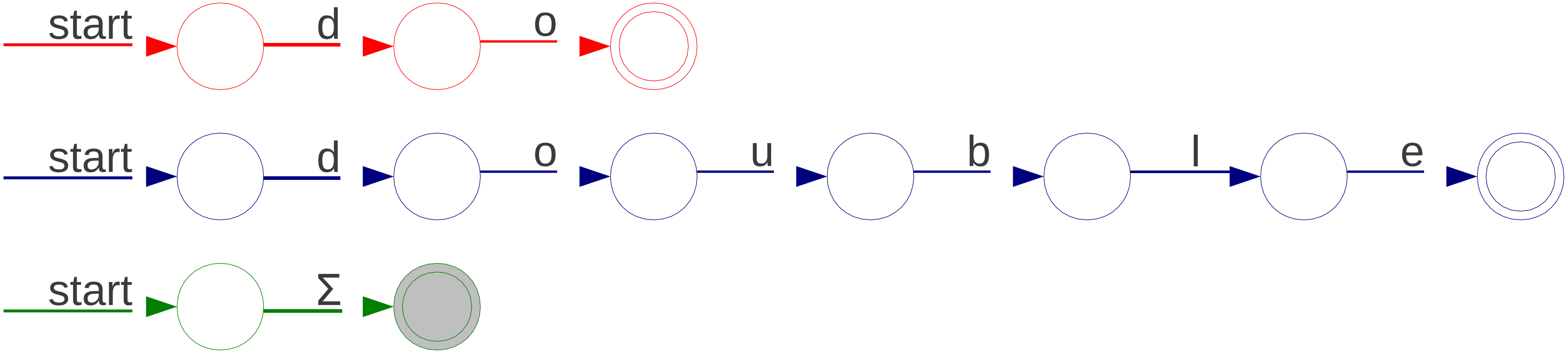


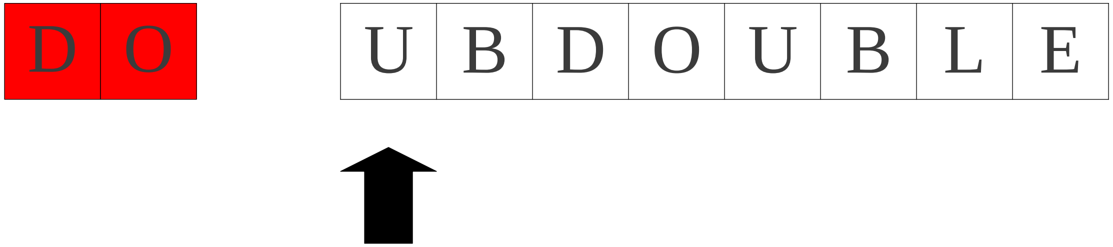
D	O

U	B	D	O	U	B	L	E

Implementing Maximal Munch

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



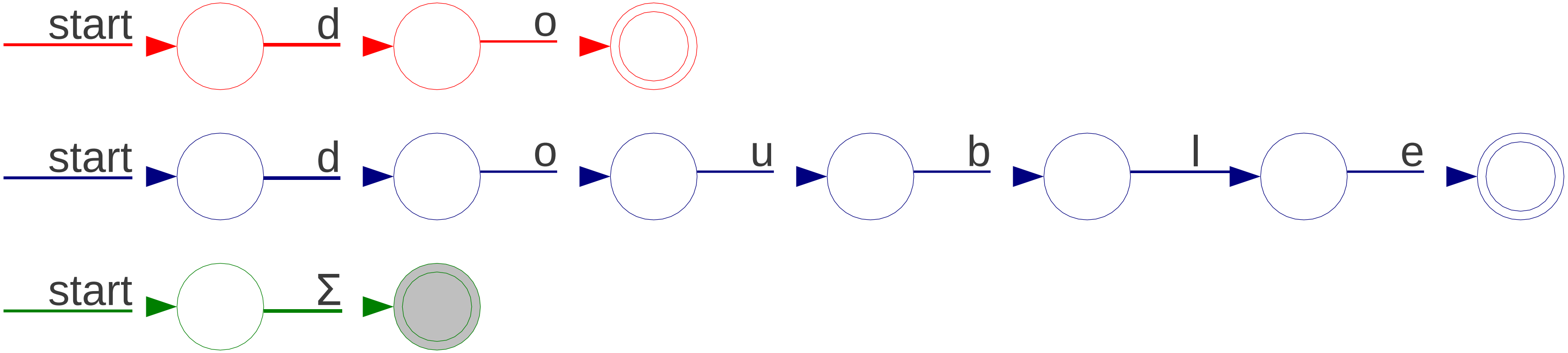


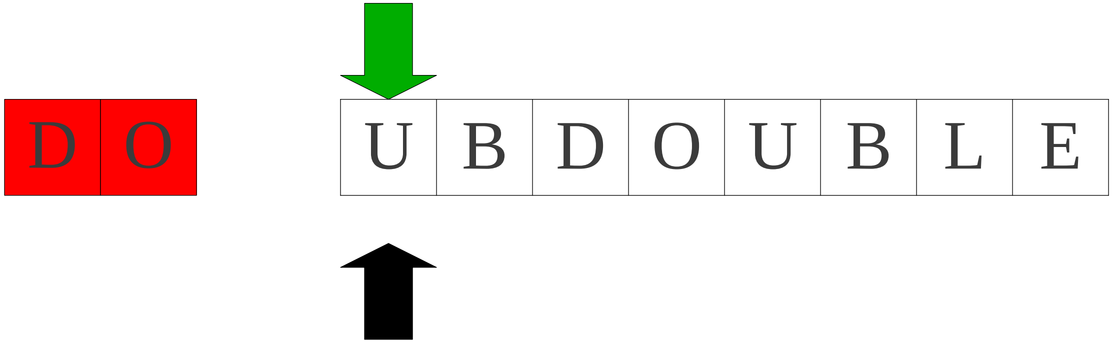
D O

U B D O U B L E

Implementing Maximal Munch

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



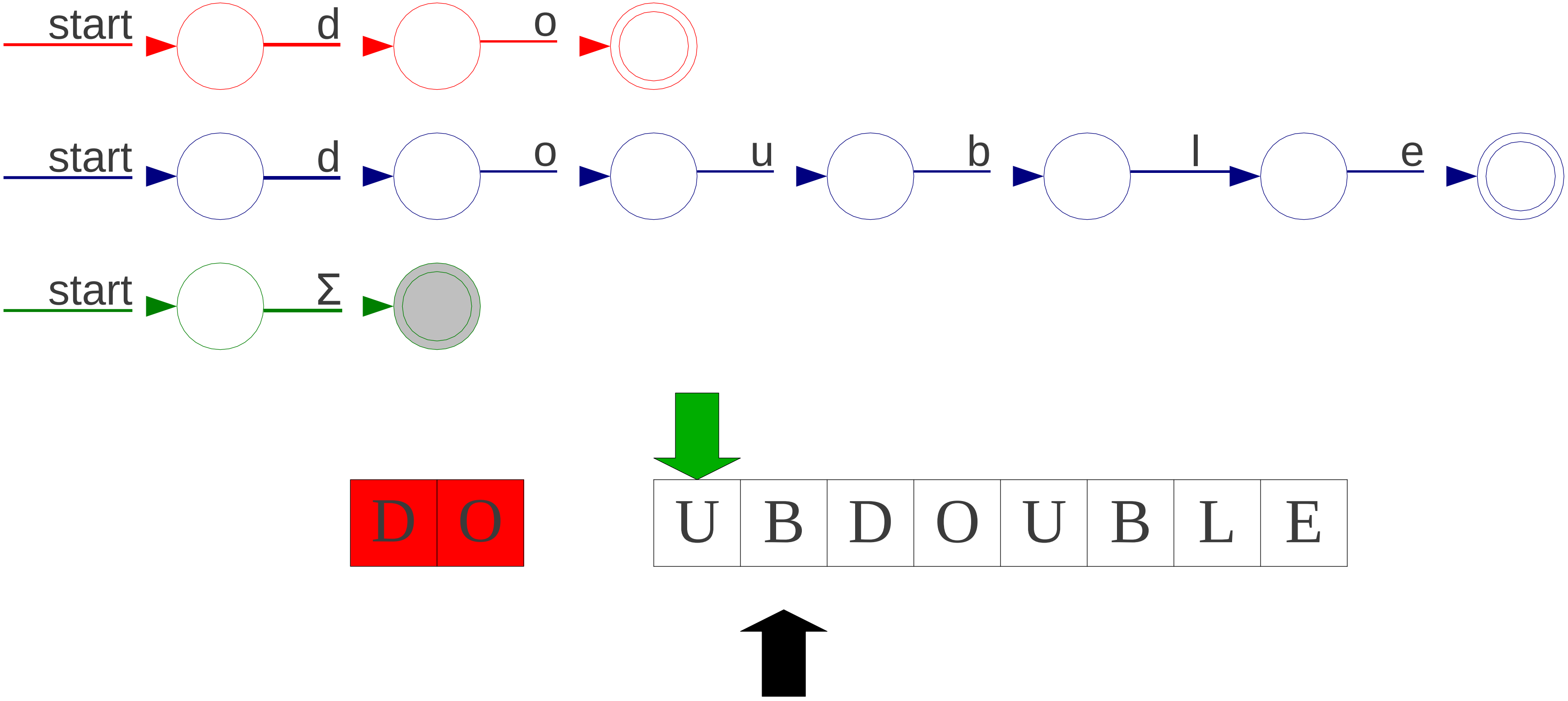


D O

U B D O U B L E

Implementing Maximal Munch

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

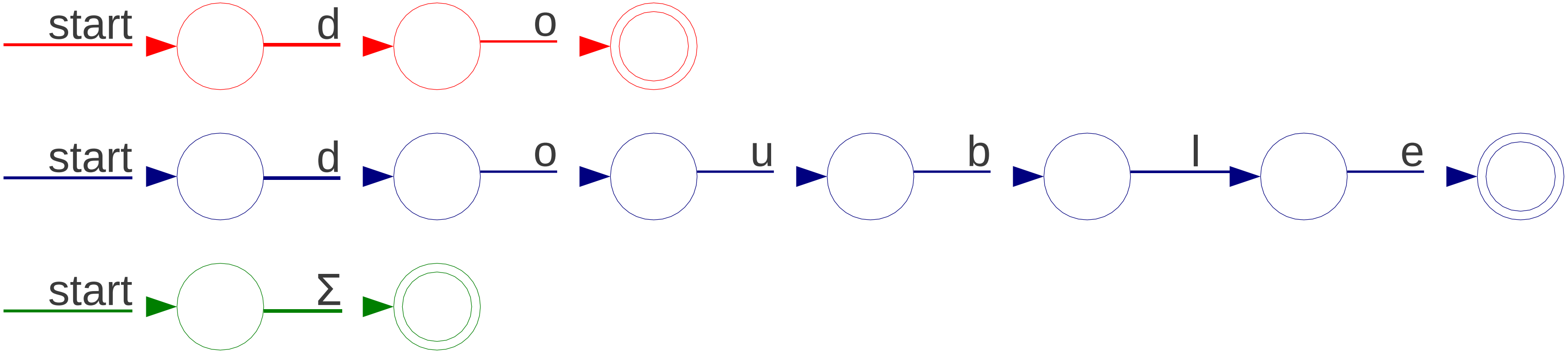


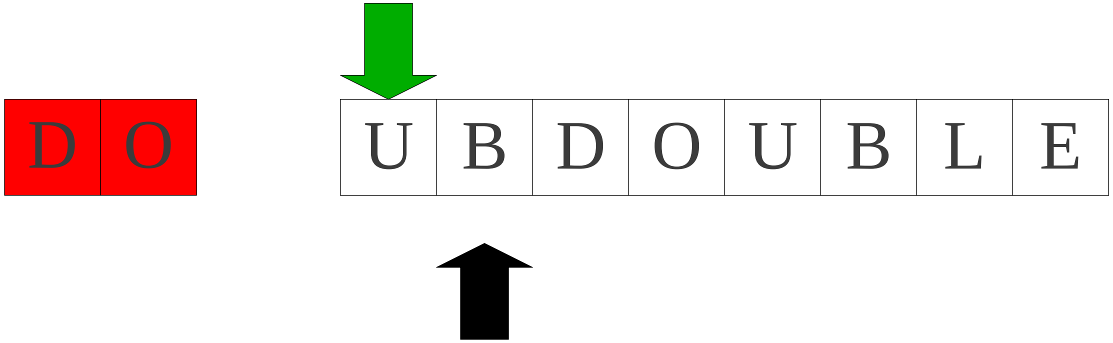
D	O

U	B	D	O	U	B	L	E

Implementing Maximal Munch

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



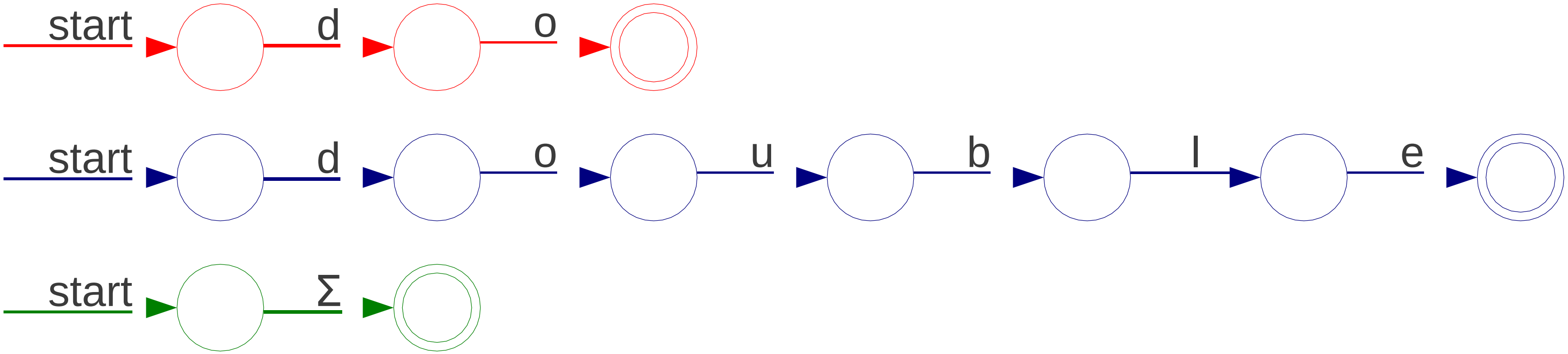


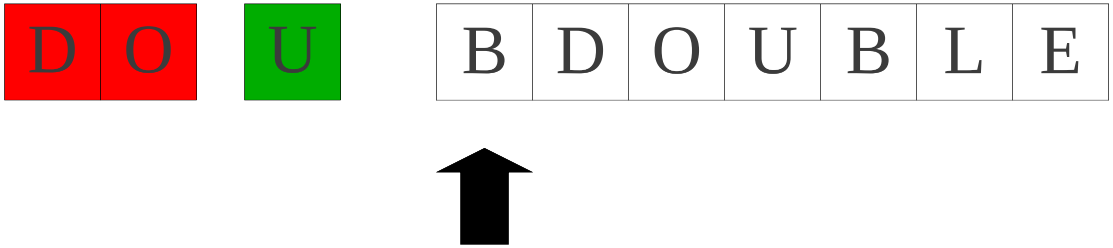
D O

U B D O U B L E

Implementing Maximal Munch

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





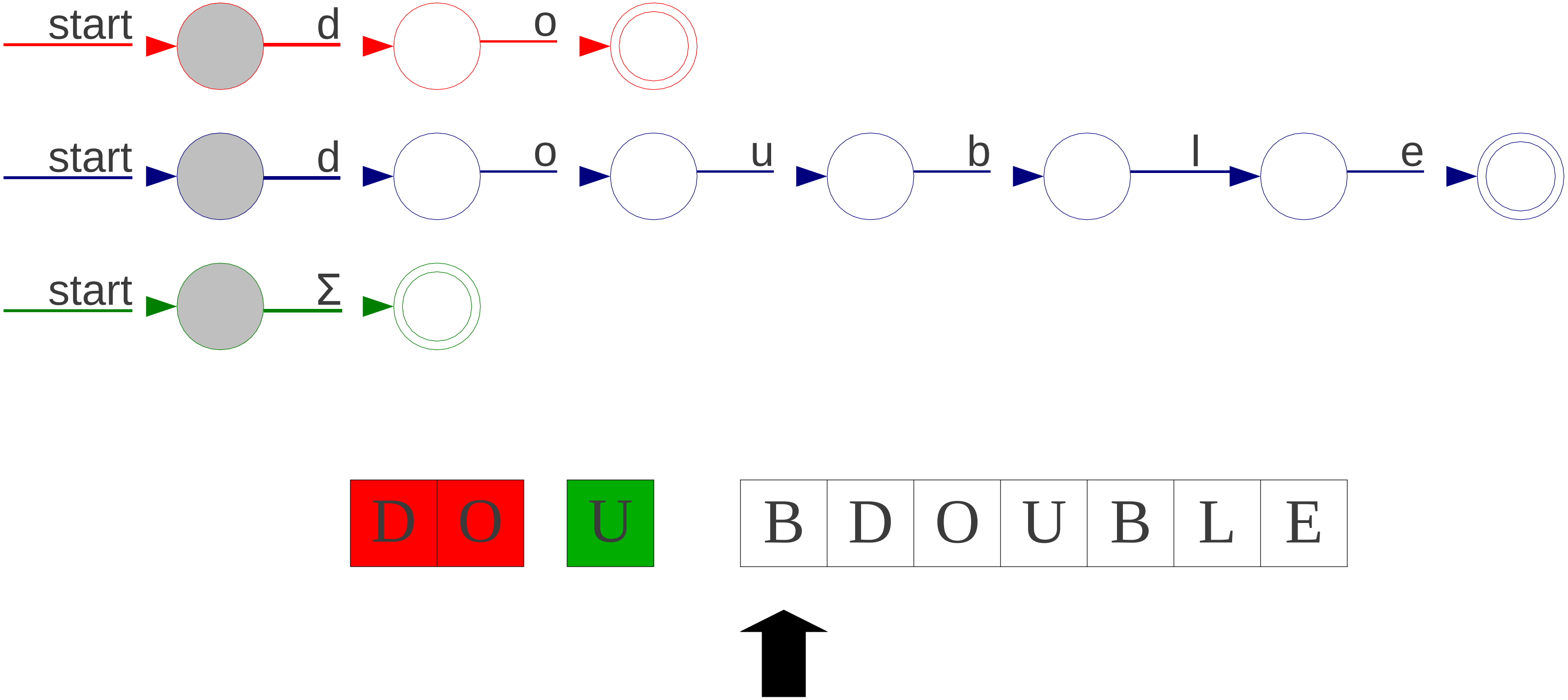
D O

U

B D O U B L E

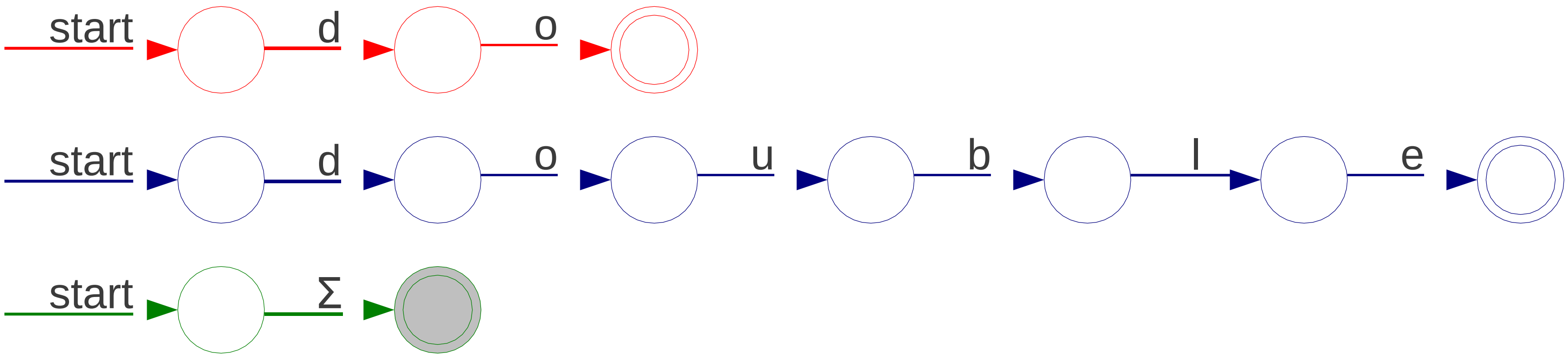
Implementing Maximal Munch

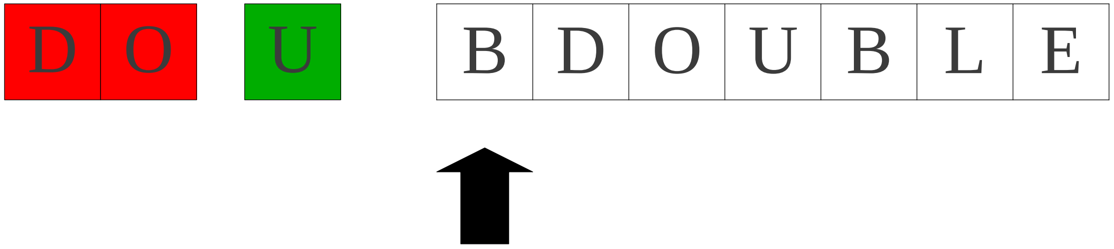
T_Do	do
T_Double	double
T_Mystery	[A-Za-z]



Implementing Maximal Munch

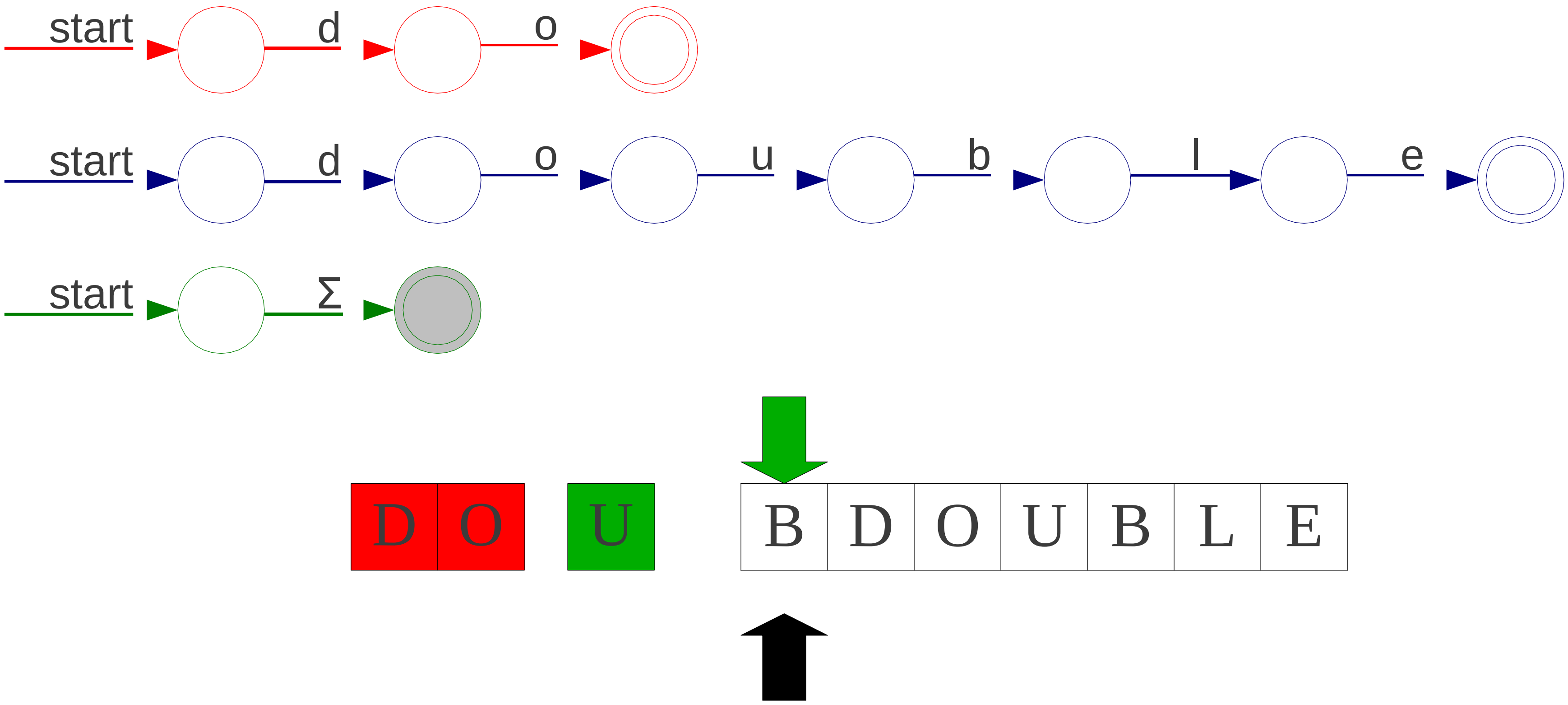
T_Do	do
T_Double	double
T_Mystery	[A-Za-z]





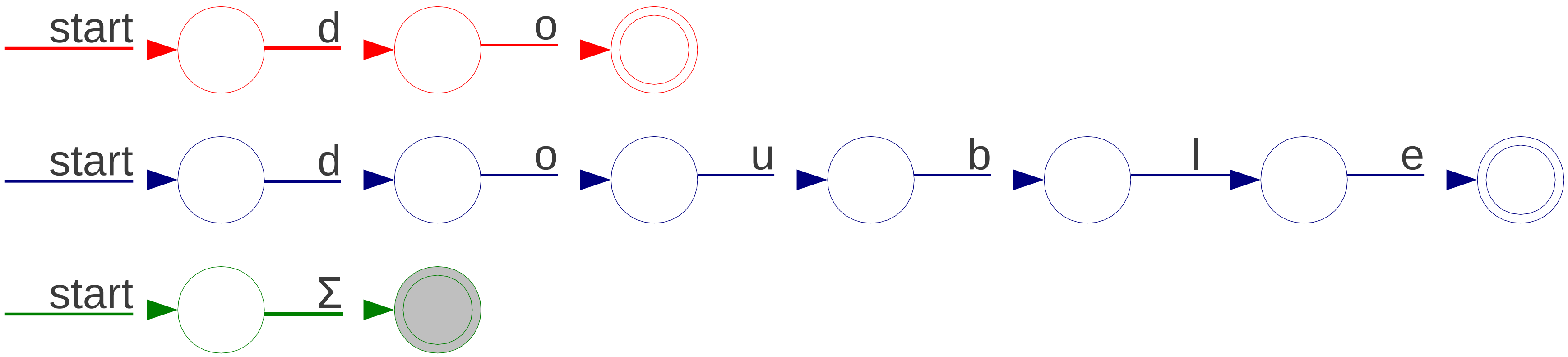
Implementing Maximal Munch

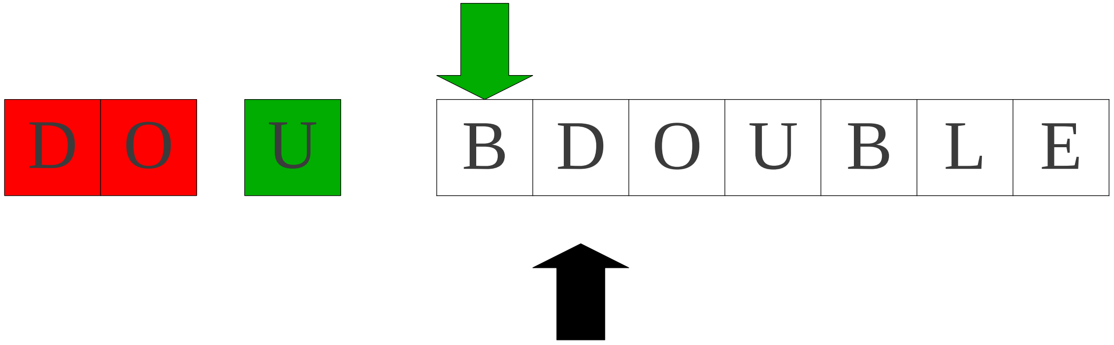
T_Do	do
T_Double	double
T_Mystery	[A-Za-z]



Implementing Maximal Munch

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





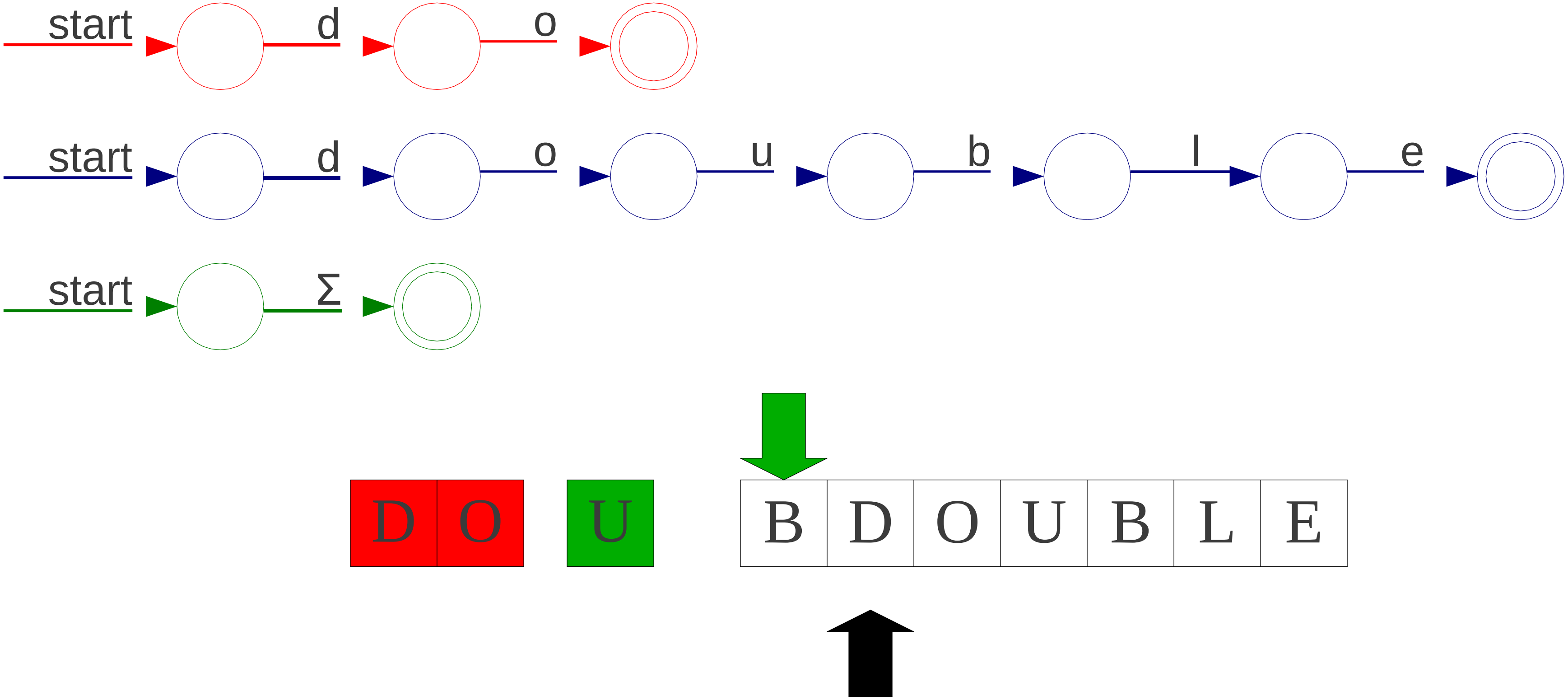
D O

U

B D O U B L E

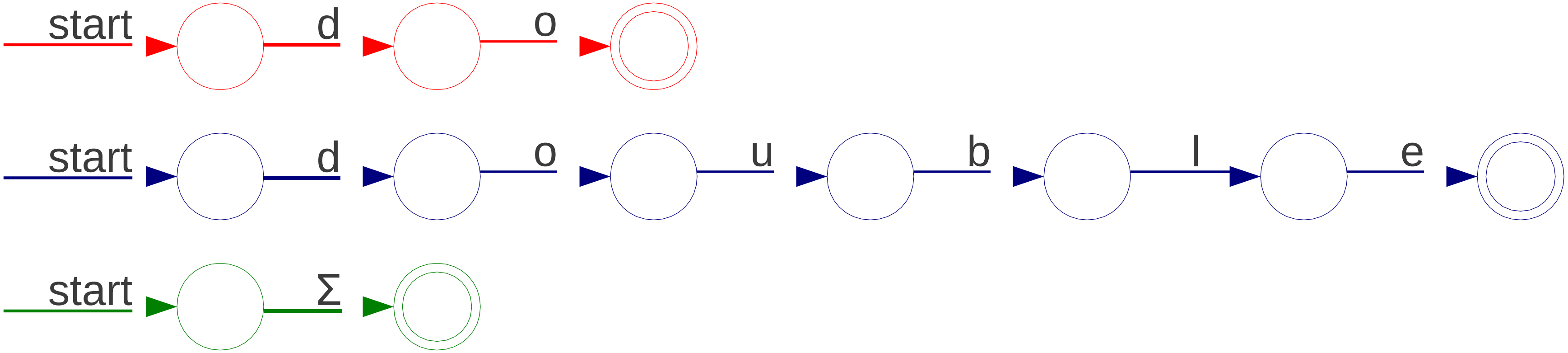
Implementing Maximal Munch

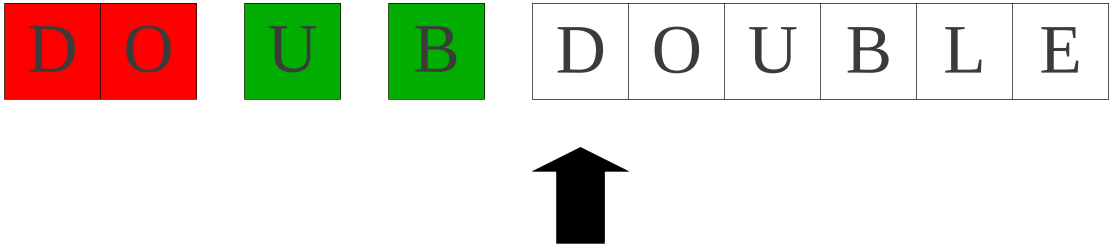
T_Do	do
T_Double	double
T_Mystery	[A-Za-z]



Implementing Maximal Munch

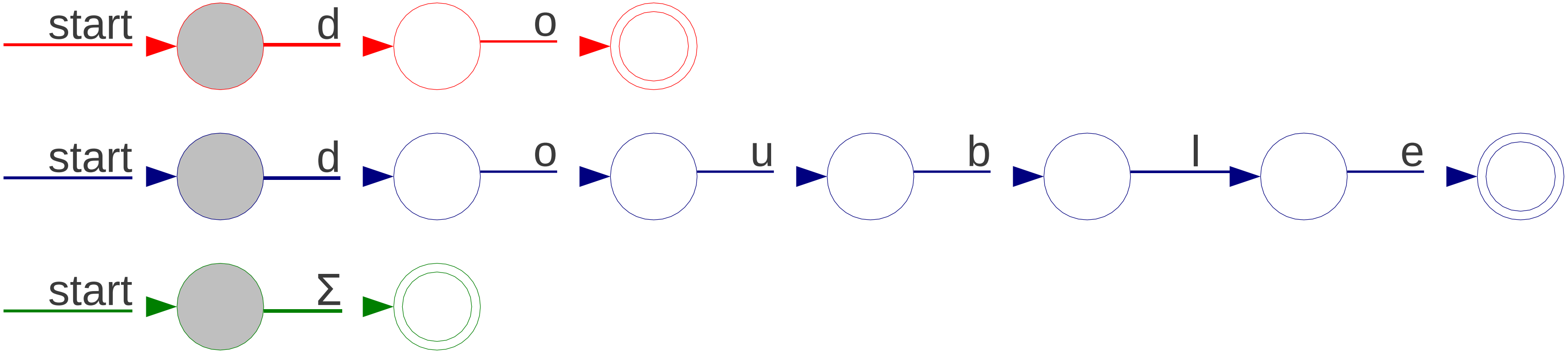
T_Do	do
T_Double	double
T_Mystery	[A-Za-z]

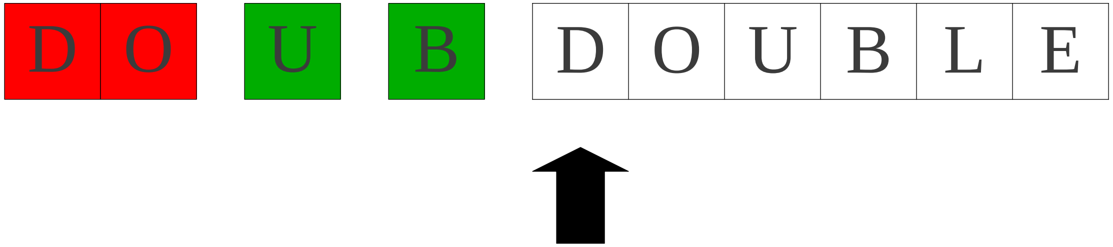



D O U B D O U B L E

Implementing Maximal Munch

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

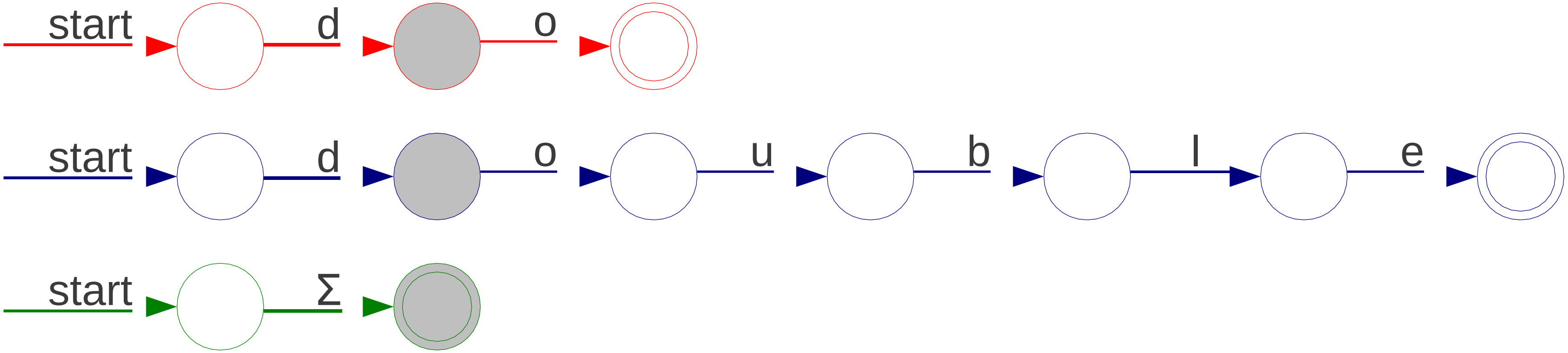


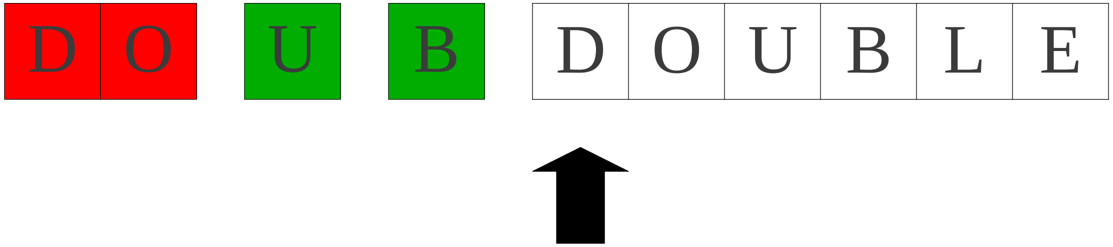


D	O	U	B	D	O	U	B	L	E

Implementing Maximal Munch

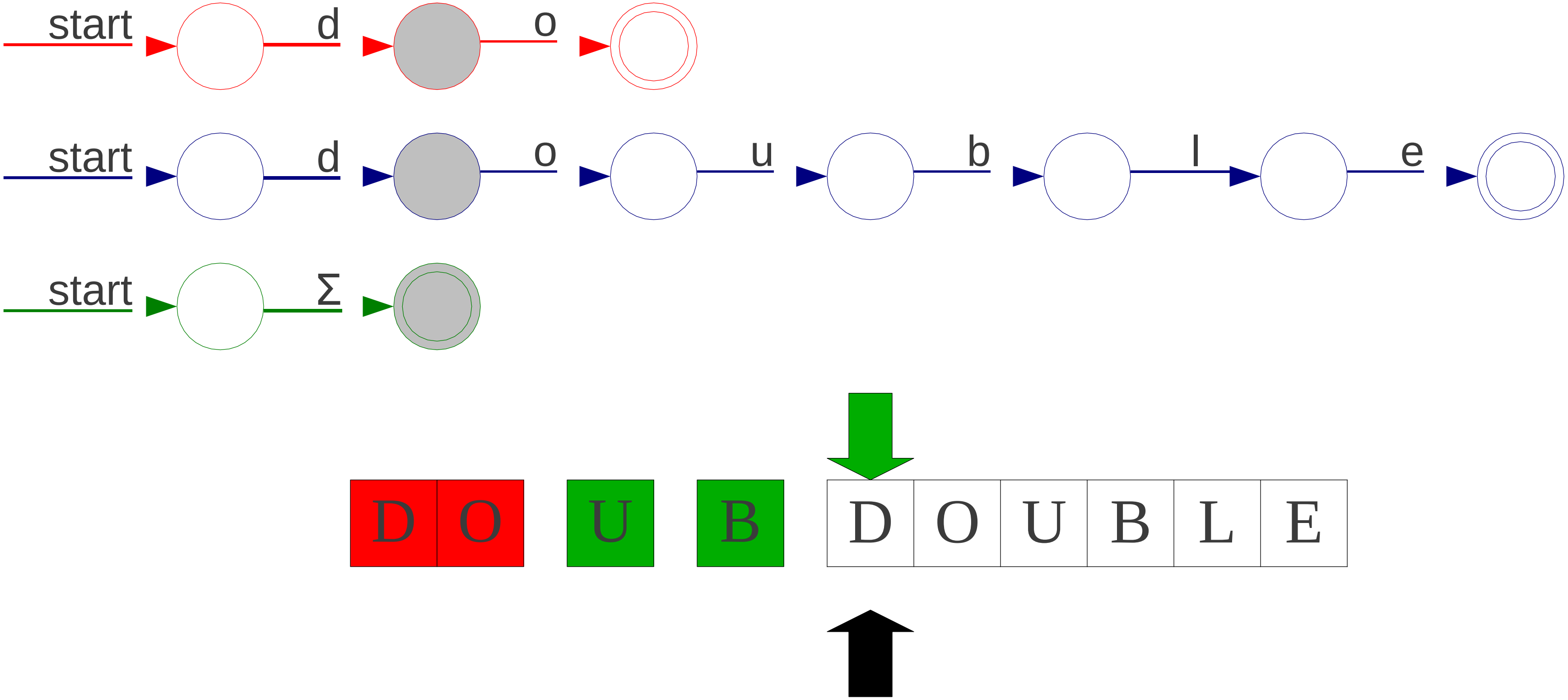
T_Do	do
T_Double	double
T_Mystery	[A-Za-z]





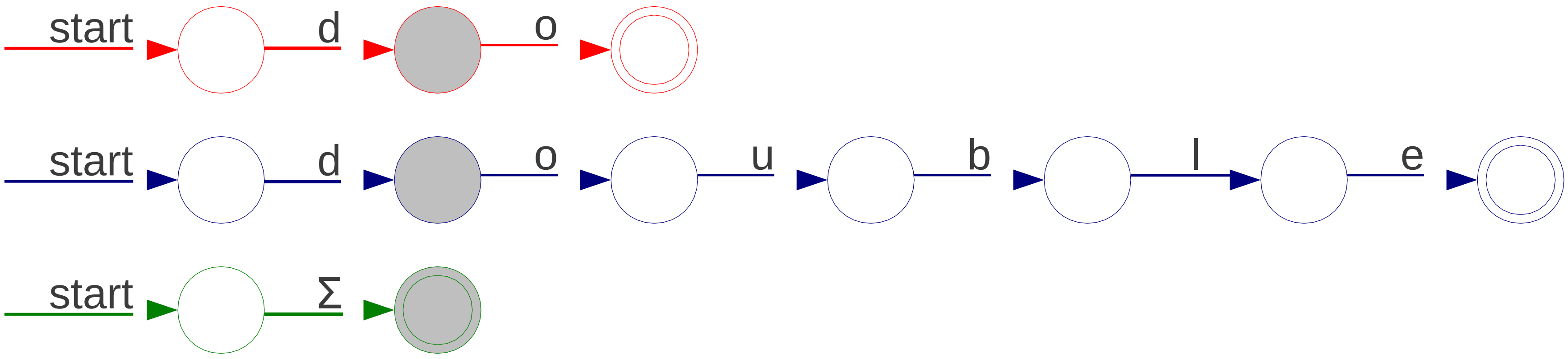
Implementing Maximal Munch

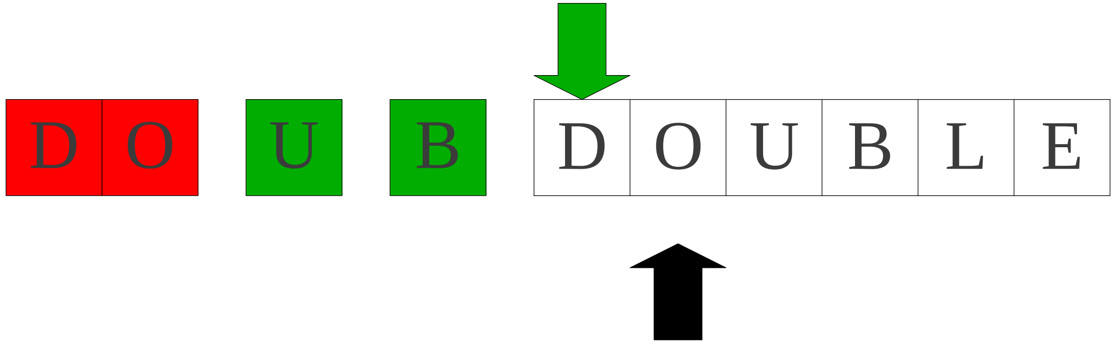
T_Do	do
T_Double	double
T_Mystery	[A-Za-z]



Implementing Maximal Munch

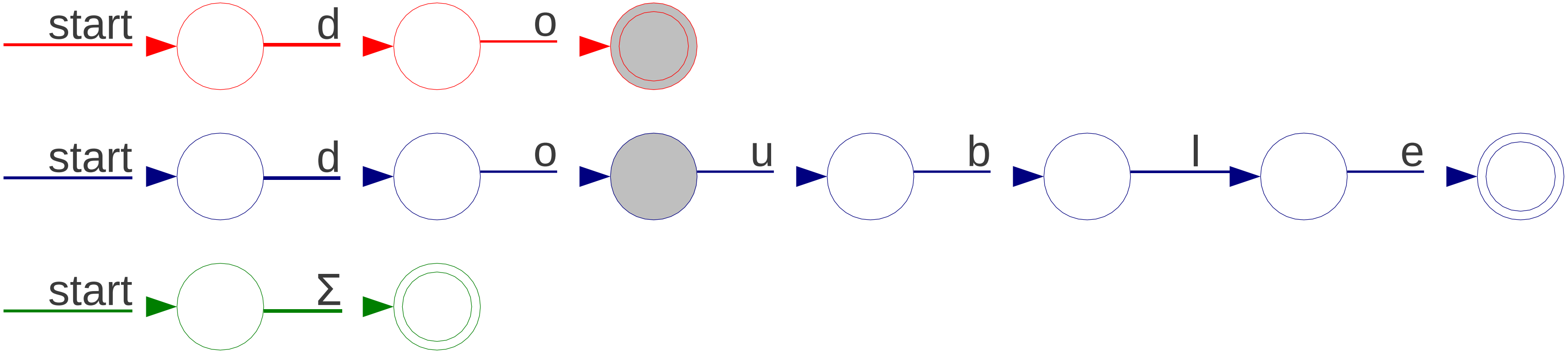
T_Do	do
T_Double	double
T_Mystery	[A-Za-z]

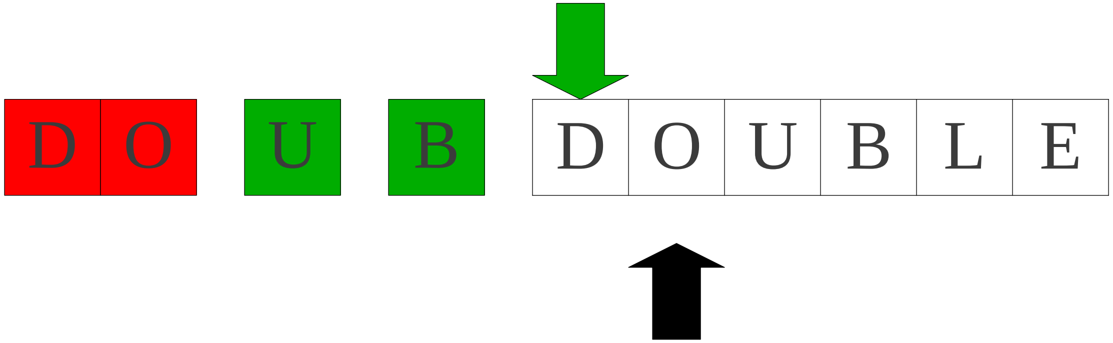




Implementing Maximal Munch

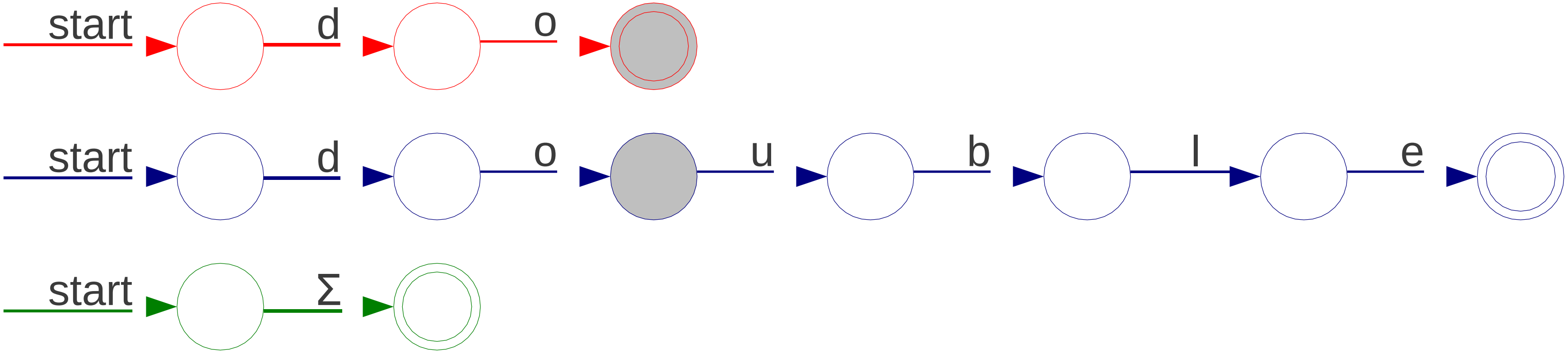
T_Do	do
T_Double	double
T_Mystery	[A-Za-z]

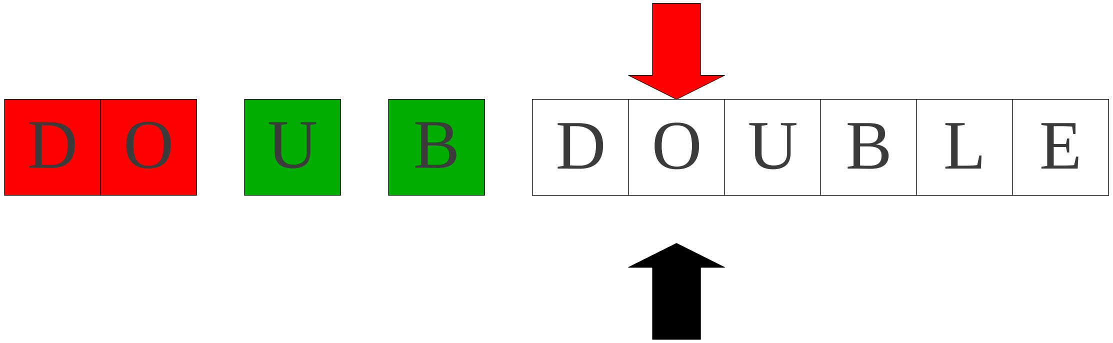




Implementing Maximal Munch

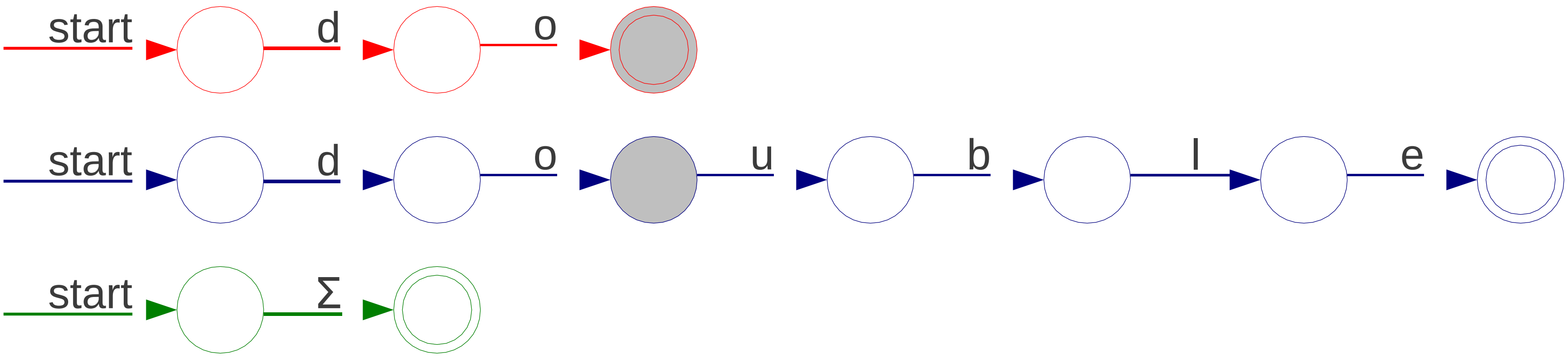
T_Do	do
T_Double	double
T_Mystery	[A-Za-z]

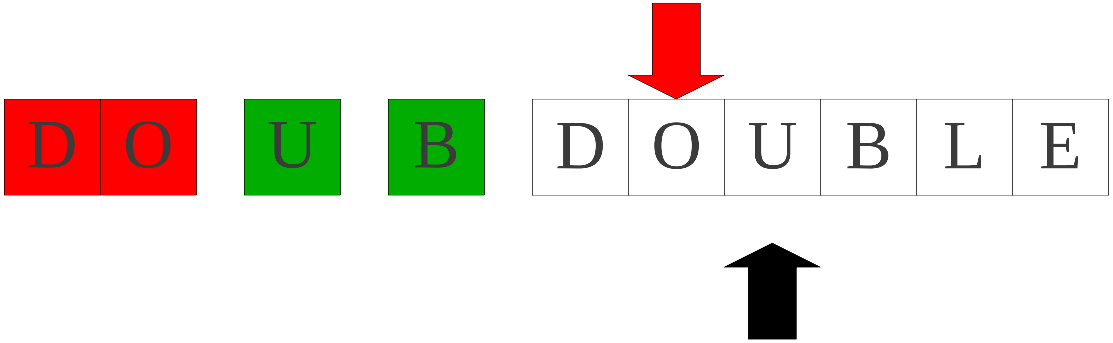




Implementing Maximal Munch

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

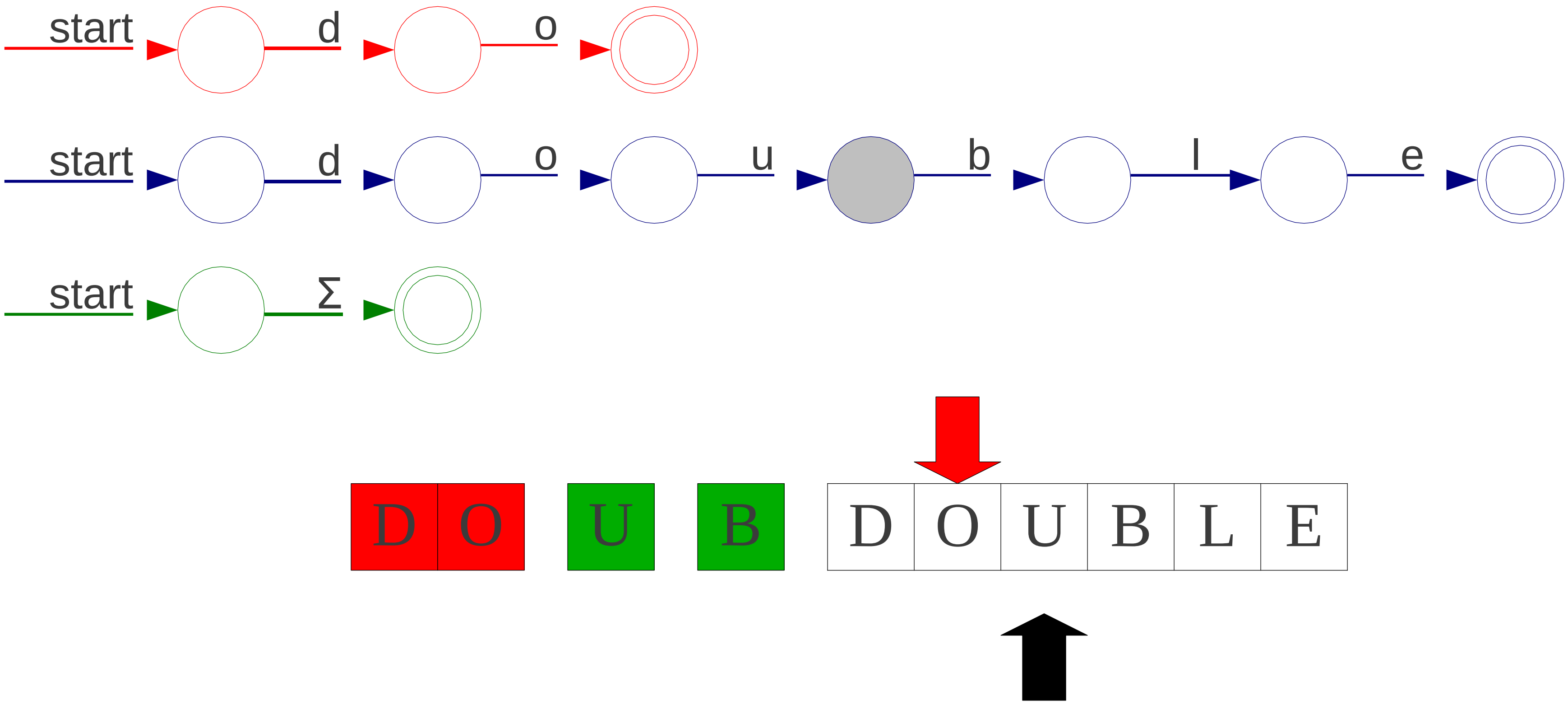




D	O	U	B	D	O	U	B	L	E

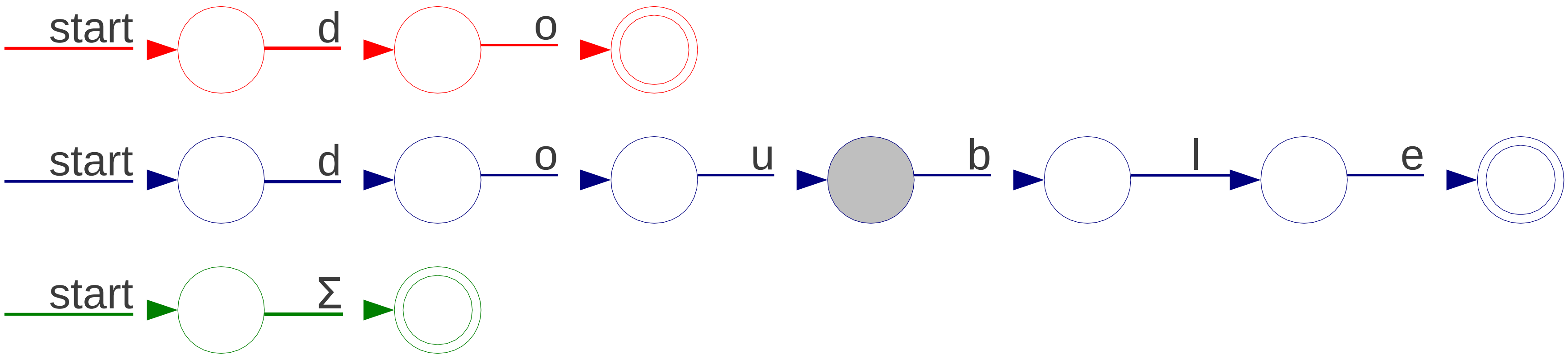
Implementing Maximal Munch

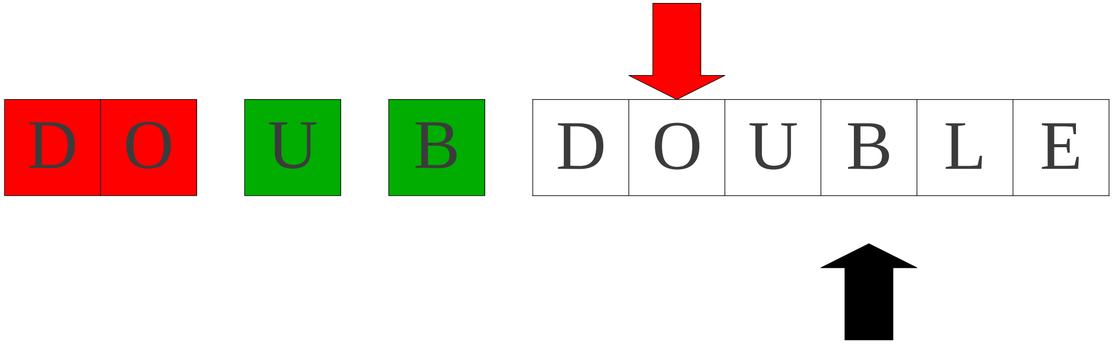
T_Do	do
T_Double	double
T_Mystery	[A-Za-z]



Implementing Maximal Munch

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




D O

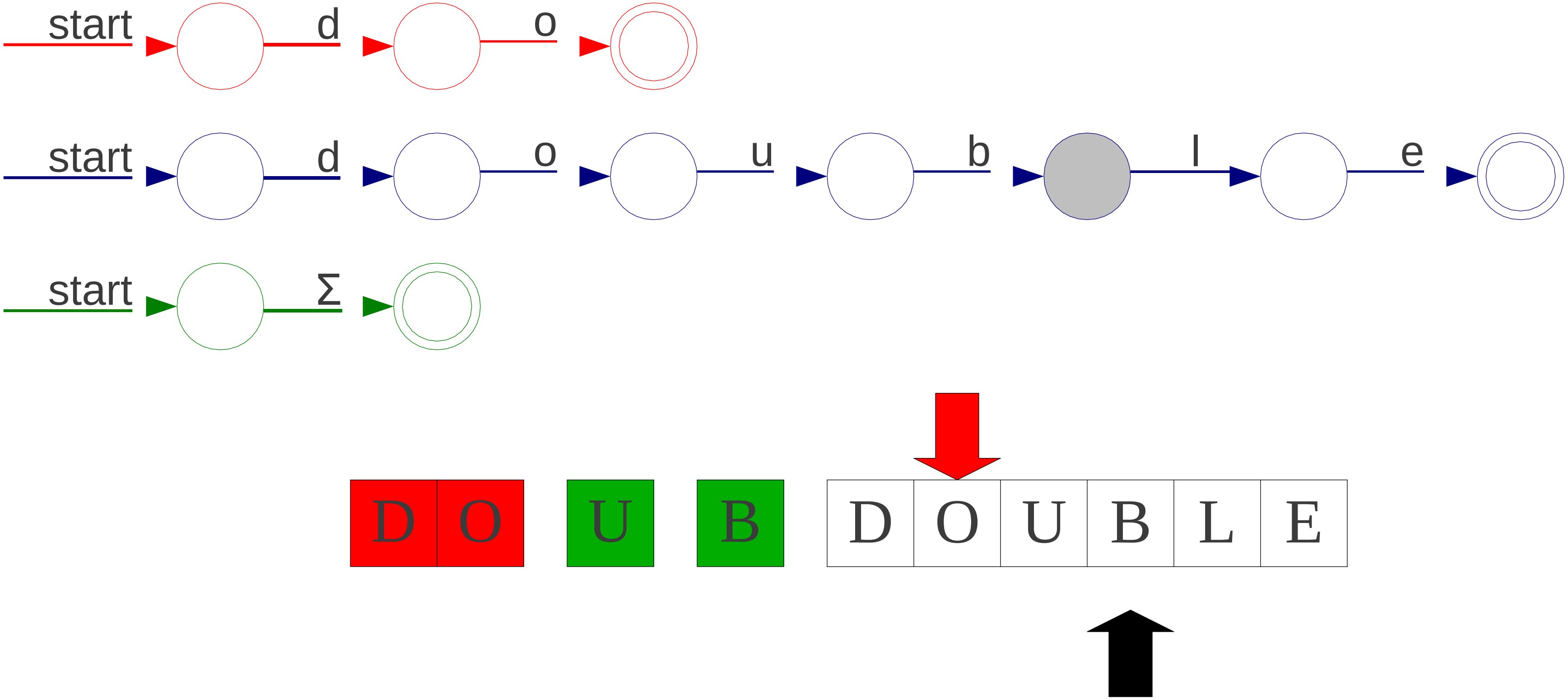
U

B

D O U B L E

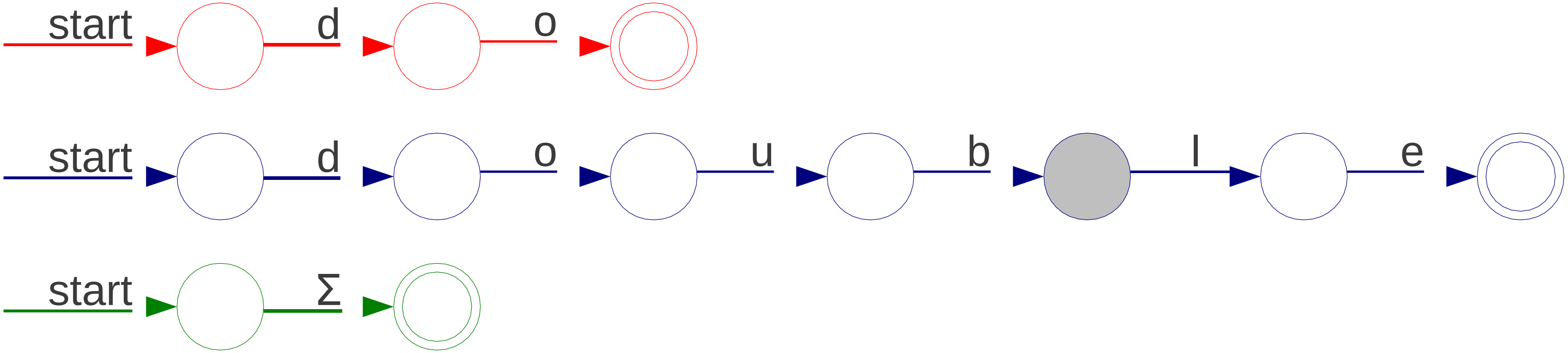
Implementing Maximal Munch

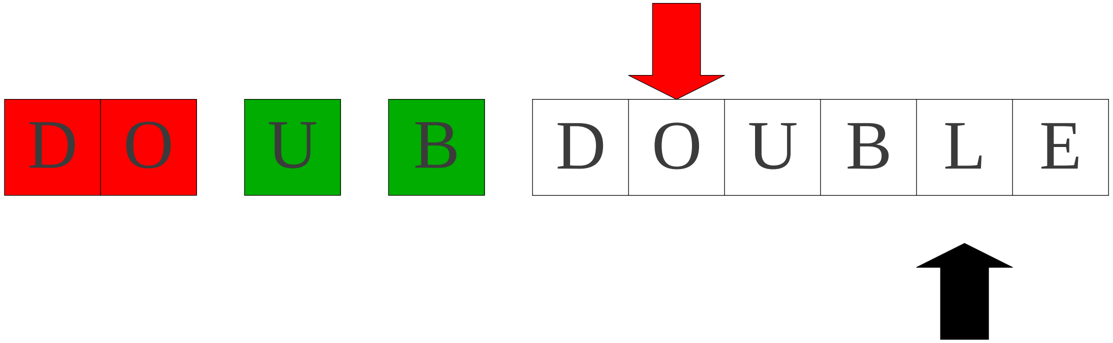
T_Do	do
T_Double	double
T_Mystery	[A-Za-z]



Implementing Maximal Munch

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

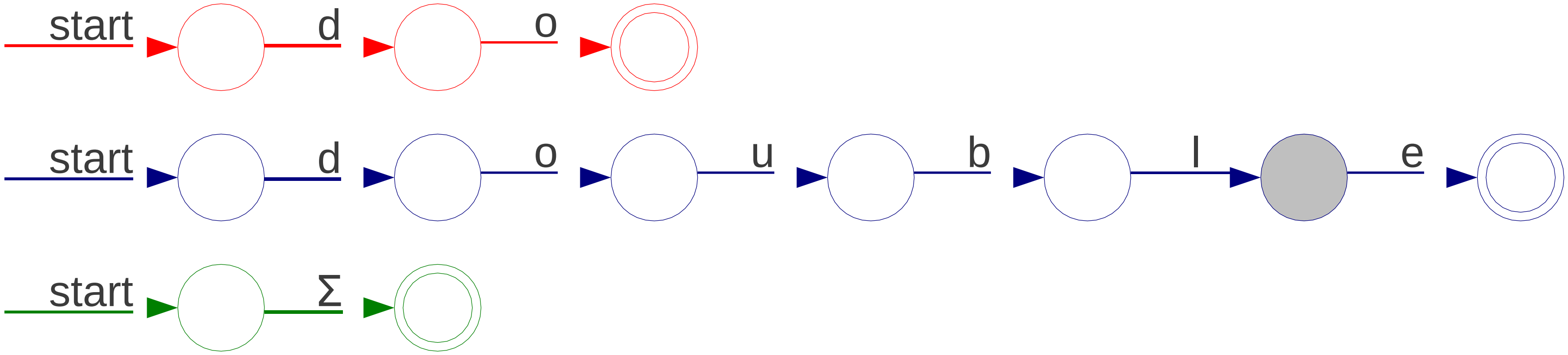


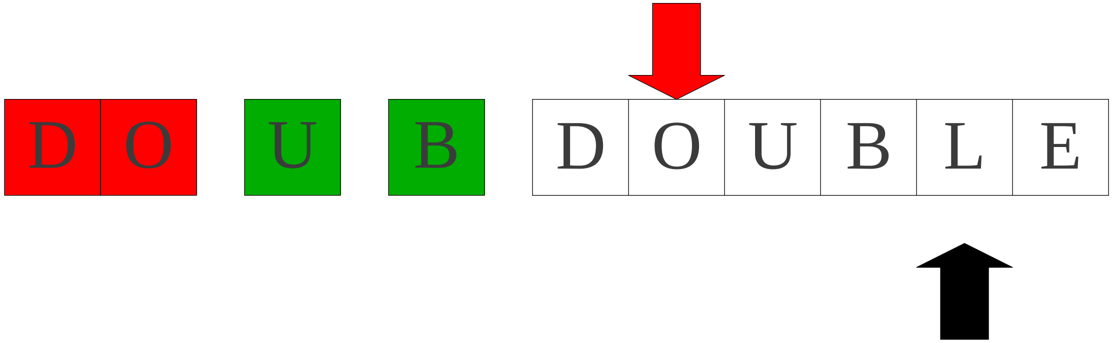


D O U B DOUBLE

Implementing Maximal Munch

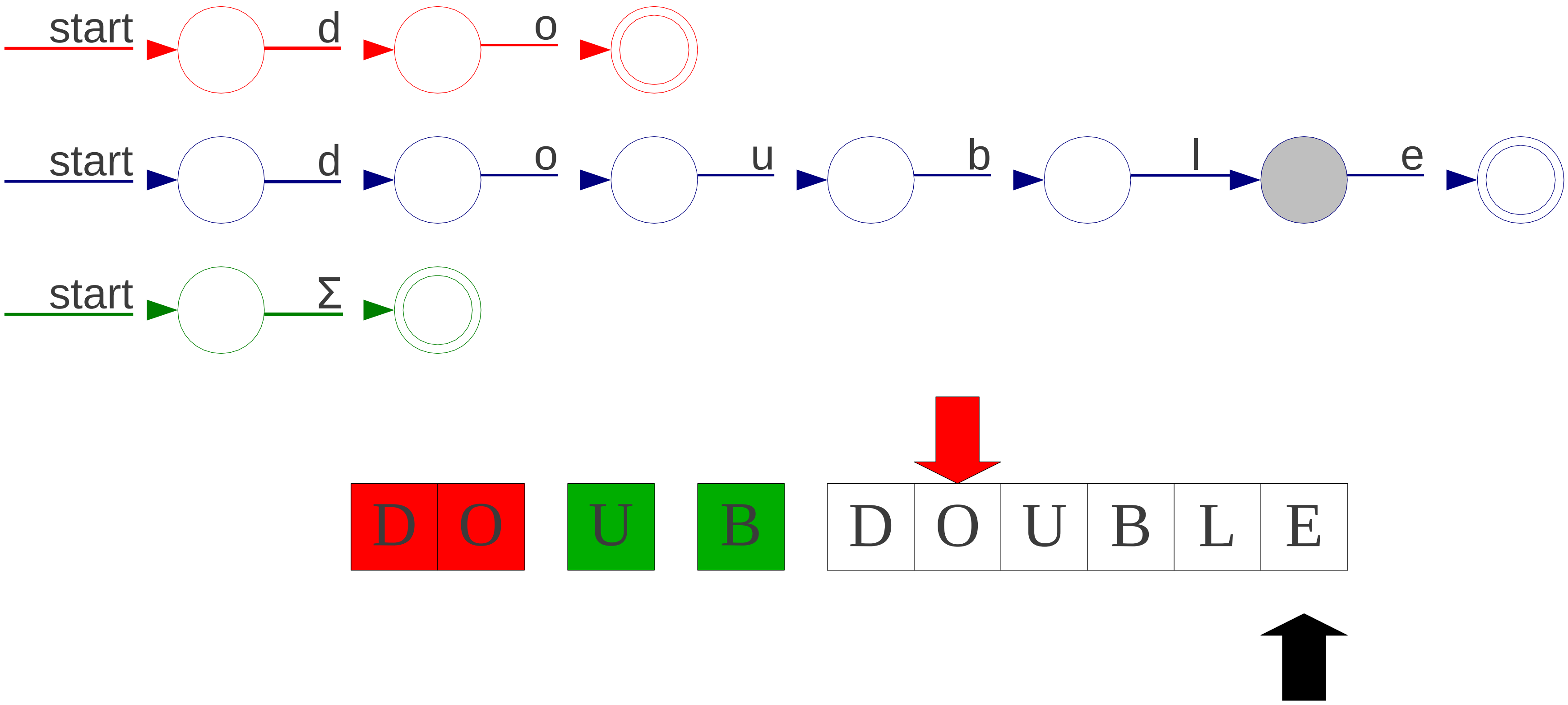
T_Do	do
T_Double	double
T_Mystery	[A-Za-z]





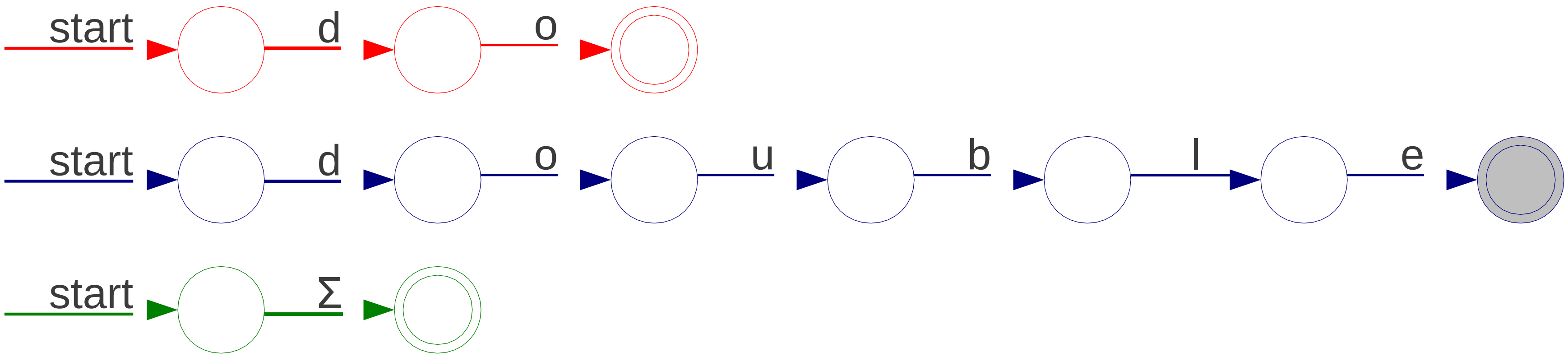
Implementing Maximal Munch

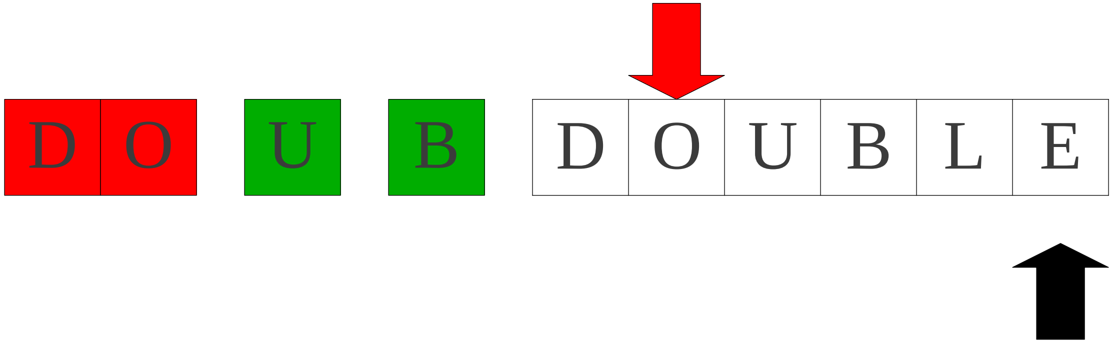
T_Do	do
T_Double	double
T_Mystery	[A-Za-z]



Implementing Maximal Munch

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

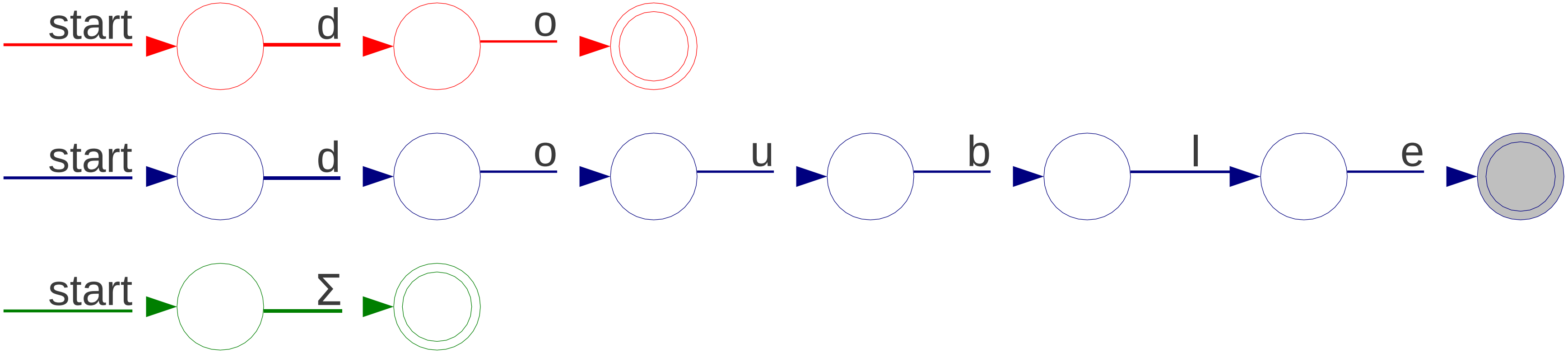


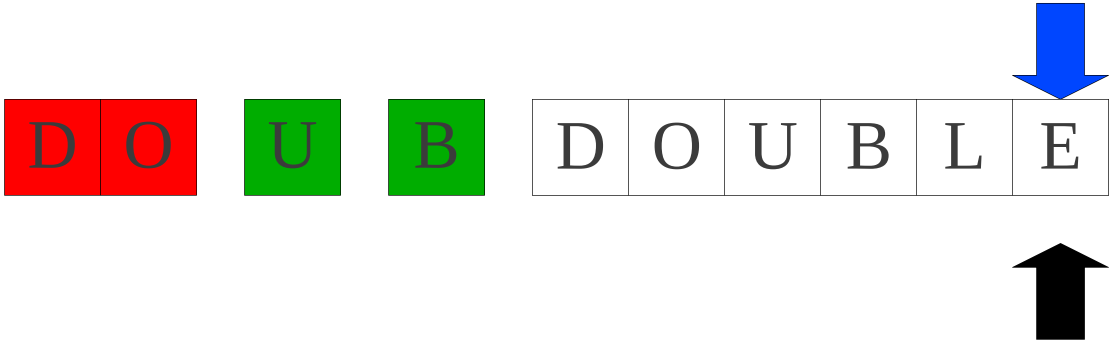


D O | U | B | D O U B L E

Implementing Maximal Munch

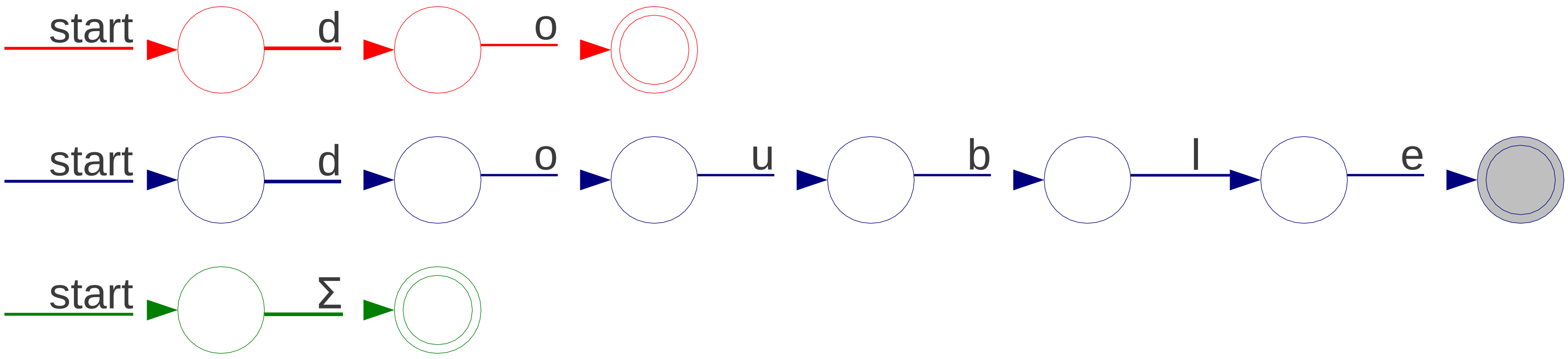
T_Do	do
T_Double	double
T_Mystery	[A-Za-z]

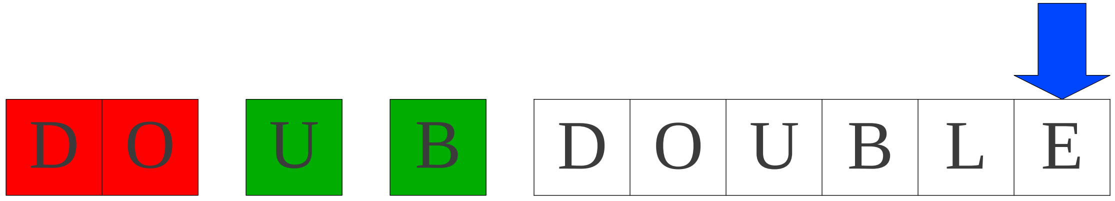



D O U B D O U B L E

Implementing Maximal Munch

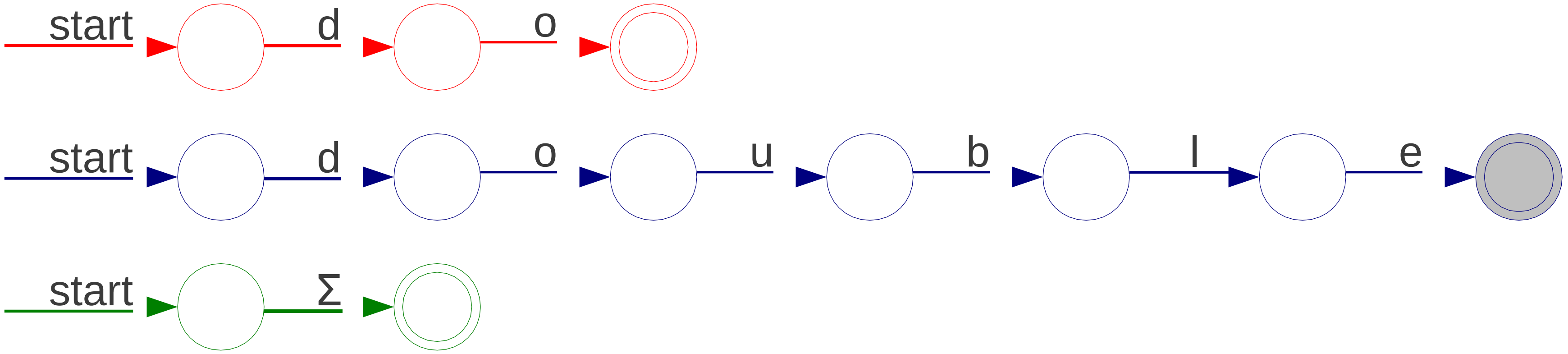
T_Do	do
T_Double	double
T_Mystery	[A-Za-z]

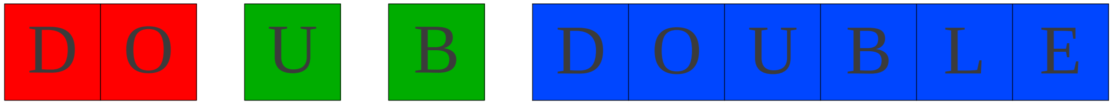




Implementing Maximal Munch

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

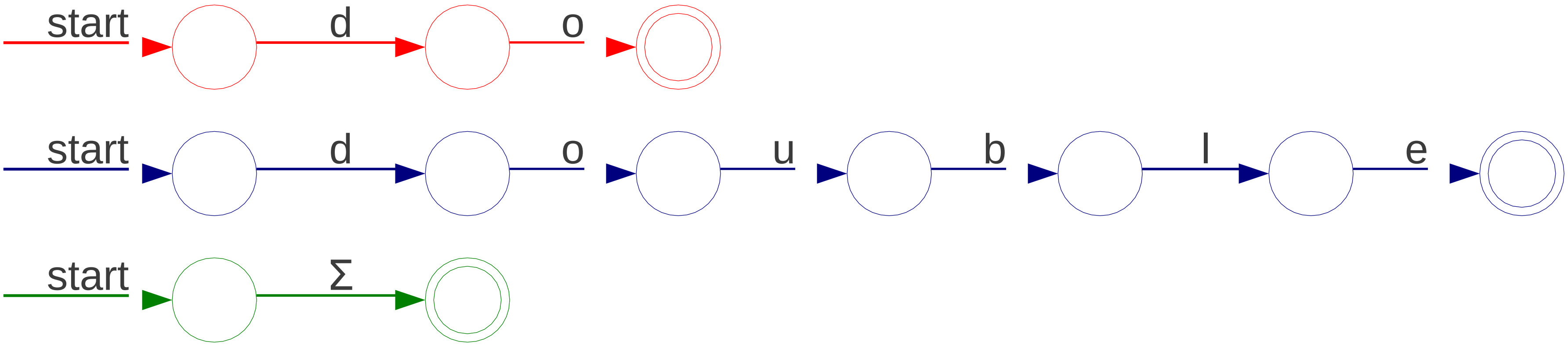




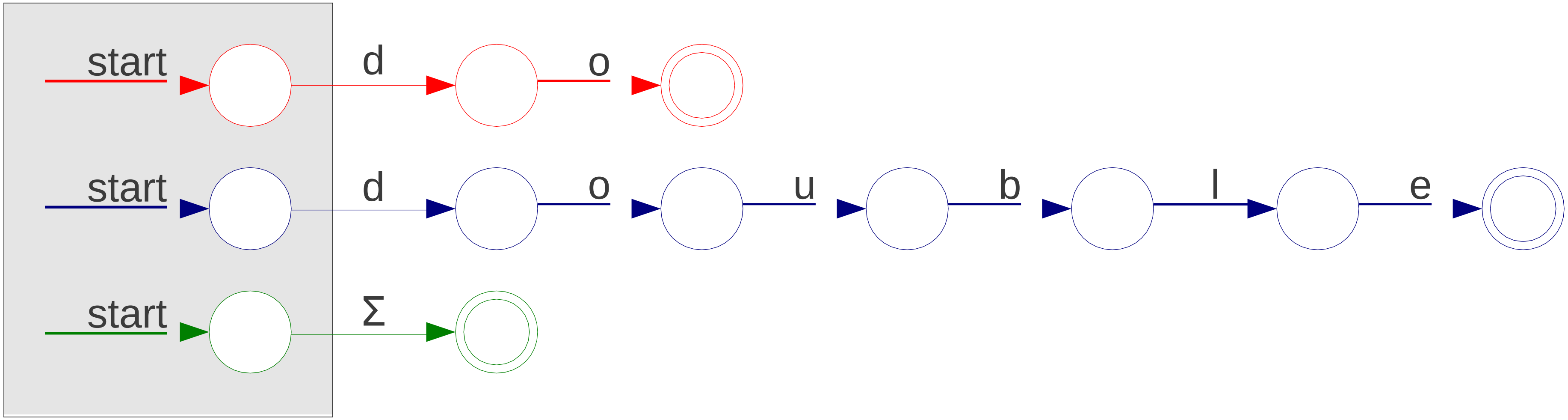
D	O	U	B	D	O	U	B	L	E

A Minor Simplification

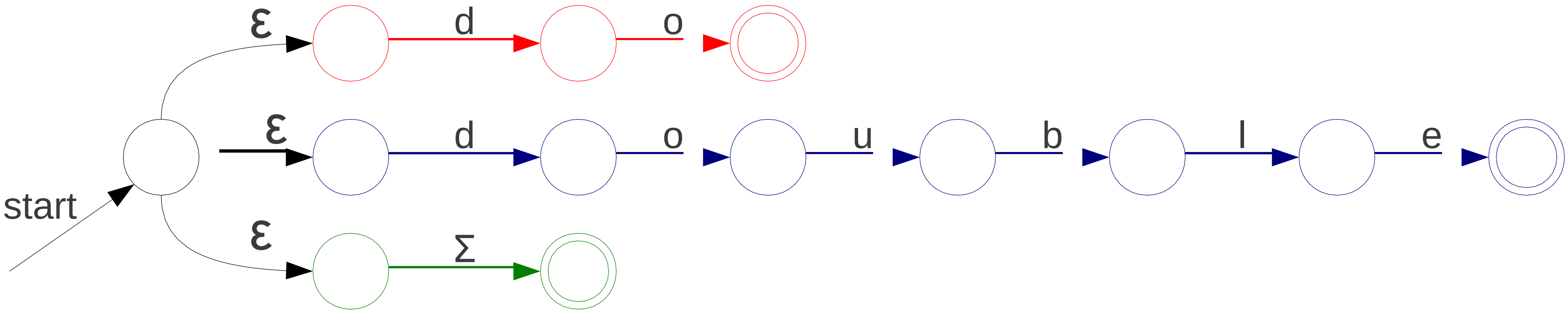
A Minor Simplification



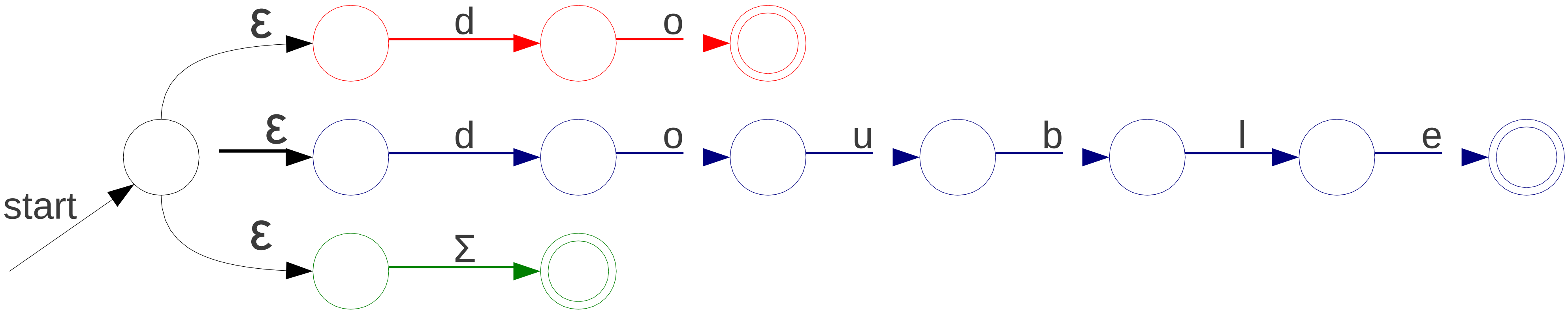
A Minor Simplification



A Minor Simplification

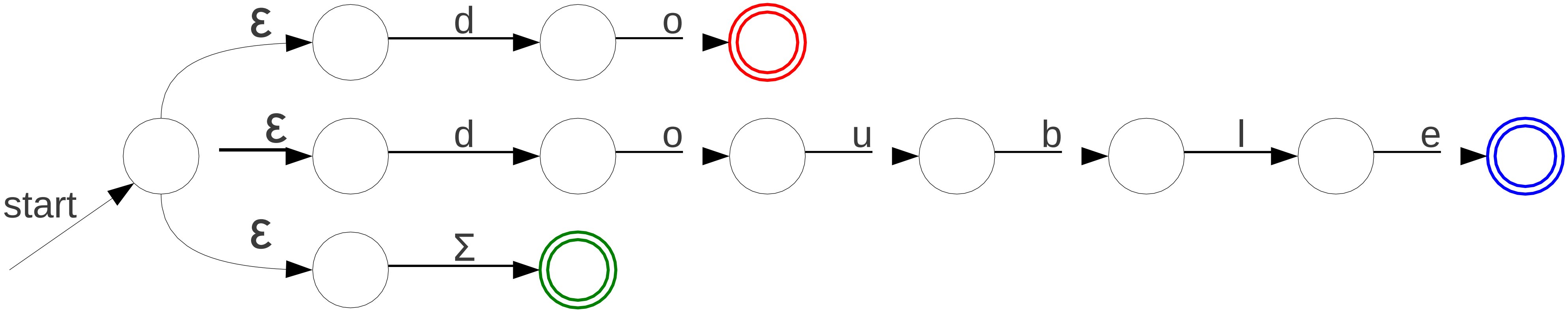


A Minor Simplification

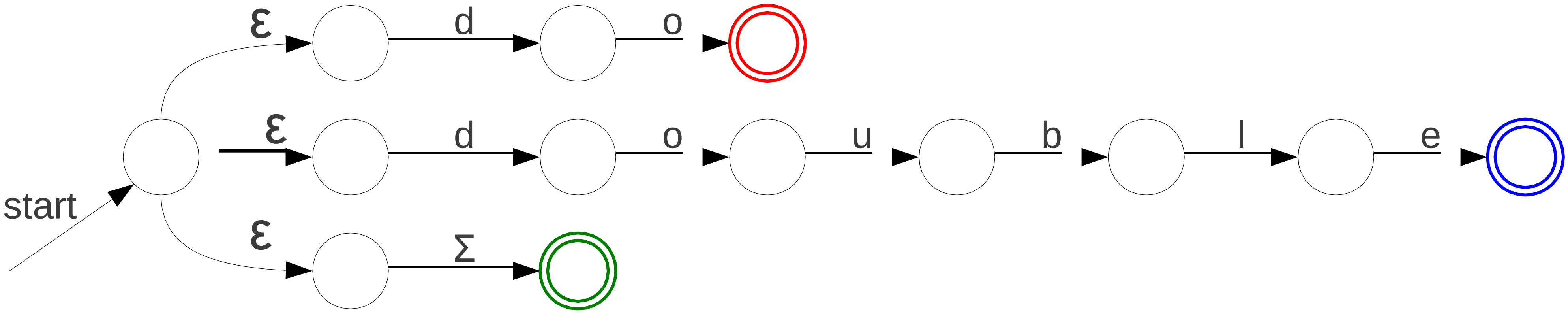


Build a single automaton that runs all the matching automata in parallel.

A Minor Simplification



A Minor Simplification



Annotate each accepting state with which automaton it came from.

Other Conflicts

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

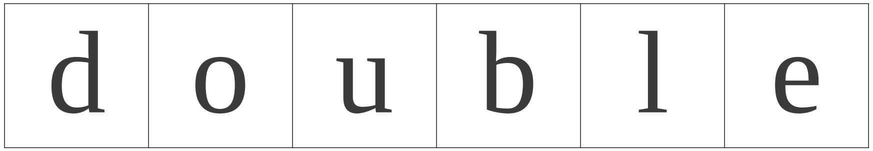
Other Conflicts

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

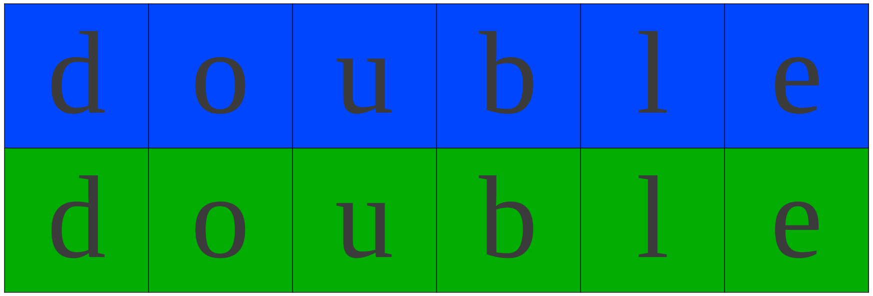
d	o	u	b	l	e

Other Conflicts

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



d	o	u	b	l	e



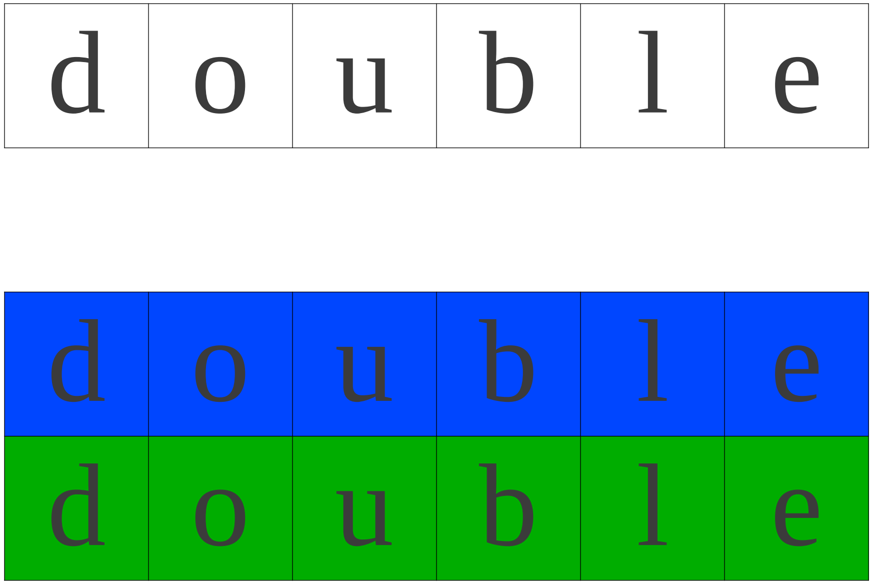
d	o	u	b	l	e
d	o	u	b	l	e

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_]*
```

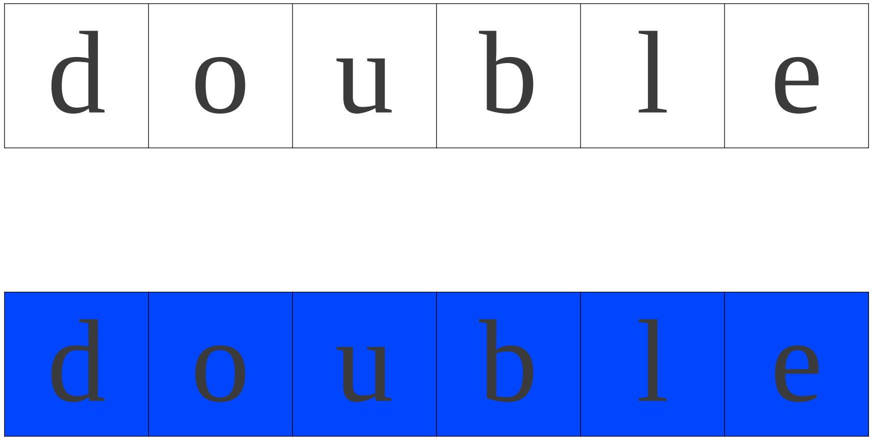


d	o	u	b	l	e

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_]*
```

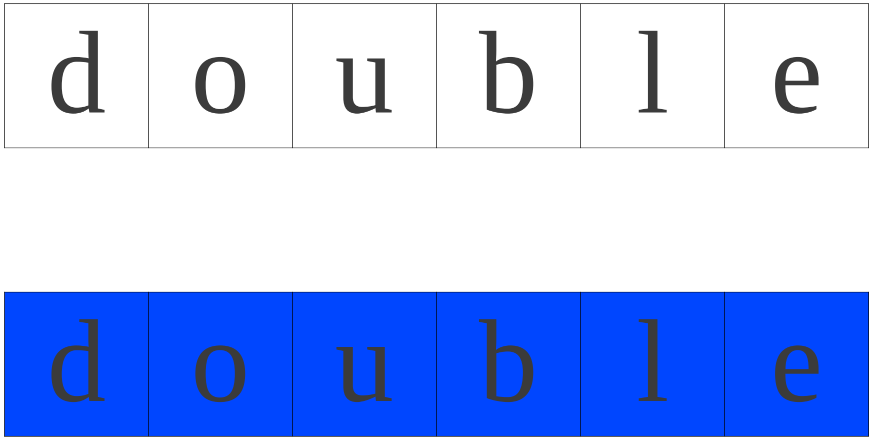


d	o	u	b	l	e

d	o	u	b	l	e

Other Conflicts

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



Why isn't this a problem?

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.

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.

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?

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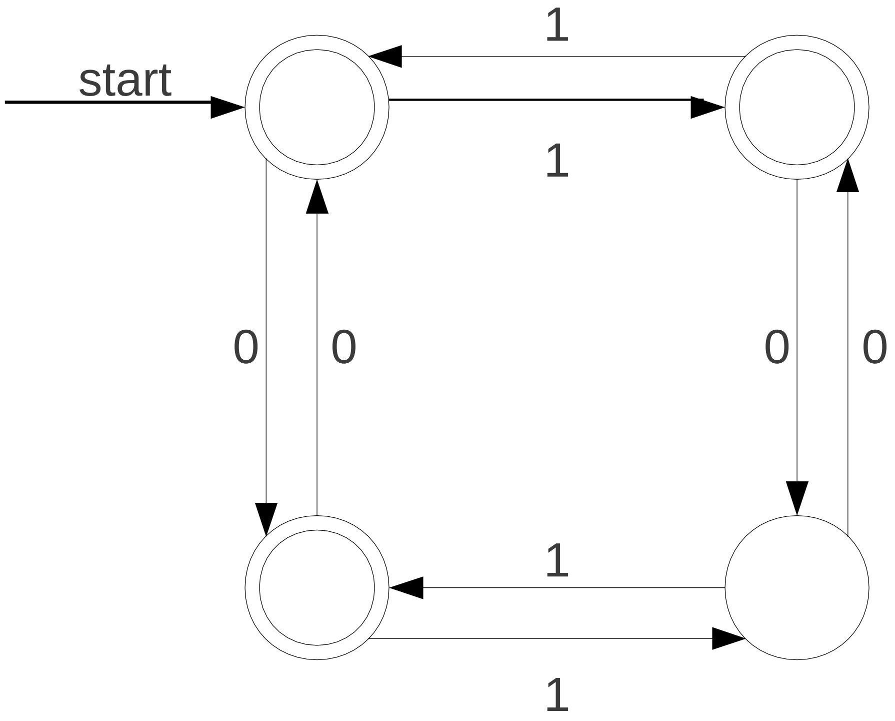
DFAs

- The automata we've seen so far have all been NFAs.
- 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.

A Sample DFA

A Sample DFA



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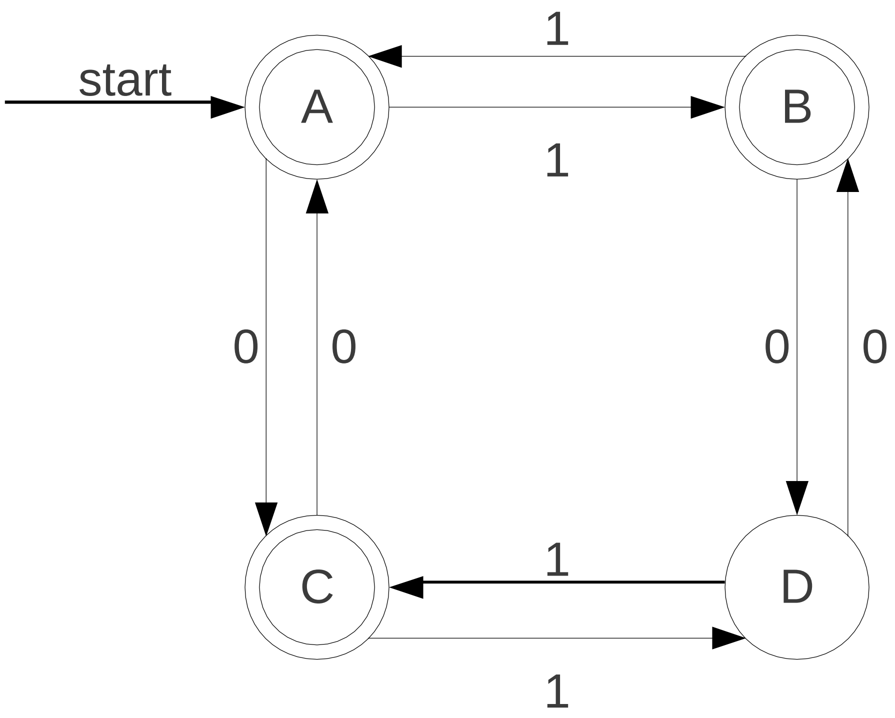

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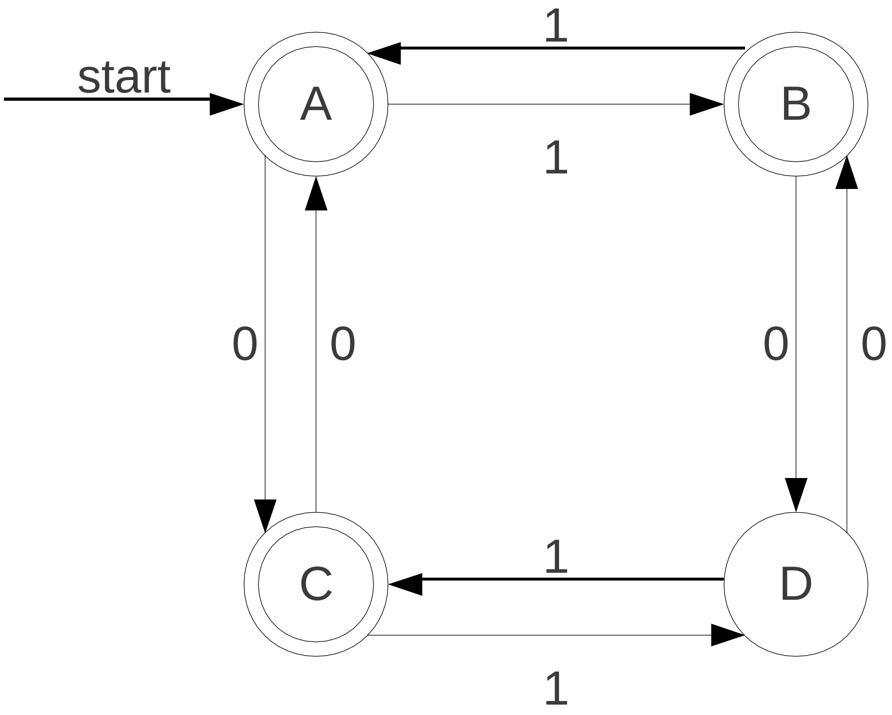

	0	1
A.	C	B
B.	D	A
C.	A	D
D.	B	C

Code for DFAs

```
int kTransitionTable[kNumStates][kNumSymbols] = {
     {0, 0, 1, 3, 7, 1, …},
      …
};
bool kAcceptTable[kNumStates] = {
    false,
    true,
    true,
    …
};
bool simulateDFA(string input) {
    int state = 0;
    for (char ch: input)
        state = kTransitionTable[state][ch];
    return kAcceptTable[state];
}
```

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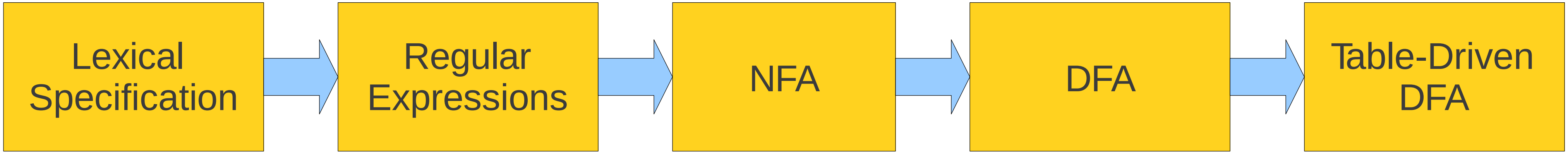
        state = kTransitionTable[state][ch];
    return kAcceptTable[state];
}
```

Runs in time O(m) on a string of length m.

Speeding up Matching

- In the worst-case, an NFA with n states takes time $O(mn^2)$ to match a string of length m.
- DFAs, on the other hand, take only $O(m)$.
- There is another (beautiful!) algorithm to convert NFAs to DFAs.

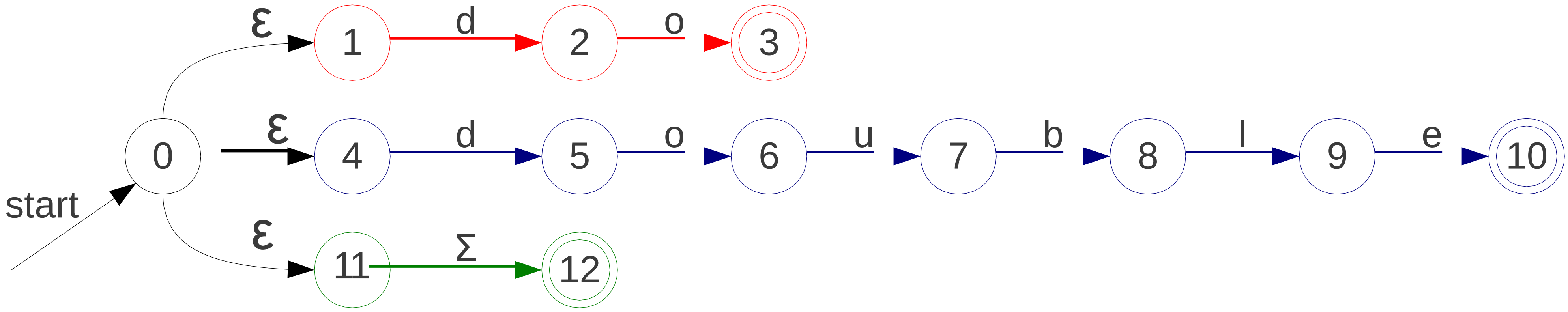


Subset Construction

- 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.

From NFA to DFA

From NFA to DFA



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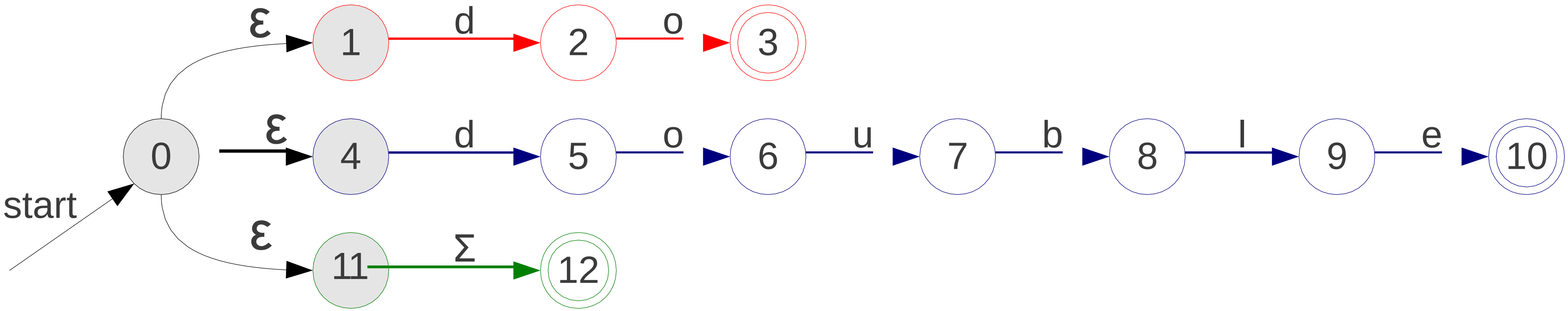

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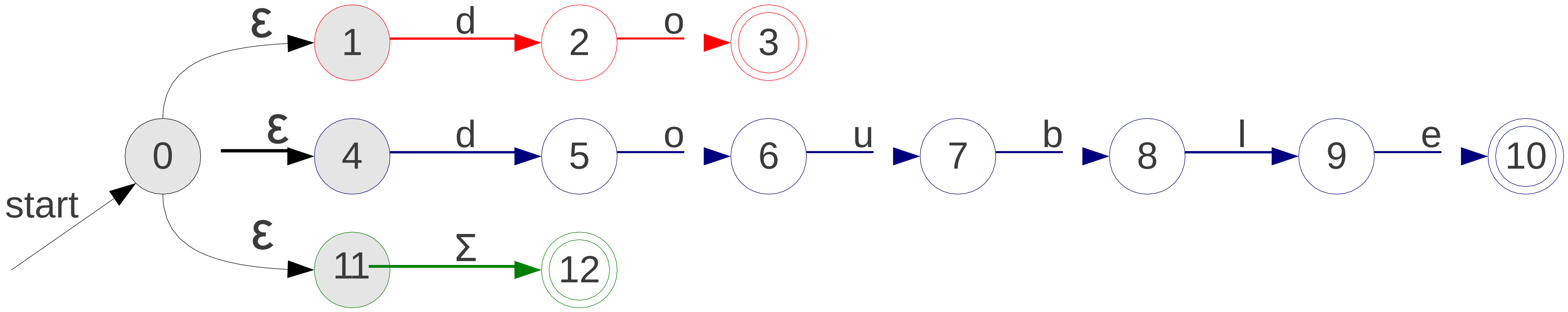

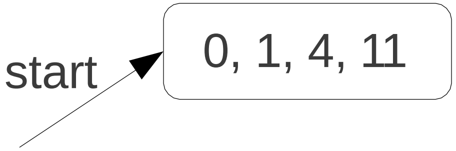

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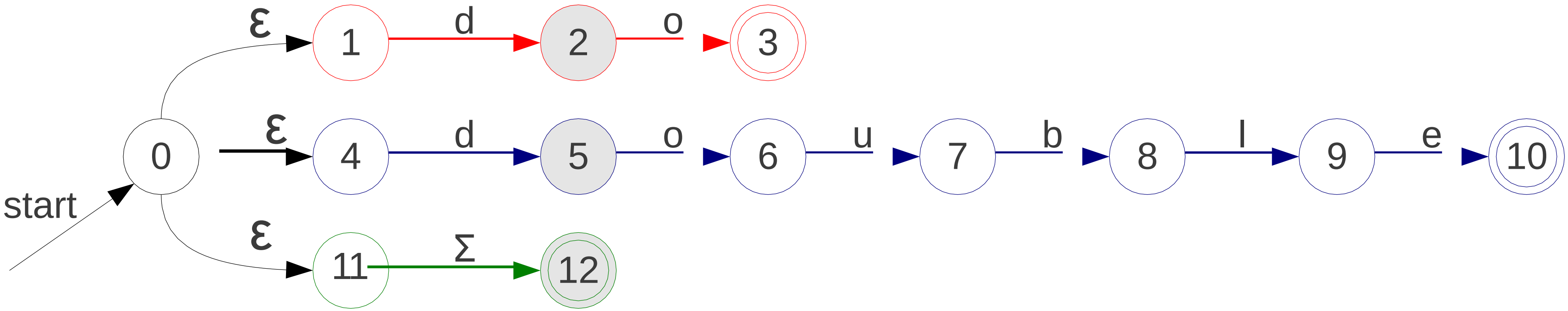

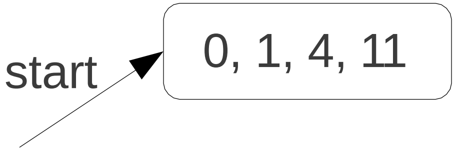

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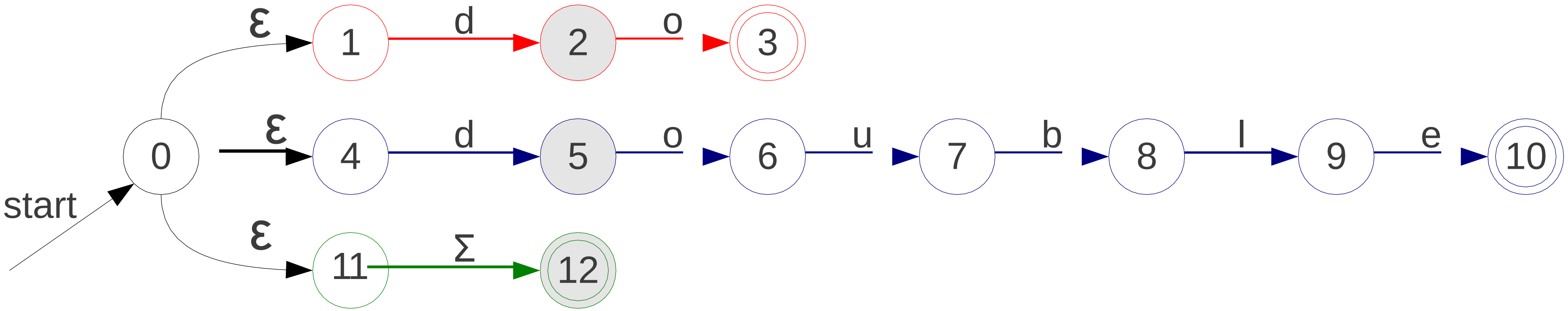

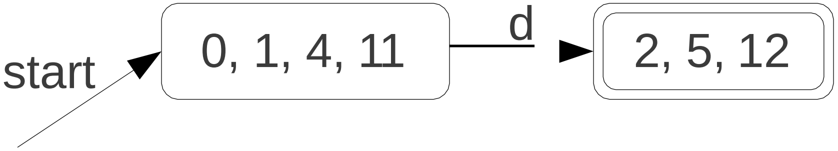

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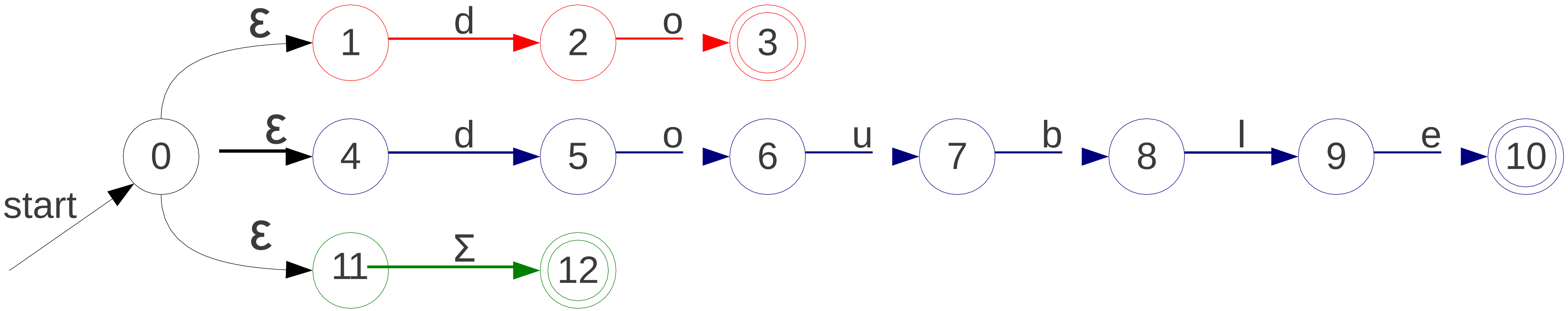

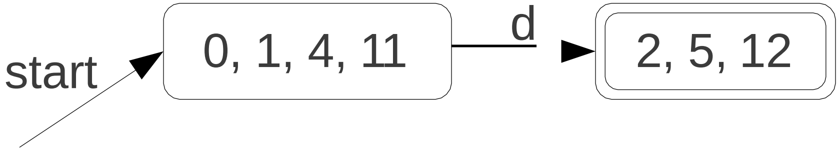

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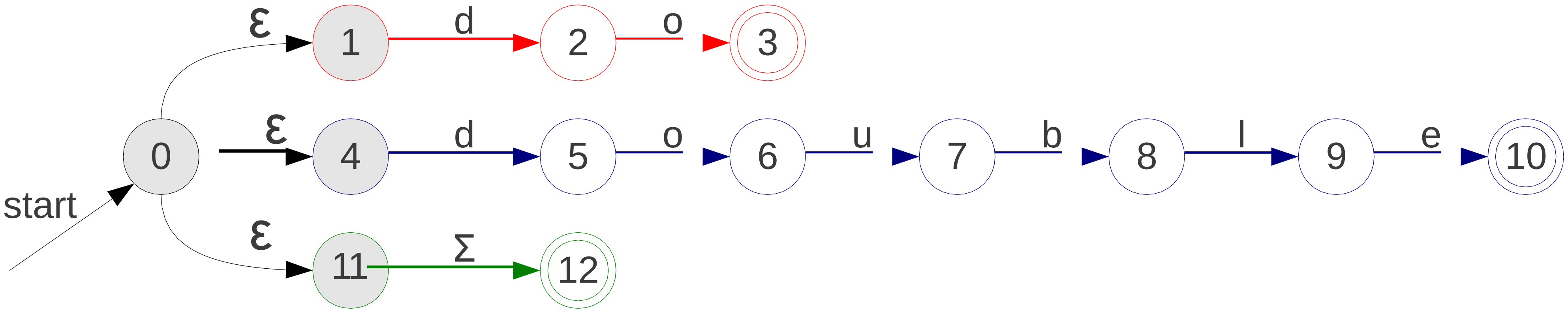

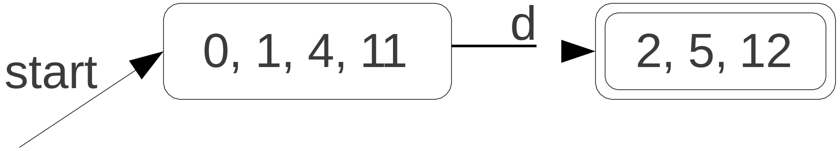

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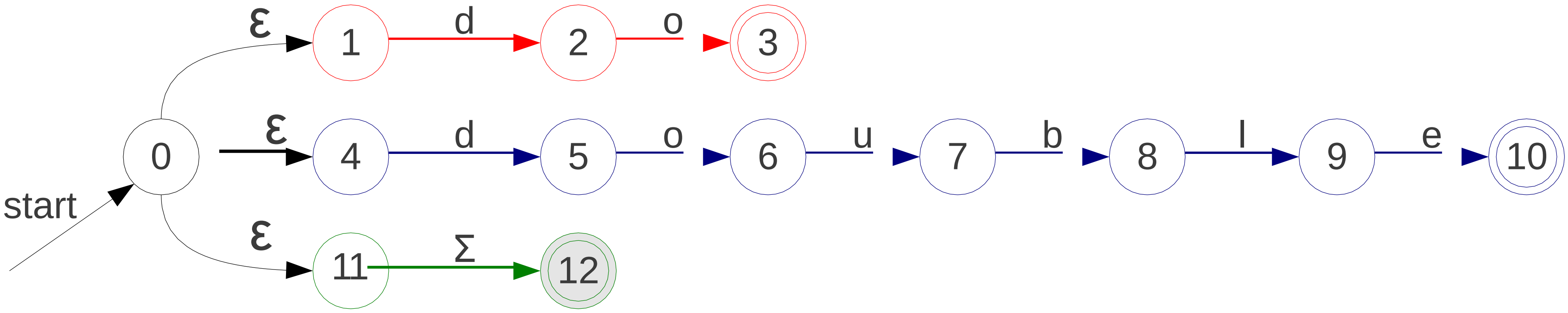

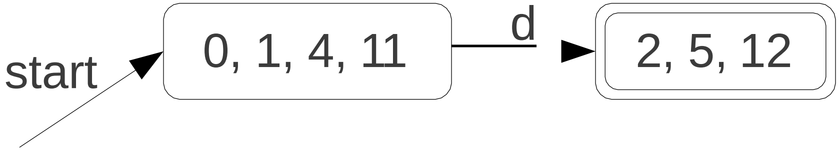

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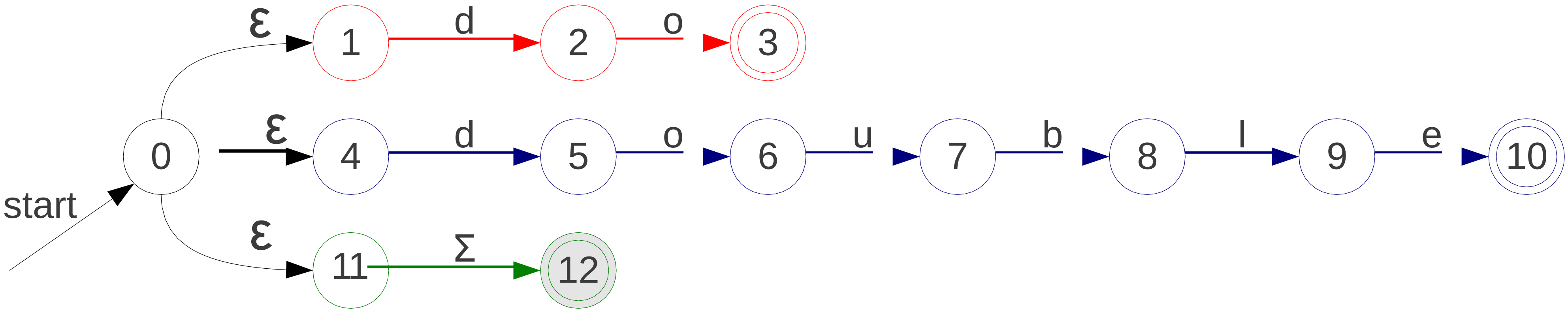

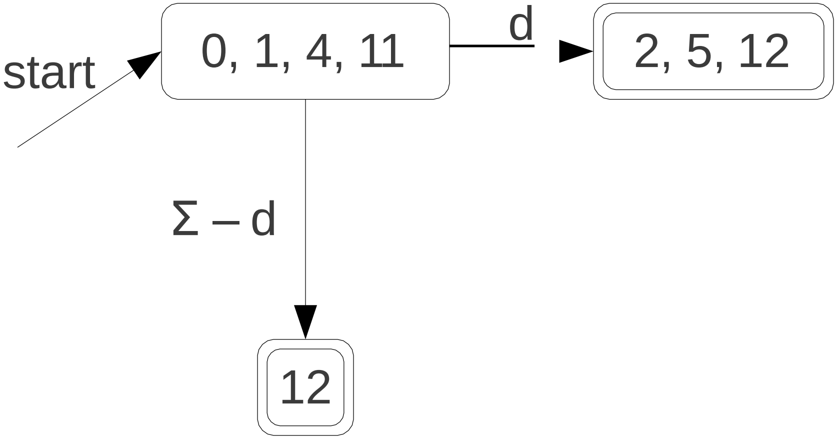

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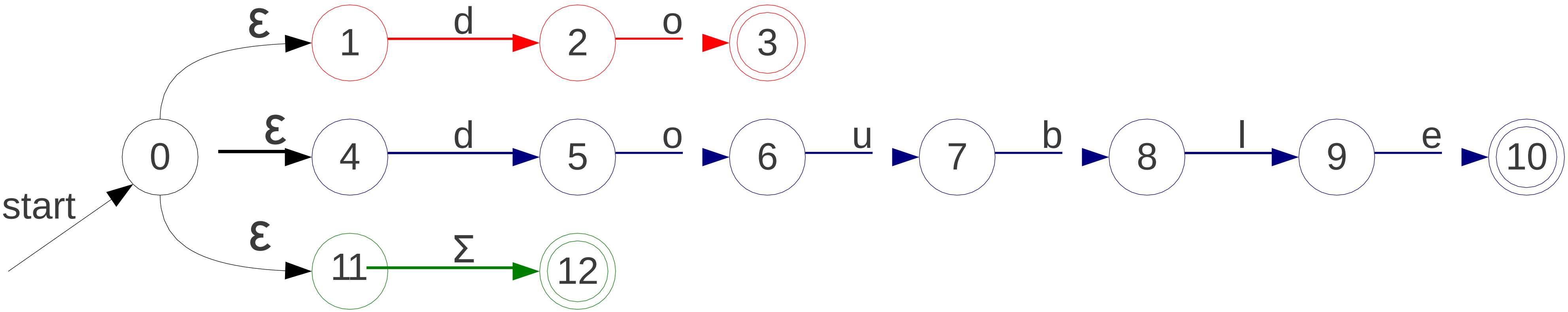

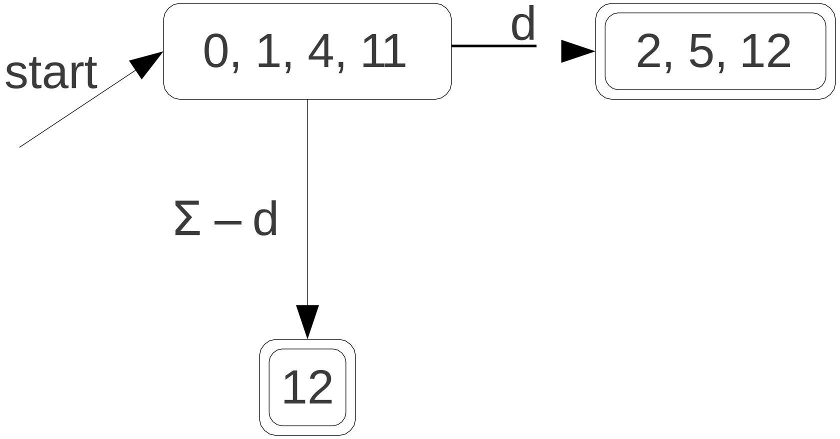

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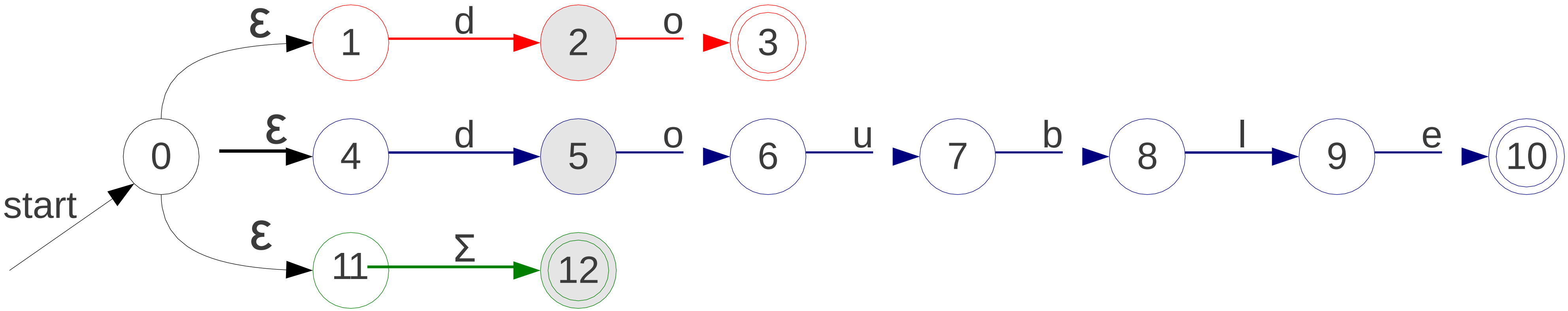

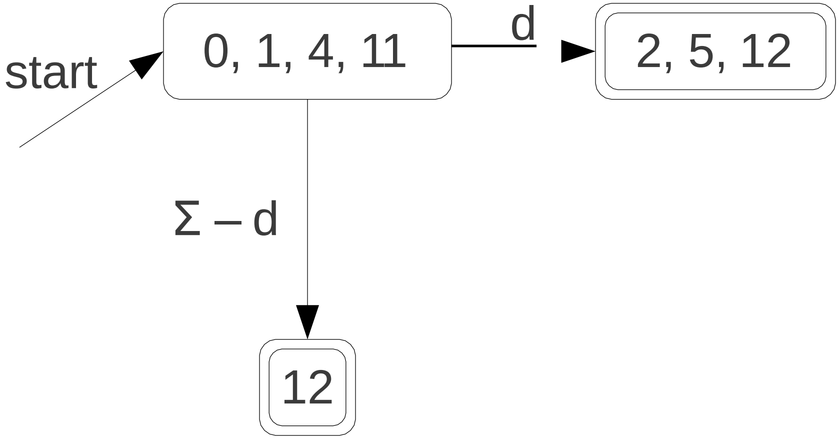

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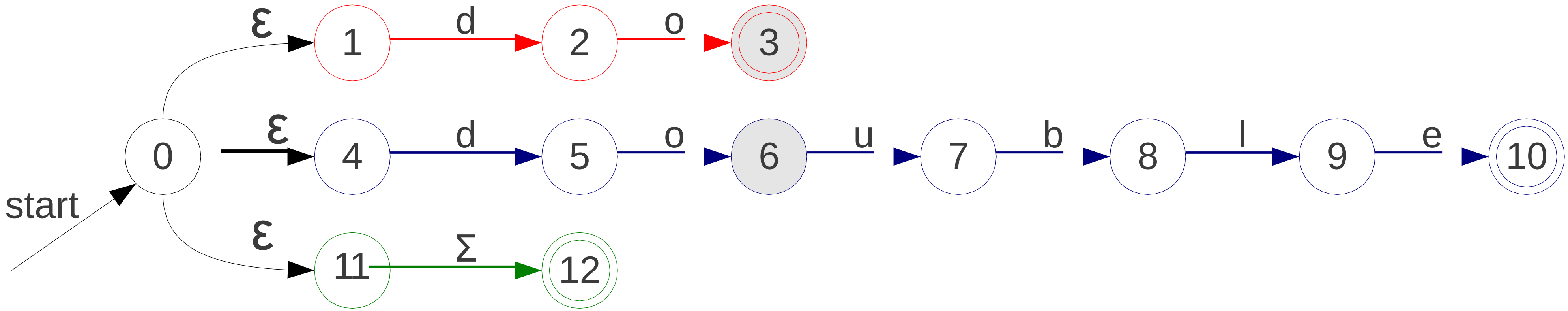

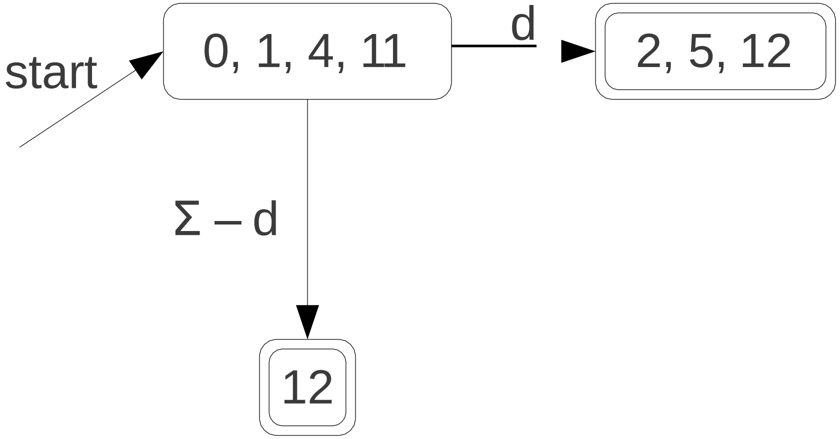

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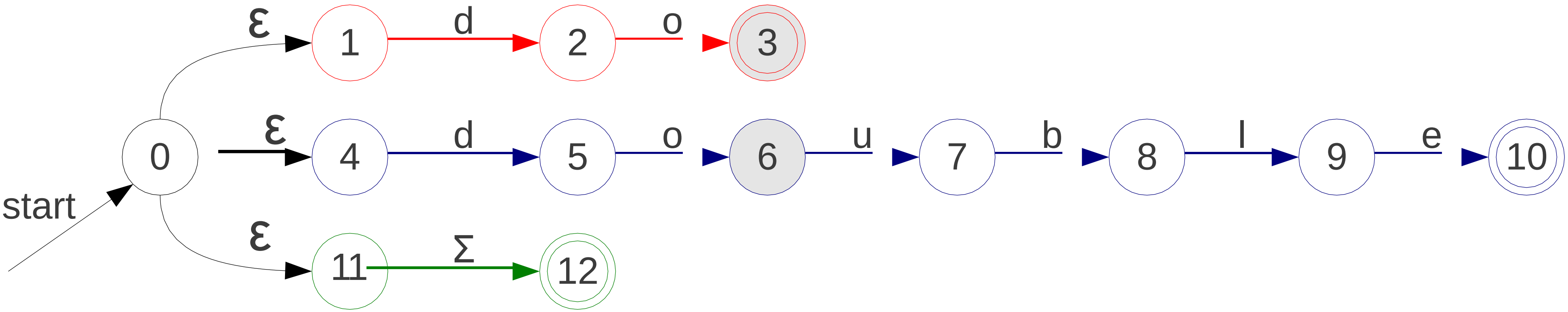

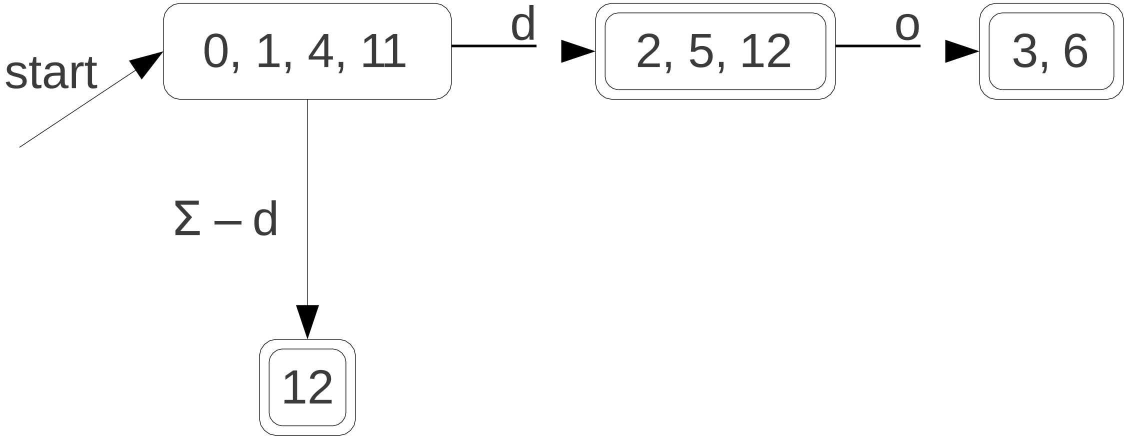

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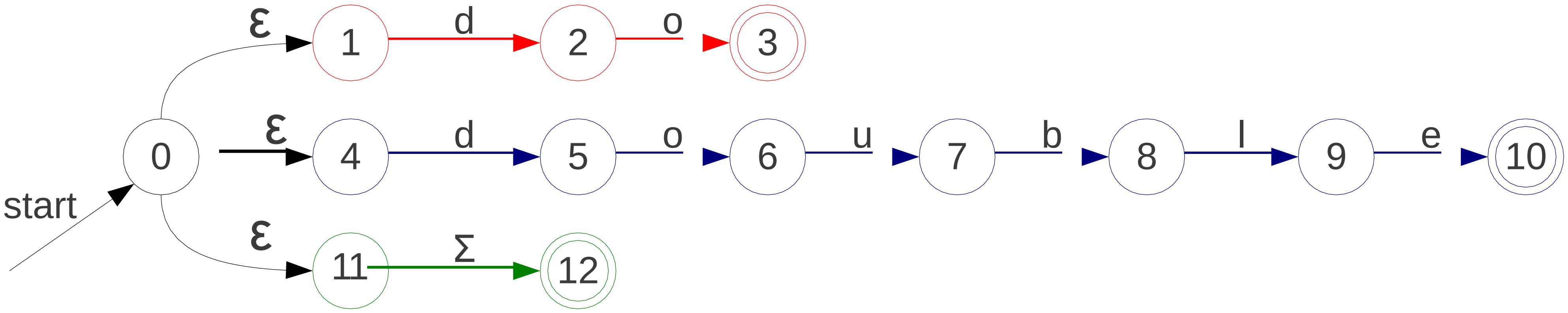

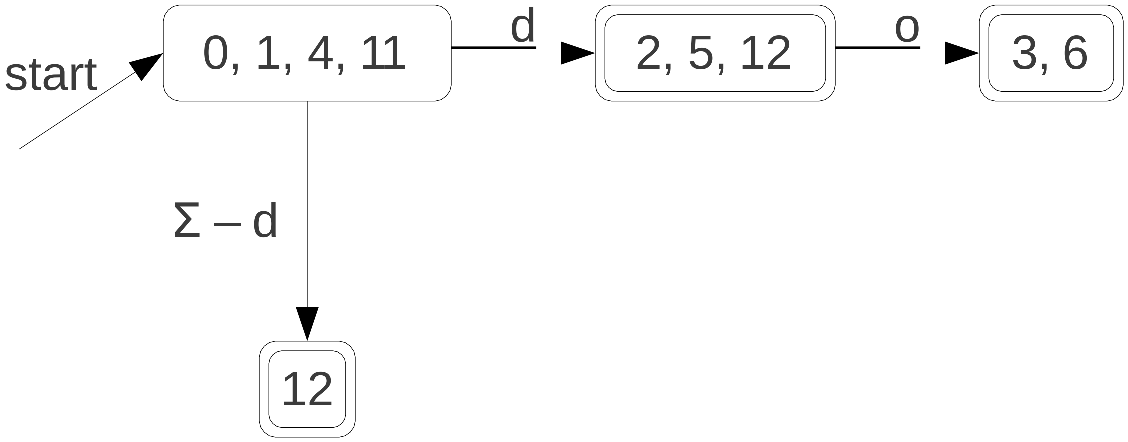

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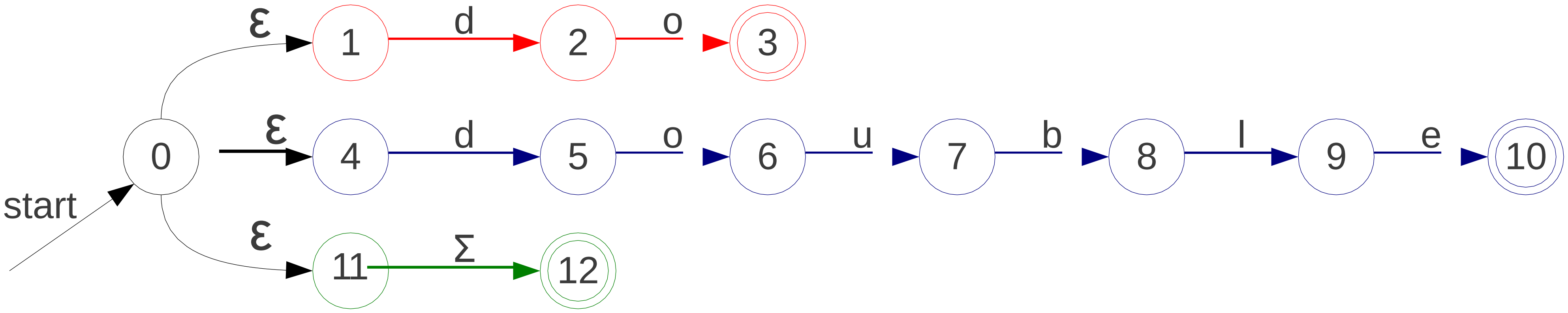

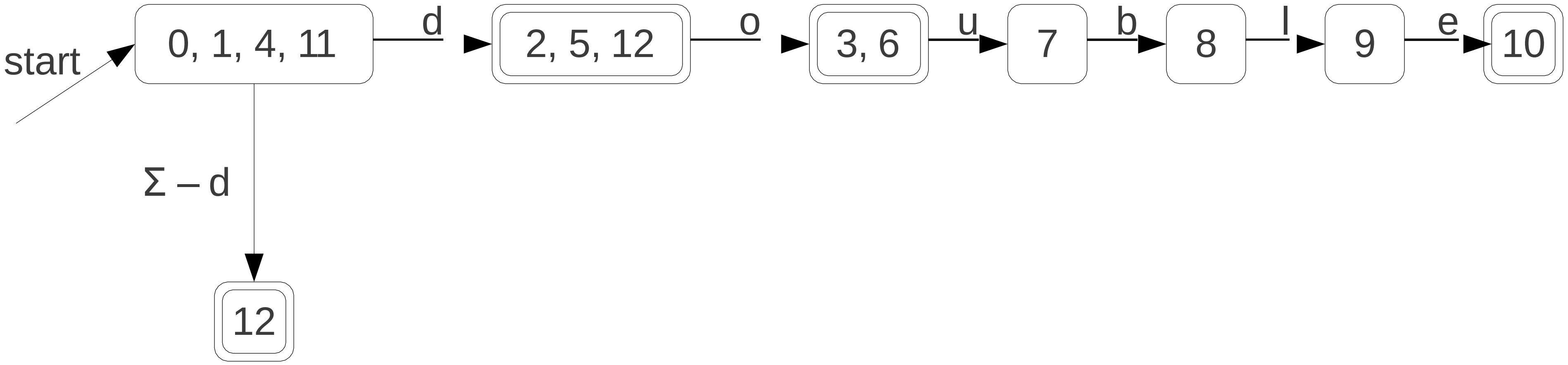

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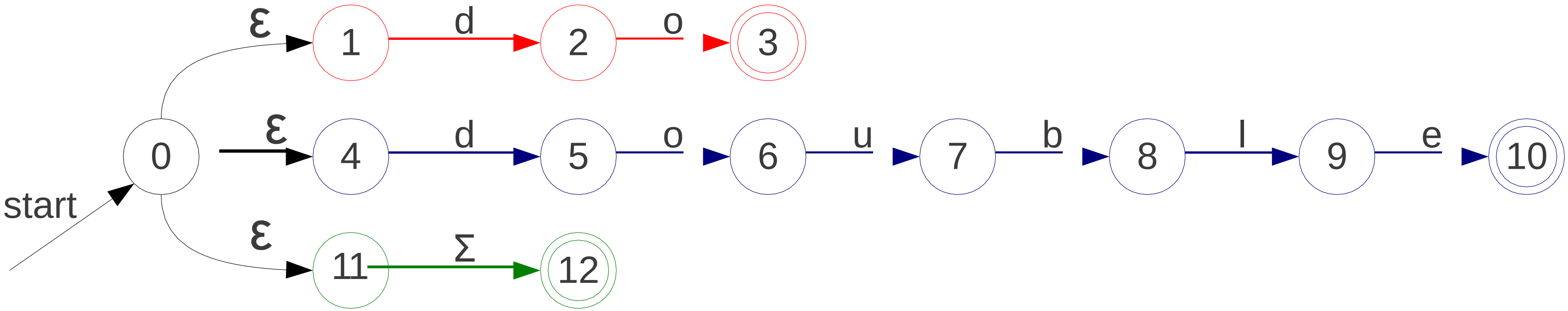

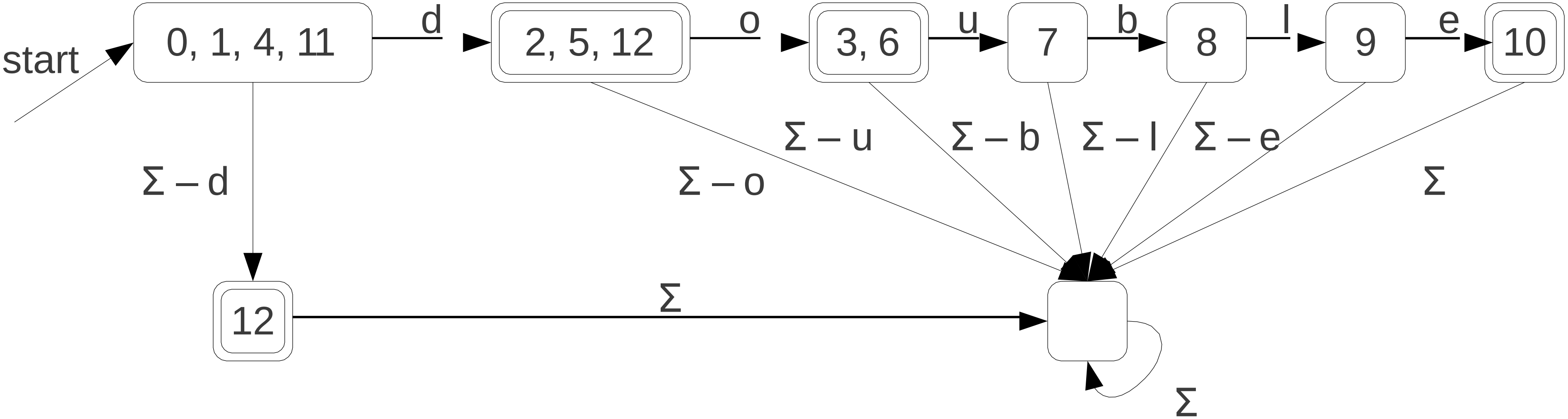

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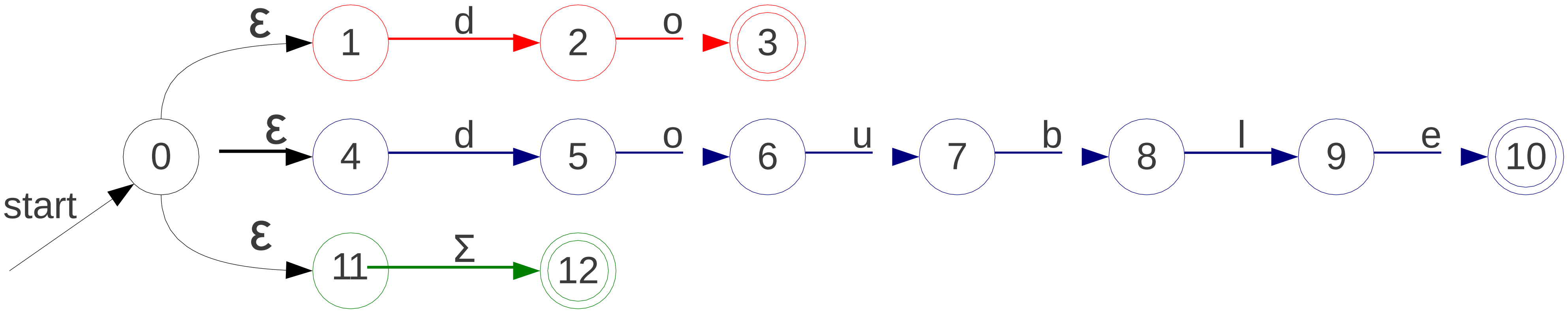
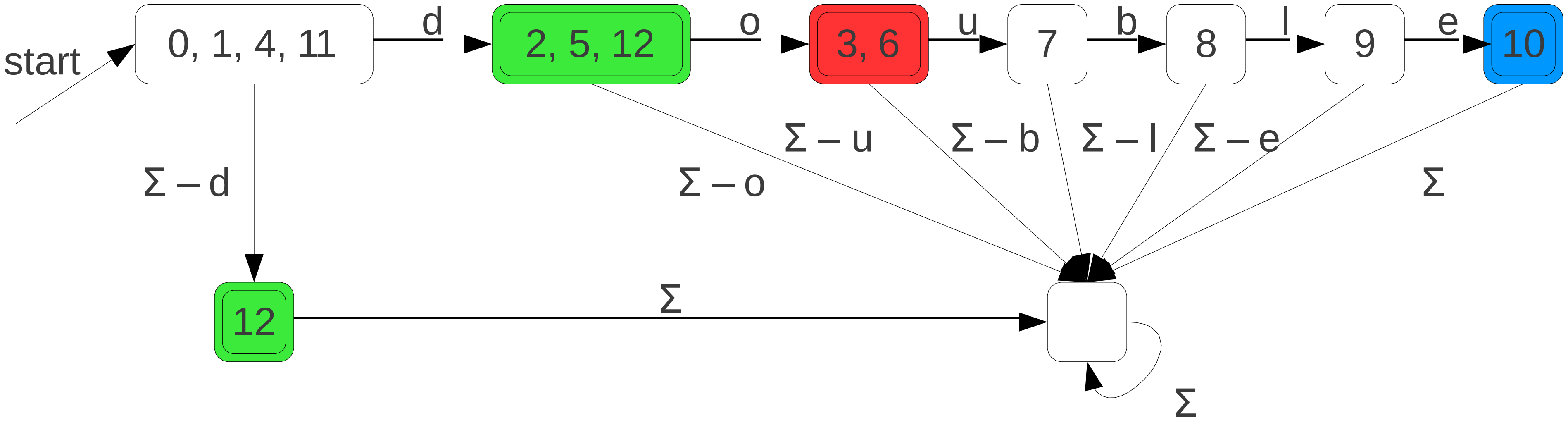




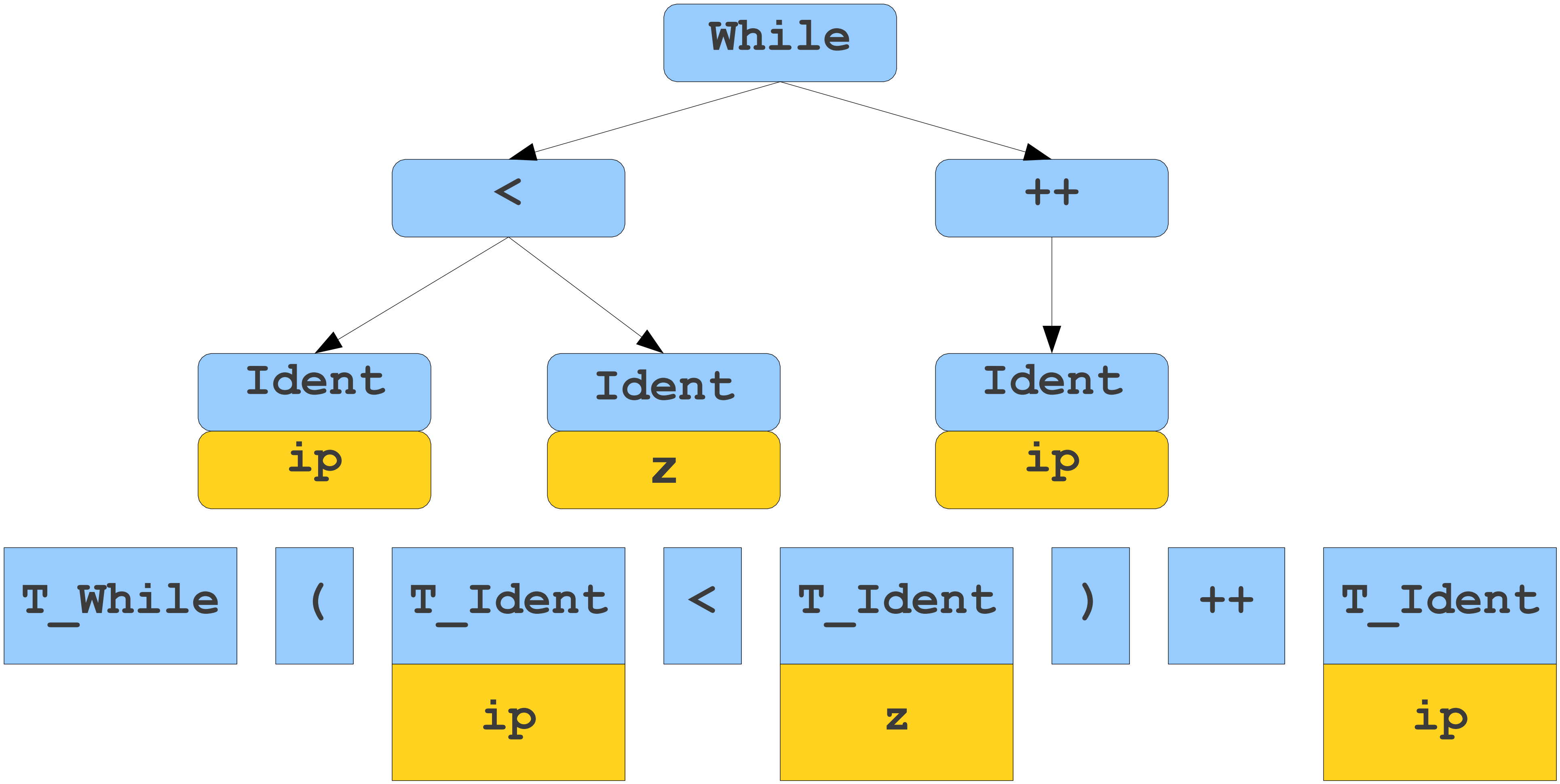
Modified Subset Construction

- Instead of marking whether a state is accepting, remember *which token type* it matches.
- Break ties with priorities.
- When using DFA as a scanner, consider the DFA “stuck” if it enters the state corresponding to the empty set.

Performance Concerns

- The NFA-to-DFA construction can introduce *exponentially* many states.
- Time/memory tradeoff:
  - Low-memory NFA has higher scan time.
  - High-memory DFA has lower scan time.
- Could use a hybrid approach by simplifying NFA before generating code.

Real-World Scanning: **Python**



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

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

Python Blocks

- Scoping handled by whitespace:

```
if w == z:
    a = b
    c = d
else:
    e = f
g = h
```

- What does that mean for the scanner?

Whitespace Tokens

- Special tokens inserted to indicate changes in levels of indentation.
- **NEWLINE** marks the end of a line.
- **INDENT** indicates an increase in indentation.
- **DEDENT** indicates a decrease in indentation.
- Note that INDENT and DEDENT encode *change* in indentation, not the total amount of indentation.

Scanning Python

```
if w == z:
    a = b
    c = d
else:
    e = f
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```

Scanning Python

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if w == z:
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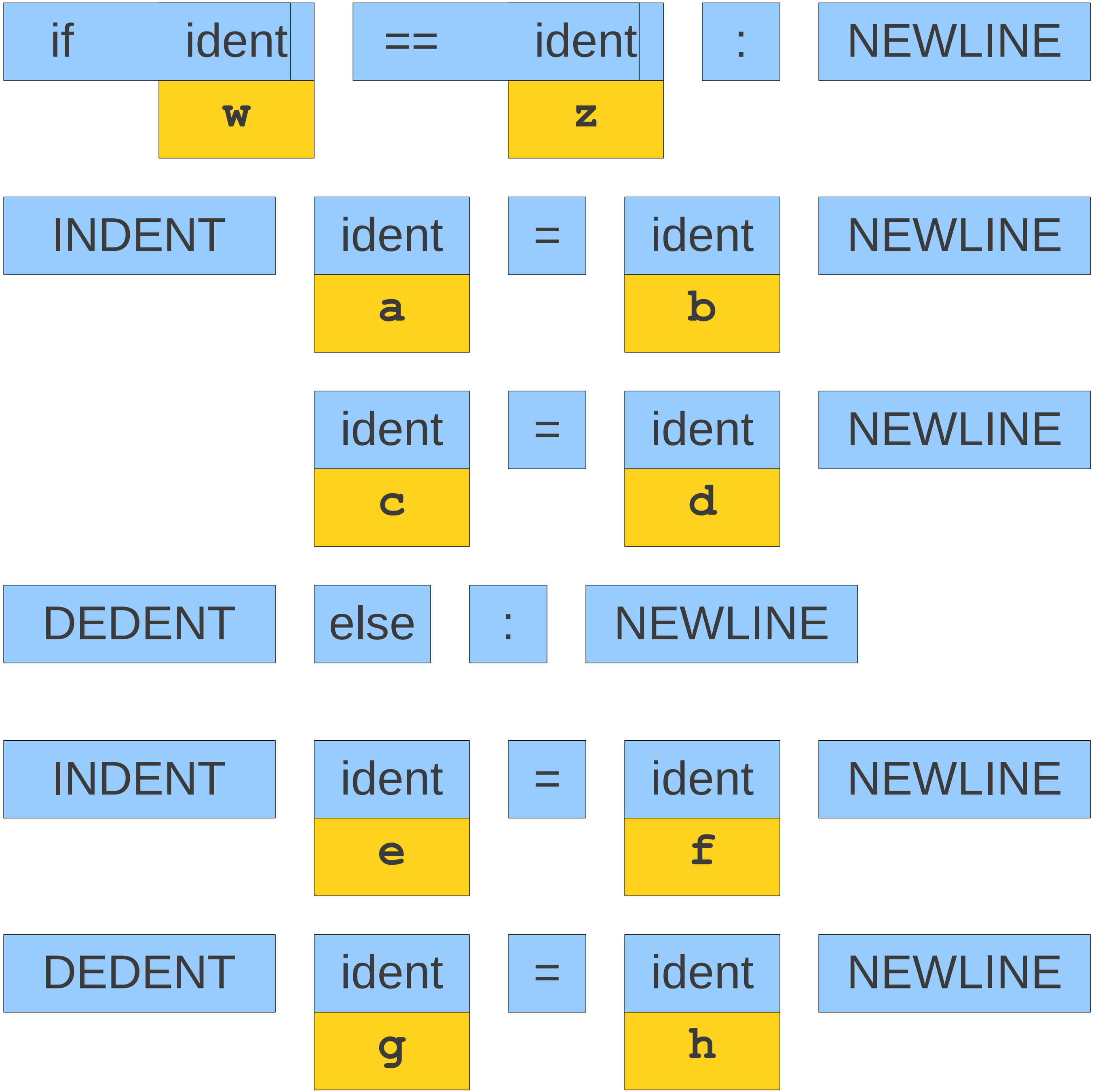


if ident w == ident z : NEWLINE

INDENT ident a = ident b NEWLINE

ident c = ident d NEWLINE

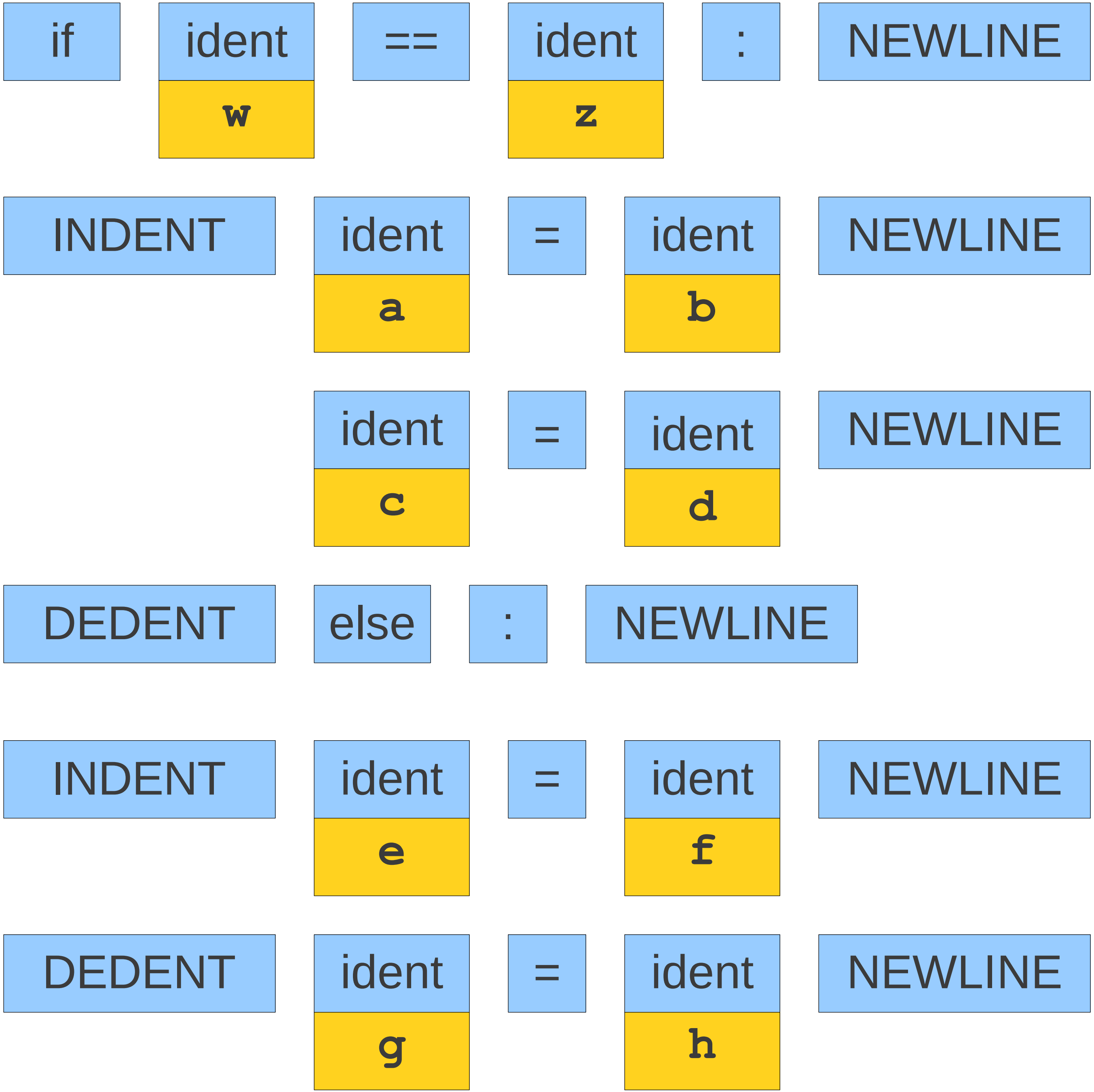
DEDENT else : NEWLINE

INDENT ident e = ident f NEWLINE

DEDENT ident g = ident h NEWLINE

Scanning Python

```
if w == z: {
    a = b;
    c = d;
} else {
    e = f;
}
g = h;
```



if | ident w | == | ident z | : | NEWLINE

INDENT | ident a | = | ident b | NEWLINE

ident c | = | ident d | NEWLINE

DEDENT | else | : | NEWLINE

INDENT | ident e | = | ident f | NEWLINE

DEDENT | ident g | = | ident h | NEWLINE

Scanning Python

```
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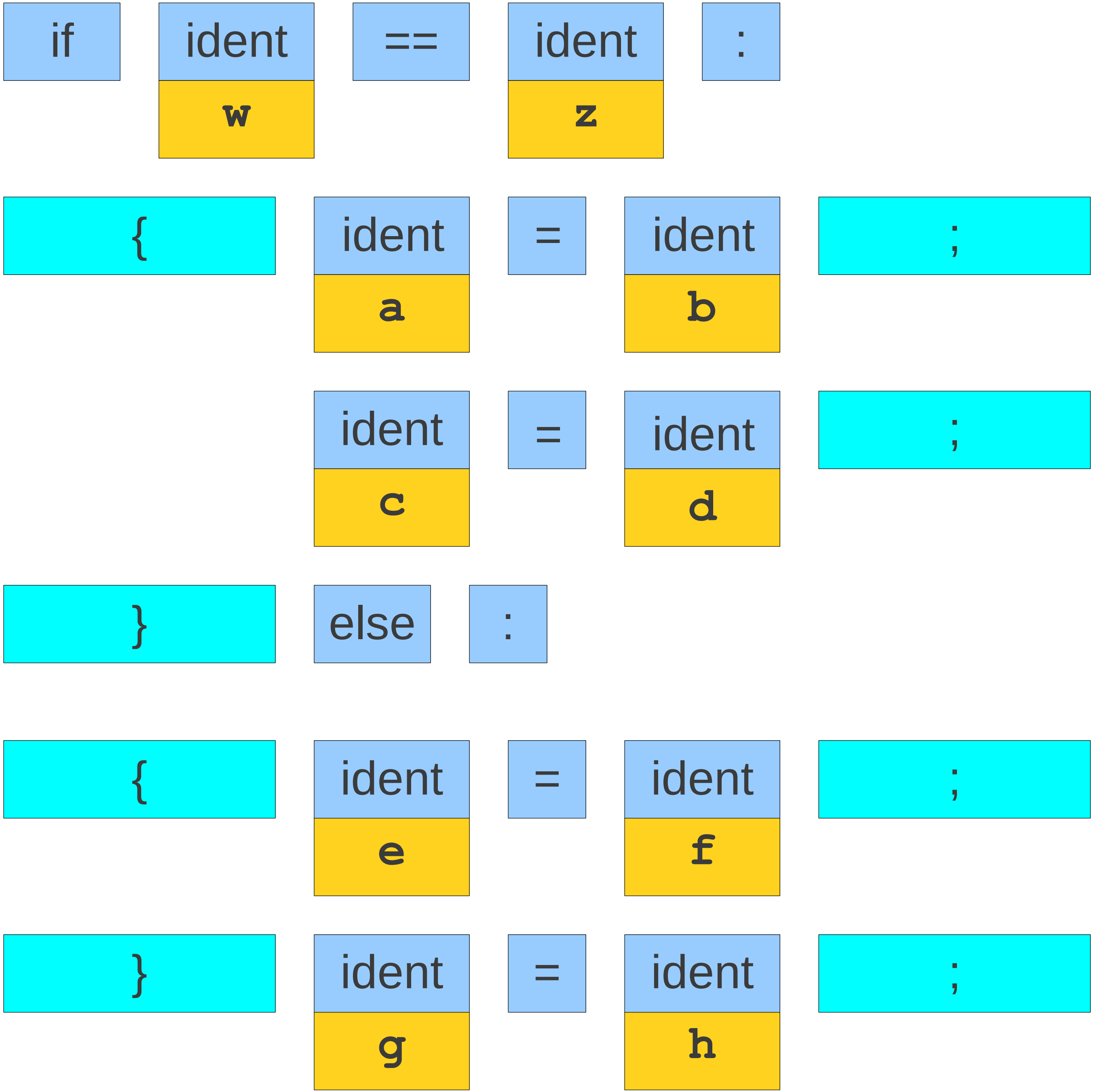


if ident w == ident z :

{ ident a = ident b ;

ident c = ident d ;

} else :

{ ident e = ident f ;

} ident g = ident h ;

Where to INDENT/DEDENT?

- Scanner maintains a stack of line indentations keeping track of all indented contexts so far.
- Initially, this stack contains 0, since initially the contents of the file aren't indented.
- On a newline:
  - See how much whitespace is at the start of the line.
  - If this value exceeds the top of the stack:
    - Push the value onto the stack.
    - Emit an INDENT token.
  - Otherwise, while the value is less than the top of the stack:
    - Pop the stack.
    - Emit a DEDENT token.

Source: http://docs.python.org/reference/lexical_analysis.html

Interesting Observation

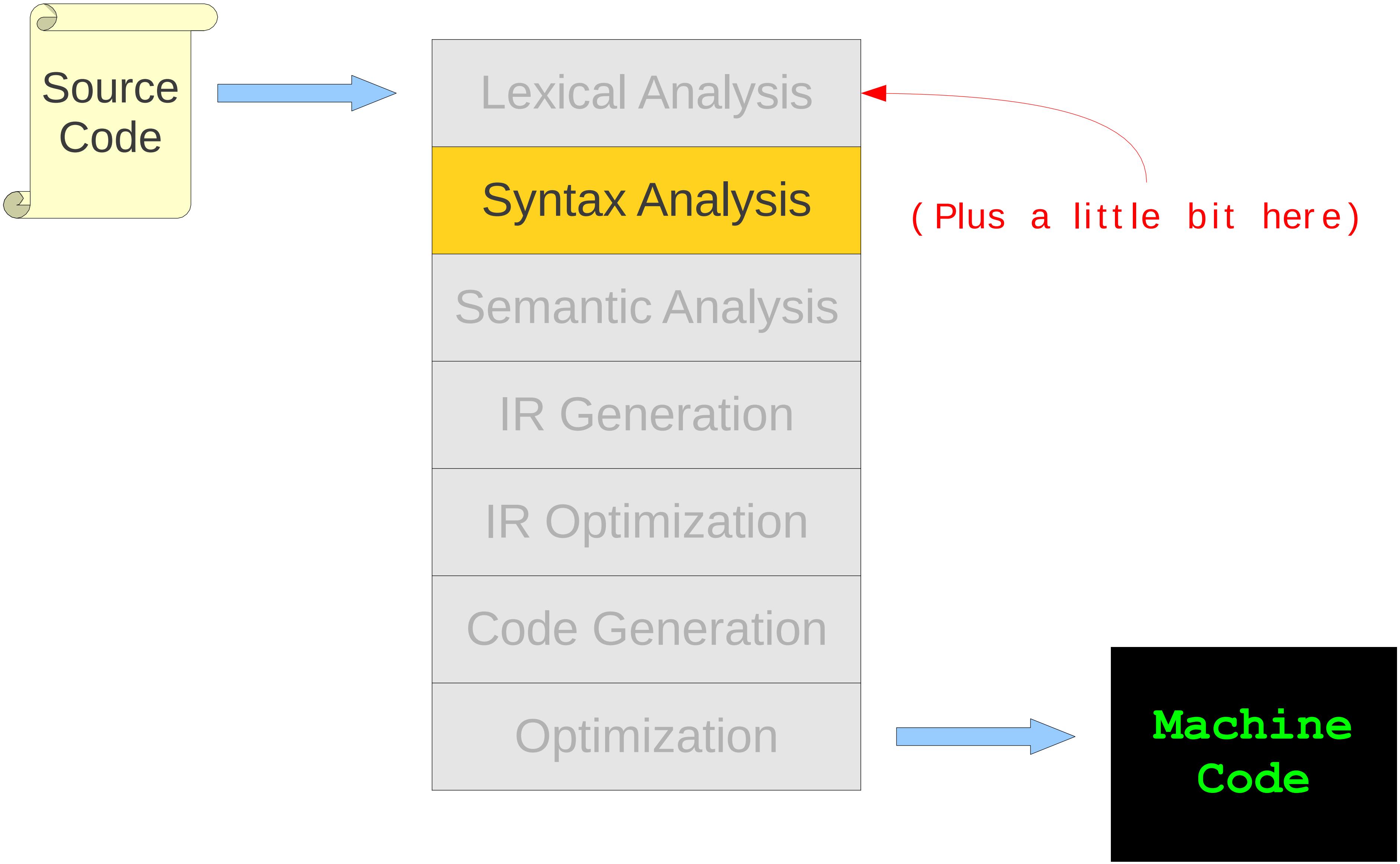
- Normally, more text on a line translates into more tokens.
- With DEDENT, *less* text on a line often means more tokens:

```
if cond1:
    if cond2:
        if cond3:
            if cond4:
                if cond5:
                    statement1
statement2
```

Summary

- Lexical analysis splits input text into **tokens** holding a **lexeme** and an **attribute**.
- Lexemes are sets of strings often defined with **regular expressions**.
- Regular expressions can be converted to **NFAs** and from there to **DFAs**.
- **Maximal-munch** using an automaton allows for fast scanning.
- Not all tokens come directly from the source code.

Next Time



Source Code

Lexical Analysis

Syntax Analysis

Semantic Analysis

IR Generation

IR Optimization

Code Generation

Optimization

(Plus a little bit here)

Machine Code